

STAINLESS
- stainless steels and their properties

by
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Introduction

Iron and the most common iron alloy, steel, are from a corrosion viewpoint relatively poor materials since they rust in air, corrode in acids and scale in furnace atmospheres. In spite of this there is a group of iron-base alloys, the iron-chromium-nickel alloys known as *stainless steels*, which do not rust in sea water, are resistant to concentrated acids and which do not scale at temperatures up to 1100°C.

It is this largely unique universal usefulness, in combination with good mechanical properties and manufacturing characteristics, which gives the stainless steels their *raison d'être* and makes them an indispensable tool for the designer. The usage of stainless steel is small compared with that of carbon steels but exhibits a steady growth, in contrast to the constructional steels. Stainless steels as a group is perhaps more heterogeneous than the constructional steels, and their properties are in many cases relatively unfamiliar to the designer. In some ways stainless steels are an unexplored world but to take advantage of these materials will require an increased understanding of their basic properties.

The following chapters aim to give an overall picture of the "stainless world" and what it can offer.

Use of stainless steel

Steel is unquestionably the dominating industrial constructional material.

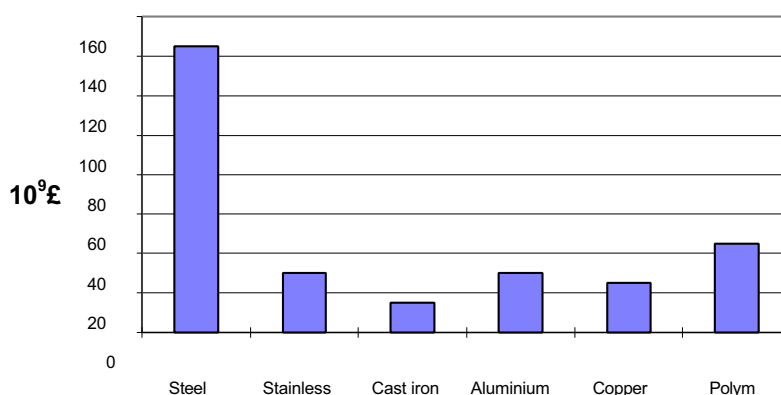


Figure 1. World consumption of various materials in the middle of the 1980's.

The annual world production of steel is approximately 400 million, and of this about 2% is stainless.

The use and production of stainless steels are completely dominated by the industrialised Western nations and Japan. While the use of steel has generally stagnated after 1975, the demand for stainless steels still increases by 3-5% per annum.

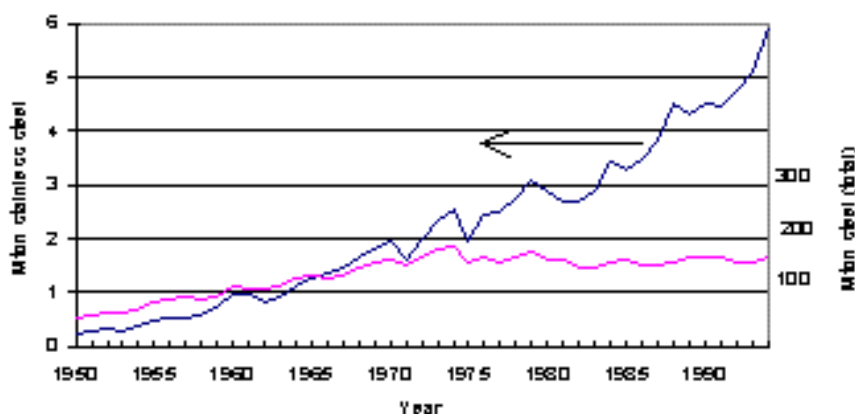


Figure 2. Steel production in western Europe 1950-1994.

The dominant product form for stainless steels is cold rolled sheet. The other products individually form only a third or less of the total amount of cold rolled sheet.

Usage is dominated by a few major areas: consumer products, equipment for the oil & gas industry, the chemical process industry and the food and beverage industry. Table 1 shows how the use of stainless steel is divided between the various applications.

Table 1. Use of stainless steel in the industrialised world, divided into various product forms and application categories.

PRODUCT FORMS		APPLICATION CATEGORIES	
Cold rolled sheet	60 %	Consumer items	26 %
Bar and wire	20 %	Washing machines and dishwashers	8 %
Hot rolled plate	10 %	Pans, cutlery, etc.	9 %
Tube	6 %	Sinks and kitchen equipment	4 %
Castings and other	4 %	Other	5 %
		Industrial equipment	74 %
		Food industry and breweries	25 %
		Chemical, oil and gas industry	20 %
		Transport	8 %
		Energy production	7 %
		Pulp and paper, textile industry	6 %
		Building and general construction	5 %
		Other	5 %

The most widely used stainless grades are the austenitic 18/9 type steels, i.e. AISI 304* and 304L, which form more than 50% of the global production of stainless steel. The next most widely used grades are the ferritic steels such as AISI 410, followed by the molybdenum-alloyed austenitic steels AISI 316/316L. Together these grades make up over 80% of the total tonnage of stainless steels.

* American standard (AISI) designations are normally used throughout this article to identify grades. If a certain grade does not have a standard designation, a trade name, e.g. '2205', is used. See Attachment 1 for chemical compositions.

How it all started

In order to obtain a perspective of the development of stainless steels, it is appropriate to look back to the beginning of the century; stainless steels are actually no older than that. Around 1910 work on materials problems was in progress in several places around the world and would lead to the discovery and development of the stainless steels.

In Sheffield, England, H. Brearly was trying to develop a new material for barrels for heavy guns that would be more resistant to abrasive wear. Chromium was among the alloying elements investigated and he noted that materials with high chromium contents would not take an etch. This discovery led to the patent for a steel with 9-16% chromium and less than 0.70% carbon; the first stainless steel had been born.

The first application for these stainless steels was stainless cutlery, in which the previously used carbon steel was replaced by the new stainless.

At roughly the same time B. Strauss was working in Essen, Germany, to find a suitable material for protective tubing for thermocouples and pyrometers. Among the iron-base alloys investigated were iron-chromium-nickel alloys with high chromium contents. It was found that specimens of alloys with more than 20% Cr did not rust even after having been left lying in the laboratory for quite some time. This discovery led to the development of a steel with 0.25% carbon, 20% chromium and 7% nickel; this was the first austenitic stainless steel.

Parallel with the work in England and Germany, F.M. Becket was working in Niagara Falls, USA, to find a cheap and scaling-resistant material for troughs for pusher type furnaces that were run at temperatures up to 1200°C. He found that at least 20% chromium was necessary to achieve resistance to oxidation or scaling. This was the starting point of the development of heat-resistant steels.

However, it was not until after the end of World War II that the development in process metallurgy led to the growth and widespread use of the modern stainless steels.

Stainless steel categories and grades

Over the years since the start of the development of stainless steels the number of grades has increased rapidly. The table in Attachment 1 shows the stainless steels that are standardised in the US and Europe. The table clearly shows that there are a large number of stainless steels with widely varying compositions. At least at some time all of these grades have been sufficiently attractive to merit the trouble of standardisation. In view of this 'jungle' of different steels grades, a broader overview may be helpful.

Since the structure has a decisive effect on properties, stainless steels have traditionally been divided into categories depending on their structure at room temperature. This gives a rough division in terms of both composition and properties.

Stainless steels can thus be divided into six groups: martensitic, martensitic-austenitic, ferritic, ferritic-austenitic, austenitic and precipitation hardening steels. The names of the first five refer to the dominant components of the microstructure in the different steels. The name of the last group refers to the fact that these steels are hardened by a special mechanism involving the formation of precipitates within the microstructure. Table 2 gives a summary of the compositions within these different categories.

Table 2. Composition ranges for different stainless steel categories.

Steel category	Composition (wt%)					Hardenable	Ferro-magnetism
	C	Cr	Ni	Mo	Others		
Martensitic	>0.10 >0.17	11-14 16-18	0-1 0-2	- 0-2	V	Hardenable	Magnetic
Martensitic-austenitic	<0.10	12-18	4-6	1-2		Hardenable	Magnetic
Precipitation hardening		15-17 12-17	7-8 4-8	0-2 0-2	Al, Al,Cu,Ti,Nb	Hardenable	Magnetic
Ferritic	<0.08 <0.25	12-19 24-28	0-5 -	<5 -	Ti	Not hardenable	Magnetic
Ferritic-austenitic (duplex)	<0.05	18-27	4-7	1-4	N, W	Not hardenable	Magnetic
Austenitic	<0.08	16-30	8-35	0-7	N,Cu,Ti,Nb	Not hardenable	Non-magnetic

The two first categories, martensitic and martensitic-austenitic stainless steels are hardenable, which means that it is possible to modify their properties via heat treatment in the same way as for hardenable carbon steels. The martensitic-austenitic steels are sometimes also referred to as ferritic-martensitic steels. The third category, the precipitation hardening steels, may also be hardened by heat treatment. The procedures used for these steels are special heat treatment or thermo-mechanical treatment sequences including a final precipitation hardening and ageing step. The precipitation hardening steels are sometimes also referred to as maraging steels. The last three steel categories, ferritic, ferritic-austenitic and austenitic are not hardenable, but are basically used in the as-received condition. The ferritic-austenitic stainless steels are often referred to as duplex stainless steels. It may be noted that there is only one category of stainless steels that is non-magnetic: the austenitic steels. All the others are magnetic.

The effects of the alloying elements

The alloying elements each have a specific effect on the properties of the steel. It is the combined effect of all the alloying elements and, to some extent, the impurities that determine the property profile of a certain steel grade. In order to understand why different grades have different compositions a brief overview of the alloying elements and their effects on the structure and properties may be helpful. The effects of the alloying elements on some of the important materials properties will be discussed in more detail in the subsequent sections. It should also be noted that the effect of the alloying elements differs in some aspects between the hardenable and the non-hardenable stainless steels.

Chromium (Cr)

This is the most important alloying element in stainless steels. It is this element that gives the stainless steels their basic corrosion resistance. The corrosion resistance increases with increasing chromium content. It also increases the resistance to oxidation at high temperatures. Chromium promotes a ferritic structure.

Nickel (Ni)

The main reason for the nickel addition is to promote an austenitic structure. Nickel generally increases ductility and toughness. It also reduces the corrosion rate and is thus advantageous in acid environments. In precipitation hardening steels nickel is also used to form the intermetallic compounds that are used to increase the strength.

Molybdenum (Mo)

Molybdenum substantially increases the resistance to both general and localised corrosion. It increases the mechanical strength somewhat and strongly promotes a ferritic structure. Molybdenum also promotes the formation secondary phases in ferritic, ferritic-austenitic and austenitic steels. In martensitic steels it will increase the hardness at higher tempering temperatures due to its effect on the carbide precipitation.

Copper (Cu)

Copper enhances the corrosion resistance in certain acids and promotes an austenitic structure. In precipitation hardening steels copper is used to form the intermetallic compounds that are used to increase the strength.

Manganese (Mn)

Manganese is generally used in stainless steels in order to improve hot ductility. Its effect on the ferrite/austenite balance varies with temperature: at low temperature manganese is a austenite stabiliser but at high temperatures it will stabilise ferrite. Manganese increases the solubility of nitrogen and is used to obtain high nitrogen contents in austenitic steels.

Silicon (Si)

Silicon increases the resistance to oxidation, both at high temperatures and in strongly oxidising solutions at lower temperatures. It promotes a ferritic structure.

Carbon (C)

Carbon is a strong austenite former and strongly promotes an austenitic structure. It also substantially increases the mechanical strength. Carbon reduces the resistance to intergranular corrosion. In ferritic stainless steels carbon will strongly reduce both toughness and corrosion resistance. In the martensitic and martensitic-austenitic steels carbon increases hardness and strength. In the martensitic steels an increase in hardness and strength is generally accompanied by a decrease in toughness and in this way carbon reduces the toughness of these steels.

Nitrogen (N)

Nitrogen is a very strong austenite former and strongly promotes an austenitic structure. It also substantially increases the mechanical strength. Nitrogen increases the resistance to localised corrosion, especially in combination with molybdenum. In ferritic stainless steels nitrogen will strongly reduce toughness and corrosion resistance. In the martensitic and martensitic-austenitic steels nitrogen increases both hardness and strength but reduces the toughness.

Titanium (Ti)

Titanium is a strong ferrite former and a strong carbide former, thus lowering the effective carbon content and promoting a ferritic structure in two ways. In austenitic steels it is added to increase the resistance to intergranular corrosion but it also increases the mechanical properties at high temperatures. In ferritic stainless steels titanium is added to improve toughness and corrosion resistance by lowering the amount of interstitials in solid solution. In martensitic steels titanium lowers the martensite hardness and increases the tempering resistance. In precipitation hardening steels titanium is used to form the intermetallic compounds that are used to increase the strength.

Niobium (Nb)

Niobium is both a strong ferrite and carbide former. As titanium it promotes a ferritic structure. In austenitic steels it is added to improve the resistance to intergranular corrosion but it also enhances mechanical properties at high temperatures. In martensitic steels niobium lowers the hardness and increases the tempering resistance. In U.S. it is also referred to as Columbium (Cb).

Aluminium (Al)

Aluminium improves oxidation resistance, if added in substantial amounts. It is used in certain heat resistant alloys for this purpose. In precipitation hardening steels aluminium is used to form the intermetallic compounds that increase the strength in the aged condition.

Cobalt (Co)

Cobalt only used as an alloying element in martensitic steels where it increases the hardness and tempering resistance, especially at higher temperatures.

Vanadium (V)

Vanadium increases the hardness of martensitic steels due to its effect on the type of carbide present. It also increases tempering resistance. Vanadium stabilises ferrite and will, at high contents, promote ferrite in the structure. It is only used in hardenable stainless steels.

Sulphur (S)

Sulphur is added to certain stainless steels, the free-machining grades, in order to increase the machinability. At the levels present in these grades sulphur will substantially reduce corrosion resistance, ductility and fabrication properties, such as weldability and formability.

Cerium (Ce)

Cerium is one of the rare earth metals (REM) and is added in small amounts to certain heat resistant temperature steels and alloys in order to increase the resistance to oxidation and high temperature corrosion.

The effect of the alloying elements on the structure of stainless steels is summarised in the Schaeffler-Delong diagram (Figure 3). The diagram is based on the fact that the alloying elements can be divided into ferrite-stabilisers and austenite-stabilisers. This means that they favour the formation of either ferrite or austenite in the structure. If the austenite-stabilisers ability to promote the formation of austenite is related to that for nickel, and the ferrite-stabilisers likewise compared to chromium, it becomes possible to calculate the total ferrite and austenite stabilising effect of the alloying elements in the steel. This gives the so-called chromium and nickel equivalents in the Schaeffler-Delong diagram:

Chromium equivalent = %Cr + 1.5 x %Si + %Mo

Nickel equivalent = %Ni + 30 x (%C + %N) + 0.5 x (%Mn + %Cu + %Co)

In this way it is possible to take the combined effect of alloying elements into consideration. The Schaeffler-Delong diagram was originally developed for weld metal, i.e. it describes the structure after melting and rapid cooling but the diagram has been found to give a useful picture of the effect of the alloying elements also for wrought and heat treated material. However, in practice, wrought or heat treated steels with ferrite contents in the range 0-5% according to the diagram contain smaller amounts of ferrite than that predicted by the diagram.

It should also be mentioned here that the Schaeffler-Delong diagram is not the only diagram for assessment of ferrite contents and structure of stainless steels. Several different diagrams have been published, all with slightly different equivalents, phase limits or general layout. The effect of some alloying elements has also been the subject of considerable discussion. For example, the austenite-stabilising effect of manganese has later been considered smaller than that predicted in the Schaeffler-Delong diagram. Its effect is also dependent on temperature.

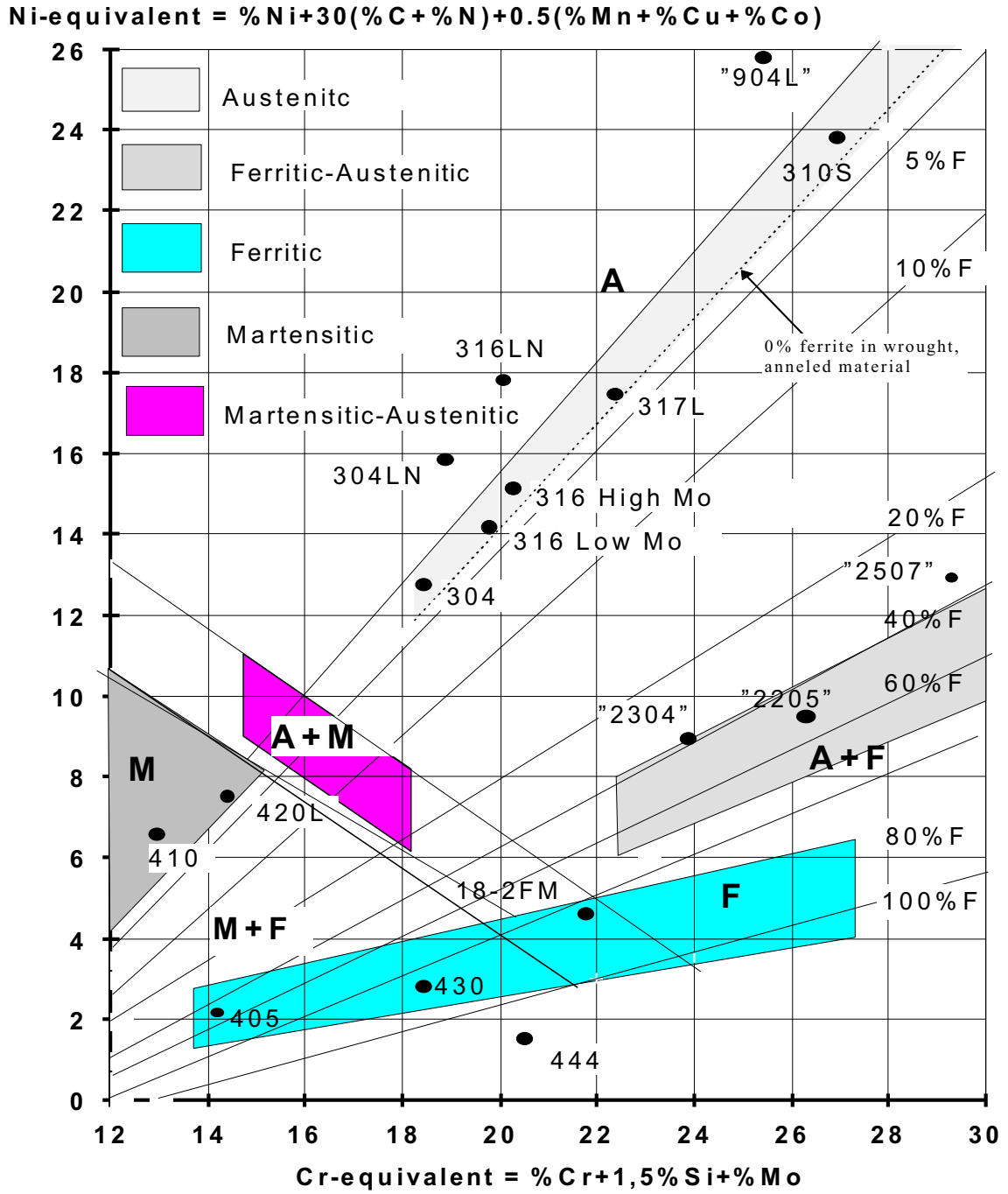


Figure 3. The Schaeffler-Delong diagram.(1)

Corrosion and corrosion properties

The single most important property of stainless steels, and the reason for their existence and widespread use, is their corrosion resistance. Before looking at the properties of the various stainless steels, a short introduction to corrosion phenomena is appropriate. In spite of their image, stainless steels can suffer both "rusting" and corrosion if they are used incorrectly.

PASSIVITY

The reason for the good corrosion resistance of stainless steels is that they form a very thin, invisible surface film in oxidising environments. This film is an oxide that protects the steel from attack in an aggressive environment. As chromium is added to a steel, a rapid reduction in corrosion rate is observed to around 10% because of the formation of this protective layer or passive film. In order to obtain a compact and continuous passive film, a chromium content of at least 11% is required. Passivity increases fairly rapidly with increasing chromium content up to about 17% chromium. This is the reason why many stainless steels contain 17-18% chromium.

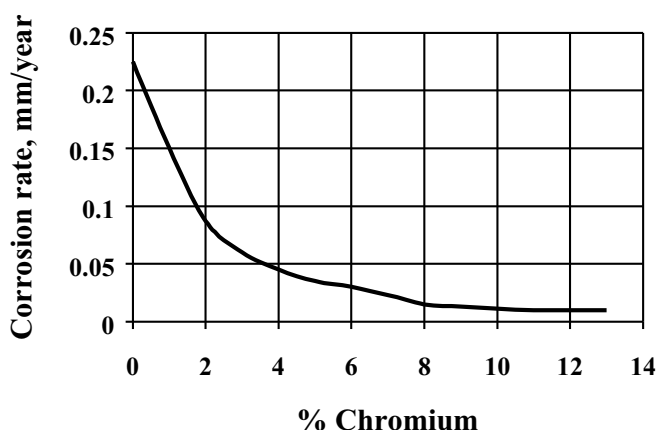


Figure 4. The effect of chromium content on passivity (2).

The most important alloying element is therefore chromium, but a number of other elements such as molybdenum, nickel and nitrogen also contribute to the corrosion resistance of stainless steels. Other alloying elements may contribute to corrosion resistance in particular environments - for example copper in sulphuric acid or silicon, cerium and aluminium in high temperature corrosion in some gases.

A stainless steel must be oxidised in order to form a passive film; the more aggressive the environment the more oxidising agents are required. The maintenance of passivity consumes oxidising species at the metal surface, so a continuous supply of oxidising agent to the surface is required. Stainless steels have such a strong tendency to passivate that only very small amounts of oxidising species are required for passivation. Even such weakly oxidising environments as air and water are sufficient to passivate stainless steels. The passive film also has the advantage, compared to for example a paint layer, that it is self-healing. Chemical or mechanical damage to the passive film can heal or re-passivate in oxidising environments. It is worth noting that stainless steels are most suitable for use in oxidising neutral or weakly reducing environments. They are not particularly suitable for strongly reducing environments such as hydrochloric acid.

Corrosion can be roughly divided into aqueous corrosion and high temperature corrosion:

- **Aqueous corrosion** refers to corrosion in liquids or moist environments at temperatures up to 300 °C, usually in water-based environments.
- **High temperature corrosion** denotes corrosion in hot gases at temperatures up to 1300 °C.

The following sections contain a brief description of the various forms of aqueous and high temperature corrosion, the factors which affect the risk for attack and the effect of steel composition on corrosion resistance.

AQUEOUS CORROSION

The term aqueous corrosion refers to corrosion in liquids or moist gases at relatively low temperatures, less than 300 °C. The corrosion process is electrochemical and requires the presence of an electrolyte in the form of a liquid or a moisture film. The most common liquids are of course water-based solutions.

General corrosion

This type of corrosion is characterised by a more or less even loss of material from the whole surface or relatively large parts of it. This is similar to the rusting of carbon steels.

General corrosion occurs if the steel does not have sufficiently high levels of the elements which stabilise the passive film. The surrounding environment is then too aggressive for the steel. The passive film breaks down over the whole surface and exposes the steel surface to attack from the environment.

General corrosion of stainless steels normally only occurs in acids and hot caustic solutions and corrosion resistance usually increases with increasing levels of chromium, nickel and molybdenum. There are, however, some important exceptions to this generalisation. In strongly oxidising environments such as hot concentrated nitric acid or chromic acid, molybdenum is an undesirable alloying addition.

The aggressivity of an environment normally increases with increasing temperature, while the effect of concentration is variable. A concentrated acid may be less aggressive than a more dilute solution of the same acid. A material is generally considered resistant to general corrosion in a specific environment if the corrosion rate is below 0.1 mm/year. The effect of temperature and concentration on corrosion in a specific environment is usually presented as isocorrosion diagrams, such as that shown in Figure 5. In this context it is, however, important to note that impurities can have a marked effect on the aggressivity of the environment (see Figure 7).

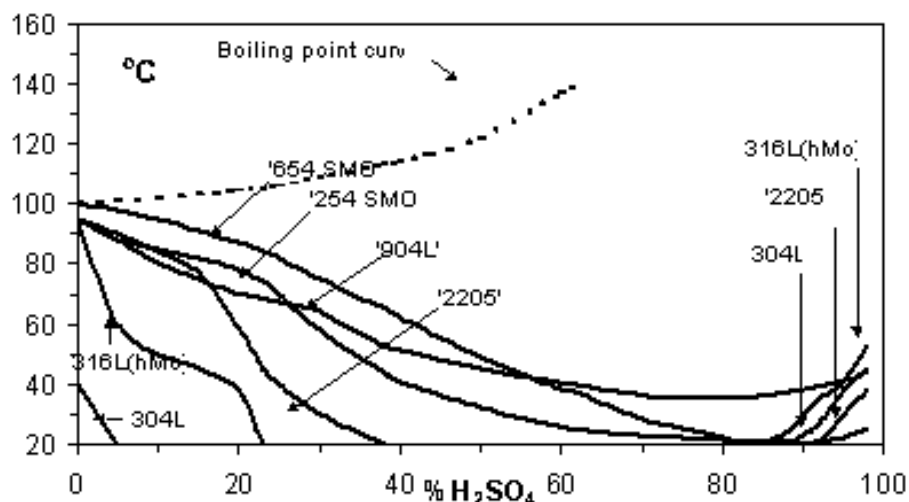


Figure 5. Isocorrosion diagram for pure sulphuric acid, 0.1 mm/year (3).

From the isocorrosion diagram in Figure 5 it is apparent that the aggressivity of sulphuric acid increases with increasing temperature, also that the aggressivity is highest for concentrations in the range 40-70%. Concentrated sulphuric acid is thus less aggressive than more dilute solutions. The grade '904L', with the composition 20Cr-25Ni-4.5Mo-1.5Cu, exhibits good corrosion resistance even in the intermediate concentration range. This steel was specifically developed for use in sulphuric acid environments.

The effect of the alloying elements may be demonstrated more clearly in another way. In Figure 6 the limiting concentrations in sulphuric acid, i.e. the highest concentration that a specific steel grade will withstand without losing passivity, are shown for various stainless steels. The beneficial effect of high levels of chromium, nickel and molybdenum is apparent, as is the effect of copper in this environment.

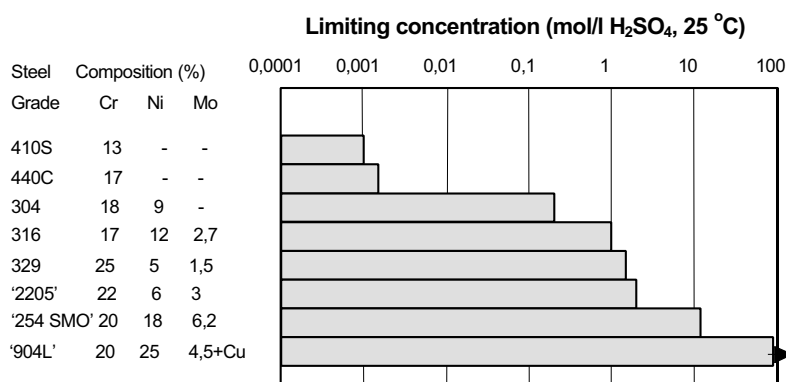


Figure 6. Limiting concentrations for passivity in sulphuric acid for various stainless steels.

The aggressivity of any environment may be changed appreciably by the presence of impurities. The impurities may change the environment towards more aggressive or towards more benevolent conditions depending on the type of impurities or contaminants that are present. This is illustrated in Figure 7 where the effect of two different contaminants, chlorides and iron, on the isocorrosion diagram of 316L(hMo) in sulphuric acid is shown. As can be clearly seen from the diagram, even small amounts of another species may be enough to radically change the environment. In practice there is always some impurities or trace compounds in most industrial environments. Since much of the data in corrosion tables is based on tests in pure, uncontaminated chemical and solutions, it is most important that due consideration is taken of any impurities when the material of construction for a certain equipment is considered.

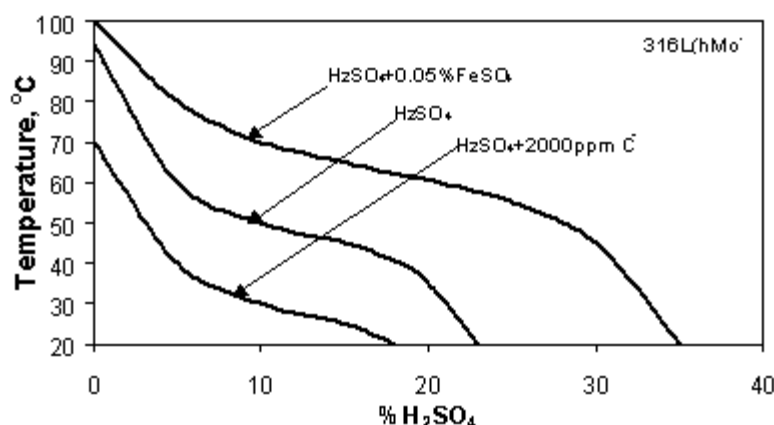


Figure 7. The effect of impurities on the corrosion resistance of 316L (2.5% Mo min.) in sulphuric acid.

Pitting and crevice corrosion

Like all metals and alloys that rely on a passive film for corrosion resistance, stainless steels are susceptible to localised corrosion. The protective passive film is never completely perfect but always contains microscopic defects, which usually do not affect the corrosion resistance. However, if there are halogenides such as chlorides present in the environment, these can break down the passive film locally and prevent the reformation of a new film. This leads to localised corrosion, i.e. pitting or crevice corrosion. Both these types of corrosion usually occur in chloride-containing aqueous solutions such as sea water, but can also take place in environments containing other halogenides.

Pitting is characterised by more or less local points of attack with considerable depth and normally occurs on free surfaces. Crevice corrosion occurs in narrow, solution-containing crevices in which the passive film is more readily weakened and destroyed. This may be under washers, flanges, deposits or fouling on the steel surface. Both forms of corrosion occur in neutral environments, although the risk for attack increases in acidic solutions.

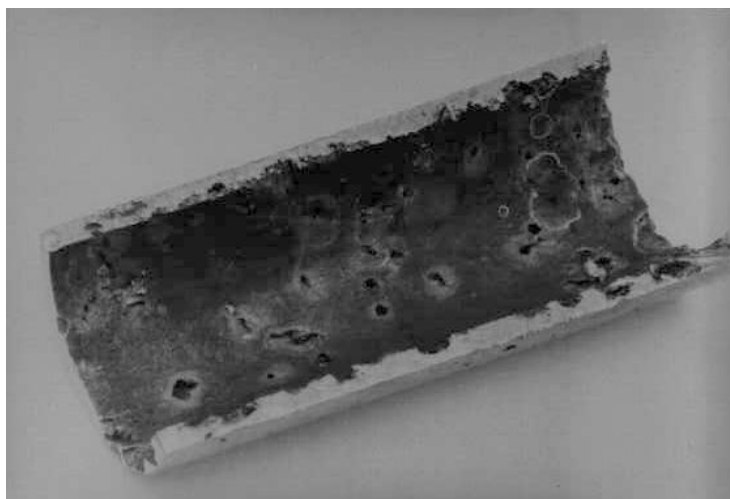


Figure 8. Pitting on a tube of AISI 304 used in brackish water.

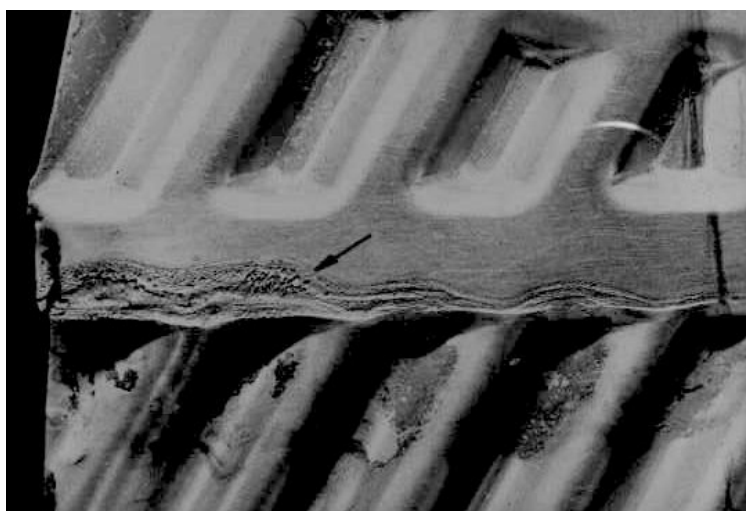


Figure 9. Crevice corrosion under a rubber washer in a flat heat exchanger used in brackish water.

Chromium, molybdenum and nitrogen are the alloying elements that increase the resistance of stainless steels to both pitting and crevice corrosion. Resistance to localised corrosion in sea water requires 6% molybdenum or more.

One way of combining the effect of alloying elements is via the so-called Pitting Resistance Equivalent (PRE) which takes into account the different effects of chromium, molybdenum and nitrogen. There are several equations for the Pitting Resistance Equivalent, all with slightly different coefficients for molybdenum and nitrogen. One of the most commonly used formula is the following:

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

This formula is almost always used for the duplex steels but it is also sometimes applied to austenitic steels. However, for the latter category the value of the coefficient for nitrogen is also often set to 30, while the other coefficients are unchanged. This gives the following formula:

$$\text{PRE} = \% \text{Cr} + 3.3 \times \% \text{Mo} + 30 \times \% \text{N}$$

The difference between the formulas is generally small but the higher coefficient for nitrogen will give a difference in the PRE-value for the nitrogen alloyed grades.

Table 3. Typical PRE-values for various stainless steels

Grade	304L	316L	'SAF 2304'	317L	'2205'	'904L'	'SAF 2507'	'254 SMO'	'654 SMO'
PRE _{16xN}	19	26	26	30	35	36	43	43	56
PRE _{30xN}	20	26		30		37		46	63

The effect of composition can be illustrated by plotting the critical pitting temperature (CPT) in a specific environment against the PRE-values for a number of steel grade, see Figure 10. The CPT values are the lowest temperatures at which pitting corrosion attack occurred during testing.

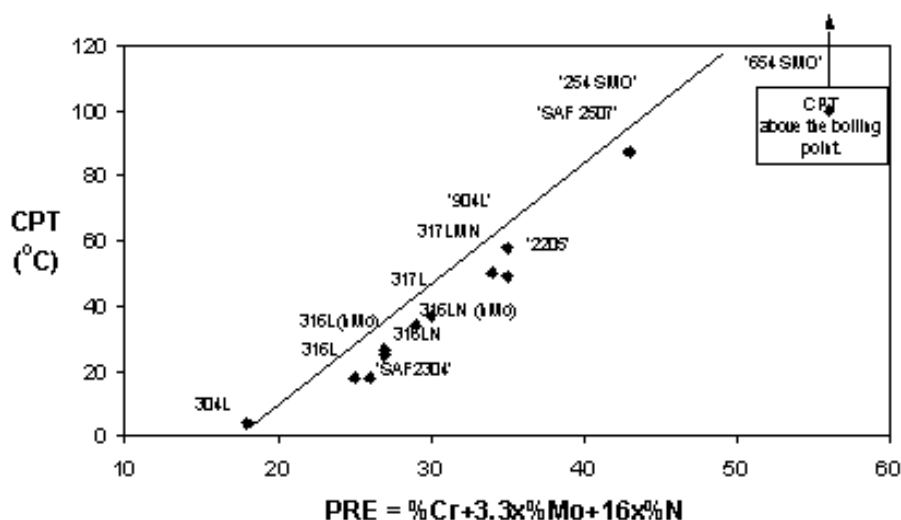


Figure 10. Critical pitting temperature (CPT) in 1 M NaCl as a function of PRE values.

Since the basic corrosion mechanism is the same for both pitting and crevice corrosion, the same elements are beneficial in combatting both types of corrosion attack. Due to this there is often a direct correlation between the CPT- and CCT-values for a certain steel grade. Crevice corrosion is the more severe of the two types of corrosion attack and the CCT-values are lower than the CPT-values for any stainless steel grade. This is illustrated in Figure 11 where the critical pitting temperature (CPT) and the critical crevice corrosion temperature (CCT) in 6% FeCl₃ has been plotted against the PRE-values for a number of stainless steels. Again the CPT and CCT values are the lowest temperatures at which corrosion attack occurred.

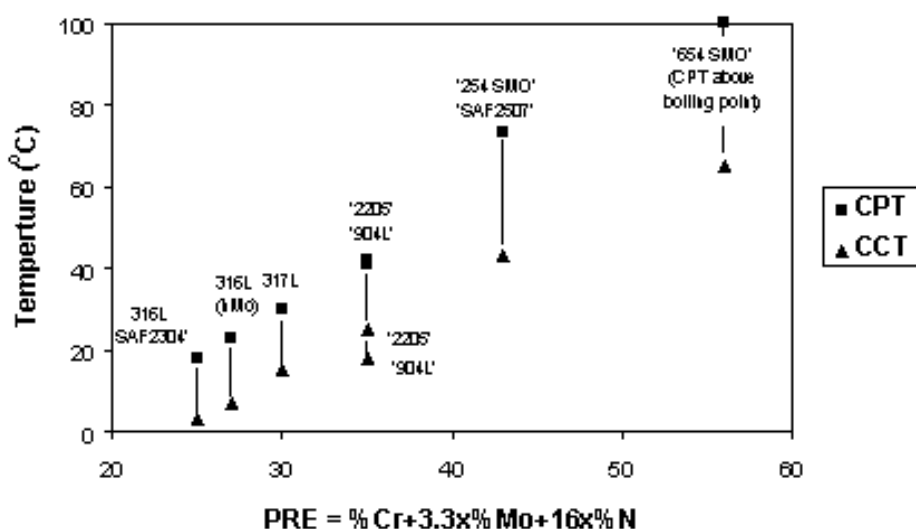


Figure 11. Critical pitting temperature (CPT) and critical crevice corrosion temperature (CCT) in ferric chloride for various stainless steels.

As can be seen from the diagrams in Figures 10 and 11 there is a relatively good correlation between the PRE-values and the CPT and CCT. Consequently the PRE-value can be used to group steel grades and alloys into rough groups of materials with similar resistance to localised corrosion attack, in steps of 10 units in PRE-value or so. However, it can not be used to compare or separate steel grades or alloys with almost similar PRE values. Finally, it must be emphasised that all diagrams of this type show comparisons between steel grades and are only valid for a given test environment. Note that the steel grades have different CPT's in NaCl (Figure 10) and FeCl₃ (Figure 11). The temperatures in the diagrams cannot therefore be applied to other environments, unless there exists practical experience that shows the relation between the actual service conditions and the testing conditions. The relative ranking of localised corrosion resistance is, however, often the same even in other environments. The closer the test environment is to the "natural" environment, i.e. the closer the test environment simulates the principal factors of the service environment, the more can the data generated in it be relied on when judging the suitability of a certain steel grade for a specific service environment. A test in sodium chloride is consequently better than a test in ferric chloride for judging whether or not a certain grade is suitable for one of the neutral pH, chloride containing water solutions which are common in many industries.

In order to obtain a good resistance to both pitting and crevice corrosion, it is necessary to choose a highly alloyed stainless steel with a sufficiently high molybdenum content. However, choosing the appropriate steel grades is not the only way to minimise the risk for localised corrosion attack. The risk for these types of corrosion attack can be reduced at the design stage by avoiding stagnant conditions and narrow crevices. The designer can thus minimise the risk for pitting and crevice corrosion both by choosing the correct steel grade and by appropriate design of the equipment.

Stress corrosion cracking

This type of corrosion is characterised by the cracking of materials that are subject to both a tensile stress and a corrosive environment. The environments which most frequently causes stress corrosion cracking in stainless steels are aqueous solutions containing chlorides. Apart from the presence of chlorides and tensile stresses, an elevated temperature (>60°C) is normally required for stress corrosion to occur in stainless steels. Temperature is a very important parameter in the stress corrosion cracking behaviour of stainless steel and cracking is rarely observed at temperatures below 60 °C. However, chloride-containing solutions are not the only environments that can cause stress corrosion cracking of stainless steels. Solutions of other halogenides may also cause cracking and caustic solutions such as sodium and potassium hydroxides can cause stress corrosion cracking at temperatures above the boiling point. Sensitised 18-8 stainless steels are also susceptible to intergranular stress corrosion cracking in the steam and water environments in boiling water reactors if the stress level is sufficiently high.

Cracking may also occur in high strength stainless steels, such as martensitic or precipitation hardening steels. This type of cracking is almost always due to hydrogen embrittlement and can occur in both environments containing sulphides and environments free of sulphides.

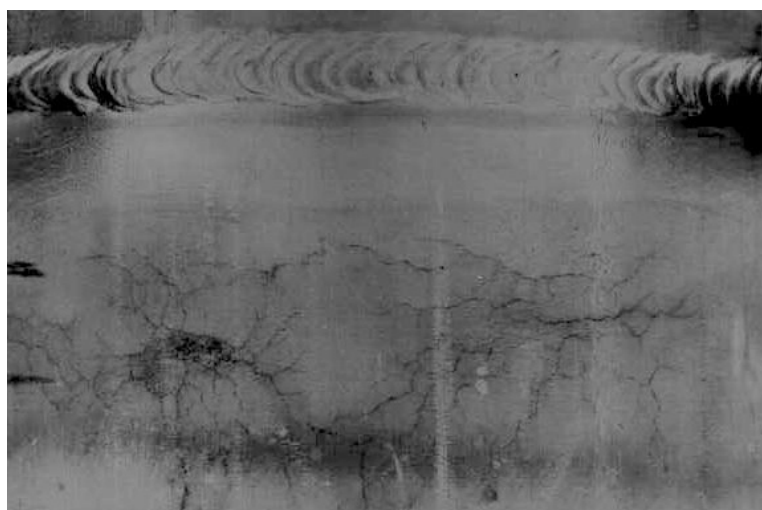


Figure 12. Stress corrosion cracking adjacent to a weld in a stainless pipe exposed to a chloride-containing environment at 100°C.

The risk for stress corrosion cracking is strongly affected by both the nickel content and the microstructure. The effect of nickel content is apparent from Figure 13. Both high and low nickel contents give a better resistance to stress corrosion cracking. In the case of the low nickel contents this is due to the structure being either ferritic or ferritic-austenitic. The ferrite phase in stainless steels with a low nickel content is very resistant to stress corrosion cracking.

For high strength steels the main factor affecting the resistance to hydrogen embrittlement is the strength. The susceptible to hydrogen embrittlement will increase with increasing strength of the steel.

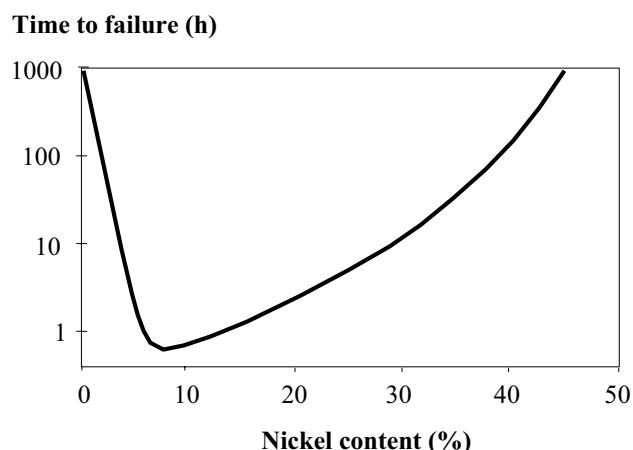


Figure 13. Stress corrosion cracking susceptibility in boiling MgCl₂ as a function of nickel content (4).

In applications in which there is a considerable danger of stress corrosion cracking, steels that either has a low or a high nickel content should be selected. The choice could be either a ferritic or ferritic-austenitic steel or a high-alloyed austenitic steel or nickel-base alloy. Although about 40% nickel is necessary to achieve immunity to chloride-induced stress corrosion cracking, the 20-30% nickel in steel grades such as ‘654 SMO’, ‘254 SMO’, ‘904L’ and ‘A 28 (commonly known by the Sandvik tradename SANICRO 28). is often sufficient in practice.

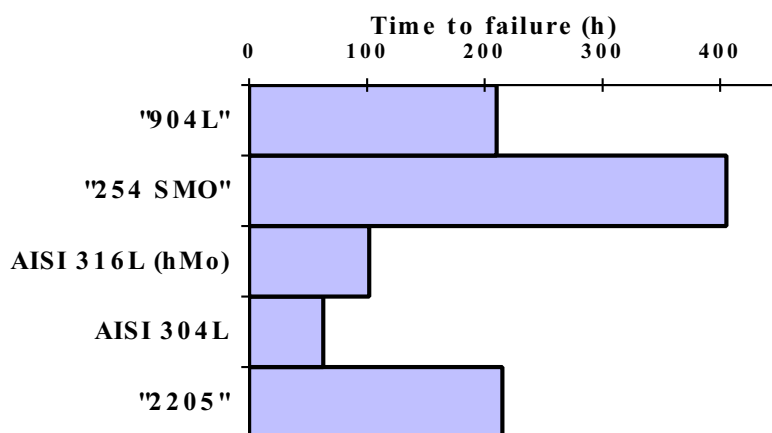


Figure 14. Comparison of stress corrosion cracking resistance of some austenitic stainless steels. Drop- evaporation method testing with loading to $0.9 \times R_{p0.2}$.

In this context it should, however, be noted that nickel content is not the only factor that governs resistance to stress corrosion cracking: the entire composition of the alloy is important. Molybdenum has been found to have a considerable effect on resistance to stress corrosion cracking. However, more than 4% molybdenum is required to obtain a significant effect, as is apparent from a comparison of ‘904L’ and ‘254 SMO’ in Figure 14. Selecting a stainless steel for service in an environment that can cause stress corrosion cracking cannot just be done on the basis of nickel content.

Stress corrosion cracking can only occur in the presence of tensile stresses. The stress to which a stainless steel may be subjected without cracking is different for different steel grades. An example of the threshold stresses for different steel grades under severe evaporative conditions is given in Figure 15.

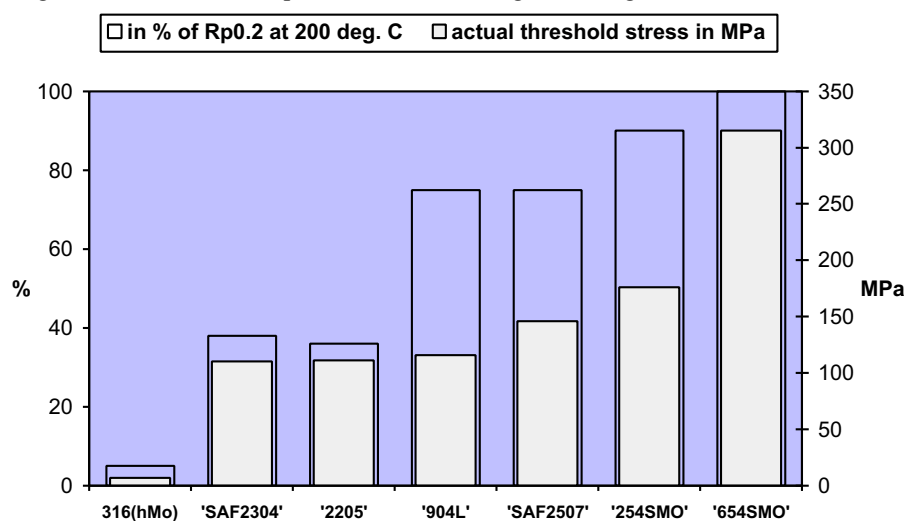


Figure 15. Threshold stresses for chloride stress corrosion cracking under severe evaporative conditions. Drop evaporation test.
For '654 SMO' 100% of $R_{p0.2}$ was the highest stress level tested. The threshold stress is above that level in this test.

As can be seen in the diagram in Figure 15 high alloy austenitic stainless steels have a very high resistance to chloride stress corrosion cracking in contrast to the lower alloyed grades of this category.

In this type of diagram the threshold stress level is often given as a percentage of the yield strength at a certain temperature, here 200 °C, which is related to the testing temperature. Due to the varying strengths of the different steel grades the actual maximum stress levels will vary. The threshold stress level gives a good indication of the stress corrosion cracking resistance of a certain grade but an adequate safety margin must also be incorporated in any design based on these threshold stresses. The reason for this is that the actual service conditions may deviate from the test conditions in many ways, for example regarding maximum temperatures, chloride levels, the effect of residual stresses, etc.

Intergranular corrosion

This type of corrosion is also called grain boundary attack and is characterised by attack of a narrow band of material along the grain boundaries.

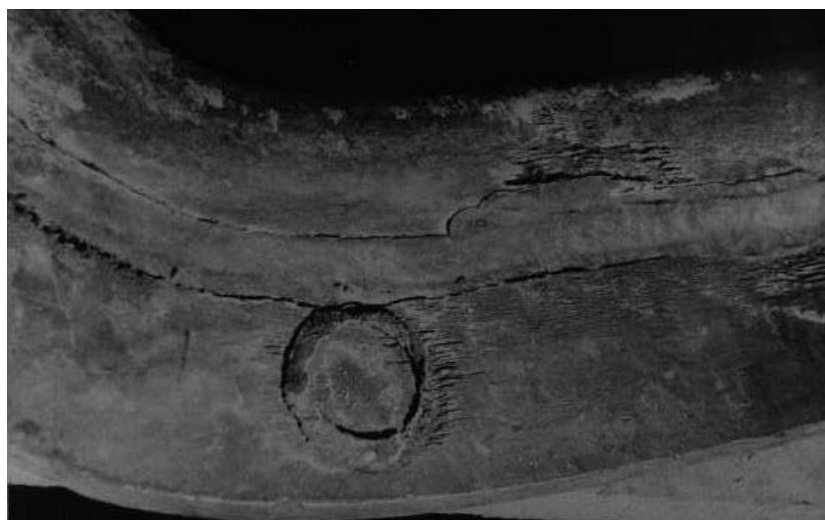


Figure 16. Intergranular corrosion adjacent to welds in a hook of AISI 316 used in a pickling bath of sulphuric acid.

Intergranular corrosion is caused by the precipitation of chromium carbides in the grain boundaries. Earlier this type of corrosion caused large problems in connection with the welding of austenitic stainless steels. If an austenitic or ferritic-austenitic steel is maintained in the temperature range 550 - 800°C, carbides containing chromium, iron and carbon are formed in the grain boundaries. The chromium content of the carbides can be up to 70%, while the chromium content in the steel is around 18%. Since chromium is a large atom with a low diffusion rate, a narrow band of material around the carbides therefore becomes depleted in chromium to such an extent that the corrosion resistance decreases. If the steel is then exposed to an aggressive environment, the chromium-depleted region is attacked, and the material along the grain boundaries is corroded away. The result is that grains may drop out of the steel surface or in severe cases that the grains are only mechanically locked together as in a jigsaw puzzle while the stiffness and strength of the material have almost disappeared. Ferritic stainless steels are also sensitive to intergranular corrosion for the same reason as the austenitic and duplex steels, although the dangerous temperatures are higher, generally above 900 - 950°C.

Temperatures that can lead to sensitisation, i.e. a sensitivity to intergranular corrosion, occur during welding in an area 3-5 mm from the weld metal. They can also be reached during hot forming operations or stress relieving heat treatments.

The risk for intergranular corrosion can be reduced by decreasing the level of free carbon in the steels. This may be done in either of two ways:

- by decreasing the carbon content.
- by stabilising the steel, i.e. alloying with an element (titanium or niobium) which forms a more stable carbide than chromium.

The effect of a decrease in the carbon content is most easily illustrated by a TTS-diagram (time- temperature-sensitisation), an example of which is shown in Figure 17. The curves in the diagram show the longest time an austenitic steel of type 18Cr-8Ni can be maintained at a given temperature before there is a danger of corrosion. This means that for standard low-carbon austenitic steels (L-grades) the risk for intergranular corrosion cracking is, from a practical point of view, eliminated. All high alloyed austenitic and all duplex grades intended for aqueous corrosion service have carbon contents below 0.03% and are consequently "L-grades". Due to the low solubility of carbon in ferrite the carbon content will have to be extremely low in ferritic stainless steels if the risk of intergranular corrosion is to be eliminated. In ferritic stainless steels stabilising and extra low carbon contents are often used to eliminate the risk for intergranular attack after welding or other potentially sensitising treatments.

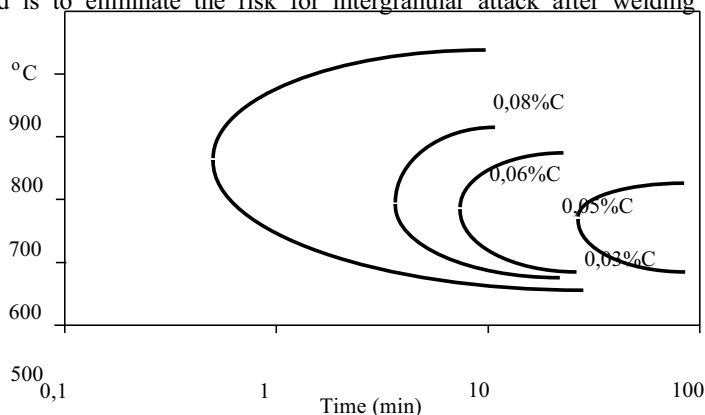


Figure 17. TTS (Time-Temperature-Sensitization) diagram for 18Cr-9Ni type steels with different carbon contents. The curves are based on the Strauss test (1).

Addition of titanium or niobium to the steel, so-called stabilisation, means that the carbon is bound as titanium or niobium carbides. Since titanium and niobium have a greater tendency to combine with carbon than does chromium, this means that carbon is not available to form chromium carbides. The risk for intergranular corrosion is therefore appreciably reduced. There is, however, a disadvantage associated with stabilisation. In the area closest to a weld, the temperature during welding can be so high that titanium or niobium carbides are dissolved. There is then a danger that they do not have time to re-precipitate before the material has cooled sufficiently to allow the formation of chromium carbides in the grain boundaries. This leads to so-called *knife line attack* in which a narrow zone of material very close to the weld suffers intergranular corrosion. Since the carbon level in stabilised steels is often quite high (0.05-0.08%) this can give serious attack.

A sensitised microstructure can be fully restored by adequate heat treatment. In the case of austenitic and ferritic-austenitic duplex stainless steels a full quench anneal heat treatment is necessary. For ferritic stainless steels an annealing treatment is normally used.

It should also be mentioned that many high temperature steels, which have high carbon contents to increase the strength, are sensitive to intergranular corrosion if they are used in aqueous environments or exposed to aggressive condensates.

Galvanic corrosion

Galvanic corrosion can occur if two dissimilar metals are electrically connected together and exposed to a corrosive environment. The corrosive attack increases on the less noble metal and is reduced or prevented on the more noble metal, compared to the situation in which the materials are exposed to the same environment without galvanic coupling.

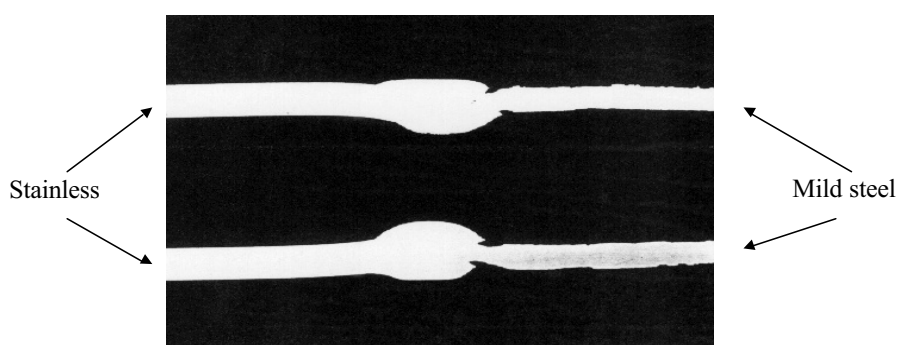


Figure 18. Galvanic corrosion on mild steel welded to stainless steel and exposed to sea water.

The difference in "nobility", the ratio of the area of the noble metal to the area of the less noble metal in the galvanic couple and the electrical conductivity of the corrosive environment are the factors that have the largest influence on the risk for galvanic corrosion. An increase in any of these factors increases the risk that corrosion will occur.

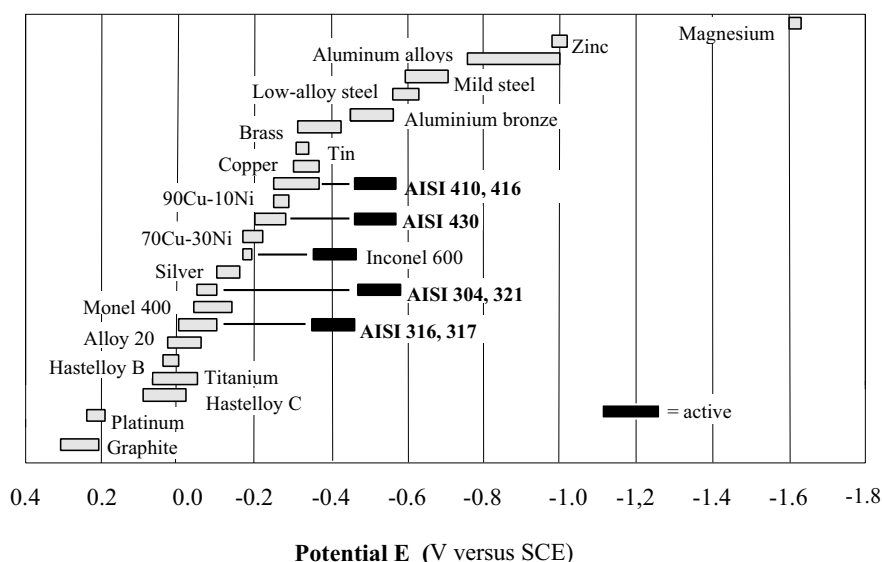


Figure 19. Corrosion potentials for various materials in flowing sea water(after 5).

The risk of galvanic corrosion is most severe in sea water applications. One way of assessing whether a certain combination of materials is likely to suffer galvanic corrosion is to compare the corrosion potentials of the two materials in the service environment. One such "electrochemical potential series" for various materials in seawater is given in Figure 19. The larger the difference between the corrosion potentials, the greater the risk for attack of the less noble component; small differences in corrosion potential have a negligible effect.

Stainless steels are more noble than most of the constructional materials and can therefore cause galvanic corrosion on both carbon steels and aluminium alloys. The risk for galvanic corrosion between two stainless steel grades is small as long as there is not a large difference in composition such as that between AISI 410S and AISI 316 or '254 SMO'. Galvanic effects to be operative when one of the materials in the galvanic couple is corroding. This means that galvanic corrosion is rarely seen on alloys that are resistant to the service environment.

HIGH TEMPERATURE CORROSION

In addition to the electrochemically-based aqueous corrosion described in the previous chapter, stainless steels can suffer attack in gases at high temperatures. At such high temperatures there are not the distinct forms of corrosion such as occur in solutions, instead corrosion is often divided according to the type of aggressive environment.

Some simpler cases of high temperature corrosion will be described here: oxidation, sulphur attack (sulphidation) carbon uptake (carburization) and nitrogen uptake (nitridation). Other more complex cases such as corrosion in exhaust gases, molten salts and chloride/fluoride atmospheres will not be treated here.

Oxidation

When stainless steels are exposed to atmospheric oxygen, an oxide film is formed on the surface. At low temperatures this film takes the form of a thin, protective passive film but at high temperatures the oxide thickness increases considerably. Above the so-called scaling temperature the oxide growth rate becomes unacceptably high.

Chromium increases the resistance of stainless steels to high temperature oxidation by the formation of a chromia (Cr_2O_3) scale on the metal surface. If the oxide forms a continuous layer on the surface it will stop or slow down the oxidation process and protect the metal from further. Chromium contents above about 18% is needed in order to obtain a continuous protective chromia layer. The addition of silicon will appreciably increase the oxidation resistance, as will additions of small amounts of the rare earth metals such as cerium. The latter also increase the adhesion between the oxide and the underlying substrate and thus have a beneficial effect in thermal cycling i.e. in cases in which the material is subject to large, more or less regular, variations in temperature. This is, at least partly, due to the fact that the addition of Ce promotes a rapid initial growth of the oxide. This leads to a rapidly formed thin and tenacious protective oxide. The scale is then thin and the chromium depleted zone below is also thin which makes reformation of the oxide rapid if cracks form in it during thermal cycling. High nickel contents also have a beneficial effect on the oxidation resistance. The scaling temperatures for various stainless steels are shown in Table 4. It is worth noting that the ranking in resistance to localized corrosion is not applicable at high temperatures and that an increase in molybdenum content does not lead to an increased scaling temperature. Compare, for example, 304L - 316 - 317L.

Table 4. Scaling temperature in air for various stainless steels.

Steel grade	Composition (%)						Scaling temperature (°C) (approx.)
	C	Cr	Ni	Mo	N	Other	
AISI 410	0.08	13	-	-	-		830
431	0.12	17	1	-			850
18-2Ti	0.01	18	-	2	0.01	Ti	1000
446	0.12	26	-	-	-	N	1075
304H	0.05	18	9	-	0.06		850
321H	0.05	17	9	-	0.01	Ti	850
316	0.04	17	12	2.7	0.06		850
'2205'	0.02	22	5	3	0.17		1000
'904L'	0.02	20	25	4.5	0.06	Cu	1000
310S	0.05	25	20	-	0.06		1150
'153 MA'	0.05	18	9	-	0.15	Si, Ce	1050
'253 MA'	0.09	21	11	-	0.17	Si, Ce, N	1150
'353 MA'	0.05	25	35	-	0.15	Si, Ce	1175

Under certain conditions heat resisting steels can suffer very rapid oxidation rates at relatively low temperatures. This is referred to as catastrophic oxidation and is associated with the formation of liquid oxides. If a liquid oxide is formed it will penetrate and disrupt the protective oxide scale and expose the metal to rapid oxidation.

Catastrophic oxidation generally occurs in the temperature range 640 - 950 °C in the presence of elements whose oxides either melt or form eutectics with the chromium oxide (Cr₂O₃) scale. For this reason molybdenum, which forms low-melting-point oxides and oxide-oxide eutectics, should be avoided in steels designed for high temperature applications. The presence of some other metals in the environment may cause catastrophic oxidation. Vanadium, which is a common contaminant in heavy fuel oils, can easily cause rapid or catastrophic oxidation due to its low melting point oxide, V₂O₅, which melts at 690 °C. Some other metals, such as lead and tungsten, may also act in this way.

Sulphur attack (Sulphidation)

At high temperatures sulphur compounds react with stainless steels to form complex sulphides and/or oxides. Sulphur also reacts with nickel and forms nickel sulphide which, together with nickel, forms a low melting point eutectic. This causes very severe attack unless the chromium content is very high. Steels with low nickel contents should be used in environments containing sulphur or reducing sulphur compounds. For this reason the chromium steels exhibit good resistance to sulphidation.

In reducing environments such as hydrogen sulphide or hydrogen sulphide/hydrogen mixtures, stainless steels are attacked at even relatively low temperatures compared to the behaviour in air. Table 5 shows examples of the corrosion rate for some stainless steels in hydrogen sulphide at high temperatures. Table 6 shows corresponding data for some austenitic stainless steels in a mixture of hydrogen sulphide and hydrogen. The beneficial effect of a high chromium content is clear from the tables.

In oxidizing - sulphidizing environments such as sulphur dioxide (SO₂) the relative performance of stainless steels is similar to that in air, but the attack is more rapid and therefore more serious. The scaling temperature typically decreases by 70-125°C compared to that in air. The decrease is smallest for the chromium steels (5).

Table 5. Corrosion rates for different steel grades in 100% H₂S at atmospheric pressure and two different temperatures (5).

Steel grade	Composition (%)		Corrosion rate (mm/year)	
	Cr	Ni	400°C	500°C
5%Cr steel	5	-	6.1	25.4
9%Cr steel	9	-	5.1	17.8
403	13	-	3.3	10.2
431	17	-	2.3	5.1
446	26	-	no attack	2.5
304	18	9	2.0	5.1
310S	25	20	1.5	2.5

Table 6. Corrosion rate of some austenitic stainless steels in 50% H₂ - 50% H₂S at atmospheric pressure and different temperatures (5).

Steel grade AISI	Composition (%)			Corrosion rate (mm/year)		
	Cr	Ni	Mo	500°C	600°C	700°C
304	18	9	-	1.1	3.0	10.2
316	17	11	2.2	1.5	4.4	10.8
310S	25	20	-	0.9	2.8	8.9

Carbon pick-up (Carburization)

If a material is exposed to gases containing carbon, e.g. in the form of CO, CO₂ or CH₄, it can pick up carbon. The degree of carburisation is governed by the levels of carbon and oxygen in the gas, also the temperature and steel composition. The carbon which is picked up by the steel will largely form carbides, primarily chromium carbides.

Carbon pick-up causes embrittlement of stainless steel because carbides, or even a network of carbides, form in the grain boundaries as well as within the grains. The formation of a large amount of chromium carbides causes chromium depletion and thus a reduced resistance to oxidization and sulphidation. The resistance to thermal cycling is reduced and, since carburization leads to an increase in volume, there is a danger of cracks developing in the material.

Carbon pick-up can occur even at relatively low temperatures (400-800°C) in purely reducing - carburizing atmospheres and gives rise to catastrophic carburisation or metal dusting. Attack is severe and characterized by "powdering" of the steel surface due to the breakdown of the protective oxide layer and inward diffusion of carbon which forms grain boundary carbides. The increase in volume on carbide formation means that grains are rapidly broken away from the steel surface, giving rapid and serious attack.

Chromium, nickel and silicon are the alloying elements which most improve resistance to carburization. Table 7 shows carburization of some stainless steels in carburizing atmospheres. Note the beneficial effect of silicon, apparent from a comparison of Type 304 and 302B. Also note the high level of carburization in Type 316. In materials selection it is however necessary to consider both carburization and the effect of an increased carbon content on mechanical properties. In general, austenitic stainless steels can tolerate an increased carbon content better than other types of stainless steel.

Table 7. Carburization after 7340 hour at 910°C in an atmosphere of 34% H₂ 14% CO, 12.4% CH₄, 39.6% N₂ (6)

Steel grade AISI	Composition (%)			Carbon uptake (%)
	Cr	Ni	Other	
304	18	9		2.6
302B	18	9	2.5 Si	0.1
321	18	10	Ti	1.5
347	18	10	Nb	0.2
316	17	11	2.0 Mo	1.0
309S	23	13		0
310S	25	20		0
314	25	20	2.5 Si	0
330	15	35		0.9

Nitrogen pick-up (Nitridation)

Stainless steels and other high temperature materials can pick up nitrogen if exposed to nitrogen-containing atmospheres such as nitrogen, nitrogen mixtures and cracked ammonia. During nitrogen pick-up nitrides and other brittle compounds of chromium, molybdenum, titanium, vanadium and aluminium are formed. Atmospheric oxygen, even at relatively low levels, reduces the risk for nitridation. At low temperature, 400-600°C, a layer of nitrides are formed at the steel surface; at higher temperatures nitrogen uptake and nitride formation occur throughout the material. Nitridation i.e. nitride formation, causes chromium depletion and reduced oxidation resistance in the same way as carburization. This can lead to catastrophically high oxidation rates on the outer surface of equipment which is subjected to a nitriding atmosphere on the inside - for example the muffles in annealing furnaces. Nitrogen pick-up can also cause embrittlement due to surface or internal nitride formation.

Nickel is the alloying element which provides the greatest protection against nitridation, due to the fact that nickel does not form stable nitrides. This is illustrated by Figure 20 which shows the nitrided depth for some austenitic high-temperature alloys after exposure to nitrogen with traces of oxygen at 825°C. If oxygen is present, i.e. in oxidising conditions, strong oxide formers such as chromium and silicon are beneficial.

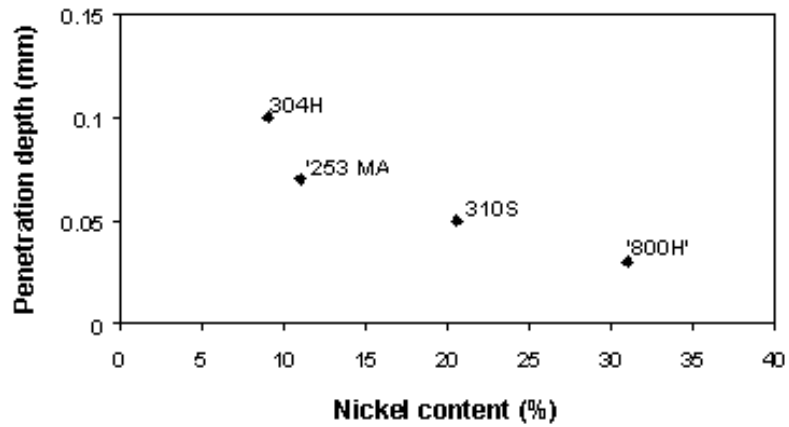


Figure 20. Nitrided depth for some stainless steels after exposure to nitrogen gas containing approximately 200 ppm oxygen at 825°C for 400 hours(7).

In view of the effect of nickel, it is inadvisable to use martensitic, ferritic-austenitic or ferritic stainless steels in nitriding atmospheres at temperature above approximately 500°C. More suitable materials are austenitic stainless steels or nickel-base alloys.

Mechanical properties

Stainless steels are often selected for their corrosion resistance, but they are at the same time constructional materials. Mechanical properties such as strength, high-temperature strength, ductility and toughness, are thus also important.

The difference in the mechanical properties of different stainless steels is perhaps seen most clearly in the stress-strain curves in Figure 21. The high yield and tensile strengths but low ductility of the martensitic steels is apparent, as is the low yield strength and excellent ductility of the austenitic grades. Ferritic-austenitic and ferritic steels both lie somewhere between these two extremes.

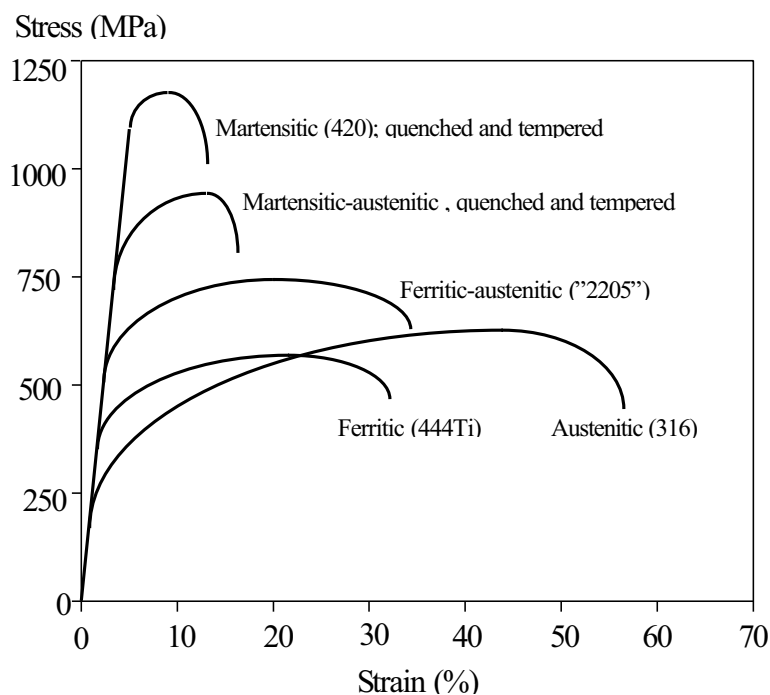


Figure 21. Stress-strain curves for some stainless steels.

The ferritic steels generally have a somewhat higher yield strength than the austenitic steels, while the ferritic-austenitic steels have an appreciably higher yield strength than both austenitic and ferritic steels. The ductility of the ferritic and ferritic-austenitic steels are of the same order of magnitude, even if the latter are somewhat superior in this respect.

Room temperature properties

In terms of mechanical properties, stainless steels can be roughly divided into four groups with similar properties within each group: martensitic and ferritic-martensitic, ferritic, ferritic-austenitic and austenitic. Table 8 gives typical mechanical properties at room temperature for a number of stainless steels in plate form.

Table 8. Typical mechanical properties for stainless steels at room temperature.

Steel grade		R _{p0.2}	R _{p1.0}	R _m	A ₅
ASTM	AvestaPolarit	(MPa)	(MPa)	(MPa)	(%)
<i>Martensitic</i>					
410S		540		690	20
“420L”		780		980	16
431		690		900	16
<i>Ferritic-martensitic</i>					
-	248 SV	790	840	930	18
446	-	340		540	25
444	Elit 18-2	390		560	30
<i>Ferritic-austenitic (Duplex)</i>					
S32304	SAF2304	470	540	730	36
S31803	2205	500	590	770	36
S32750	SAF2507	600	670	850	35
<i>Austenitic</i>					
304	18-9	310	350	620	57
304L	18-10L	290	340	590	56
304LN	18-9LN	340	380	650	52
304N	18-8N	350	400	670	54
321	18-10Ti	280	320	590	54
316L	17-11-2L	310	350	600	54
316Ti	17-11-2Ti	290	330	580	54
316	17-12-2.5	320	360	620	54
316L	17-12-2.5L	300	340	590	54
317L	18-13-3L	300	350	610	53
S31726	17-14-4LN	320	360	650	52
N08904	904L	260	310	600	49
S31254	254 SMO	340	380	690	50
S32654	654 SMO	520	560	890	55
<i>Austenitic (heat resistant steels)</i>					
310S	25-20	290	330	620	50
S30415	153 MA	380	410	700	50
S30815	253 MA	410	440	720	52
S35315	353 MA	360	400	720	50

Stress values have been rounded off to the nearest 10MPa. Standard deviations are normally 17-20MPa for R_{p0.2}, R_{p1.0} and R_m; 3% for A₅. More detailed information can be found in reference (8).

Martensitic and ferritic-martensitic steels are characterised by high strength and the fact that the strength is strongly affected by heat treatment. The martensitic steels are usually used in a hardened and tempered condition. In this condition the strength increases with the carbon content. Steels with more than 13% chromium and a carbon content above 0.15% are completely martensitic after hardening. A decrease in the carbon content causes an increase in the ferrite content and therefore a decrease in strength. The ductility of the martensitic steels is relatively low. The ferritic-martensitic steels have a high strength in the hardened and tempered condition in spite of their relatively low carbon content, and good ductility. They also possess excellent hardenability: even thick sections can be fully hardened and these steels will thus retain their good mechanical properties even in thick sections.

The mechanical properties of martensitic stainless steels are heavily influenced by the heat treatments to which the steels are subjected. A brief description of the general heat treatment of martensitic stainless steels and the effect on the mechanical properties is given below. Further information on the effects of various factors on the mechanical properties of the different martensitic stainless steels may be found in references 5 and 9.

In order to obtain a useful property profile martensitic stainless steels are normally used in the hardened and tempered condition. The hardening treatment consists of heating to a high temperature in order to produce an austenitic structure with carbon in solid solution followed by quenching. The austenitizing temperature is

generally in the range 925 - 1070 °C. The effect of austenitizing temperature and time on hardness and strength varies with the composition of the steel, especially the carbon content. In general the hardness will increase with austenitizing temperature up to a maximum and then decrease. The effect of increased time at the austenitizing temperature is normally a slow reduction in hardness with increased time. Quenching, after austenitizing, is done in air, oil or water depending on the steel grade. On cooling below the M_s - temperature, the starting temperature for the martensite transformation, the austenite transforms to martensite. The M_s - temperature lies in the range 300 - 70 °C and the transformation is finished of about 150 - 200 °C below the M_s - temperature. Almost all alloying elements will lower the M_s - temperature with carbon having the greatest effect. This means that in the higher alloyed martensitic grades the microstructure will contain retained austenite due to the low temperature (below ambient) needed in order to finish the transformation of the austenite into martensite.

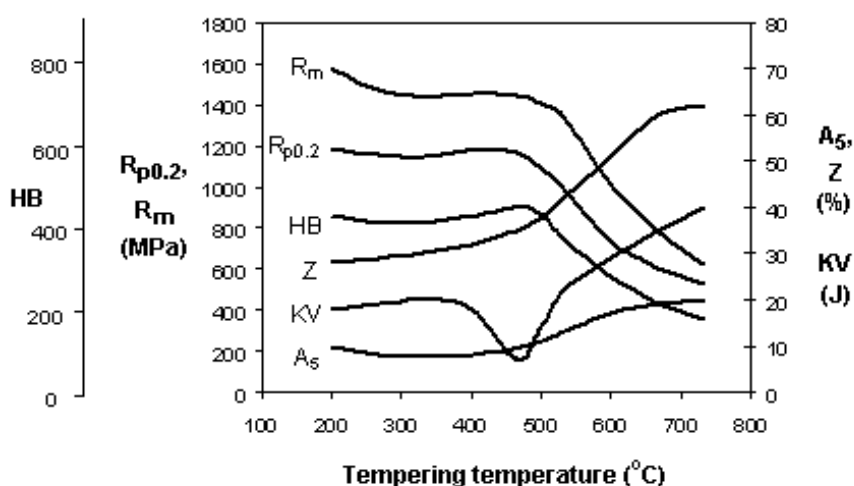


Figure 22. Effect of tempering temperature on the mechanical properties of AISI 431. Hardening treatment: 1020°C/30^m/Oil quench

In the hardened condition the strength and hardness are high but the ductility and toughness is low. In order to obtain useful engineering properties martensitic stainless steels are normally tempered. The tempering temperature used has a large influence on the final properties of the steel. The effect of tempering temperature on the mechanical properties of a martensitic stainless steel (AISI 431) is shown in Figure 22. Normally, increasing tempering temperatures below about 400 °C will lead to a small decrease tensile strength and an increase in reduction of area while hardness, elongation and yield strength are more or less unaffected. Above this temperature there will be a more or less pronounced increase in yield strength, tensile strength and hardness due to the secondary hardening peak, around 450 - 500 °C. In the temperature range around the secondary hardening peak there is generally a dip in the impact toughness curve. Above about 500 °C there is a rapid reduction in strength and hardness, and a corresponding increase in ductility and toughness. Tempering at temperatures above the A_{C1} temperature (780 °C for the steel in Figure 22) will result in partial austenitizing and the possible presence of untempered martensite after cooling to room temperature.

Ferritic steels have relatively low yield strength and the work hardening is limited. The strength increases with increasing carbon content, but the effect of chromium content is negligible. However, ductility decreases at high chromium levels and good ductility requires very low levels of carbon and nitrogen.

Ferritic-austenitic (duplex) steels have a high yield stress with increases with increasing carbon and nitrogen levels. An increased ferrite content will, within limits, also increase the strength of duplex steels. Their ductility is good and they exhibit strong work hardening.

Austenitic steels generally have a relatively low yield stress and are characterised by strong work hardening. The strength of the austenitic steels increases with increasing levels of carbon, nitrogen and, to a certain extent, also molybdenum. The detrimental effect of carbon on corrosion resistance means that this element cannot be used for increasing strength. Austenitic steels exhibit very high ductility: they have a high elongation and are very tough.

Some austenitic stainless steels with low total content of alloying elements, e.g. Type 301 and 304, can be metastable and may form martensite either due to cooling below ambient temperature or through cold deformation

or a combination of both. The formation of martensite will cause a considerable increase in strength, as illustrated in Figure 23. The temperature below which α' martensite will form is called the M_d temperature. The stability of the austenite depends on the composition, the higher the content of alloying elements the more stable will it be. A common equation for relating austenite stability and alloy composition is the M_{d30} , which is defined as the temperature at which martensite will form at a strain of 30% (10):

$$M_{d30} = 551 - 462(C+N) - 9.2Si - 8.1Mn - 13.7Cr - 29(Ni+Cu) - 18.5Mo - 68Nb - 1.42(GS - 8.0) \quad (^\circ C)$$

where GS = grain size, ASTM grain size number

This type of equation gives a good idea of the behaviour of lean austenitic stainless steels but it must be noted that it is only approximate since interactions between the alloying elements are not taken into account.

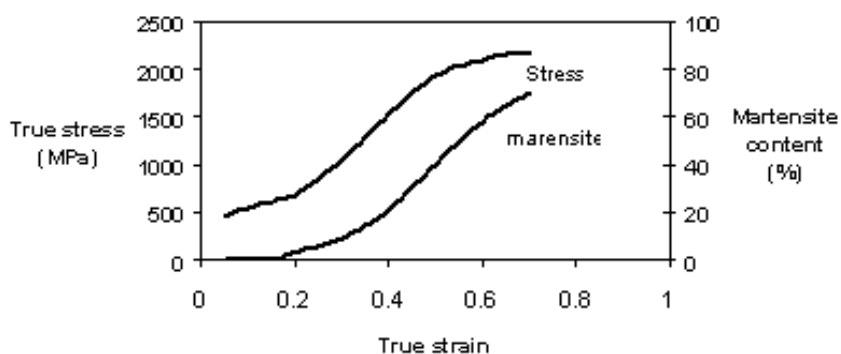


Figure 23. The effect of strain on martensite and yield strength of AISI 301. (5)

The effect of alloying elements and structure on the strength of austenitic and ferritic-austenitic steels is apparent from the following regression equations:

$$R_{p0,2} = 120 + 210\sqrt{N + 0.02} + 2Mn + 2Cr + 14Mo + 10Cu + (6.15 - 0.054\delta)\delta + (7 + 35(N + 0.2))d^{-1/2} \quad (MPa)$$

$$R_{p1,0} = R_{p0,2} + 40 \quad (MPa)$$

$$R_m = 470 + 600(N + 0.02) + 14Mo + 1.5\delta + 8d^{-1/2} \quad (MPa)$$

where N, Mn, etc. denote the level of the alloying elements in wt%.

δ is the ferrite content in %.

d is the grain size in mm.

These regression equations can be used to estimate the strength of an austenitic and ferritic-austenitic steel with an uncertainty of approximately 20MPa (11).

In contrast to the constructional steels, austenitic steels do not exhibit a clear yield stress but begin to deform plastically at a stress around 40% of $R_{p0,2}$.

It may be noted that although the different elements are included in the equation through rather simple expressions, the actual strengthening mechanism may be more complex. Both chromium and nitrogen work through more complex effects than may be seen at first sight. At chromium contents over 20% an austenitic steel with 10% Ni will contain δ -ferrite which in turn causes a smaller grain size and this will increase both the yield strength and the tensile strength. Nitrogen is an element that has a strong strengthening effect but it is also a powerful austenite stabiliser. In duplex stainless steels the strengthening effect of nitrogen is to a certain extent countered by the increased austenite content caused by the addition of nitrogen.

Stainless steels will harden during deformation. The amount of hardening depends on both the composition and the type of steel. The work hardening exponent (n) defined as

$$\sigma = K \cdot \varepsilon^n$$

where σ and ε are true stress and true strain respectively gives a simple measure of the tendency to work harden. Ferritic steels have a work hardening exponents of about 0.20. For austenitic steels the work hardening exponent is strain dependent. For the stable grades it lies in the range 0.4 to 0.6 and for the unstable grades, i.e. those that form martensite at large deformations, it lies in the range 0.4 to 0.8. The higher values are valid for higher strains. Nickel, copper and nitrogen tend to reduce the work hardening. Most other elements will increase the work hardening.

The effect of cold work

The mechanical properties of stainless steels are strongly affected by cold work. In particular the work hardening of the austenitic steels causes considerable changes in properties after, e.g. cold forming operations. The general effect of cold work is to increase the yield and tensile strengths and at the same time decrease the elongation. Figure 24 shows cold work curves for some stainless steels.

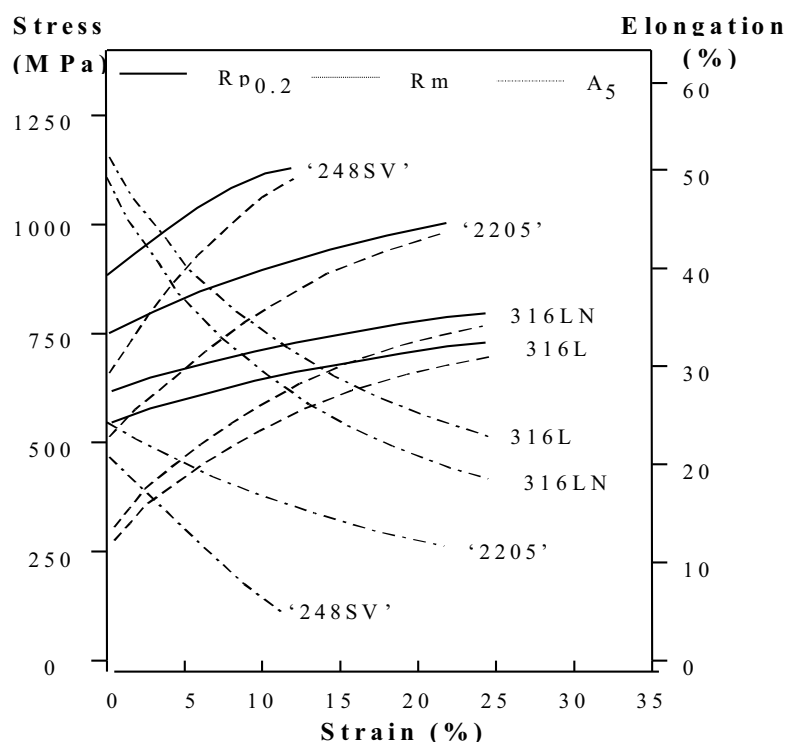


Figure 24. Effect of cold work on some stainless steels.

The work hardening is larger for austenitic steels than for ferritic steels. The addition of nitrogen in austenitic steels makes these grades particularly hard and strong: compare 316L and 316LN. The strong work hardening of the austenitic steels means that large forces are required for forming operations even though the yield strength is low. Work hardening can, however, also be deliberately used to increase the strength of a component.

Toughness

The toughness of the different types of stainless steels shows considerable variation, ranging from excellent toughness at all temperatures for the austenitic steels to the relatively brittle behaviour of the martensitic steels. Toughness is dependent on temperature and generally increases with increasing temperature.

One measure of toughness is the impact toughness, i.e. the toughness measured on rapid loading. Figure 25 shows the impact toughness for different categories of stainless steel at temperatures from -200 to $+100$ °C. It is apparent from the diagram that there is a fundamental difference at low temperatures between austenitic steels and martensitic, ferritic and ferritic-austenitic steels.

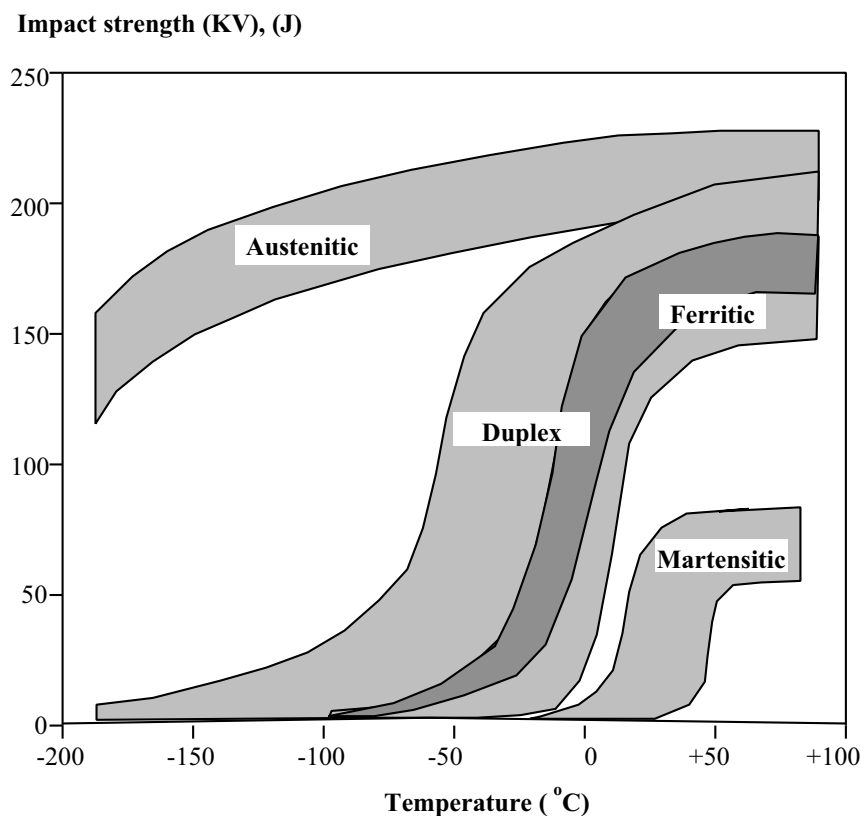


Figure 25. Impact toughness for different types of stainless steels.

The martensitic, ferritic and ferritic-austenitic steels are characterised by a transition in toughness, from tough to brittle behaviour, at a certain temperature, the transition temperature. For the ferritic steel the transition temperature increases with increasing carbon and nitrogen content, i.e. the steel becomes brittle at successively higher temperatures. For the ferritic-austenitic steels, an increased ferrite content gives a higher transition temperature, i.e. more brittle behaviour. Martensitic stainless steels have transition temperatures around or slightly below room temperature, while those for the ferritic and ferritic-austenitic steels are in the range 0 to - 60°C, with the ferritic steels in the upper part of this range.

The austenitic steels do not exhibit a toughness transition as the other steel types but have excellent toughness at all temperatures. Austenitic steels are thus preferable for low temperature applications.

Fatigue properties

During cyclic loading stainless steels, as other materials, will fail at stress levels considerably lower than the tensile strength measured during tensile testing. The number of load cycles the material can withstand is dependent on the stress amplitude. The life time, i.e. the number of cycles to failure, increases with decreasing load amplitude until a certain amplitude is reached, below which no failure occurs (Figure 26). This stress level is called the fatigue limit. In many cases there are no fatigue limit but the stress amplitude shows a slow decrease with increasing number of cycles. In these cases the fatigue strength, i.e. the maximum stress amplitude for a certain time to failure (number of cycles) is called the fatigue strength and it is always given in relation to a certain number of cycles.

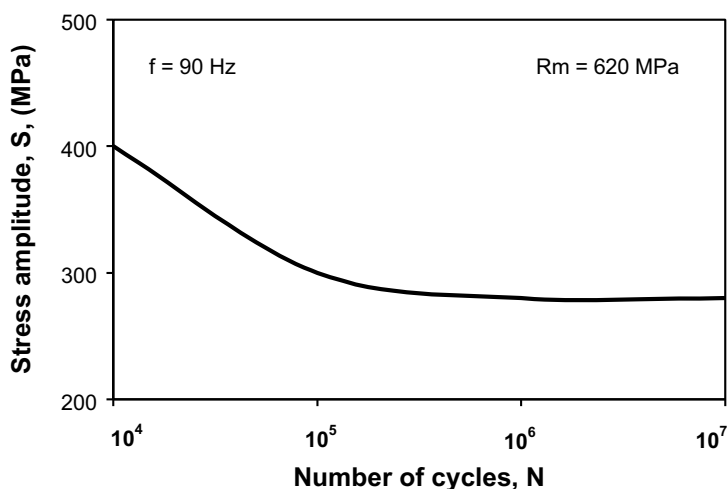


Figure 26. S-N curve (Wohler curve) for an austenitic stainless steel of Type 316(hMo) in air.

The fatigue properties, described by the Wohler or S-N curve with a fatigue limit (S_0 = load amplitude) at a lifetime of 10^6 - 10^7 load cycles, of ferritic-austenitic and austenitic stainless steels can be related to their tensile strength as shown in Table 9. The relation between the fatigue limit and the tensile strength is also dependent on the type of load, that is the stress ratio (R). The stress ratio is ratio of the minimum stress to the maximum stress during the loading cycle (compressive stresses are defined as negative).

Table 9. Fatigue properties of stainless steels, relation between tensile strength and fatigue strength.

Steel category	S_0/R_m		Maximum stress
	Stress ratio		
	R = -1	R = 0	
Ferritic	0.7	0.47	Yield strength
Austenitic	0.45	0.3	Yield strength
Ferritic-austenitic	0.55	0.35	Yield strength

The fatigue strength is sensitive to the service environment and under both cyclic loading and corrosive conditions, corrosion fatigue, the fatigue strength will generally decrease. In many cases there is no pronounced fatigue limit, as observed in air, but a gradual lowering of the fatigue strength with increasing number of load cycles. The more aggressive the corrosive conditions and the lower the loading frequency the higher the effect of the environment. During very high frequency loads there is little time for the corrosion to act and the fatigue properties of the material will mostly determine the service life. At lower frequencies the corrosive action is more pronounced and an aggressive environment may also cause corrosion attacks that will act as stress concentrations and thus contribute to a shorter life. As can be seen from Fig. 27, a lower pH, i.e. a more aggressive condition, gives a lower fatigue strength. Comparison of the two austenitic steels shows that the higher alloyed grade, 316LN, that has the higher corrosion resistance also has a higher corrosion fatigue strength.

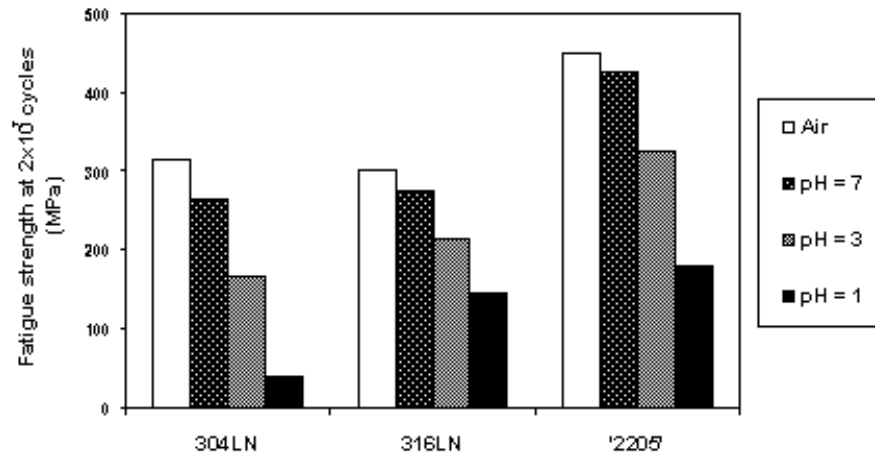


Figure 27. Effect of environment on fatigue strength for some stainless steels (12). Fatigue strength at 40 °C and rotating bending stress at 100Hz. Tested in air and 3% NaCl at various pH.

High temperature mechanical properties

The high temperature strength of various steel grades is illustrated by the yield strength and creep rupture strength curves in Figure 28.

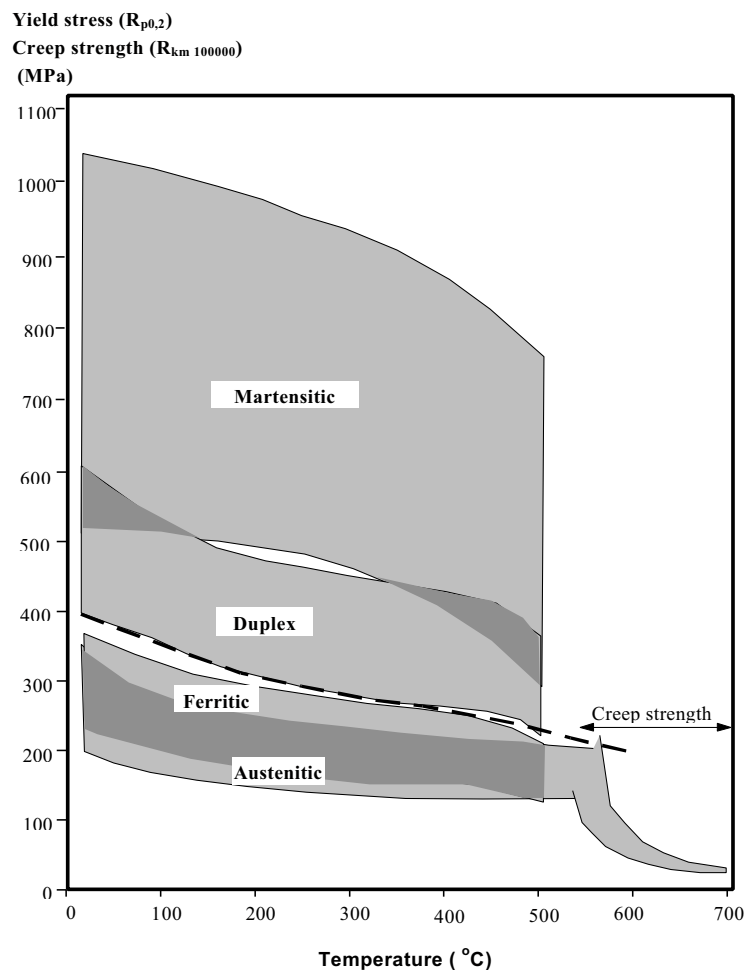


Figure 28. Elevated temperature strength of stainless steels. The dashed line shows the yield stress of some very high alloyed and nitrogen alloyed austenitic steels.

Martensitic and martensitic-austenitic steels in the hardened and tempered condition exhibit high elevated temperature strength at moderately elevated temperatures. However, the useful upper service temperature is limited by the risk of over-tempering and embrittlement. The creep strength is low. This type of stainless steel is not usually used above 300°C but special grades are used at higher temperatures. The wide range of elevated temperature strength shown in Figure 28 is due to the wide range of strength levels offered by different grades and heat treatments.

Ferritic steels have relatively high strength up to 500°C. The creep strength, which is usually the determining factor at temperatures above 500°C, is low. The normal upper service temperature limit is set by the risk of embrittlement at temperatures above 350°C. However, due to the good resistance of chromium steels to high temperature sulphidation and oxidation a few high chromium grades are used in the creep range. In these cases special care is taken to ensure that the load is kept to a minimum.

The **ferritic-austenitic (duplex) steels** behave in the same way as the ferritic steels but have higher strength. The creep strength is low. The upper service temperature limit is normally 350°C due to the risk of embrittlement at higher temperatures.

Most **austenitic steels** have lower strength than the other types of stainless steels in the temperature range up to about 500 °C. The highest elevated temperature strength among the austenitic steels is exhibited by the nitrogen alloyed steels and those containing titanium or niobium. In Figure 28 the elevated temperature strengths of most of the ordinary austenitic steels fall within the marked area. The dashed line represents the elevated temperature strength of a few high alloyed and nitrogen alloyed austenitic steels. In terms of creep strength the austenitic stainless steels are superior to all other types stainless steel (see Figure 29).

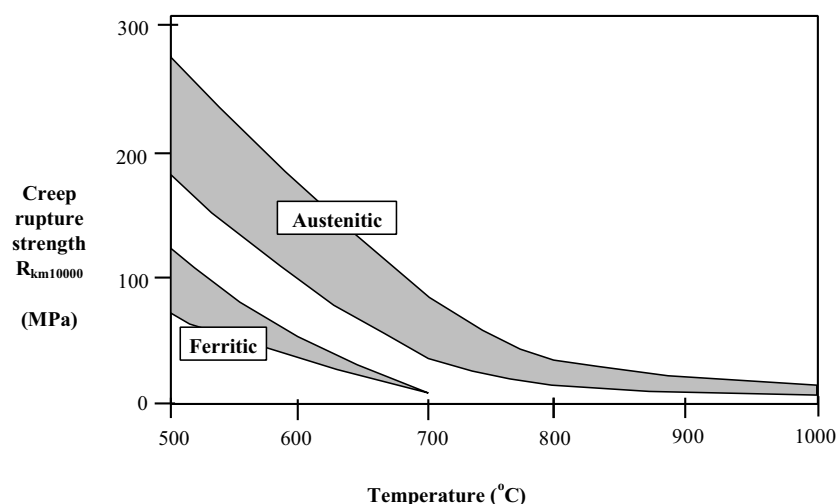


Figure 29. Creep strength for austenitic and ferritic steels.

Precipitation and embrittlement

Under various circumstances, the different stainless steel types can suffer undesirable precipitation reactions which lead to a decrease in both corrosion resistance and toughness. Figure 30 gives a general overview of the characteristic critical temperature ranges for the different steel types.

475°C embrittlement

If martensitic, ferritic or ferritic-austenitic steels are heat treated or used in the temperature range 350-550°C, a serious decrease in toughness will be observed after shorter or longer times. The phenomenon is encountered in alloys containing from 15 to 75 % chromium and the origin of this embrittlement is the spinodal decomposition of the matrix into two phases of body-centered cubic structure, α and α' . The former is very rich in iron and the latter very rich in chromium. This type of embrittlement is usually denoted 475°C embrittlement.

Carbide and nitride precipitation

If ferritic steels are heated to temperatures above approximately 950°C, they suffer precipitation of chromium carbides and chromium nitrides during the subsequent cooling, and this causes a decrease in both toughness and corrosion resistance. This type of precipitation can be reduced or eliminated by decreasing the levels of carbon and nitrogen to very low levels and at the same time stabilizing the steel by additions of titanium as in 18Cr-2Mo-Ti.

Carbide and nitride precipitation in the austenitic and ferritic-austenitic steels occurs in the temperature range 550-800°C. Chromium-rich precipitates form in the grain boundaries and can cause intergranular corrosion and, in extreme cases, even a decrease in toughness. However, after only short times in the critical temperature range, e.g. in the heat affected zone adjacent to welds, the risk of precipitation is very small for the low-carbon steels.

Intermetallic phases

In the temperature range 700-900°C, iron alloys with a chromium content above about 17% form intermetallic phases such as sigma phase, chi phase and Laves phase. These phases are often collectively called "sigma phase" and all have the common features of a high chromium content and brittleness. This means that a large amount of the precipitated phase leads to a drop in toughness and a decrease in resistance to certain types of corrosion. The size of the deterioration in properties is to some extent dependent on which of the phases that actually is present.

Alloying with molybdenum and silicon promotes the formation of intermetallic phases, so the majority of ferritic, ferritic-austenitic and austenitic steels show some propensity to form "sigma phase". Intermetallic phases form most readily from highly-alloyed ferrite. In ferritic and ferritic-austenitic steels, intermetallic phases therefore form readily but are on the other hand relatively easy to dissolve on annealing. In the austenitic steels, it is the highly alloyed grades which are particularly susceptible to intermetallic phase formation. Austenitic steels which have low chromium content and do not contain molybdenum require long times to form intermetallics and are therefore considerably less sensitive to the precipitation of these phases.

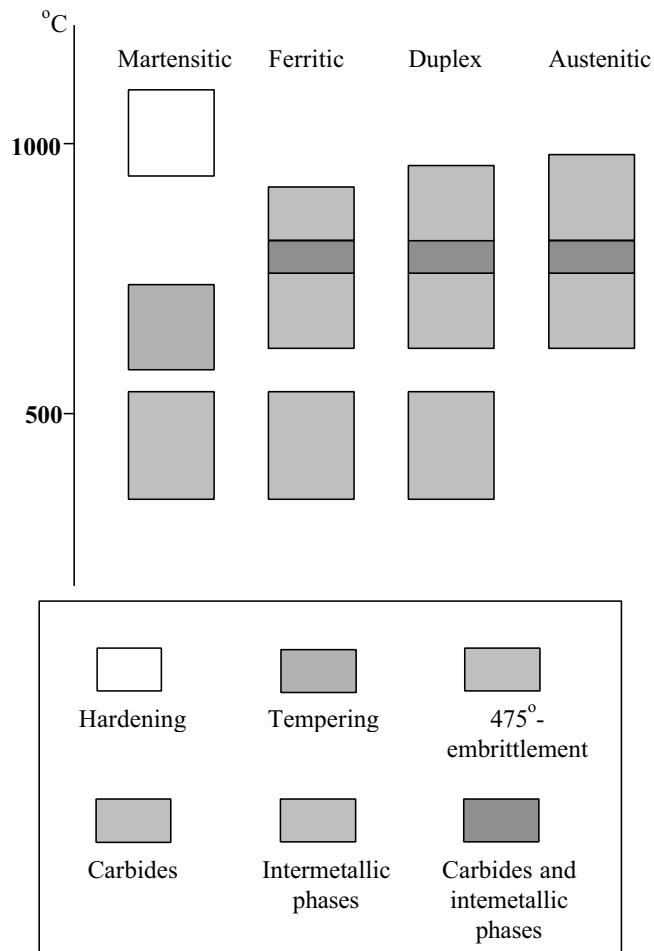


Figure 30. Characteristic temperature ranges for stainless steels.

Finally, it should be noted that all types of precipitates can be dissolved on annealing. Re-tempering martensitic steels and annealing and quenching ferritic, ferritic-austenitic or austenitic steels restores the structure. Relatively long times or high temperatures may be required for the dissolution of intermetallic phases in highly alloyed steels.

Physical properties

In terms of physical properties, stainless steels are markedly different from carbon steels in some respects. There are also appreciable differences between the various categories of stainless steels. Table 10 and Figures 31-33 shows typical values for some physical properties of stainless steels.

Table 10. Typical physical properties for various stainless steel categories.

Property	Type of stainless steel			
	Martensitic *	Ferritic	Austenitic	Ferritic-austenitic
Density (g/cm ³)	7.6-7.7	7.6-7.8	7.9-8.2	.8
Young's modulus (N/mm ²) or (MPa)	220,000	220,000	195,000	200,000
Thermal expansion (x 10 ⁻⁶ /°C) 200-600°C	12-13	12-13	17-19	13
Thermal conductivity (W/m°C) 20°C	22-24	20-23	12-15	20
Heat capacity (J/kg°C) 20°C	460	460	440	400
Resistivity (nΩm) 20°C	600	600-750	850	700-850
Ferromagnetism	Yes	Yes	No	Yes

* in the hardened and tempered condition

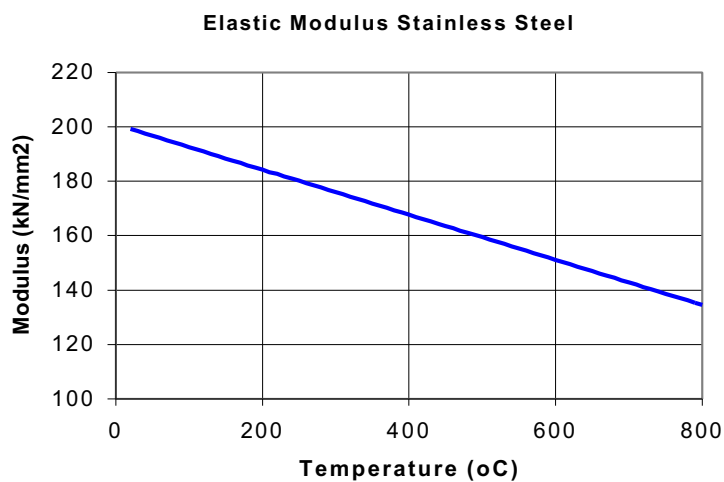


Figure 31 Elastic Modulus of Austenitic Stainless Steels .

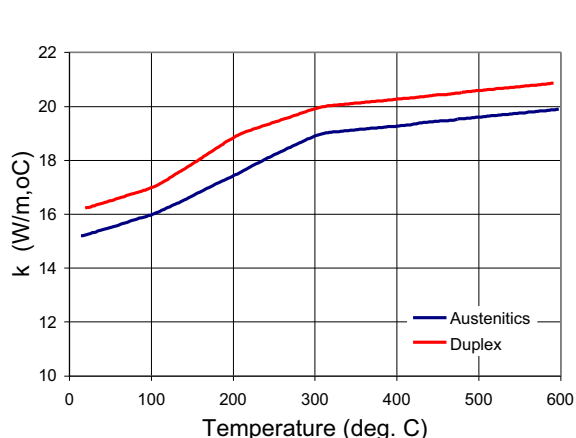


Figure 32 Thermal Conductivity for Austenitic and Duplex Stainless Steels.

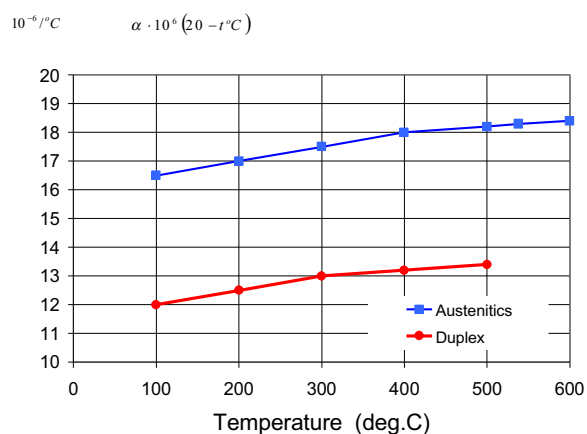


Figure 33 Mean Linear Thermal Expansion for Austenitic and Duplex Stainless Steels.

The austenitic steels generally have a higher density than the other stainless steel types. Within each steel category, density usually increases with an increasing level of alloying elements, particularly heavy elements such as molybdenum.

The two important physical properties that show greatest variation between the stainless steel types, and are also markedly different for stainless steels and carbon steels, are thermal expansion and thermal conductivity. Austenitic steels exhibit considerably higher thermal expansion than the other stainless steel types. This is can cause thermal stresses in applications with temperature fluctuations, heat treatment of complete structures and on welding. Thermal conductivity for stainless steels is generally lower than for carbon steels and decreases with increasing alloying level for each stainless steel category. The thermal conductivity decreases in the following order: martensitic steels, ferritic and ferritic-austenitic steel and finally austenitic steels which have the lowest thermal conductivity.

Property relationships for stainless steels

Using one stainless steel grade in each group or category as a starting point, i.e. regarding it as the archetype for the category, it is now possible to see how the other steel grades within the category have evolved or how they are related. In this way the full range of stainless steels may be systematised. The property and alloying relationships between the different grades in the group are shown in the overview in Figures 34 and 35.

Martensitic and martensitic-austenitic steels

The steels in this group are characterised by high strength and limited corrosion resistance.

An increased carbon content increases strength, but at the expense of lower toughness and considerable degradation of weldability. Strength thus increases in the series: AISI 420R, 420L and 420 while toughness and weldability decrease. The martensitic 13% chromium steels with higher carbon contents are not designed to be welded, even though it is possible under special circumstances. In order to increase high temperature strength, alloying with strong carbide formers such as vanadium and tungsten are used in 13Cr-0.5Ni-1Mo+V. An increase in the nickel content also increases toughness and leads to the martensitic-austenitic steels 13Cr-5Ni and 16Cr-5Ni-1Mo. These are characterised by high strength, good high temperature strength and, because of the low carbon content in the martensite, good toughness even when welded. In contrast to the martensitic steels, the martensitic-austenitic steels do not have to be welded at elevated temperatures except in thick section, even then only limited preheating is required.

An increased chromium content increases corrosion resistance, while an increased carbon content has the opposite effect due to the formation of chromium carbides. Alloying with molybdenum improves corrosion resistance and it is molybdenum, in combination with the higher chromium content, which gives 16Cr-5Ni-1Mo superior corrosion resistance to the other hardenable stainless steels. The martensitic stainless steels are resistant to damp air, steam, freshwater, alkaline solutions (hydroxides) and dilute solutions of organic and oxidising inorganic acids. The martensitic-austenitic steels, in particular 16Cr-5Ni-1Mo, exhibit better corrosion resistance than the other steels in the group. 16Cr-5Ni-1Mo can be used in the same environments as the martensitic steels with 13% or 17% chromium, but can withstand higher concentrations and higher temperatures. The martensitic steels have poor resistance to pitting and crevice corrosion but are largely immune to stress corrosion cracking. They should not normally be used in sea water without cathodic protection. 16Cr-5Ni-1Mo is comparable with the low alloyed austenitic stainless steels in terms of resistance to pitting and crevice corrosion in sea water but is not susceptible to stress corrosion cracking.

The areas of use of martensitic and martensitic-austenitic steels are naturally those in which the high strength is an advantage and the corrosion requirements are relatively small. The martensitic steels with low carbon contents (AISI 410S and 410) and the martensitic-austenitic steels are often used as stainless constructional materials. In addition, AISI 410S is used for, among other things, tubes for heat exchangers in the petrochemical industry, while AISI 410 is used for stainless cutlery. The martensitic steels with a high carbon content (AISI 420L and 420) are used for springs, surgical instruments and for sharp-edged tools such as knives and scissors. The higher chromium content in AISI 431 means that it is often used for marine fittings and for components in the nitric acid industry.

Ferritic steels

The ferritic steels are characterised by good corrosion properties, very good resistance to stress corrosion cracking and moderate toughness.

The toughness of ferritic stainless steels are generally not particularly high. Lower carbon and nitrogen levels, as in AISI 444, give a considerable improvement in both toughness and weldability, although toughness is limited for thicker dimensions. Consequently ferritic steels are usually only produced and used in thinner dimensions.

The ferritic steels exhibit good corrosion resistance: AISI 444 is comparable to the austenitic AISI 316 in this respect. However, the ferritic steels are also very resistant to stress corrosion cracking. Higher levels of chromium yield better oxidation resistance and the absence of nickel results in good properties in sulphur-containing environments at high temperatures. This is one of the major areas of use of AISI 446.

Use of AISI 430 and AISI 444 includes piping, heat exchanger tubes, vessels and tanks in the food, chemical and paper industries. AISI 444 can also be used in water with moderately high levels of chlorides in applications where there is a danger of stress corrosion cracking. Low alloyed ferritic stainless steels are also used in mild environments where freedom from maintenance is sought or where a 'non-rusting' material is required.

Ferritic-Austenitic (Duplex) steels

The modern duplex steels span the same wide range of corrosion resistance as the austenitic steels. The corrosion resistance of the duplex steels increases in the order “2304” (23Cr-4Ni) — “2205” (22Cr-5Ni-3Mo) — “2507” (25Cr-7Ni-4Mo). Duplex equivalents can be found to both the ordinary austenitic grades, such as 316L, and to the high alloyed austenitic grades, such as ‘254 SMO’. The corrosion resistance of “2304” type duplex is similar that of 316L while “2205” is similar to “Type” 904L and “2507” is similar to the high alloyed austenitic grades with 6% molybdenum, such as ‘254 SMO’.

The ferritic-austenitic (duplex) steels are characterised by high strength, good toughness, very good corrosion resistance in general and excellent resistance to stress corrosion cracking and corrosion fatigue in particular. An increased level of chromium, molybdenum and nitrogen increases corrosion resistance, while the higher nitrogen level also contributes to a further increase in strength above that associated with the duplex structure.

Applications of ferritic-austenitic steels are typically those requiring high strength, good corrosion resistance and low susceptibility to stress corrosion cracking or combinations of these properties. The lower alloyed “2304 type” is used for applications requiring corrosion resistance similar to 316L or lower and where strength is an advantage. Some examples of such applications are: hot water tanks in the breweries, pulp storage towers in the pulp and paper industry, tanks for storage of chemical in the chemical process industry and tank farms in tank terminals in the transportation industry. The higher alloyed “2205 type” is for example used in pulp digesters and storage towers in the pulp and paper industry where it is rapidly becoming a standard grade. It is also used in piping systems, heat exchangers, tanks and vessels for chloride-containing media in the chemical industry, in piping and process equipment for the oil and gas industry, in cargo tanks in ships for transport of chemicals, and in shafts, fans and other equipment which require resistance to corrosion fatigue. High alloyed grades, e.g. “2507”, are used in piping and process equipment for the offshore industry (oil and gas) and in equipment for environments containing high chloride concentrations, such as sea water.

Austenitic steels

The austenitic steels are characterised by very good corrosion resistance, very good toughness and very good weldability; they are also the most common stainless steels.

Resistance to general corrosion, pitting and crevice corrosion generally increases with increasing levels of chromium and molybdenum, while high levels of nickel and molybdenum are required to increase resistance to stress corrosion cracking. Resistance to pitting and crevice corrosion thus increases in the order: AISI 304 / 304L - 316 / 316L - 317L - ‘904L’ - ‘254 SMO’ — ‘654 SMO’. The low-carbon grades exhibit good resistance to intergranular corrosion and consequently the higher alloyed steels are only available with low carbon contents. The stabilised steels (AISI 321, 347 and 316Ti) and the nitrogen-alloyed steels (304LN and 316LN) have roughly the same corrosion properties in most environments as the equivalent low-carbon grades: 304L and 316L respectively. There are however, exceptions to this rule so it should be treated with some caution. Austenitic steels are generally susceptible to stress corrosion cracking; only the highly alloyed steels ‘904L’, ‘254 SMO’ and ‘654 SMO’ exhibit good resistance to this type of corrosion. An increased level of chromium and silicon, in combination with additions of rare earth metals (cerium), gives an increased resistance to high temperature corrosion, which is exploited in ‘153 MA’, ‘253MA’ and ‘353MA’.

The austenitic stainless steels are used in almost all types of applications and industries. Typical areas of use include piping systems, heat exchangers, tanks and process vessels for the food, chemical, pharmaceutical, pulp and paper and other process industries. Non-molybdenum alloyed grades, e.g. 304 and 304L, are normally not used in chloride-containing media but are often used where demands are placed on cleanliness or in applications in which equipment must not contaminate the product. The molybdenum-alloyed steels are used in chloride-containing environment with the higher alloyed steels, ‘904L’, ‘254 SMO’ and ‘654 SMO’, being chosen for higher chloride contents and temperatures. Grades such as ‘254 SMO’ and ‘654 SMO’ are used to handle sea water at moderate or elevated temperatures. Applications include heat exchangers, piping, tanks, process vessels, etc. within the offshore, power, chemical and pulp & paper industries.

The low alloyed grades, especially 304, 304LN and 304N but also 316LN, are used in equipment for cryogenic applications. Examples are tanks, heaters, evaporator and other equipment for handling of condensed gases such as liquid nitrogen.

Another use is in high temperature applications or equipment designed for elevated temperature service. In these cases both the good creep resistance and the good oxidation resistance of the austenitic steels are exploited. High carbon grades (AISI 304H) and stabilised steels (AISI 321, 347 and 316Ti) or nitrogen-alloyed steels (AISI 304LN and 316LN) are used at elevated and moderately high temperatures depending on the service temperature and environment. At higher temperatures (above about 750 °C) special high temperature or heat resistant grades are needed, such as 310, ‘153 MA’, ‘253MA’ and ‘353MA’. Typical applications for the heat resistant steels are furnace components, muffles, crucibles, hoods, recuperators, cyclones and conveyor belts working at high

temperatures. The high alloyed heat resistant grades, such as '353MA', are used in aggressive high temperature environments, such as those encountered in waste incineration.

Finally it is worth mentioning that austenitic stainless steels are often used in applications requiring non-magnetic materials since they are the only non-magnetic steels.

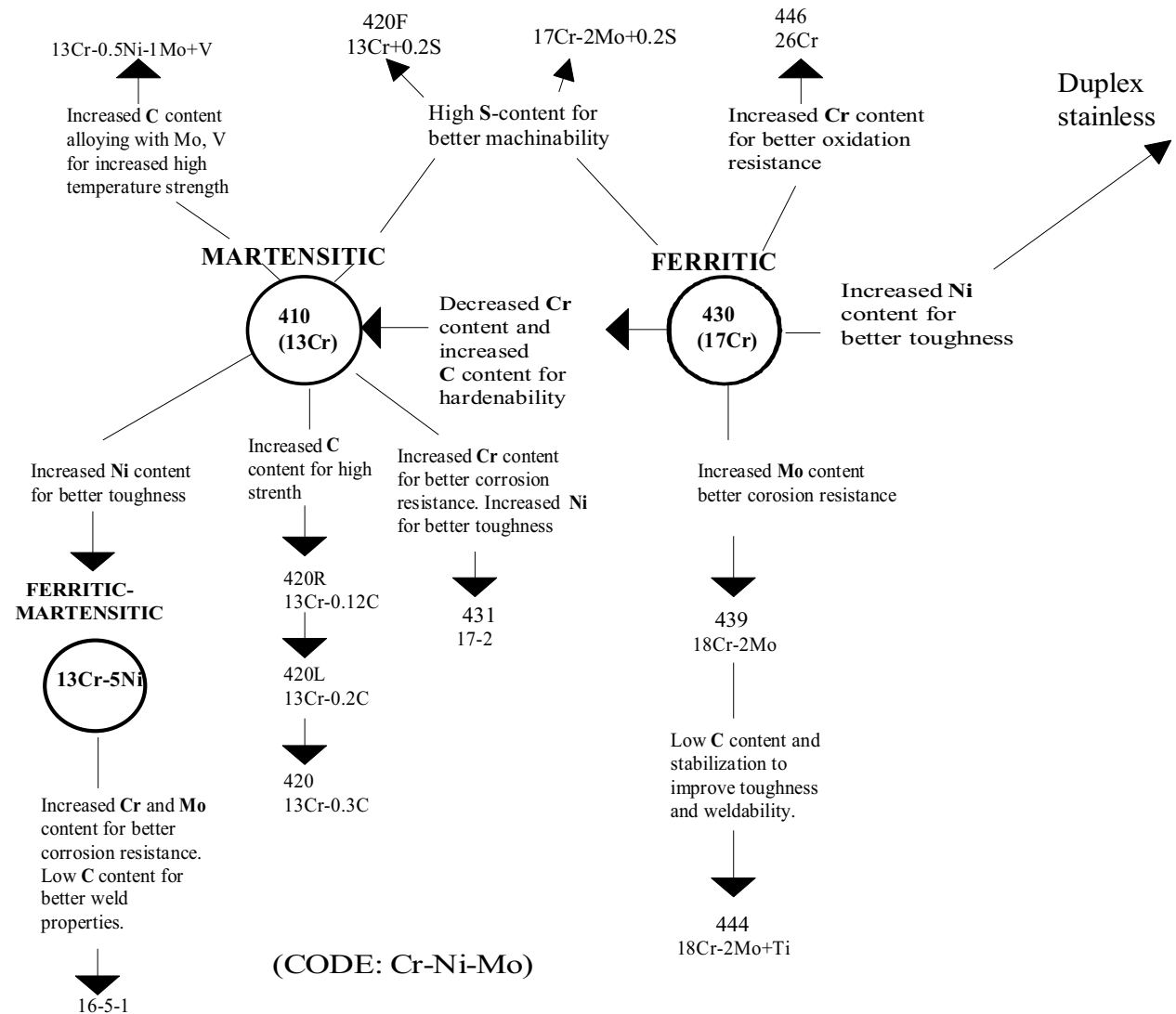


Figure 34 Compositional and property relations for martensitic and ferritic stainless steels.

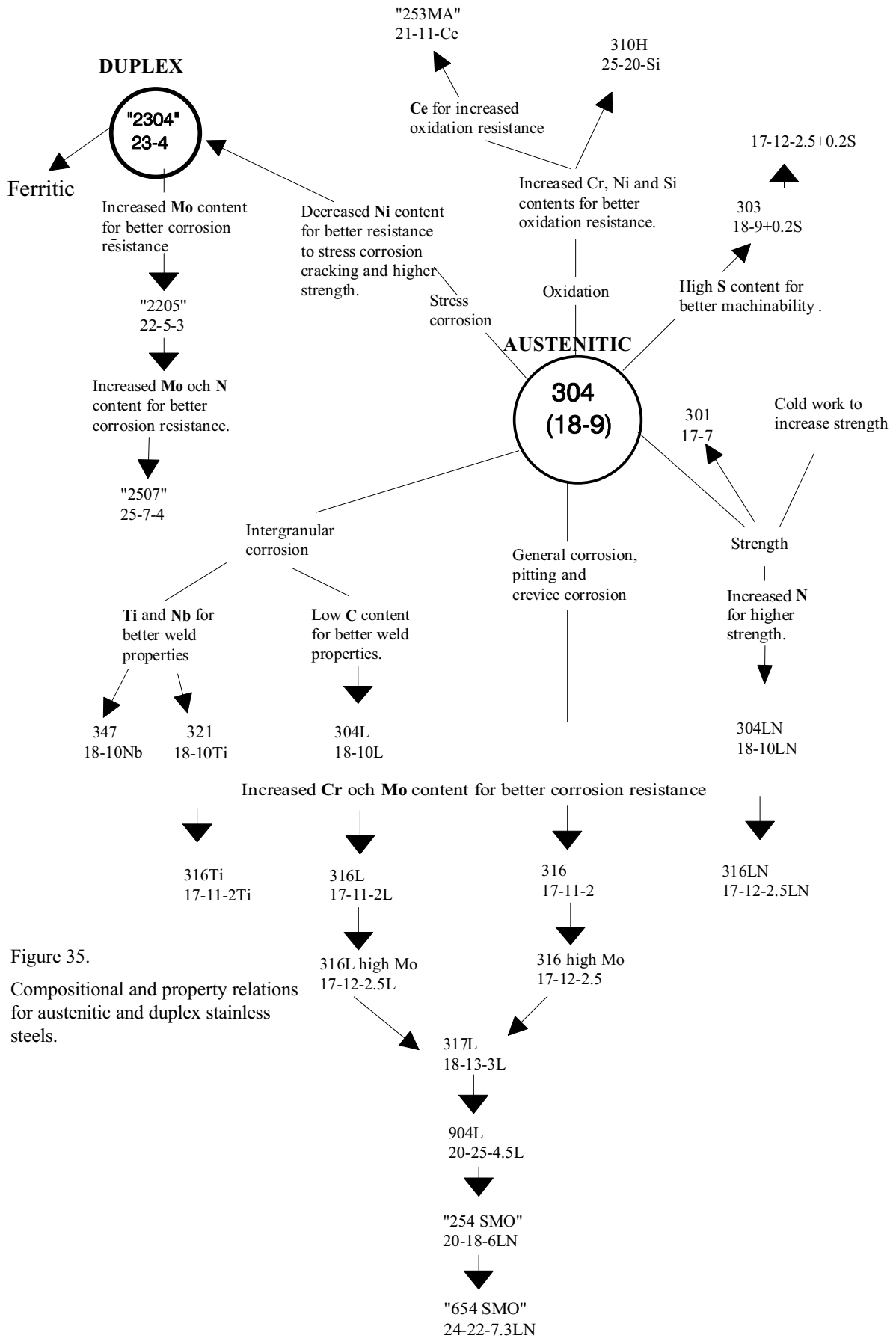


Figure 35. Compositional and property relations for austenitic and duplex stainless steels.

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In Nordic Symposium on Mechanical Properties of Stainless Steels.
H. Nordberg, K. Fernheden (ed.)
Avesta Research Foundation, 1990.

Attachment 1.1

Chemical composition and US, European and British Standard designations for Stainless Steels

The composition ranges given are valid for the European standards (EN) and the US standards (AISI/ASTM). The different standards should be consulted for detailed information regarding compositions and composition ranges. Equivalent American and European grades are grouped together and marked with { . The BS grade designations are the equivalents or the closest available equivalents to the AISI or EN grades.

ASTM	EN	C (%)	N (%)	Cr (%)r	Ni (%)	Mo (%)	Others (%)	BS	Avesta Polaris grade
Ferrite and martensitic steels									
409		≤ 0.08		10.5 - 11.75	≤ 0.5		Ti	409S19	409
	1.4512	≤ 0.03		10.5 - 12.5			Ti	409S19	409
410S		≤ 0.08		11.5 - 13.5	≤ 0.6			403S17	410S
	1.4000	≤ 0.08		12.0 - 14.0				403S17	410S
410		≤ 0.15		11.5 - 13.5	≤ 0.75			410S21	393 HCR
	1.4006	0.08 - 0.15		11.5 - 13.5	≤ 0.75			410S21	
		0.18 - 0.25		12.0 - 14.0	≤ 1.0			420S29	13XH
420		≥ 0.15		12.0 - 14.0				420S45	420
	1.4028	0.26 - 0.35		12.0 - 14.0				420S45	420
"420L"	1.4021	0.16 - 0.25		12.0 - 14.0				420S29	420L
430		≤ 0.12		16.0 - 18.0	≤ 0.75			430S17	430
	1.4016	≤ 0.08		16.0 - 18.0				430S17	430
431		≤ 0.20		15.0 - 17.0	1.25 - 2.5			431S29	16-2XH
	1.4057	0.12 - 0.22		15.0 - 17.0	1.5 - 2.5			431S29	16-2XH
434		≤ 0.08		16.0 - 18.0		0.75 - 1.25			
444		≤ 0.025	≤ 0.035	17.5 - 19.5	≤ 1.0	1.75 - 2.5	Ti		ELI-T 18-2
	1.4521	≤ 0.025	≤ 0.030	17.0 - 20.0		1.8 - 2.5	Ti		ELI-T 18-2
446		≤ 0.20	≤ 0.25	23.0 - 27.0	-		-		
416		≤ 0.15		12.0 - 14.0		≤ 0.6	S*	416S21	416
	1.4005	0.08 - 0.15		12.0 - 14.0		≤ 0.6	S*	416S21	

*Sulfur addition (normally S = 0.20 - 0.30 %) ** Trademark owned by Sandvik AB

ASTM	EN	C (%)	N (%)	Cr (%)r	Ni (%)	Mo (%)	Others (%)	BS	Avesta Polarit grade
Martensitic-austenitic steels									
								316S33	
	1.4313	≤ 0.05	≥ 0.020	12.0 - 14.0	3.5 - 4.5	0.3 - 0.7			
	1.4418	≤ 0.06	≥ 0.020	15.0 - 17.0	4.0 - 6.0	0.8 - 1.5			248 SV
Ferritic-austenitic (Duplex) steels									
329		≤ 0.080		23.0 - 28.0	2.5 - 5.0	1.0 - 2.0			
S31500		≤ 0.030		18.0 - 19.0	4.25 - 5.25	2.5 - 3.0			3RE60
	1.4460	≤ 0.05	0.05 - 0.20	25.0 - 28.0	4.5 - 6.5	1.3 - 2.0			25-5-1L
S32304		≤ 0.030	0.05 - 0.20	21.5 - 24.5	3.0 - 5.5	0.05 - 0.6	Cu		SAF 2304**
	1.4362	≤ 0.030	0.05 - 0.20	22.0 - 24.0	3.5 - 5.5	0.1 - 0.6	Cu		SAF 2304**
S31803		≤ 0.030	0.08 - 0.20	21.0 - 23.0	4.5 - 6.5	2.5 - 3.5		318S13	2205
	1.4462	≤ 0.030	0.10 - 0.22	21.0 - 23.0	4.5 - 6.5	2.5 - 3.5		318S13	2205
S32750		≤ 0.030	0.24 - 0.32	24.0 - 26.0	6.0 - 8.0	3.0 - 5.0			SAF 2507**
	1.4410	≤ 0.030	0.20 - 0.35	24.0 - 26.0	6.0 - 8.0	3.0 - 4.5			SAF 2507**

*Sulfur addition (normally S = 0.20 - 0.30 %)

** Trademark owned by Sandvik AB

Attachment 1.2

ASTM	EN	C (%)	N (%)	Cr (%)	Ni (%)	Mo (%)	Others (%)	BS	Avesta Polarity grade
Austenitic steels									
301		≤ 0.15	≤ 0.10	16.0 - 18.0	6.0 - 8.0			301s21	17-7
	1.4310	0.05 - 0.15	≤ 0.11	16.0 - 19.0	6.0 - 9.5	≤ 0.8		301s21	17-7
303		≤ 0.15		17.0 - 19.0	8.0 - 10.0		S*	303s31*	18-9S
	1.4305	≤ 0.10	≤ 0.11	17.0 - 19.0	8.0 - 10.0		S*	303s31*	18-9S
304L		≤ 0.030	≤ 0.10	18.0 - 20.0	8.0 - 12.0			304s11	18-9L
	1.4307	≤ 0.030	≤ 0.11	17.5 - 19.5	8.0 - 10.0			304s11	18-9L
	1.4306	≤ 0.030	≤ 0.11	18.0 - 20.0	10.0 - 12.0			304s11	19-11L
304		≤ 0.08	≤ 0.10	18.0 - 20.0	8.0 - 10.5			304s31	18-9
	1.4301	≤ 0.07	≤ 0.11	17.0 - 19.5	8.0 - 10.5			304s31	18-9
304LN		≤ 0.030	0.10 - 0.16	18.0 - 20.0	8.0 - 12.0			304s61	18-9LN
	1.4311	≤ 0.030	0.12 - 0.22	17.0 - 19.5	8.5 - 11.5			304s61	18-9LN
321		≤ 0.08	≤ 0.10	17.0 - 19.0	9.0 - 12.0		Ti	321s31	18-10Ti
	1.4541	≤ 0.08		17.0 - 19.0	9.0 - 12.0		Ti	321s31	18-10Ti
347		≤ 0.08		17.0 - 19.0	9.0 - 13.0		Nb	347s31	18-10Nb
	1.4550	≤ 0.08		17.0 - 19.0	9.0 - 12.0		Nb	347s31	18-10Nb
316L		≤ 0.030	≤ 0.10	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0		316s11	17-11-2L
	1.4404	≤ 0.030	≤ 0.11	16.5 - 18.5	10.5 - 13.0	2.0 - 2.5		316s11	17-11-2L
“316L(hMo)”	1.4432	≤ 0.030	≤ 0.11	16.5 - 18.5	10.5 - 13.0	2.5 - 3.0		316s13	17-12-2.5L
“316L(hMo)”	1.4435	≤ 0.030	≤ 0.11	17.0 - 19.0	12.5 - 15.0	2.5 - 3.0		316S13	17-12-2.5L
316		≤ 0.08	≤ 0.10	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0		316s31	17-11-2
	1.4401	≤ 0.07	≤ 0.11	16.0 - 18.5	10.0 - 13.0	2.0 - 2.5		316s31	17-11-2
“316(hMo)”	1.4436	≤ 0.05	≤ 0.11	16.5 - 18.5	10.5 - 13.0	2.5 - 3.0		316S33	17-12-2.5
316LN		≤ 0.030	0.10 - 0.16	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0		316s33	17-11-2LN
	1.4406	≤ 0.03	0.12 - 0.22	16.5 - 18.5	10.0 - 12.0	2.0 - 2.5		316s33	17-11-2LN
	1.4429	≤ 0.03	0.12 - 0.22	16.5 - 18.5	11.0 - 14.0	2.5 - 3.0			17-13-3LN
316Ti		≤ 0.08	≤ 0.10	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0	Ti	320s31	17-11-2Ti
	1.4571	< 0.08		16.5 - 18.5	10.5 - 13.5	2.0 - 2.5	Ti	320s31	17-11-2Ti

ASTM	EN	C (%)	N (%)	Cr (%)	Ni (%)	Mo (%)	Others (%)	BS	Avesta Polarit grade
Austenitic steels (cont.)									
317L		≤ 0.030	≤ 0.10	18.0 - 20.0	11.0 - 15.0	3.0 - 4.0		317s12	18-14-3L
1.4438		≤ 0.030	≤ 0.11	17.5 - 19.5	13.0 - 16.0	3.0 - 4.0		317s12	18-14-3L
S31726		≤ 0.030	0.10 - 0.20	17.0 - 20.0	13.5 - 17.5	4.0 - 5.0			17-14-4LN
1.4439		≤ 0.030	0.12 - 0.22	16.5 - 18.5	12.5 - 14.5	4.0 - 5.0			17-14-4LN
N08904		≤ 0.020		19.0 - 23.0	23.0 - 28.0	4.0 - 5.0	Cu	904s13	904L
1.4539		≤ 0.020	≤ 0.15	19.0 - 21.0	24.0 - 26.0	4.0 - 5.0	Cu	904s13	904L
S31254		≤ 0.020	0.18 - 0.22	19.5 - 20.5	17.5 - 18.5	6.0 - 6.5	Cu		254 SMO
1.4547		≤ 0.020	0.18 - 0.25	19.5 - 20.5	17.5 - 18.5	6.0 - 6.5	Cu		254 SMO
S32654		≤ 0.020	0.45 - 0.55	24.0 - 25.0	21.0 - 23.0	7.0 - 8.0	Cu, Mn		654 SMO
1.4652		≤ 0.020	0.45 - 0.55	24.0 - 25.0	21.0 - 23.0	7.0 - 8.0	Cu, Mn		654 SMO
N08028		≤ 0.030		26.0 - 28.0	30.0 - 34.0	3.0 - 4.0	Cu		A 28
1.4563		≤ 0.020	≤ 0.11	26.0 - 28.0	30.0 - 32.0	3.0 - 4.0	Cu		A 28
Heat resistant austenitic steels									
304H		0.04 - 0.10	18.0 - 20.0	8.0 - 10.5					
321H		0.04 - 0.10		17.0 - 19.0	9.0 - 12.0		Ti		
309S									23-13
1.4833									23-13
310S		≤ 0.08		24.0 - 26.0	19.0 - 22.0			310S16	25-20
1.4845		≤ 0.08		24.0 - 26.0	19.0 - 22.0			310S16	25-20
1.4828									20-12Si
S30415		0.04 - 0.06	0.12 - 0.18	18.0 - 19.0	9.0 - 10.0		Ce, Si		153MA
1.4818		≤ 0.08		18.0 - 20.0	9.0 - 11.0		Ce, Si		153MA
S30815		0.05 - 0.10	0.14 - 0.20	20.0 - 22.0	10.0 - 12.0		Ce, Si		253MA
1.4835		≤ 0.10		20.0 - 22.0	10.0 - 12.0		Ce, Si		253MA
S35315		0.04 - 0.08	0.12 - 0.20	24.0 - 26.0	34.0 - 36.0		Ce, Si		353MA
1.4854		≤ 0.08		24.0 - 26.0	34.0 - 36.0		Ce, Si		353MA

* Free machining steel, Sulfur addition (normally S = 0.20 - 0.30 %)

