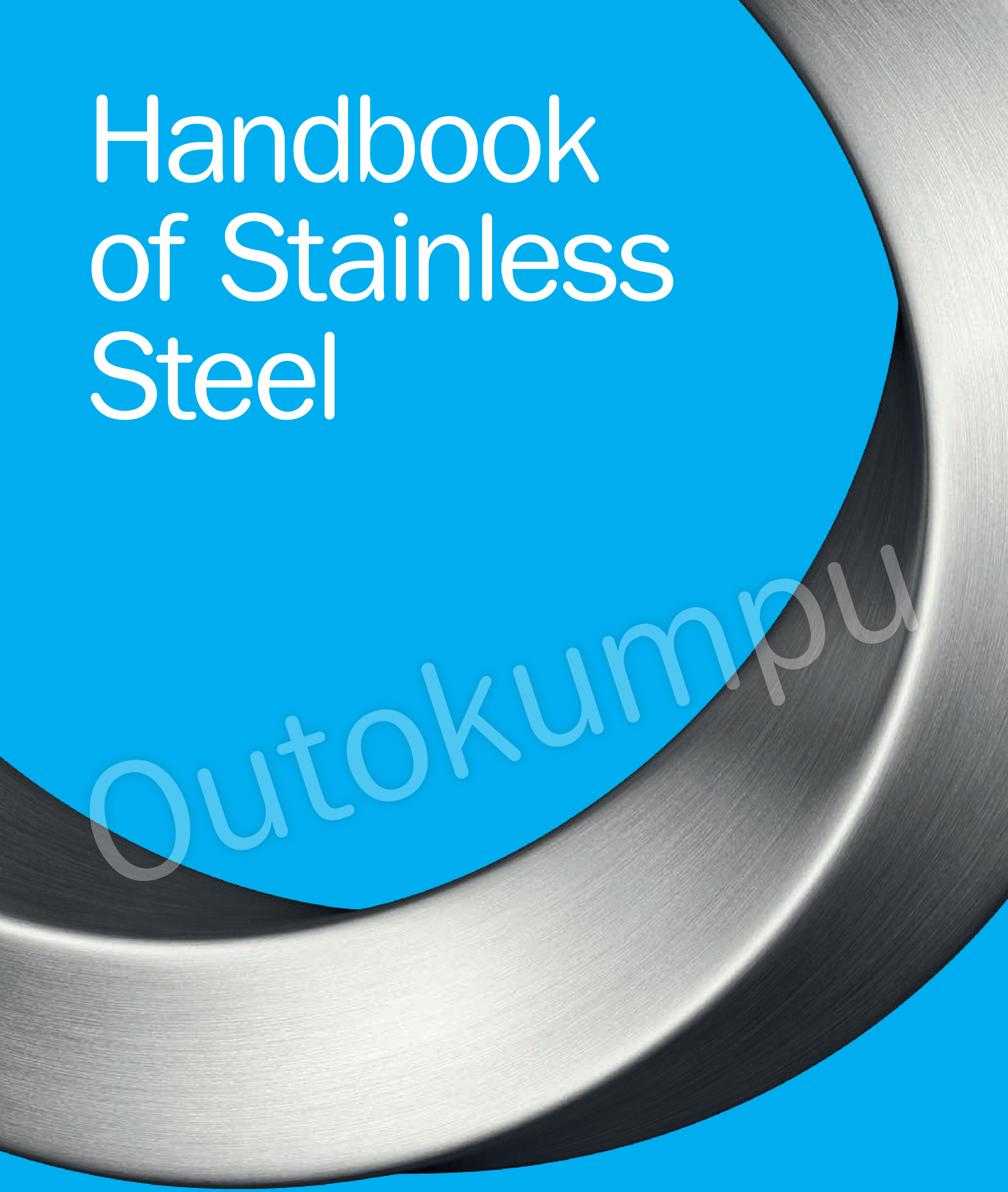
Handbook of Stainless Steel



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high performance stainless steel

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Preface

The world consumption of stainless steels has shown a more or less constant increase of 6 % per annum since the middle of the 20th century. The rapidly increasing number of applications has led to a need among engineers, designers and materials specifiers for an introduction to stainless steel which provides basic and readable information. This need will at least partly be fulfilled by the present handbook. The handbook is also aimed to be useful to students by providing a complement to the general and often limited information on stainless steels in the existing student literature.

The reader will become acquainted with the commodity stainless steel grades and also introduced to the most common specialty steels, e.g. the modern weldable duplex grades with reduced alloying content and increased strength. The handbook gives a broad view of the properties of different types of stainless steels, their production and physical metallurgy, applications of stainless steels and fabrication techniques. It also reflects the rapidly increasing use of stainless steels in load bearing constructions, such as bridges and buildings, where the low maintenance costs, high recycling ratio and thus low environmental impact and carbon footprint contributes to a sustainable society.

This handbook has been written by a group of specialists at Outokumpu, with each person contributing their special competence. It can act as an introduction to the other stainless steel handbooks produced by Outokumpu, such as the Welding Handbook, the Corrosion Handbook and the handbook Machining of Stainless, in which more in depth knowledge is presented.

It is our hope that after reading the handbook you should have a reasonably clear picture of the variety and the versatility of the most important available stainless steels on the market today, keeping in mind the constantly on-going development work within Outokumpu and elsewhere. We have strived to provide technical objective knowledge and not to include subjective marketing.

Espoo, October 2013

Mika Seitovirta

Chief Executive Officer
Outokumpu

Read this note

This handbook provides a guide to the history, production, performance and use of stainless steel. The information herein is intended to facilitate understanding of the properties of the different types of stainless steels available from Outokumpu. It is, however, well known that the performance of stainless steel in service can be profoundly affected by minor changes in the environment or use. Accordingly Outokumpu Oyj makes no representation or warranties, expressed or implied, and have no liability, compensatory or consequential, for the performance of any stainless steel in any individual application that may be made based on the information provided in this handbook. See also the disclaimer on page 89.

Contents

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 high temperature furnace atmospheres. In spite of this there is a group of iron-base alloys, the iron-chromium (Fe-Cr) alloys, often with nickel (Ni) additions, 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 indispensable for the designer. The usage of stainless steel is small compared with that of carbon steels but exhibits a steady growth, Figure 1:1. Stainless steels as a group are perhaps more heterogeneous than the constructional steels, and their properties are in many cases relatively unfamiliar to the designer. To take full advantage of these materials requires an increased understanding of their basic properties, so 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 primary industrial constructional material.

The dominant product form for stainless steels is cold rolled sheet, Figure 1:2. 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 and gas industry, the chemical process industry and the food and beverage industry. Figure 1:3 shows how the use of stainless steel is divided between the various applications.

The most widely used stainless grades are the austenitic Cr-Ni 18-8 type steels, i.e. EN 1.4301/1.4307, which form more than 50 % of the global production of stainless steel. The next most widely used grades are the ferritic Cr-steels such as 1.4512 and 1.4016, followed by the molybdenum-alloyed Cr-Ni-Mo austenitic steels 1.4401/1.4404. Together these grades make up over 80 % of the total tonnage of stainless steels. The remaining part contains other austenitic grades like high performance austenitic grades as well as duplex and martensitic grades.

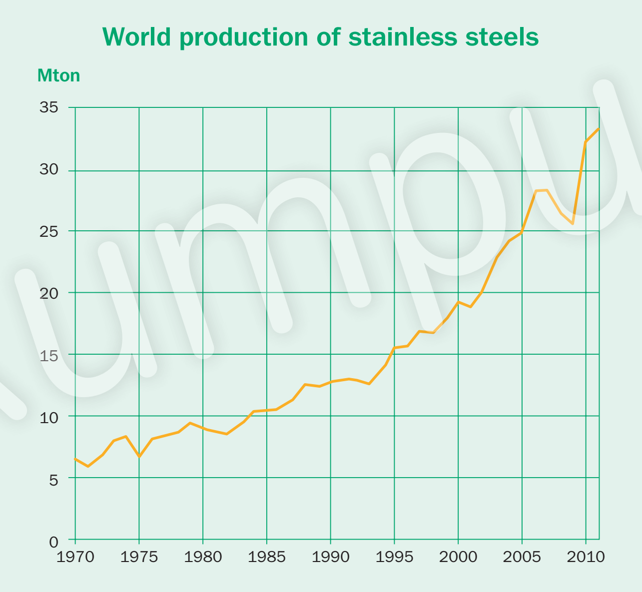

Figure 1:1. World stainless steel production 1970-2010.

How it all started

Scientists and industrial developers from three countries; France, Germany and the UK, were involved in the development of stainless steel. The French mineralogist Berthier reported as early as 1821 about Cr-steels resistance to acid attack. The situation was for some time obscured by the famous English metallurgist Robert Hadfield who reported in 1892 that Cr was not beneficial for the corrosion resistance. He based this statement on tests in 50 % sulphuric acid. Had he used seawater or nitric acid in his tests he would have been the discoverer of stainless steels. In 1911 Monnartz published a thorough article on Fe-Cr-alloys and specially their acid-resistance and pointed out that the results from traditional testing with sulphuric acid could not be generalised. He was also the first to point out the beneficial effect of Mo on the corrosion resistance of Cr-steel.

In an attempt by Krupp in Germany to find a suitable material for thermocouple tubes Pasel, Strauss and Maurer investigated Cr- and Cr-Ni-steels. They stated that steels with high contents of Cr or Cr-Ni could be stored for months in humid and aggressive environment without rusting. The first patent claim for a ferritic or martensitic 14 Cr steel (V1M) and an austenitic 20 Cr, 7 Ni steel (V2A) was filed in 1912.

At the same time in Sheffield, England, Brearley was experimenting with 12–14 % Cr steels and observed that they did not etch in normal etching acids. He also noticed that Cr steels resisted corrosion much better in the hardened than in the annealed condition. Brearley saw commercial possibilities of this material in cutlery and gave non-rusting steel the name Stainless Steel. In 1916 he was granted patents in the USA and a number of European countries.

Parallel with the work in England and Germany, 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-resisting steels.

In Sweden the interest was increased after the Baltic exhibition in Malmö in 1914 where stainless steels from Krupp were presented. This lead to investing in a Rennerfeldt furnace in Avesta and the production rapidly increased in the early 1920's. This was not least due to the recruitment of Bo Kalling in 1923 from the company Ferrolegeringar in Vargön and the first commercial chromium steel 393 was produced in March/April 1924. In April 1925 18-8 type steel (Avesta 832) was produced and in the following year a Mo alloyed grade was produced. The very first stainless steel produced in Sweden was made in Långshyttan by Kloster AB; a 15 % Cr steel in 1921. However, it was not until after World War II that the development in process metallurgy lead to the growth and widespread use of the modern stainless steels.

The production stainless steel in Krefeldt, Germany, followed after October 17, 1912, when the firm of Fried Krupp, in Essen, applied for a patent for the "manufacture of objects requiring high resistance to corrosion ..." with the German patent office in Berlin. Krupp Thyssen Nirosta GmbH (KTN) was formed in 1995 by combining the stainless flat-rolled activities of the Krupp and Thyssen groups. Outokumpu today comprise stainless production sites in Finland, Sweden, Germany (KTN), UK, Mexico (Mexinox founded in 1976), US, and China, and is the leading stainless producer in the world.

In Tornio, Finland, the stainless steel production started in 1976 and has after strong expansion emerged to be one of the world's largest production sites of stainless steel.

Duplex stainless steels were first developed in Avesta in 1930 with two main target properties – heat resistance and acid resistance, the latter with a composition of 26Cr–5Ni–1Mo. These grades were however not weldable due to the high ferrite content formed in the heat affected zone. This was mastered in the 1970's by the addition of nitrogen which together with a more austenitic alloying led to the modern duplex grades exemplified by the Sandvik SAF 2205 and not least by the German Krupp Südwestfalen FALC223. The 2205 grade was a great success and is still the workhorse of the duplex grades today.

Where does science stand today?

With the advent of the AOD (Argon Oxygen Decarburisation) process in the 1970's, a new development ensued since the process allowed high accuracy in the control of nitrogen and carbon. The

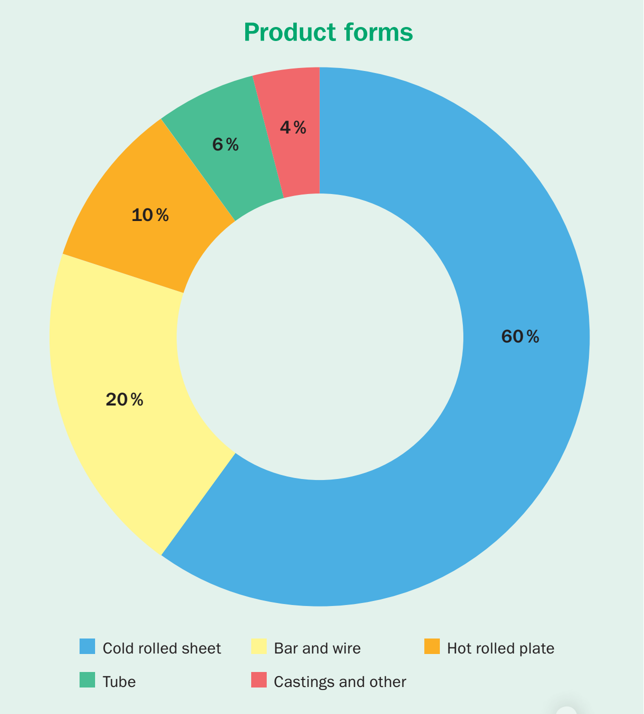

Figure 1:2. Use of stainless steel in the industrialised world, divided into various product forms. Ref.: Leffler Béla.

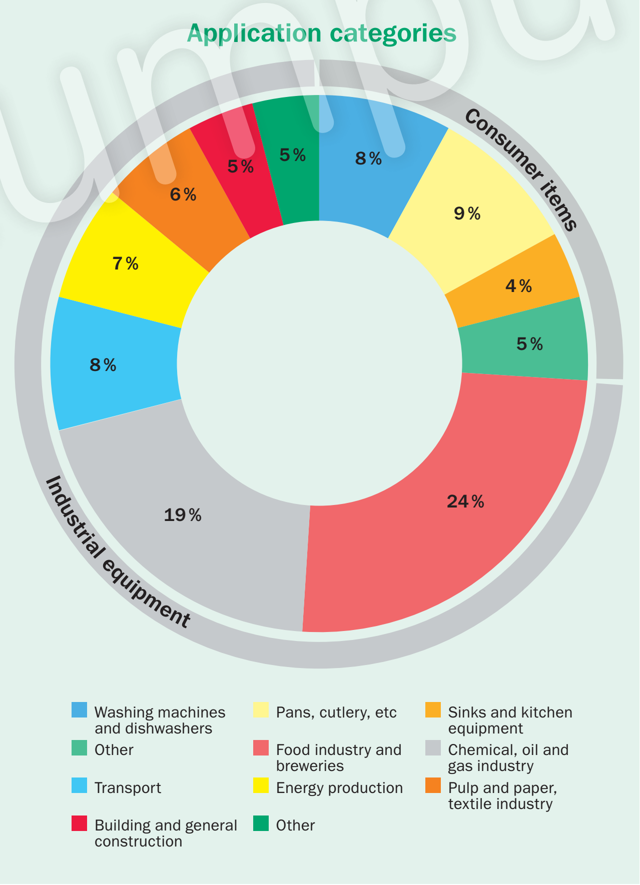

Figure 1:3. Use of stainless steel in the industrialised world, divided into various application categories. Ref.: Leffler Béla.

carbon content could be significantly reduced and the old problem of intergranular attack could be more or less eliminated since the precipitation of chromium carbides could be avoided with normal welding procedures. The favourable effect of nitrogen in terms of delaying the precipitation of sigma-phase was discovered and nitrogen was introduced in a number of highly alloyed stainless steels. Higher contents of Mo and Cr could now be added without the detrimental effects of sigma-phase. The mechanisms were discussed and the argument of “increased austenite stability” was frequently forwarded. This lead to research efforts at the Royal Institute of Technology (KTH) in Stockholm, Sweden, where the effect of nitrogen in terms of phase equilibria in the Fe-Cr-Ni-Mo system was studied and the nitrogen effect could be rationalized. The results were added to the evolving thermodynamic database Thermo-Calc which became the primary alloy development tool in the stainless steel area, particular for duplex stainless steels. This development is on-going and the coupling of critical experiments and thermodynamic calculations has led to a decrease in lead times in product development by a factor of 5–10, in addition to the increased understanding of alloying element effects in general. The laborious experimental mapping can then be replaced by simulations, both in terms of equilibria and kinetics of phase transformations.

The IDS (InterDendritic Solidification) program package, a dedicated thermodynamic-kinetic-empirical tool has been developed to simulate complex solidification phenomena in casting of e. g. stainless steels. The predictions include phase transformations from melt down to room temperature. The model was developed in the Laboratory of Metallurgy, Helsinki University of Technology, Finland.

The thermodynamic databases were, and still are, strongly dependent on accurate experimental data which was collected in temperature regions where equilibrium could be expected. In order to understand the lower temperature reactions, ab-initio or first principles calculations are now being used. No experimental information is needed and the results are truly predictions. Walter Kohn was awarded Nobel prize in 1998 for the density functional theory, DFT, which is the basic building block for this approach. Advanced calculations can contribute to the understanding of atomic movement and preferred positioning in metallic microstructures, and hence new insights into hardening due to martensite formation and cold deformation, and physical properties like anisotropy of elastic modulus. This technique will not within reasonable future replace the thermodynamic databases but will have an increasingly important role as a complement.

Two examples of the application of different types of modelling to stainless steels are given in Figures 1:4 and 1:5.

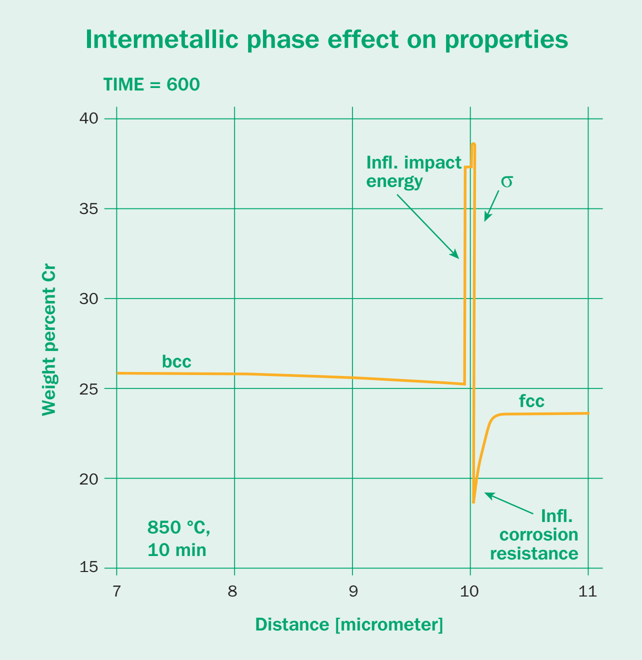

Figure 1:4. Calculated chromium profile, simulating growth of sigma-phase in a duplex stainless steel, using the kinetic Dictra program in the Thermo-Calc database system. The rapid growth of sigma-phase into the ferrite explains the effect on impact energy and the chromium depletion adjacent to sigma phase on the austenite side explains the detrimental effect on corrosion resistance.

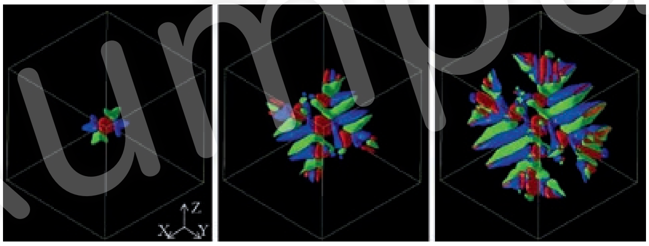

Figure 1:5. Calculated stress-assisted martensitic microstructure evolution under uni-axial tensile loading of a stainless steel. Snapshot taken at three different time steps.

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Stainless steel categories and grades

Over the years, ever since the start of the development of stainless steels, the number of grades have increased rapidly. Tables 2:1 and 2:2 show most of the stainless steel grades, together with their chemical compositions, that are produced by Outokumpu today. There are a large number of stainless steels with widely varying chemical compositions and at least at some time all of these grades have been sufficiently attractive to merit the trouble of standardisation. For more information see the standards EN 10088-1, ASTM A240 and ISO 15510. In view of this 'jungle' of different steel grades, a broader overview is helpful, and in Table 2:3 and 2:4, the stainless steel designations according to different standards are shown.

Since the microstructure has a decisive effect on properties, stainless steels have traditionally been divided into categories depending on their microstructure at room temperature. This gives a rough division in terms of both composition and properties. Typical microstructures are seen in Figures 2:1 to 2:4.

The Outokumpu stainless steels can be divided into four main groups: ferritic, martensitic and precipitation hardening, duplex (ferritic-austenitic) and austenitic stainless steels. The different categories of stainless steel are suited for different applications, and a number of examples are given in Figures 2:5 to 2:9.

Ferritic stainless steel

The standard ferritic grades are alloyed with chromium (11.2–19 %), but with no, or very small addition of nickel. As nickel is one of the most expensive alloying elements and has demonstrated high price volatility, the low nickel content of the ferritic grades make them more price stable compared to grades with high nickel content. Molybdenum is added to some grades to improve the corrosion resistance, while alloying with niobium and/or titanium improves the weldability.

The ferritic grades, also referred to as Cr-steels, are magnetic due to the ferritic microstructure.

Ferritic high temperature grades

There are also high temperature ferritic grades with increased resistance to high temperatures (800–1150 °C). These are mainly used in applications with sulphurous atmospheres (as sulphur may react with nickel in austenitic grades) and/or at low tensile loads. These grades are typically alloyed with more carbon compared to standard ferritic grades, in order to increase the creep strength, and with silicon and aluminium to improve the resistance to oxidation.

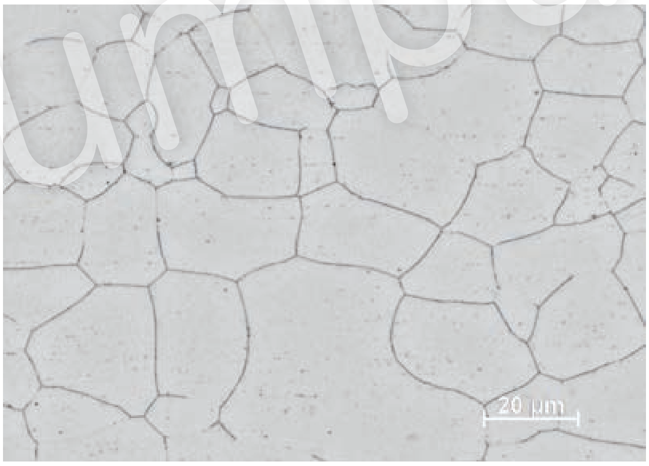


Figure 2:1. Ferritic microstructure showing equiaxed grains. Some presence of small inclusions and Ti(CN) can be observed.

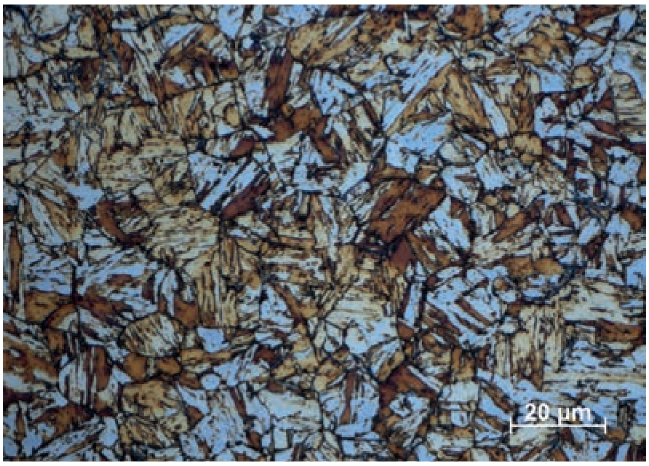


Figure 2:2. Martensitic microstructure showing fine-scale martesnite which has formed within the prior austenite grains. Smaller dark carbides can also be observed.

Martensitic and precipitation hardening stainless steel

The martensitic grades are the smallest group of stainless steel. To improve the strength and hardenability of the martensitic grades they have higher carbon content compared to other grades, and nitrogen is sometimes added to further improve the strength. These grades contain no or rather small amounts of nickel, and molybdenum is seldom added. By adding some nickel and reducing the carbon content the rather poor weldability of martensitic grades can be improved. Sometimes sulphur is added to improve the machinability. The martensitic grades are magnetic and hardenable.

The precipitation hardening grades are hardened by a special mechanism involving the formation of precipitates within the microstructure. Also these grades are magnetic.

Duplex stainless steel

Duplex grades have a ferritic-austenitic microstructure, with a phase balance of approximately 50 % ferrite and 50 % austenite. Duplex grades combine many of the beneficial properties of ferritic and austenitic stainless steels. The duplex microstructure also contributes to the high strength and high resistance to stress corrosion cracking. Characteristic for the duplex stainless steels is high chromium content (20.1–25.4 %), but rather low nickel content (1.4–7 %) compared to the austenitic grades. The low nickel content of the duplex grades makes them more price stable. Molybdenum (0.3–4 %) and nitrogen are added to improve the corrosion resistance and balance the microstructure. Nitrogen also increases the strength. Manganese is added to some grades, as partial replacement of nickel, but also to increase the solubility of nitrogen in the material.

The duplex grades LDX 2101® and 2304 are sometimes referred to as lean duplex grades. The duplex grade 2205 is sometimes referred to as 22Cr duplex and grades 2507 and 4501 as 25Cr superduplex grades. The duplex grades are magnetic due to the ferrite content.

Recently a new group of duplex grades with better formability has been introduced, the so called FDX-grades.

Austenitic stainless steel

The austenitic grades are the largest group of stainless steels, and can be divided into five sub-groups, Cr-Mn grades, Cr-Ni grades, Cr-Ni-Mo grades, high performance austenitic grades and high temperature austenitic grades. The austenitic grades have good to excellent corrosion resistance, good formability and weldability. Their good impact strength at low temperatures is often exploited in cryogenic applications. The austenitic grades are non-magnetic in the solution annealed condition due to the austenitic microstructure. Cold working increases their strength and certain grades are therefore supplied in the temper rolled condition and may then be magnetic due to the presence of some martensite.

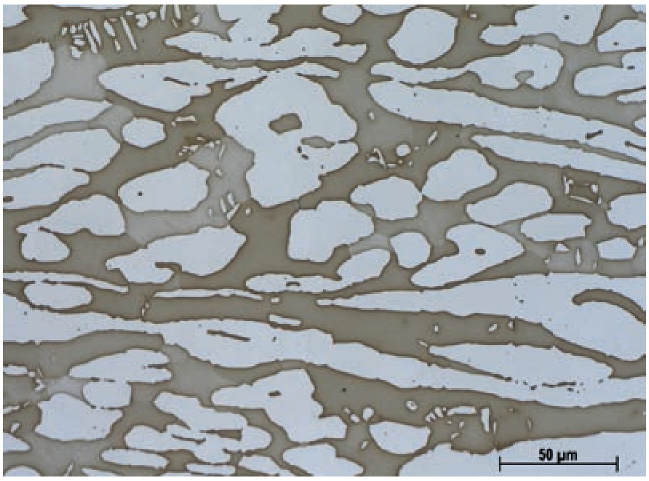


Figure 2:3. Duplex microstructure showing an elongated lamella structure of darker etched ferritic regions and brighter austenitic regions.

Figure 2:4. Austenitic microstructure showing equiaxed grains and characteristic annealing twins. Normal presence of small inclusions can be observed.

Figure 2:5. Ferritic stainless steel is commonly used for e.g. washing machine drums.

Cr-Ni grades

The Cr-Ni grades are “general purpose grades” mainly alloyed with chromium and nickel, but with no molybdenum. These grades are sometimes referred to as 18-8 type of stainless steels, indicating the approximate chromium and nickel content respectively.

Some grades are alloyed with nitrogen to improve the strength, or with sulphur to improve machinability. There are also stabilized grades where titanium or niobium is added to increases the mechanical properties at high temperatures by the formation of hardening carbides. Earlier, titanium and niobium stabilisation was also used to avoid detrimental carbide precipitates on welding, but for modern low-carbon Cr-Ni steels this is not necessary.

Cr-Mn grades

In the Cr-Mn grades, also referred to as “200-series” grades following the AISI/ASTM nomenclature, the nickel content is decreased and the austenitic microstructure is maintained by replacing some of the nickel with manganese and nitrogen. The chemical composition of grade 4372 is around 17 % Cr, 4 % Ni and 7 % Mn. This grade has almost the same formability, corrosion resistance and weldability as grade 4301, but with higher strength.

Cr-Ni-Mo

These are also “general purpose grades”, but with increased corrosion resistance owing to alloying with molybdenum (2–3 %), and are sometimes referred to as “acid-proof” type of stainless steels. The chromium content is around 17 % and the nickel content 10–13 %.

Some grades are alloyed with nitrogen to improve the strength, or with sulphur to improve machinability. There are also stabilized grades where titanium or niobium is added to increases the mechanical properties at high temperatures by the formation of hardening carbides. Earlier, titanium and niobium stabilisation was also used to avoid detrimental carbide precipitates on welding, but in modern, low carbon Cr-Ni-Mo steels this is not necessary.

High performance austenitics

The high performance austenitic stainless steels were developed for use in very demanding environments and have even higher alloying content. The chromium content varies between 17 and 25 %, nickel between 14 and 25 % and molybdenum between 3 and 7 %. Many of the grades are also alloyed with nitrogen to further increase the corrosion resistance and strength. Some grades are alloyed with copper to increase the resistance to certain acids.

The austenitic grades 254 SMO® and 4529 are sometime referred to as 6Mo superaustenitic grades, and 654 SMO® as a 7Mo superaustenitic grade.

High temperature austenitic grades

The high temperature austenitic stainless steels are designed primarily for use at temperatures exceeding 550 °C, i.e. in the temperature range where creep strength is the dimensioning factor. The compositions of these steels are designed to provide a long service life in dry gases at high temperatures (800–1150 °C), i.e. good oxidation resistance rather than resistance to aqueous corrosion.

The high temperature austenitic grades are characterised by high chromium (17–25 %) and high nickel (8–20 %) content but containing no molybdenum. Silicon is added in some grades to increase the oxidation resistance. The Outokumpu MA grades are alloyed with silicon and also with cerium to further increase the resistance to oxidation, and with nitrogen to improve the creep strength.

Figure 2:6. Continuous digester at Veracel in Brazil made in duplex 2205.

Figure 2:7. Savoy Hotel, London. The sign, made of standard austenitic Cr-Ni type of stainless steel with a polished surface, was completed in 1929.

The effects of alloying elements

The different alloying elements have specific effects on the properties of the stainless steel. It is the combined effect of all the alloying elements, heat treatment 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 is given of the main alloying elements and their effects on the microstructure and properties. The effects on important material properties are discussed in more detail in the later chapters. It should be noted that the effect of the alloying elements differs in some aspects between the different categories of stainless steels.

Figure 2:8. Lloyds' Building, London, completed 1986. Cladding in the austenitic Cr-Ni-Mo stainless steel 316 with HyClad® Linen surface finish.

Figure 2:9. The sculpture "God our father, on the Rainbow", Nacka Strand, Stockholm, Sweden. Sculpture designed by Carl Milles, made in the superaustenitic grade 254 SMO®.

Chromium (Cr)

This is the most important alloying element and it gives stainless steels their basic corrosion resistance. All stainless steels have a Cr-content of at least 10.5 % and the corrosion resistance increases with increasing chromium content. Chromium also increases the resistance to oxidation at high temperatures and promotes a ferritic microstructure.

Nickel (Ni)

The main reason for the nickel addition is to promote an austenitic microstructure. Nickel generally increases ductility and toughness. It also reduces the corrosion rate in the active state 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. In martensitic grades nickel addition combined with lowered carbon content improves the weldability.

Molybdenum (Mo)

Molybdenum significantly increases the resistance to both uniform and localised corrosion. It somewhat increases the mechanical strength and strongly promotes a ferritic microstructure. However, molybdenum also enhances the risk for the formation of secondary phases in ferritic, duplex 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 microstructure. It can also be added to decrease work hardening in grades for improved machinability. It may also be added to improve formability.

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 an 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 duplex and austenitic stainless steels. Manganese, as an austenite former, can also replace some of the nickel in the stainless steel.

Silicon (Si)

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

Carbon (C)

Carbon is a strong austenite former that also significantly increases the mechanical strength. However, it also reduces the resistance to intergranular corrosion caused by carbide formation, which was a problem in the early stainless steels. The modern grades do not suffer from intergranular corrosion due to the low carbon content. In ferritic stainless steels carbon will strongly reduce both toughness and corrosion resistance. In the martensitic steels carbon increases hardness and strength, but decrease the toughness.

Nitrogen (N)

Nitrogen is a very strong austenite former that also significantly 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 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 with increased carbon content it is added to increase the resistance to intergranular corrosion (stabilised grades) but it also increases the mechanical properties at high temperatures. In ferritic stainless steels titanium is added to improve toughness, formability and corrosion resistance. In martensitic steels titanium lowers the martensite hardness by combining with carbon 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. Like titanium it promotes a ferritic structure. In austenitic steels it is added to improve the resistance to intergranular corrosion (stabilised grades) but it also enhances mechanical properties at high temperatures. In ferritic stainless steels niobium and/or titanium is sometimes added to improve toughness and to improve resistance to sensitization to minimize the risk for intergranular corrosion. In martensitic steels niobium lowers the hardness and increases the tempering resistance. In the US it is designated Columbium (Cb).

Aluminium (Al)

Aluminium improves oxidation resistance, if added in substantial amounts. It is used in certain heat resisting grades 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 is used as an alloying element in martensitic steels where it increases the hardness and tempering resistance, especially at higher temperatures.

Vanadium (V)

Vanadium forms carbides and nitrides at lower temperatures, promotes ferrite in the microstructure, and increases the toughness. It increases the hardness of martensitic steels due to its effect on the type of carbide present. It also increases tempering resistance. It is only used in hardenable stainless steels.

Tungsten (W)

Tungsten is present as an impurity in most stainless steels although some special grades have additions for improving pitting corrosion resistance, e.g. the superduplex grade 4501.

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 slightly reduce corrosion resistance, ductility, weldability and formability. At Outokumpu the trademark PRODEC® (PRODuction EConomy) is used for some grades with balanced sulphur levels to improve machinability. Lower levels of sulphur can be added to decrease work hardening in grades for improved formability. Slightly increased sulphur content also improves the weldability of the steel.

Cerium (Ce)

Cerium is one of the rare earth metals (REM) and is added in small amounts to certain heat resisting grades in order to increase the resistance to oxidation at high temperature.

Effect on microstructure

The effect of the alloying elements on the microstructure of stainless steels is summarised in the empirical Schaeffler DeLong diagram (Figure 2:10). 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 microstructure. 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:

Nickel equivalent = %Ni + 0.5 x %Mn + 30 x (%C + %N)
Chromium equivalent = %Cr + %Mo + 1.5 x %Si + 0.5 x %Nb

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 it has also been found to give a useful preview of the effect of the alloying elements for wrought and annealed material. However, annealed steels with predicted ferrite contents in the range 0–5 % according to the diagram contain in practice smaller amounts of ferrite.

It should also be mentioned 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 WRC-92 diagram developed through collaboration in the international welding community is widely used.

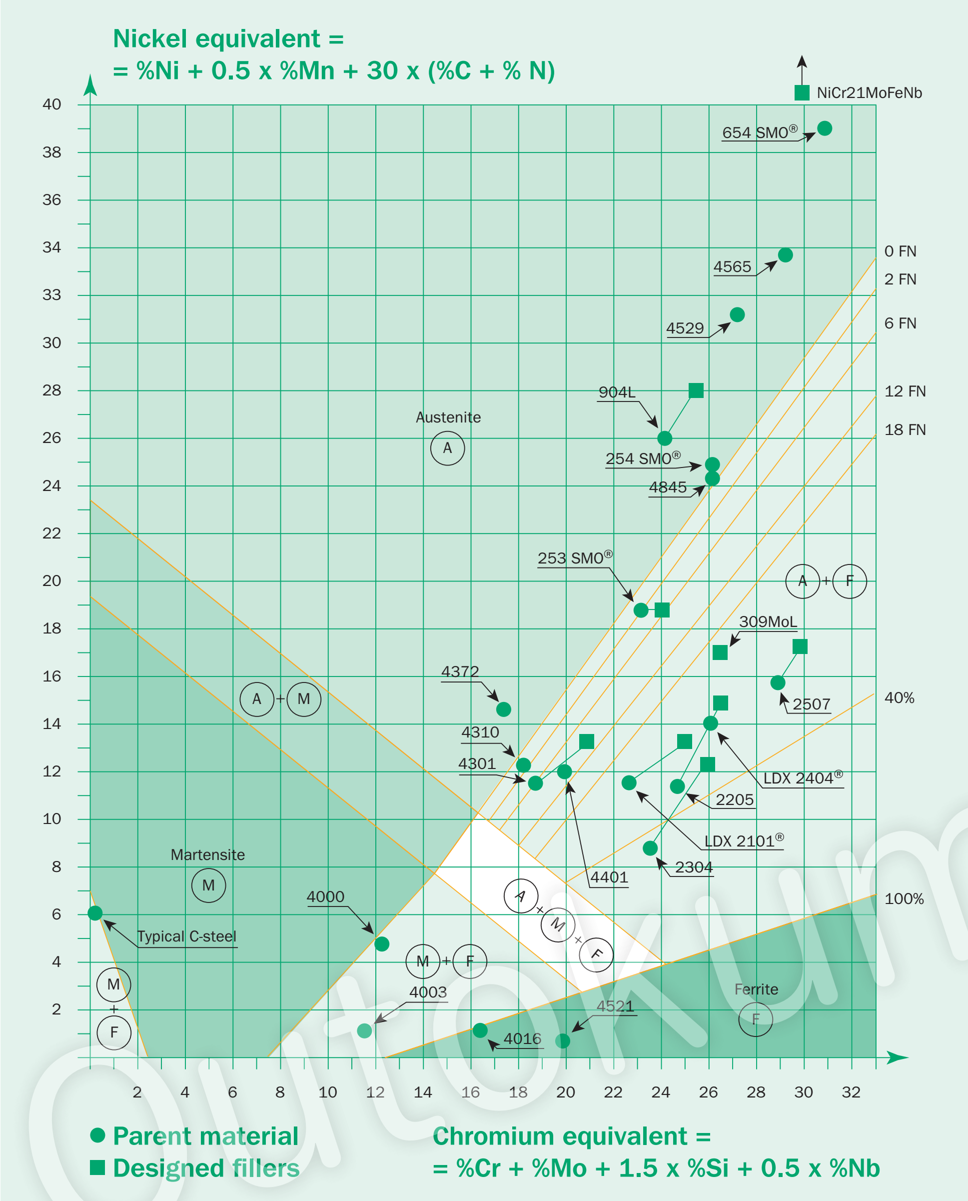


Figure 2:10. Modified (by Outokumpu) Schaeffler DeLong diagram showing the different microstructures in welds. A more modern constitutional diagram for weld metals is the WRC-92 diagram but this diagram is limited to standard stainless steel compositions.

References

EN 10088-1, “Stainless steels - Part 1: List of stainless steels”.

ASTM A240, “Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications”.

ISO 15510, “Stainless steels - Chemical composition”.

Outokumpu Welding Handbook.

Steel grades, chemical composition

Table 2:1

Outokumpu steel name	International steel designation				Typical chemical composition, %					
	EN	ASTM	UNS	JIS	C	N	Cr	Ni	Mo	Others
FERRITIC GRADES										
4600	1.4600	–	–	–	0.02		11.2	0.85		Ti
4512	1.4512	409	–	SUS 409	0.02		11.5	0.2		Ti
4003	1.4003	–	S40977	–	0.02		11.5	0.5		
4000	1.4000	410S	S41008	SUS 403	0.03		12.5			
4589	1.4589	–	S42035	–	0.045		14	1.65	0.25	Ti
4016	1.4016	430	S43000	SUS 430	0.05		16.2			
4511	1.4511	–	–	–	0.02		16.2			Nb
4520	1.4520	–	–	–	0.02		16.2			Ti
4510	1.4510	439	S43035	SUS 430LX	0.02		17			Ti
4509	1.4509	–	S43940	–	0.02		18			Ti Nb
4607	1.4607[1]	–	–	–	0.02		19			Ti Nb
4113	1.4113	434	S43400	–	0.045		16.5		1	
4513	1.4513	–	S43600	–	0.02		17		1	Ti
4521	1.4521	444	S44400	SUS 444	0.02		18		2	Ti Nb
MARTENSITIC AND PRECIPITATION HARDENING GRADES										
4006	1.4006	410	S41000	SUS 410	0.12		12			
4005	1.4005	416	S41600	SUS 416	0.10		13			S
4021	1.4021	420	S42000	SUS 420J1	0.20		13			
4031	1.4031	420	S42000	–	0.38		13.5			
4034	1.4034	420	S42000	–	0.45		13.7			
4028	1.4028	420	S42000	SUS 420J2	0.30		12.5			
4313	1.4313	–	S41500	SUS Ti6NM	0.03		12.5	4.1	0.6	
4542	1.4542	630	S17400[3]	SUS 630	0.02		15.5	4.8		3.4Cu Nb
4116	1.4116	–	–	–	0.5		14.4		0.55	V
4110	1.4110	–	–	–	0.5		14.8		0.63	
4568	1.4568	631	S17700	SUS 631	0.08		17	7		1Al
4122	1.4122	–	–	–	0.41		16.1		1	
4574	1.4574	632	S15700	–	0.08		14.5	7.5	2.2	1.1Al
FERRITIC HIGH TEMPERATURE GRADES										
4713	1.4713	–	–	–	0.06		6.5			0.8Si 0.8Al
4724	1.4724	–	–	–	0.07		12.5			1Si 0.9Al
4736	1.4736	–	–	–	0.02		17.5			1.8Al Ti
4742	1.4742	–	–	–	0.07		17.5			1Si 1Al
4762	1.4762	–	–	–	0.08		23.5			1Si 1.5Al
AUSTENITIC HIGH TEMPERATURE GRADES										
4948	1.4948	304H	S30409	SUS 304	0.05		18.1	8.3		
4878	1.4878[2]	321H	–	SUS 321	0.05		17.3	9.1		Ti
153 MA™	1.4818	–	S30415	–	0.05	0.15	18.5	9.5		1.3Si Ce
4833	1.4833[2]	309S[2]	S30908	SUS 309	0.06		22.3	12.6		
4828	1.4828	–	–	SUH 309	0.04		20	12		2Si
253 MA®	1.4835	–	S30815	–	0.09	0.17	21	11		1.6Si Ce
4845	1.4845[2]	310S[2]	S31008	SUS 310S	0.05		25	20		
4841	1.4841	314	S31400	–	0.07		24.5	19.5		2Si

[1] Designation according to Stahl Eisen Liste (register of European Steels).
[2] Additional creep resisting grades are: 1.4941, 1.4950, 1.4951.
[3] Also available as S15500.

Steel grades, chemical composition

Table 2:2

Outokumpu steel name	International steel designation				Typical chemical composition, %					
	EN	ASTM	UNS	JIS	C	N	Cr	Ni	Mo	Others
DUPLEX GRADES										
FDX 25™	1.4635*	–	S82012	–	0.022	0.23	20.2	1.4	0.4	Mn Cu Si B
FDX 27™	1.4637*	–	S82031	–	0.023	0.18	20.1	3.0	1.25	Mn Cu Si B
LDX 2101®	1.4162	–	S32101	–	0.03	0.22	21.5	1.5	0.3	5Mn Cu
2304[1]	1.4362	–	S32304	–	0.02	0.10	23	4.8	0.3	Cu
LDX 2404®	1.4662*	–	S82441	–	0.02	0.27	24	3.6	1.6	3Mn Cu
2205	1.4462	–	S32205[2]	SUS 329J3L	0.02	0.17	22	5.7	3.1	
4501	1.4501	–	S32760	–	0.02	0.27	25.4	6.9	3.8	W Cu
2507	1.4410	–	S32750	–	0.02	0.27	25	7	4	
AUSTENITIC GRADES										
4310	1.4310	301	S30100	SUS 301	0.10		17	7		
4618	1.4618	–	–	–	0.06		16.6	4.6		7.9Mn 1.7Cu
4318	1.4318	301LN	S30153	SUS 301L	0.02	0.14	17.7	6.5		
4376	1.4376	–	–	–	0.035	0.2	17.5	4		6.8Mn
4372	1.4372	201	S20100	SUS 201	0.05	0.20	17	4		7Mn
4301	1.4301	304	S30400	SUS 304	0.04		18.1	8.1		
4307	1.4307	304L	S30403	–	0.02		18.1	8.1		
4311	1.4311	304LN	S30453	SUS 304LN	0.02	0.14	18.5	9.2		
4541	1.4541	321	S32100	SUS 321	0.04		17.3	9.1		Ti
4550	1.4550	347	S34700	SUS 347	0.05		17.5	9.5		Nb
4305	1.4305	303	S30300	SUS 303	0.05		17.3	8.2		S
4303	1.4303	305	S30500	SUS 305J1	0.04		17.7	12.5		
4306	1.4306	304L	S30403	SUS 304L	0.02		18.2	10.1		
4567	1.4567	–	S30430	SUS XM7	0.01		17.7	9.7		3Cu
4640	1.4640	–	–	–	0.06		18	6.5		1.7Cu 1.8Mn
4401	1.4401	316	S31600	SUS 316	0.04		17.2	10.1	2.1	
4404	1.4404	316L	S31603	–	0.02		17.2	10.1	2.1	
4427	1.4427*	–	–	–	0.05		16.9	10.7	2.5	S
4436	1.4436	316	S31600	SUS 316	0.04		16.9	10.7	2.6	
4432	1.4432	316L	S31603	–	0.02		16.9	10.7	2.6	
4406	1.4406	316LN	S31653	SUS 316LN	0.02	0.14	17.2	10.3	2.1	
4441	1.4441	–	–	–	0.02		17.6	14.5	2.8	
4429	1.4429	–	S31653	SUS 316LN	0.02	0.14	17.3	12.5	2.6	
4571	1.4571	316Ti	S32100	SUS 316Ti	0.04		16.8	10.9	2.1	Ti
4435[3]	1.4435[3]	316L	–	SUS 316L	0.02		17.3	12.6	2.6	
3952	1.3952*	–	–	–	0.02	0.18	16.9	13.2	2.7	
HIGH PERFORMANCE AUSTENITIC GRADES										
4438	1.4438	317L[6]	S31703	SUS 317L	0.02		18.2	13.7	3.1	
4439	1.4439	317LMN[4]	S31726	–	0.02	0.14	17.3	13.7	4.1	
725LN	1.4466	–	S31050	–	0.01	0.12	25	22.3	2.1	
3964	1.3964*	–	–	–	0.02	0.27	20.5	15.4	3.2	4.3Mn Nb
904L	1.4539	904L	N08904	–	0.01		20	25	4.3	1.5Cu
254 SMO®	1.4547	–	S31254	SUS 312L	0.01	0.20	20	18	6.1	Cu
4529	1.4529	–	N08926[5]	–	0.01	0.20	20.5	24.8	6.5	Cu
4565	1.4565	–	S34565	–	0.02	0.45	24	17	4.5	5.5Mn
654 SMO®	1.4652	–	S32654	–	0.01	0.50	24	22	7.3	3.5Mn Cu

* Designation according to Stahl Eisen Liste (Register of European Steels).
[1] Also available as EDX 2304™ with enhanced properties.
[2] Also available as S31803.
[3] 724L is a modified version of 4435 for Urea applications.
[4] 317LMN not available in all product forms.
[5] Also available as N08367.
[6] Also available as 317L with 11.7 % Ni which is not consistent with 1.4438.

Steel grade designations according to different standards

Table 2:3

Outokumpu steel name	ISO	National designations superseded by EN						
		BS/UK	DIN/Germany	NF/France	SS/Sweden	GB/PR China	KS/Korea	GOST/Russia
FERRITIC GRADES								
4600	–	–	1.4600	–	–	–	–	–
4512	–	409S 19	1.4512	Z3 CT12	–	–	–	–
4003	4003-410-77-I	–	1.4003	–	–	–	–	–
4000	4000-410-08-I	403S17	1.4000	Z8 C12	2301	–	–	08X13
4589	4589-429-70-E	–	1.4589	–	–	–	–	–
4016	4016-430-00-I	430S17	1.4016	Z8 C17	2320	1Cr17	STS 430	12X17
4511	4511-430-71-I	–	1.4511	Z4 CNb17	–	–	–	–
4520	4520-430-70-I	–	1.4520	–	–	–	–	–
4510	4510-430-35-I	–	–	–	–	–	–	–
4509	4509-439-40-X	–	1.4509	Z3 CT Nb 18	–	–	–	–
4607	–	–	1.4607	–	–	–	–	–
4113	4113-434-00-I	434S 17	1.4113	–	–	–	–	–
4513	4513-436-00-J	–	1.4513	–	–	–	–	–
4521	4521-444-00-I	–	1.4521	Z3 CDT 18-02	2326	–	–	–
MARTENSITIC AND PRECIPITATION HARDENING GRADES								
4006	4006-410-00-I	410S21	1.4006	Z10 C13	2302	1Cr12	STS 410	12X13
4005	4005-416-00-I	416S21	1.4005	Z11 CF13	2380	Y1Cr13	STS 416	–
4021	4021-420-00-I	420S29	1.4021	Z20 C13	2303	2Cr13	STS 420J1	20X13
4031	4031-420-00-I	420S45	1.4031	Z33 C13	2304	–	–	–
4034	4034-420-00-I	–	1.4034	Z44 C14	–	–	–	–
4028	4028-420-00-I	420S45	1.4028	Z33 C13	2304	3Cr13	STS 420J2	30X13
4313	4313-415-00-I	–	1.4313	Z6 CN 13-04	2385	–	–	–
4542	–	–	1.4542	Z7 CNU 16-04	–	–	–	–
4116	4116-420-77-E	–	1.4116	Z50 CD15	–	–	–	–
4110	4110-420-69-E	–	1.4110	–	–	–	–	–
4568	–	–	1.4568	Z9 CNA 17-07	2388	–	–	–
4122	4122-434-09-I	–	1.4122	–	–	–	–	–
4574	–	–	1.4574	–	–	–	–	–
FERRITIC HIGH TEMPERATURE GRADES								
4713	–	–	1.4713	–	–	–	–	–
4724	4724-405-77-I	–	1.4724	Z13 C13	–	–	–	10X13CЮ
4736	–	–	1.4736	–	–	–	–	–
4742	4742-430-77-I	–	1.4742	Z12 CAS18	–	–	–	–
4762	4762-445-72-I	–	1.4762	Z12 CAS25	–	–	–	–
AUSTENITIC HIGH TEMPERATURE GRADES								
4948	4948-304-09-I	304S51	1.4948	Z6 CN 18-09	2333	1Cr18Ni9	STS 304	08X18H10
4878	–	321S51	1.4878	Z6 CNT 18-10	2337	1Cr18Ni9Ti	STS 321	08X18H10T
153 MA™	4818-304-15-E	–	–	–	2372	–	–	–
4833	4833-309-08-I	309S16	1.4833	Z15 CN 23-13	–	0Cr23Ni13	STS 309S	20X23H13
4828	4828-305-09-I	–	1.4828	Z17 CNS 20-12	–	1Cr20Ni14Si2	–	08X20H14C2
253 MA®	4835-308-15-U	–	1.4835	–	2368	–	–	–
4845	4845-310-08-E	310S16	1.4845	Z8 CN 25-20	2361	0Cr25Ni20	–	10X23H18
4841	4841-314-00-E	–	1.4841	Z15 CNS 25-20	–	–	–	20X25H2052

Steel grade designations according to different standards

Table 2:4

Outokumpu steel name	ISO	National designations superseded by EN						
		BS/UK	DIN/ Germany	NF/France	SS/Sweden	GB/PR China	KS/Korea	GOST/Russia
DUPLEX GRADES								
FDX 25™	–	–	–	–	–	–	–	–
FDX 27™	–	–	–	–	–	–	–	–
LDX 2101®	4162-321-01-E	–	–	–	–	–	–	–
2304	4362-323-04-I	–	1.4362	Z3 CN 23-04 Az	2327	–	–	–
LDX 2404®	–	–	–	–	–	–	–	–
2205	4462-318-03-I	318S13	1.4462	Z3 CND 22-05 Az	2377	00Cr22Ni5Mo3N	STS 329J3L	–
4501	4501-327-60-I	–	–	–	–	–	–	–
2507	4410-327-50-E	–	–	Z3 CND 25-06 Az	2328	–	STS 329J4L	–
AUSTENITIC GRADES								
4310	4310-301-00-I	301S21	1.4310	Z11 CN 18-08	2331	1Cr17Ni7	STS 301	07X16H6
4618	4618-201-76-E	–	1.4618	–	–	–	–	–
4318	4318-301-53-I	–	–	Z3 CN 18-07 Az	–	–	STS 301L	–
4376	–	1.4376	–	–	–	–	–	
4372	4372-201-00-I	284S16	–	Z12 CMN 17-07 Az	–	1Cr17Mn6Ni5N	STS 201	–
4301	4301-304-00-I	304S31	1.4301	Z7 CN 18-09	2333	0Cr18Ni9	STS 304	08X18H10
4307	4307-304-03-I	304S11	1.4307	Z3 CN 18-10	2352	00Cr19Ni10	STS 304L	3X18H11
4311	4311-304-53-I	304S61	1.4311	Z3 CN 18-10 Az	2371	00Cr18Ni10N	STS 304LN	–
4541	4541-321-00-I	321S31	1.4541	Z6 CNT 18-10	2337	0Cr18Ni10Ti	STS 321	08X18H10T
4550	4550-347-00-I	347S31	1.4550	Z6 CNNb 18-10	2338	0Cr18Ni11Nb	STS 347	08X18H12Б
4305	4305-303-00-I	303S31	1.4305	Z8 CNF 18-09	2346	Y1Cr18Ni9	–	12X18H10E
4303	4303-305-00-I	305S19	1.4303	Z1 CN 18-12	2333	1Cr18Ni12	STS 305	06X18H11
4306	4306-304-03-I	304S11	1.4306	Z3 CN 18-10	2352	00Cr19Ni10	STS 304L	03X18H11
4567	4567-304-30-I	304S17	1.4567	Z3 CNU 18-09 FF	–	0Cr18Ni9Cu3	–	–
4640	–	–	1.4640	–	–	–	–	–
4401	4401-316-00-I	316S31	1.4401	Z7 CND 17-11-02	2347	0Cr17Ni12Mo2	STS 316	–
4404	4404-316-03-I	316S11	1.4404	Z3 CND 17-11-02	2348	00Cr17Ni14Mo2	STS 316L	03X17H14M2
4427	–	–	–	–	–	–	–	–
4436	4436-316-00-I	316S33	1.4436	Z7 CND 18-12-03	2343	0Cr17Ni12Mo2	STS 316	–
4432	4432-316-03-I	316S13	1.4432	Z3 CND 18-14-03	2353	00Cr17Ni14Mo2	STS 316L	03X17H14M3
4406	4406-316-53-I	316S61	1.4406	Z3 CND 17-11 Az	–	00Cr17Ni12Mo2N	STS 316LN	–
4441	–	–	1.4441	–	–	–	–	–
4429	4429-316-53-I	316S63	1.4429	Z3 CND 17-12 Az	2375	00Cr17Ni13Mo2N	STS 316LN	–
4571	4571-316-35-I	320S31	1.4571	Z6 CNDT 17-12	2350	0Cr18Ni12Mo2Ti	STS 316Ti	08X17H13M2T
4435	4435-316-91-I	316S13	1.4435	Z3 CND 18-14-03	2353	00Cr17Ni14Mo2	STS 316L	03X17H14M3
3952	–	–	–	–	–	–	–	–
HIGH PERFORMANCE AUSTENITIC GRADES								
4438	4438-317-03-I	317S12	1.4438	Z3 CND 19-15-04	2367	00Cr19Ni13Mo3	STS 317L	–
4439	4439-317-26-E	–	1.4439	Z3 CND 18-14-05 Az	–	–	–	–
725LN	4466-310-50-E	–	–	–	–	–	–	–
3964	–	–	–	–	–	–	–	–
904L	4539-089-04-I	904S13	1.4539	Z2 NCDU 25-20	2562	–	STS 317J5L	–
254 SMO®	4547-312-54-I	–	–	–	2378	–	–	–
4529	4529-089-26-I	–	–	–	–	–	–	–
4565	4565-345-65-I	–	1.4565	–	–	–	–	–
654 SMO®	4652-326-54-I	–	–	–	–	–	–	–

Physical metallurgy

Phase transformations in stainless steels

Stainless steels are designed by carefully balancing the alloying elements so that an appropriate microstructure is maintained during processing and the required final structure and properties are achieved by heat treatment. Inappropriate heat treatment, service at high temperatures or welding can, however, lead to the formation of other phases. These may be thermodynamically stable or kinetically favoured in lower temperature regimes and can have a major influence on mechanical properties and corrosion resistance.

Solidification and solid state transformations

As a stainless steel solidifies from the melt, dendrites are formed when the temperature drops below the liquidus, Figure 3:1. These may be austenite (which has an fcc structure) or ferrite (which has a bcc structure) depending on the composition of the steel, see Figure 3:6). For some steel compositions the other phase may also solidify directly from the melt, giving rise to a solidification structure denoted AF or FA depending on whether the first solidifying phase is austenite or ferrite respectively. This situation, with two phases forming from the melt, is denoted peritectic solidification and is often desirable in austenitic grades, because the small amount of ferrite has a higher solubility for impurities such as sulphur and phosphorus and can therefore counteract a tendency to hot cracking. Figure 3:2 shows the calculated phase fractions as a function of temperature for the superaustenitic grade 254 SMO®, which shows primary austenite solidification with a small amount of ferrite. In order to obtain an austenitic structure but avoid the precipitation of intermetallic phases, a final annealing process is done at 1000–1200 °C, with the higher temperatures being used for higher alloyed grades.

Below the solidus, further transformations occur in the solid state. An important example is the formation of austenite in duplex grades which have a primary ferritic solidification mode. This is illustrated in Figure 3:2 for the duplex grade 2205, which solidifies ferritically and then undergoes solid state transformation. The austenite forms both along grain boundaries and in a so-called Widmanstätten pattern within the ferrite grains as seen in the microstructure in Figure 3:3. The final microstructure after annealing contains approximately equal fractions of austenite and ferrite. In order to achieve the correct phase balance it is important that duplex stainless steels are annealed within a fairly narrow temperature window, typically 950–1120 °C.

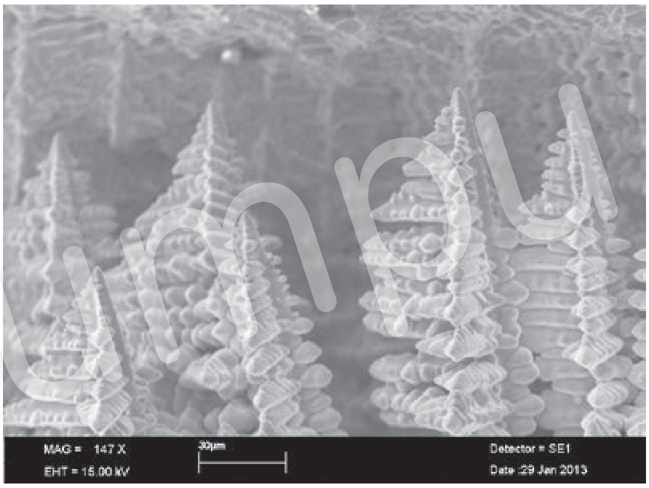


Figure 3:1. Solidification structure showing dendrites which have grown into the melt.

Ferritic grades show ferritic solidification and are annealed at lower temperature, typically 750–1000 °C, to avoid ferrite grain growth. For some grades, particularly those which are not stabilized, there is a risk of partial austenitisation, and subsequent martensite formation on quenching, if the annealing temperature is too high.

In martensitic steels, the austenite begins to transform to martensite on quenching below the temperature denoted M_s (martensite start). Some martensite can also form in so-called metastable austenitic, and recently also in duplex grades, where it is promoted by deformation. This process is typically characterized by the M_{d30} temperature, at which 30 % deformation (strictly speaking a true strain of 0.3) gives 50 % martensite. Various empirical formulae exist to describe the effect of composition on M_{d30} (in °C), one of the most common is that developed by Nohara which also takes the effect of grain size into account:

$$\mathbf{M_{d30} = 552\text{-}462(C+N)\text{-}9.2Si\text{-}8.1Mn\text{-}13.7Cr\text{-}29(Ni+Cu)\text{-}18.5Mo\text{-}68Nb+1.42(ASTM\text{-}8)}$$

Intermetallic phases

In the temperature range of typically 600–1000 °C, stainless steels can form intermetallic phases such as sigma phase, chi phase and Laves phase. These phases have historically often been collectively denoted “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 extent of the deterioration in properties is to some extent dependent on which of the phases is actually present.

Intermetallic phase are promoted by alloying with silicon, molybdenum and tungsten and form most readily from highly-alloyed ferrite. In ferritic and duplex steels, intermetallic phases precipitate rapidly but are relatively easy to dissolve by annealing. In the austenitic steels, it is the highly alloyed grades which are particularly susceptible to intermetallic phase formation. The predicted amounts of intermetallic phases as a function of temperature is seen for 254 SMO® and 2205 in Figure 3:2, but this says nothing about the kinetics of precipitation, only that it is thermodynamically possible. Kinetics are described in experimentally-determined TTT (time-temperature-transformation diagrams) such as those shown in Figure 3:4.

Austenitic steels which have low chromium content and do not contain molybdenum require long times at elevated temperatures to form intermetallics and are therefore considerably less sensitive to the precipitation of these phases. In all grades, precipitates can be dissolved by annealing. Re-tempering martensitic steels and annealing and quenching ferritic, duplex or austenitic steels restores the structure. Relatively long times at high temperatures may be required for the dissolution of intermetallic phases in highly alloyed steels.

Carbide and nitride precipitation

Since ferrite has a low solubility for interstitials, ferritic steels may suffer precipitation of chromium carbides, nitrides or even borides during cooling after annealing, 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, for example by additions of titanium and niobium as in grades 4509 and 4521.

Carbide and nitride precipitation in the austenitic grades 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. This precipitation was once a problem with austenitic stainless steels, giving rise to a sensitization after welding and a risk for so-called weld decay or knife-line attack, but is rarely encountered with modern lower carbon stainless steels unless they are subjected to extreme thermal treatment. Nitrides and carbides can also precipitate in phase boundaries in duplex stainless steels as a result of heat treatment in the same temperature range. In addition, clusters of very small nitrides can form within the ferrite phase if there is insufficient time during cooling for the nitrogen to repartition to the austenite.

In higher alloyed steels complex nitrides such as pi phase, eta phase or Z-phase may occur as precipitating phases, but the most frequently encountered phases are still the $M_{23}C_6$ carbide and M_2N nitride.

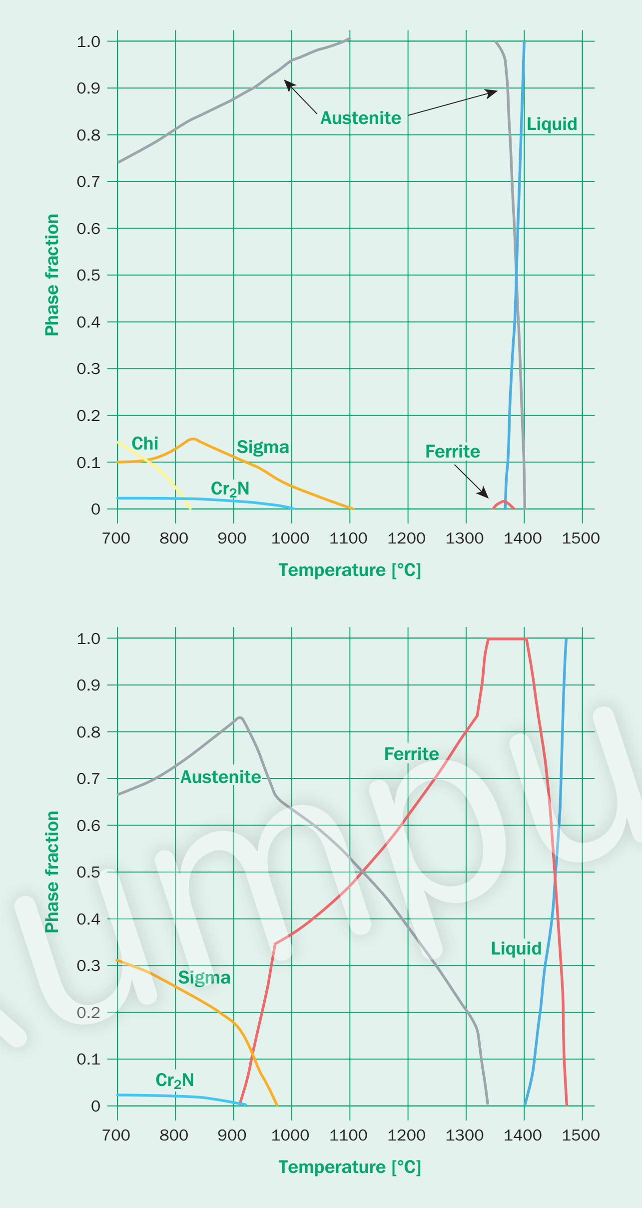


Figure 3:2. Phase fractions as a function of temperature for 254 SMO® (top) and 2205 (below) calculated using ThermoCalc. For 254 SMO® austenite is the primary solidification phase and intermetallic phases appear below ~1100 °C. For 2205 the primary solidification is ferritic and solid state transformation to austenite starts below ~1350 °C.

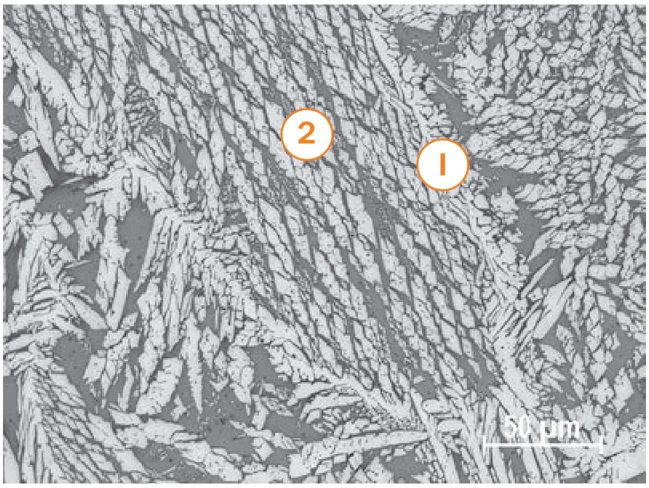


Figure 3:3. Microstructure of an as-welded duplex stainless steel with grain boundary (1) and Widmanstätten austenite (2).

475 °C embrittlement

If martensitic, ferritic or duplex steels are heat treated or used in the temperature range 300–500 °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-centred cubic structure, α and α'. The former is rich in iron and the latter in chromium. This type of embrittlement is usually denoted 475 °C embrittlement and is seen in the TTT-curves for the duplex stainless steels in Figure 3:4. It can be reversed by annealing at temperatures above 550 °C.

Non-metallic inclusions

All steels contain some non-metallic inclusions. These are small particles in the micrometer range or smaller which may be isolated or in the form of stringers parallel to the rolling direction. Oxide inclusions reflect the deoxidization process employed and can contain aluminium, silicon and/or calcium, as shown in the ternary phase diagram in Figure 3:5. Sulphides typically contain manganese which is deliberately added to combine with residual sulphur. In cases in which there are strict requirements of low inclusion levels, e.g. to give superior surface polishability, additional production routines may be used to give a cleaner steel. In order to produce steels with superior machinability, such as the Outokumpu PRODEC® grades, a higher inclusion population with carefully-designed composition is present.

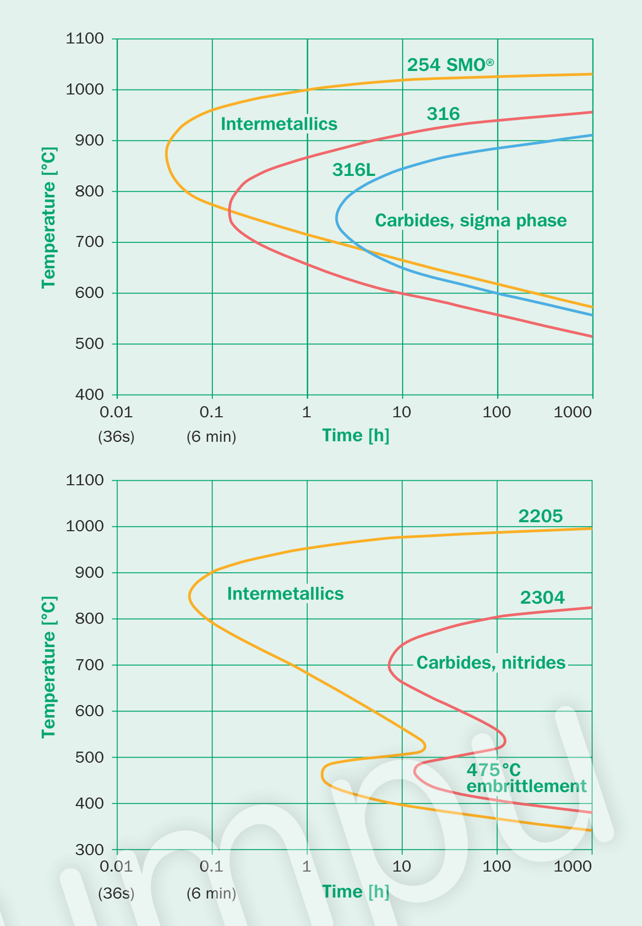
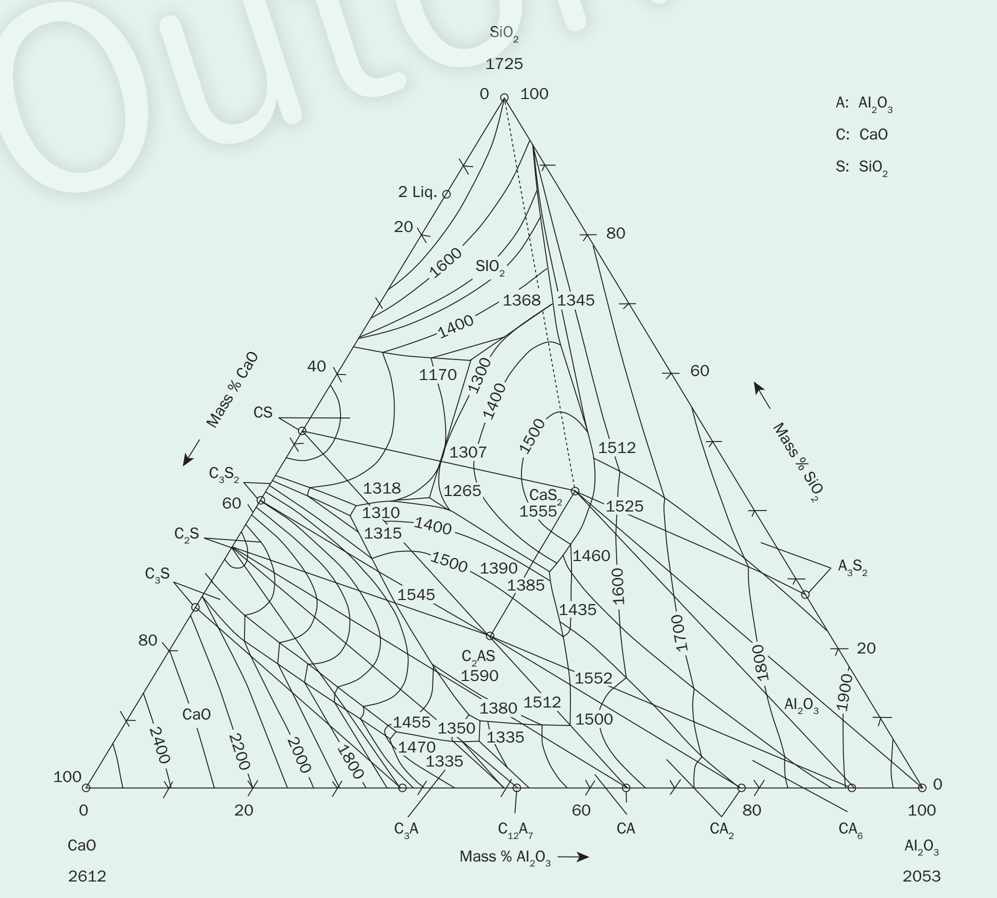


Figure 3:4. Experimentally determined TTT diagrams for conditions causing a 50 % reduction in impact toughness for austenitic grades (top) and two duplex grades (below).

Figure 3:5. Ternary diagram typically used for classification of the oxide inclusions in stainless steels.



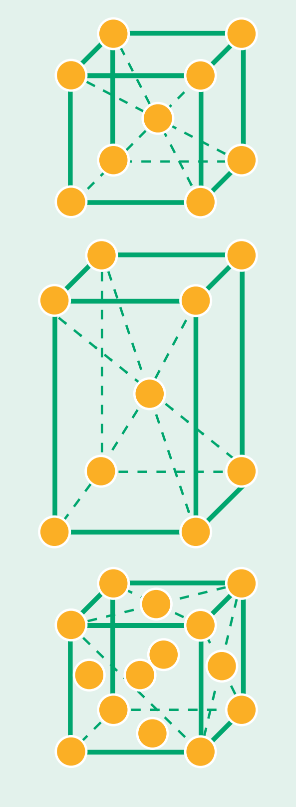


Figure 3:6. Atom positions in, from top to bottom, BCC, BCT and FCC structures.

Stainless steel production

Raw materials

The main raw material for production of stainless steel is recycled steel scrap, mostly stainless steel scrap. At Outokumpu, 85-90 % recycled scrap is used in the production. The rest is virgin material in the form of different alloying elements.

To handle such big volumes of steel scrap, rigorous purchase routines are needed. At arrival, before entering the melt shop site, the steel scrap is tested to ensure that no radioactive components are present. The steel scrap is then tested, analysed and sorted according to its alloying content to ensure that as little virgin material as possible is needed to get the right chemical composition of the stainless steel produced.

Ferrochrome

The ferrochrome plant is an integral part of the steel production at Outokumpu Tornio Works. In ferrochrome production, the mined chromite ore is crushed and pelletized before it is further processed in a sintering plant. The sintered chromite pellets are brought to the ferrochrome plant where they are charged to a pre-heater, heated by the off-gases from the actual smelting process. The ferrochrome smelting is done in a closed submerged arc furnace (SAF) equipped with shafts to charge material from the pre-heater situated on-top of the SAF. To preheat the charged material up to 700 °C decreases the specific electric energy consumption in the smelting process and significantly improves the overall operation. The finished ferrochrome (FeCr) contains approximately 52 % chromium, 4 % silicon and 7 % carbon. The main part of the produced FeCr is cast and solidified in large castings, which then are crushed for sale, or further processed; see Figure 4:1. At Outokumpu Tornio Works, part of the ferrochrome is transferred to the steel melting shop as a liquid, and is pre-processed in a ferrochrome converter to remove the silicon and part of the carbon content. The reaction energy from burning the silicon and carbon with oxygen is utilized to melt more material fed into the converter. As the charge weight increases, the chrome content decreases from 52 % to about 35 %. This liquid is then used as part of the raw material charged to the AOD converter for the next step in the stainless steel production.

Figure 4:1. Liquid ferrochrome casting.

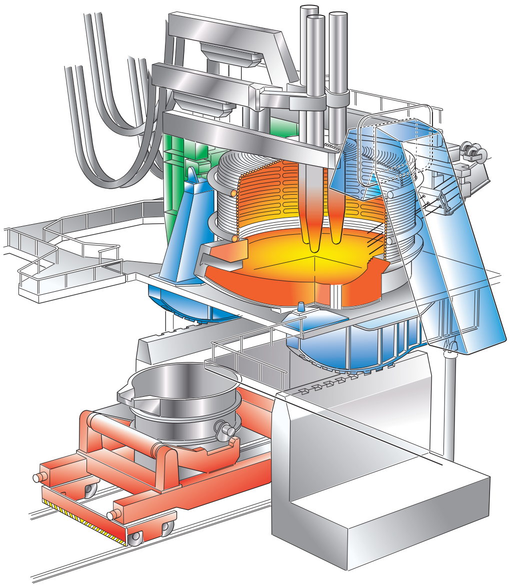


Figure 4:2. Schematic illustration of an electric arc furnace (EAF).

Meltshop

Processing steel scrap and alloys in the melt shop is the first step in the production of stainless steel. The configuration of the meltshop depends on the capabilities of the steel works, but consists of several combinations of equipment. Typically there are four main steps, each in different units: 1) melting of raw materials in an electric arc furnace (EAF); 2) removal of carbon, sulphur and possibly also nitrogen in a steel converter; 3) tuning of the steel composition and temperature in ladle treatment; 4) casting of slabs or ingots.

The most conventional method is to melt the raw materials, scrap (alloyed and unalloyed) and ferro-alloys in an electric arc furnace, Figure 4:2. The scrap is charged into the furnace using large baskets. The lid is closed and the electrodes are lowered, and powerful electric arcs start to melt the scrap and alloys. During the melting process, the arc reaches temperatures of up to 3500 °C, and the molten steel can reach up to 1800 °C. Additional injection of chemical energy in the form of carbon, ferrosilicon, oxygen or fuel gas mixtures speeds up the melting process.

After melting, the steel is further processed in an AOD (Argon Oxygen Decarburization) converter, Figure 4:3. The main objective of this step is to reduce the carbon content to a target amount by injecting an oxygen-argon mixture but also to supply additional alloying elements. After the AOD treatment, the molten material is poured into a ladle.

In the case when liquid ferrochrome is used, an iron rich scrap mix with low alloy content is melted in the arc furnace. Nickel and molybdenum together with the liquid ferrochrome are then added in the AOD converter.

An alternative decarburization process is the VOD (Vacuum Oxygen Decarburization), which is especially suitable when very low carbon or nitrogen content is required, for instance in the case for some high chromium ferritic stainless steels.

The quality requirements for most stainless steels make a secondary metallurgical treatment necessary. This is done in a ladle station, ladle furnace, or as a vacuum treatment of the liquid steel, Figure 4:4. The goal of this process step is to make the final adjustment to the chemical composition; the steel is calmly stirred to remove unwanted inclusions and to homogenize both temperature and chemistry of the molten material, maintaining a tight specified composition within exact temperature limits.

At the correct time, and placed in such a way that the next heat will be ready for casting when needed, the liquid steel ladle is transported to the continuous casting machine or, in some special cases, to the ingot casting area. Continuous casting is a process in which molten steel is converted into slabs of manageable size, Figures 4:5 and 4:6. The ladle with molten steel is placed in a holder or on a turret. From the ladle, the steel is tapped through a nozzle into the tundish. The tundish is an intermediate vessel designed to maintain a constant weight and allows for flying ladle changes during the course of casting in a continuous process. From the tundish the steel flows through a submerged entry nozzle (SEN) into the water cooled copper mould. The steel flow is often automatically controlled to maintain a constant steel-level in the mould as the bottom of the mould is slowly retracted and follows an arc shaped set of top and bottom rollers which support the solidified strand shell. Molten casting powder is used to reduce friction and ensure good contact between the mould and the solidified shell. Intensive water spray cooling of the strand starts immediately below

Figure 4:3. AOD converter.

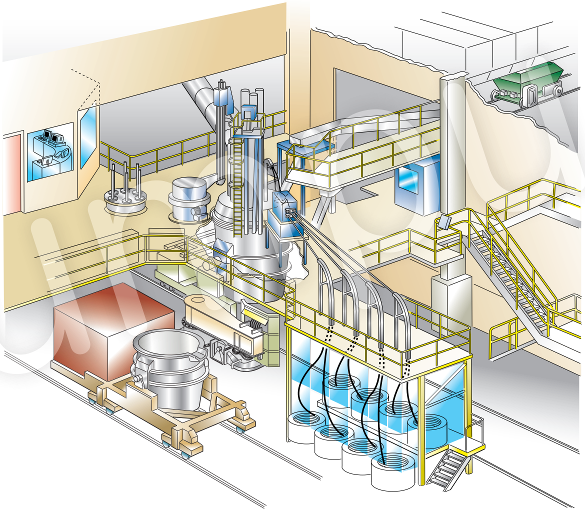


Figure 4:4. Schematic illustration of a ladle furnace.

Figure 4:5. Continuous casting. Turret with ladle and tundish, from which the molten steel is led down into the mould by the submerged entry nozzle (SEN).

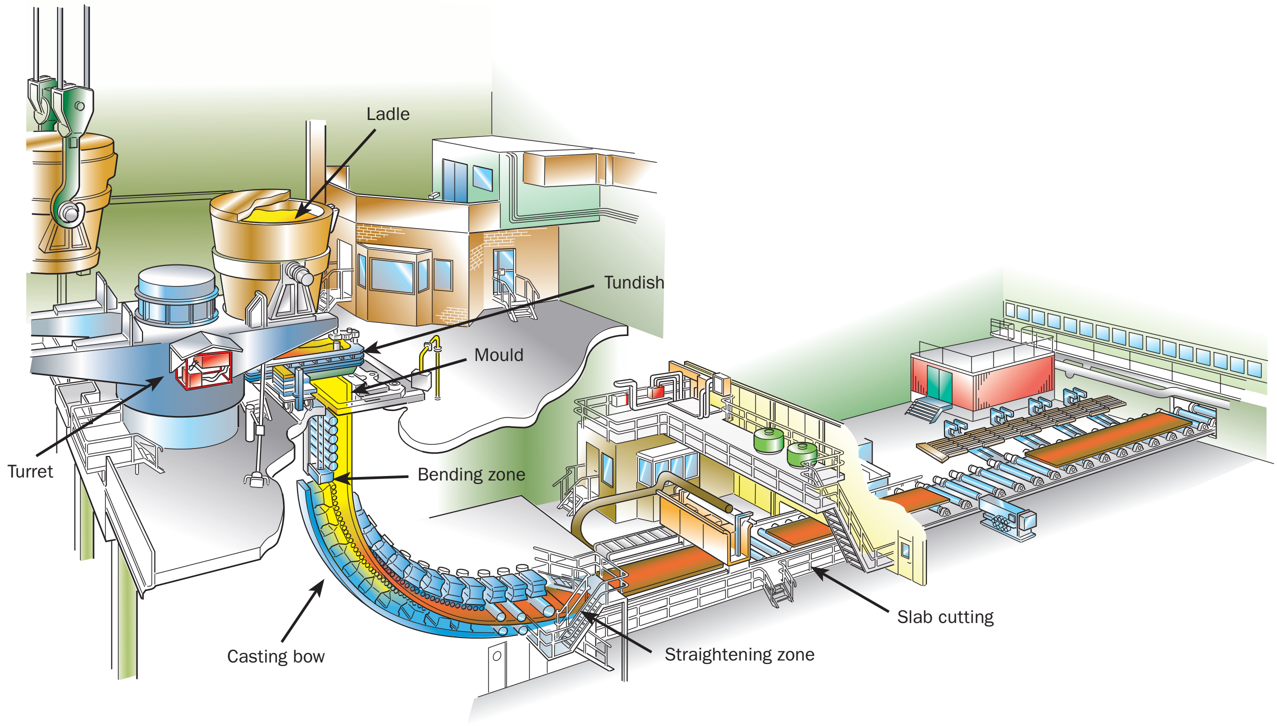


Figure 4:6. Schematic illustration of a continuous casting machine.

the mould and in-between the supporting rollers, to solidify the hot melt inside the solidified shell to form a solid strand of steel. The strand is continuously cooled and shrinks in volume as it is withdrawn on its arc-shaped path down to the cutting station. At this stage, the steel is still hot and glowing, but is sufficiently solid to enable the strand to be cut with movable oxygen lances into manageable pieces called slabs. Slabs serve as the feedstock for the flat hot rolling mills. The process is similar for the semi-finished casting products like blooms and billets which are starting material for the long product production.

Every slab has a unique identity number and is carefully tracked. This identity (slab/coil number) follows the material through the whole production line and is written in the material certificate. This makes it possible to back-track the material all the way back to the melt shop. Recorded production parameters are linked to the identity number to ensure that the individual end product fulfils the requirements given by the customer. All slabs are inspected to ensure a high quality. Slabs for more demanding stainless steel grades are ground to ensure a high quality surface finish on the final product, Figure 4:7.

Figure 4:7. Hot grinding of slab.

Hot rolling

Hot rolling is a metalworking process that occurs at a temperature above the recrystallization temperature of the material. The starting material is usually semi-finished casting products such as slabs, blooms, or billets. The cast microstructure is broken down and deformed during processing and the deformed grains recrystallize, which maintains an equiaxed microstructure (a structure in which the grains have approximately the same dimensions in all directions) and prevents the steel from work hardening. While the finished product is of good quality, the surface is covered in mill scale, which is an iron and chromium rich oxide that forms at high-temperatures. It is usually removed in the annealing and pickling line, which restores the smooth metallic surface.

Figure 4:8. Walking beam furnace.

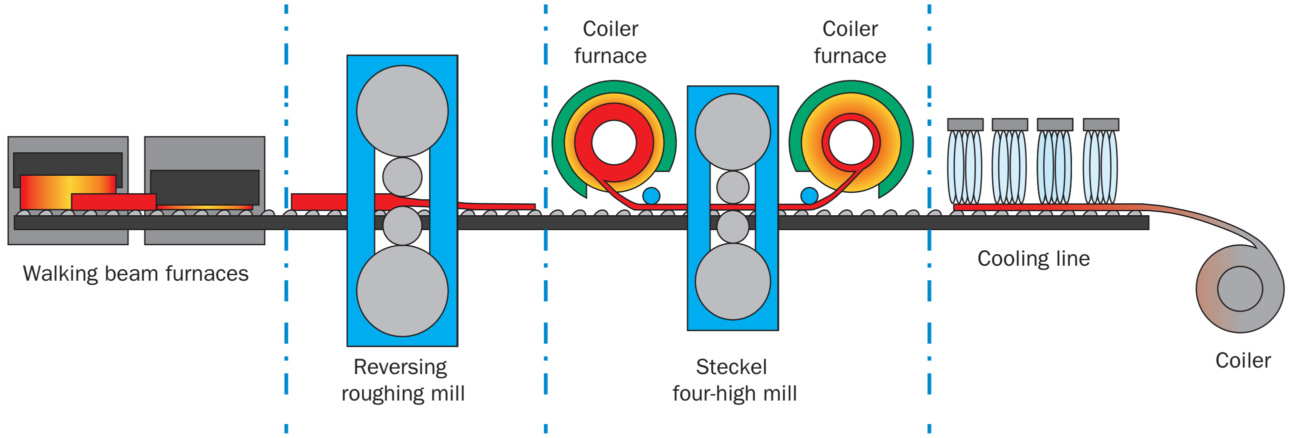


Figure 4:9. Schematic illustration of the complete Steckel rolling mill line.

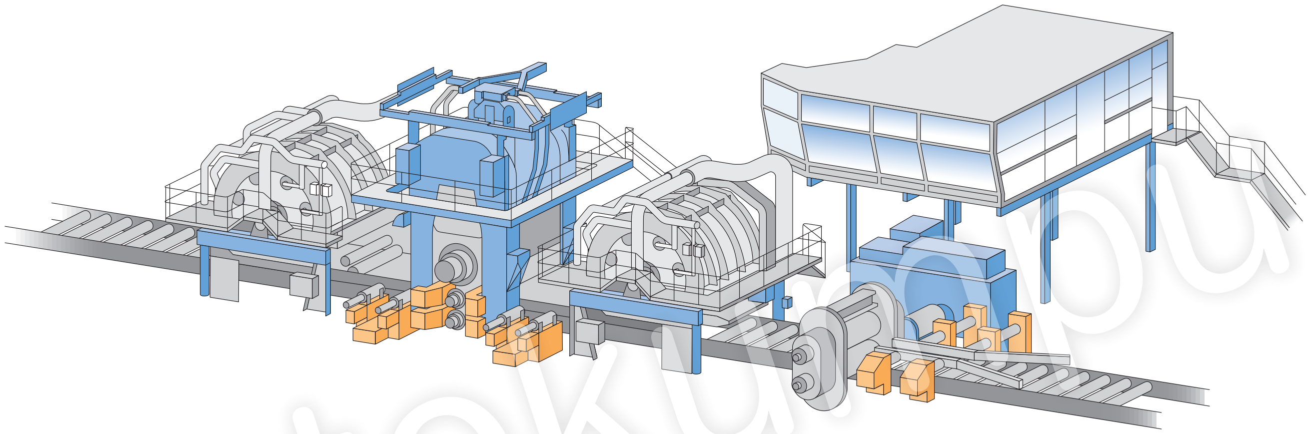


Figure 4:10. Schematic illustration of the Steckel rolling mill at Outokumpu Avesta Works.

Hot strip rolling

In the hot rolling mill, the slabs with a thickness of 140–300 mm, each weighing up to 30 tons, are reheated in walking beam furnaces to a temperature often above 1200 ˚C and then discharged to the rolling mill train, Figure 4:8. Depending of maximum capacity, the rolling mill can be fully continuous with many individual rolling stands, for example with a reversing roughing mill and five to seven four-high stands lined up one after the other.

At Outokumpu Avesta Works, a reversing roughing mill and a finishing Steckel four-high mill are used. In the Steckel mill the strip is rolled back and forth between two coiler furnaces and the strip is reduced in thickness in each pass between the coilers, Figures 4:9 and 4:10. At Outokumpu Tornio Works, a reversing roughing mill and a finish train consisting of a Steckel mill and three separate finishing stands are used.

Maintaining a uniform gap between the rolls is the key to achieving close thickness tolerance control during rolling, but it is difficult because the rolls deflect under the load required to deform the workpiece. The workpiece temperature is not uniform and the flow of the material will occur more in the warmer parts and less in the cooler parts. In summary these effects causes the workpiece to be thinner at the edges and thicker in the middle and this feature is called the crown of the strip. It is desirable to have some controlled crown on the workpiece as this gives better workpiece centring during rolling and increased rolling stability. There are many ways to control the crown and the interlinked property flatness. This can be done by using crowned work rolls, parabolic or with a continual varying crown (CVC) or by work roll bending using hydraulic cylinders at the ends of the rolls to counteract roll deflection. It can also be done tapered support rolls that are sideways shifted, or by work roll pair that are slightly crossed (pair-cross control) so that the gap between the edges of the rolls will increase or decrease, thus allowing for dynamic crown control.

Downstream of the finishing train is an exit roller run-out table with cooling devices and a coiler. As the strip leaves the rolling mill after the last pass, a set of lamellar water cooling banks with controlled water flow ensures that the desired coiling temperature is obtained. The coiling temperature can for some stainless steel grades be crucial for the final quality of the coil. The coiled black hot rolled band is covered with a thick oxide scale layer and is after annealing and pickling used as feedstock for the cold rolling mill. It can also be annealed and pickled followed by shearing into plates and supplied as a hot rolled continuous produced plate, CPP or as annealed and white pickled hot rolled coils.

Hot plate rolling

Similar to hot strip rolling, the slabs or ingots are reheated to the desired temperature in a walking beam furnace, a pusher furnace or a pit furnace. In hot plate rolling the slabs are much smaller and suitable for processing one, or multiple plate length mother plates. In contrast to strip rolling, the plate mill has capabilities to rotate the slab and roll it in both longitudinal and transverse directions, thus spreading the plate to wider widths as well as rolling to the desired plate thickness and length. The rolled plate product is sometimes referred to as "Quarto Plate", giving reference to the type of four-high rolling stand used for the best dimensional tolerances. Depending on the plate mill's maximum capacity the operation can be done in a reversing single stand, where the steel is passed backwards and forwards through the mill, or divided between a roughing and a finishing plate stand. As in strip rolling the hot operation is followed by an annealing and pickling step.

Hot rolling of long products

Blooms or billets are heated in a pit furnace or a pusher furnace and, in the case of billets; induction heating can be used as an alternative or a supplement. Blooms are processed to rolled billets or bars/transfer bars before being sent on to the finishing train to produce thinner bars or wire rods. In the early mill stand, only two sides of the steel are rolled at any one time, and the piece of steel is then turned over to allow the other two sides to be rolled. The finishing train is made up from a series of universal mills and often a finishing wire rod block mill. In these mills all faces of the workpiece are rolled at the same time. The hot working is so intense in wire rod mills that the steel temperature increases during the rolling sequence and must be limited by controlling the rolling speed and using water cooling. When the piece of steel passes through this series of stands it is not only reduced in size, but also changes shape. Long products come off the mill as long bars of steel or coiled wire rod and are produced in a vast range of different shapes and sizes. Bars can have cross-sections in the shape of squares, rectangles, circles, hexagons, angles or have cross-sections shaped like an H or I (called joists, beams and columns), a U (channels) or a T.

Annealing and pickling of hot rolled products

The hot rolled product, strip or plate needs to be heat-treated and pickled before it is cold rolled or released to the finishing operations. For strip, this is often done in a continuous annealing and pickling line (CAPL or AP-line) consisting of one or several annealing furnaces followed by a mechanical descaling step, such as shot blasting. The scale is then removed by a mixed acid pickling system based on nitric acid and hydrofluoric acid and sometimes even some added sulphuric acid, Figure 4:11. The continuous strip passes a series of shallow, high turbulence mixed acid pickling baths followed by high pressure water rinsing and drying. The result is a scale-free surface denoted as 1D/No. 1 finish according to EN10088-2/ASTM A480 respectively. A similar sequence is used for hot rolled plates but is often carried out at linked separate stations, sometimes connected by automatic transport systems. The optimized pickling process, with individual circulation and heating systems, ensures minimum consumption of utilities and acids. The most modern CAPL lines can include one or several rolling mills that reduce the strip thickness by in-line reduction passes before or after the heat treatment. Such lines are sometimes referred to as RAP-lines (Rolling, Annealing, Pickling) and the resulting surface finish is denoted as 2E/2D, or 2B/2B if the line includes in-line skin passing.

Figure 4:11. Mixed-acid pickling line.

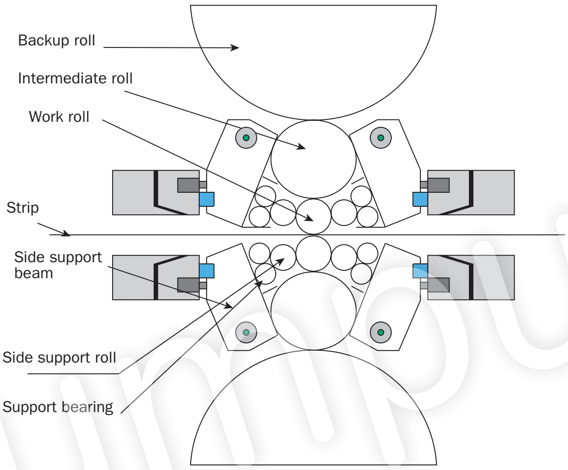


Figure 4:12. Rolls configuration in a Z-high mill.

Cold rolling, annealing and pickling

The cold rolling of stainless steel is predominately carried out in cluster mills such as Sendzimir 20-high mills, Z-high mills and similar, Figure 4:12. These mills have small-diameter working rolls each backed by two or three layers of supporting rolls, and are very suitable for cold-rolling wide sheets of stainless steel to close tolerances and improved surface finish. The typical configuration uses a separate pay-off reel and coiler on each side of the rolling mill, allowing for several passes back and forth. The pay-off reel allows for preparation of the next strip during rolling, as the pay-off reel is only used during the first pass or as an uncoiler.

The mills have equipment to measure the strip thickness, the strip profile and the strip flatness and have various actuators to control the strip profile and flatness. The rolling schedule, which is often computer generated, automatically takes the mills specific limitations and strip material characteristics into account. The rolling schedule defines the number of passes the strip has to go through and which thickness reduction per pass shall be used when rolling from the starting gauge to the desired final gauge. During the cold rolling process the material deforms and strain hardens to the extent that only a few per cent of the original tensile elongation remains. Typical cold rolling reduction is 50–90 % and depends on the work hardening behaviour of the steel grade.

Figure 4:13. Skin pass mill at Outokumpu Tornio Works.

To restore the material properties after cold rolling, a heat treatment to recover and recrystallize the deformed microstructure is needed. This is again done in a continuous annealing and pickling line, ideally, in a separate CAPL only used for thin cold rolled strip. If the strip is thicker than 2-3 mm this can be done in a combi-line used for both hot and cold rolled strip. A typical cold rolled AP-line has a pre-treatment phase, often an electrolytic pickling step in a neutral solution based on sodium sulphate, or an acidic step based on nitric acid. The majority of the cold rolled products have a 2B/2B surface, which means that no mechanical scale breaking is used, all oxide scale is removed by chemical means. This is achived by passing the strip through several consecutive mixed acid pickling baths and finishing off by high pressure water rinsing. Many of these lines also have some type of flatness improvement equipment installed.

Another route after cold rolling is to use a bright annealing line (BA-line) to restore the material properties. In such a line, the strip is heat treated in a protective atmosphere, often hydrogen or a mixture of hydrogen and nitrogen. As no oxygen is available inside the furnace, no additional oxide scale is formed and whatever oxide remains on the strip is reduced to metal. If the cooling is also done in a protective environment, such strip can after skin pass rolling exhibit a mirror like finish, referred to as 2R or BA (Bright Annealed).

Skin pass rolling

Following annealing and pickling and to produce the common 2B surface quality the coils should be given a further very light cold rolling treatment in a single stand SPM (skin pass mill), Figure 4:13, or in a roller leveller. The rolling mill operation has different names and is called skin pass or temper or planish pass rolling and involves the least amount of reduction: 0.5–1 %. The purpose of skin passing is;

Figure 4:14. A coil that has been slitted into several narrow coils.

- to improve the strip shape and remove minor surface blemishes
- to create the desired surface finish
- to produce the appropriate mechanical properties

The last purpose is mainly applicable to ferritic stainless steels where the upper yield point disappears and there is no yield point elongation which prevent Lüders band formation during subsequent forming. Skin passing breaks down the Cottrell atmospheres created by interstitials around dislocations thus removing the yield point phenomenon permanently in ferritic stainless steels (if additional heat treatments are not applied in later process operations).

Final processing

The final operations before sending the product to the customer are called finishing. This is where coils and plates are tailored to customer requirements which can include;

- Levelling a plate or coil with a roller leveller or a stretch leveller, or a combination of both techniques. Such operations are often combined with other finishing operations.
- Edge trimming of the coil to the desired width.
- Slitting a coil into several narrow coils suitable for the end-users following production steps, see Figure 4:14.
- Cutting a coil into customer-specified or standard length sheets/plates in dedicated cut-to-length (CTL) lines.
- Shearing or cutting into an order sized square/rectangular plate or customized special shape plate from a larger quarto mother plate.
- Applying a plastic film coat to provide surface protection for further processing by the customer.
- Edge preparation for special welding requirements.
- Surface preparation such as grinding, brushing, pattern rolling or embossing.

Product forms

Product forms of finished stainless steel products and their terminologies

Steel is not a single product. There are many thousands different grades of steel with a variety of properties – physical, chemical and mechanical. Some of the stainless steel product forms and terminologies will be discussed below. More detailed definitions can be found in the two standards ISO 6927 and EN 10079.

Starting from a geometrical point of view the product forms can be divided in flat and long products.

An alternative way to describe the product forms is to follow the production route starting with semi-finished products, rolled products and products finished by additional operations.

Flat products

A flat product is a plate product or a (hot or cold) rolled coil product, Figures 5:1 and 5:2. Typically, it is rolled in a rolling mill to produce the final thickness. Plate products vary in thickness from 5 mm to 200 mm and thin flat rolled products from 50 µm to 5 mm. In addition there is an intermediate thickness range covered by hot rolled coiled flat products. Plate products are used for construction, large diameter welded pipes and boiler applications. Thin flat products find end use applications in chemical process industry, domestic ‘white goods’ products, welded tubes and a host of other products from minute springs to huge heat exchangers and storage tanks.

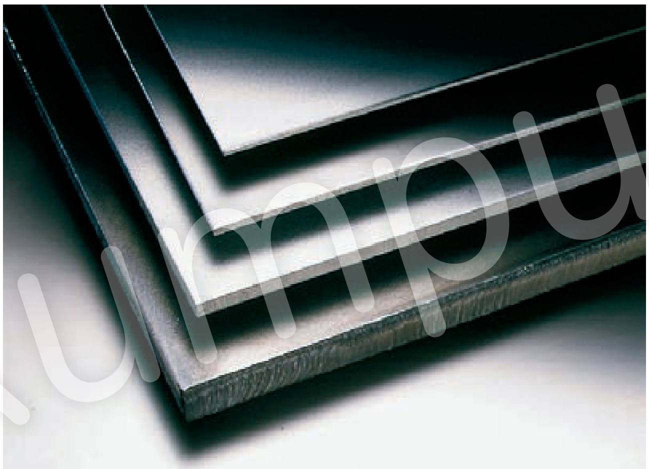


Figure 5:1. Hot rolled quarto plate.

Figure 5:2. Cold rolled 2m wide coils.

Long products

The long products include a variety of products such as rods, bars, wires, rails, tubes and sections, Figure 5:3. Many of the products originate from hot-rolled rod coil that is further processed into wires or cold-drawn bar. The rod coil itself can have a round, square, hexagonal or octagonal shape. Final products include reinforcing bars (Figure 5:4) for concrete, engineering products such as gears, tools etc. from bar stock and large rolled steel joists (RSJ) that are used in building construction projects.

Semi-finished products

Steel products such as ingots, billets, blooms and slabs fall under the category semi-finished products. These products can be made by direct continuous casting of liquid steel or by pouring the liquid steel into ingots, which are then hot rolled into semi-finished products.

Ingots

Ingot is a semi-finished steel product obtained by casting the melt into fixed size moulds. This product must be processed by a breakdown rolling mill or forged into desired wrought semi-finished products or in some cases rolled/forged into thicker finished sections.

Slab

Slab is a semi-finished steel product obtained by rolling or forging ingots or by casting a melt in a continuous caster and cut the strand into suitable lengths. The slab has a rectangular cross section and is used as a starting material in the production process of flat products, i.e. hot rolled coils or plates.

Blooms

Bloom, Figure 5:5, is a cast semi-finished steel product with a smaller cross section than slabs, often rectangular, typically larger than 200 mm × 200 mm. Blooms can also be cast to different shapes like I or H-beam profiles or rounds.

Billet

Billet, Figure 5:6, is a semi-finished steel product with a square cross section up to 200 mm × 200 mm. This product is either rolled or continuously cast and then further processed by rolling to produce finished products like wire rods, merchant bars and other sections. Billets, especially rolled billets, are used as a starting workpiece in many forging operations, e.g. flange production.

Rolled products

Hot rolling

Hot rolling is a metalworking process that occurs above the recrystallization temperature of the stainless steel, Figure 5:7. The starting material is usually semi-finished casting products, such as slabs, blooms, and billets. The semi-finished products are sometimes directly fed into the rolling mill but more often reheated from room temperature to the proper hot working temperature. This is done in a gas- or oil-fired furnace for slabs and blooms. For billets, a billet induction heating can be used.

The final flat products are either sheet or plate. According to the standard ASTM A480, the former are less than 4.76 mm thick and the latter thicker than this. According to the European standard EN 10079 a sheet has as a square or rectangular shape with a thickness less than 3 mm. The product can be rolled into coils or individual plates. In the latter case the plate are sometimes referred to as quarto plate, acknowledging the type of rolling mill used to produce the plate. The hot rolled coil product can be sheared into plates and supplied as a hot rolled product, CPP (Continuous Produced Plate) or as a hot band for the next processing step, often cold rolling. A special case of this is SHRP (Steckel Hot Rolled Plate), where a 10–25 mm thick strip is cut into plates directly in the hot

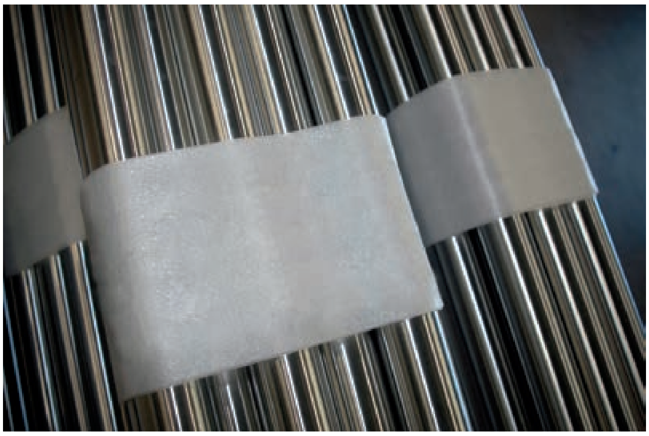


Figure 5:3. Long products, bar bundles.

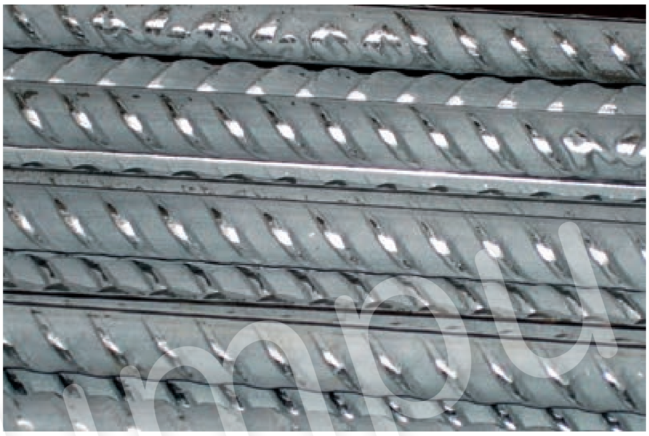


Figure 5:4. Long products, stainless steel reinforcing bars.

Figure 5:5. Long products, blooms.

Figure 5:6. Long products, billets.

rolling mill without coiling. Products produced in narrow coil widths are referred to as strip. This means less than 600 mm for hot rolled products and less than 500 mm for cold rolled products. For long products the main hot rolled products are rods which are wound into coils, or bars that are produced as straight lengths, Figure 5:8.

The resulting surface on hot rolled products depends on the finishing operation and several types of finishes can be found in the standard EN 10088-2 (European designations) and in ASTM A480 (American designations). The most common is 1D/No. 1 finish according to EN 10088-2/ASTM A480 respectively, defined as hot rolled, heat treated, pickled and free of scale, Figure 5:10. This standard is used for most steel types to ensure good corrosion resistance and is also a common finish for further processing.

Cold rolling

Cold rolling occurs with the metal below its recrystallization temperature (usually at room temperature), which increases the material strength via strain hardening (work hardening). It also improves the surface finish and gives tighter tolerances compared to hot rolling. Cold-rolled products such as sheets, strips and bars are usually thinner than the same products that are hot rolled. Because of the smaller size of the workpieces and their greater strength compared to hot rolled stock, four-high or cluster mills are often used. Cold rolling cannot reduce the thickness of a workpiece as much as hot rolling in a single pass.

After cold rolling, the normal procedure is to recrystallize the material by annealing and remove the newly formed scale by pickling, Figure 5:9.

The most common cold rolled finish is 2B/2B defined as; cold rolled, heat treated, pickled and skin passed, Figure 5:11. This procedure ensures good corrosion resistance, tolerances, smoothness and flatness. It is also a common finish for further processing. Skin passing may also be done by tension levelling.

A second common cold rolling finish is 2E/2D defined as; cold rolled, heat treated, mechanically descaled, which is usually applied to steels with a scale which is very resistant to pickling solutions, Figure 5:12. The most modern processing lines include one or more cold rolling mills. The cold rolling can be carried out on a pickled surface similar to off-line cold rolling or on a black unpickled coil as in the Outokumpu RAP processing line. This line also include a skin pass mill and can produce both 2E/2D or 2B/2B products directly without any additional process steps.

The 2E surface is optimal for further fabrication and manufacturing of high quality stainless steel products like tubes and hollow sections. The surface has typically a rough and dull appearance, but can depending on the type of mechanical descaling in some cases compare with 2B surface roughness values. A third common practice is to use a bright annealing furnace where the material is heated in a protective atmosphere and no additional scale forms and thereby no further pickling is needed. This type of processes is often referred to as 2R/BA (Bright Annealed) and produces a surface that is smoother and brighter than 2B and with high reflectivity, Figure 5:13.

The ferritic grade 4016 is also produced with a 2BB surface (Figure 5:14) defined as; cold rolled, heat treated, bright pickled and skin passed. This surface is comparable to the bright annealed finish 2R/BA. The 2BB finish is an Outokumpu designation, but the product conforms to the standard 2B surface definition.

Skin pass rolling utilise a low amount of reduction: typical 0.5–1 %. It is used to produce a smooth surface, a uniform thickness and for ferritic grades reduces the yield point phenomenon (by preventing Lüders bands from forming in later processing).


Figure 5:7. Hot rolling.


Figure 5:8. Long products, hot rolled rod coil.

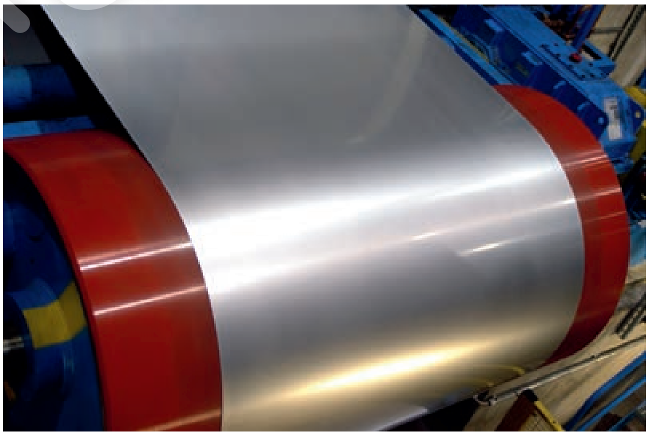


Figure 5:9. Cold rolled coil after annealing and pickling.

Finished cold-rolled sheets and strips may come in various conditions; fully annealed or work hardened (temper rolled) to certain tensile strength levels such as C700, C850 etc., indicating a tensile strength of 700 or 850 MPa. The temper rolled finish is designated as 2H/TR finish and exhibits a bright surface that is cold worked to obtain higher strength level.

For long products, cold working is most often achieved by cold-drawing, in which the cross section area reduction is achieved by drawing the rod coil or bar on a draw-bench or more commonly through a die. This process results in a hardness profile of the bar or wire, with a harder surface and softer middle.

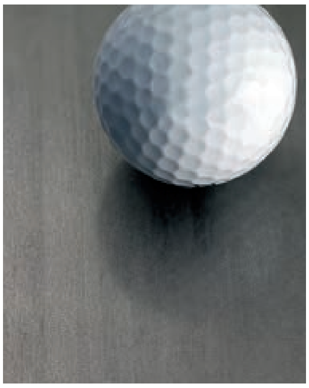


Figure 5:10. Hot rolled 1D/No. 1 finish surface.

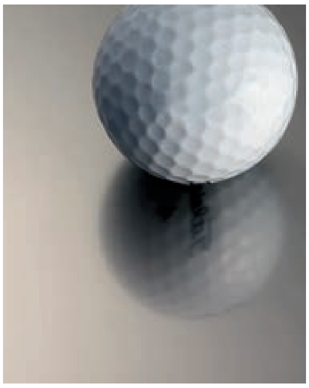


Figure 5:11. Cold rolled 2B/2B surface.

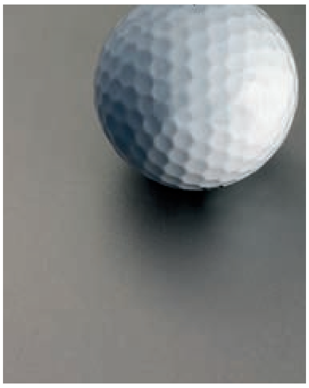


Figure 5:12. Cold rolled 2E/2D surface.

Figure 5:13. Cold rolled 2R/BA surface.

Figure 5:14. Cold rolled 2BB surface.

References

ISO 6927, "Buildings and civil engineering works – Sealants – Vocabulary".

EN 10079, "Definition of steel products".

ASTM A480, "Standard Specification for General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip".

EN 10088-2, "Stainless steels – Part 2: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes".

Corrosion and corrosion properties

Corrosion is the gradual degradation of a metal by chemical, often electrochemical, reaction with the surrounding environment. A result of corrosion can be loss of material properties such as mechanical strength, appearance and impermeability to liquids and gases. Stainless steels are often chosen because of their resistance to corrosion, but they are not immune to corrosion. Whether a stainless steel is corrosion resistant in a specific environment depends on the combination of the chemical composition of the stainless steel and the aggressiveness of the environment.

Corrosion can be divided into wet corrosion and high temperature corrosion:

- Wet (or aqueous) corrosion refers to corrosion in liquids or moist environments, and includes atmospheric corrosion.
- High temperature corrosion denotes corrosion in hot gases at temperatures from around 500 °C to 1200 °C.

The corrosion resistance of stainless steel is attributed to the thin passive film that forms spontaneously on the stainless steel surface in oxidising environments if the chromium content in the steel is minimum ~10.5 %. A special passivating treatment is not required as the film forms instantly in oxidising media such as air or aerated water. This passive film is very thin (1–3 nm) and consists mainly of iron and chromium oxides and hydroxides as shown in Figure 6:1. As the passive film adheres strongly to the metal substrate and protects it from contact with the surrounding environment, the electrochemical reactions causing corrosion are effectively brought to a halt. Moreover, if locally destroyed, e.g. by scratching, the passive film has the ability to ‘heal’ by spontaneously repassivating in an oxidising environment.

All corrosion types affecting stainless steel are related to permanent damage of the passive film, either complete or local breakdown. Factors such as chemical environment, pH, temperature, surface finish, product design, fabrication method, contamination and maintenance procedures will all affect the corrosion behaviour of stainless steel and the type of corrosion that may occur.

This chapter gives a brief introduction to corrosion that can occur on stainless steel. More information on corrosion types, corrosion testing, and corrosion in specific environments and applications can be found in the Outokumpu Corrosion Handbook. It also contains a large collection of corrosion data for stainless steels.

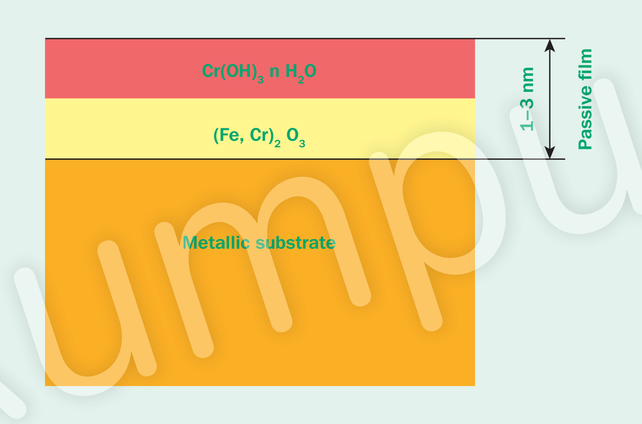


Figure 6:1. Two layer model of passive film on stainless steel.

Wet corrosion

Wet (or aqueous) corrosion of metals is an electrochemical process that involves an anode and a cathode, as well as an electrolyte connecting the two. At the anode the metal oxidises (corrodes) and forms rust or some other corrosion product:

$$\mathrm{Me} \rightarrow \mathrm{Me}^{n+} + ne^-$$

At the cathode, a reduction reaction takes place. This is typically the reduction of oxygen or hydrogen evolution:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \text{ (neutral or alkaline environments)}$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \text{ (acid environments)}$$

$$2H^+ + 2e^- \rightarrow H_2 \text{ (strongly reducing environments)}$$

In order to prevent corrosion these reactions must be prevented.

Stainless steel typically does not corrode in the same manner as carbon steel or low alloy steel that rusts through constantly changing anodes and cathodes on the whole surface. In order for this to occur on stainless steel, the passive film needs to be completely broken down in environments such as non-oxidising acids, e.g. hydrochloric acid.

More commonly the passive film is attacked at certain points, causing various types of localised corrosion. If localised corrosion occurs it is difficult to estimate the propagation rate to calculate for a corrosion allowance.

Pitting and crevice corrosion

Pitting and crevice corrosion are very similar with regards to the factors that affect their occurrence. Stainless steels are particularly susceptible to pitting and crevice corrosion in media containing halide ions such as chlorides. Therefore, environments that represent a risk for pitting and crevice corrosion include seawater and process solutions containing high concentrations of chlorides, but also low concentration of chlorides (< 100 ppm) can under unfortunate circumstances cause pitting or crevice corrosion. The presence of sulphides can increase the aggressiveness of the media, while sulphates can decrease the risk for corrosion. Other factors that increase the probability for pitting and crevice corrosion are increasing temperature, low pH and addition of oxidative chemicals (e.g. by chlorination).

For both types of corrosion an incubation period is observed before corrosion is initiated. The duration of the incubation period can vary from a few hours to many months, but once initiated propagation can be very fast. Therefore pitting and crevice corrosion must be avoided; otherwise the consequences can be serious damage and leakage.

Pitting corrosion

Pitting corrosion is highly localised corrosion with discrete pits on the free surface of stainless steels as shown in Figure 6:2.

If the passive layer is damaged or locally weak, pitting corrosion can initiate and the small area which is unprotected by the passive film becomes the anode. As this anodic area is very small compared to the large cathode area of the undamaged passive film, the corrosion rate is high and a pit is formed. Once initiated the pH in the pit will become lower than that of the surrounding environment due to hydrolysis of dissolved metal ions such as Fe^{2+} and Cr^{3+}. Moreover, the chloride concentration in the pit increases due to chloride ions migrating into the pit to balance the positive charge of the metal ions. Thus, the conditions in the pit gradually become more aggressive and propagation can continue at a high rate.

The size, shape and morphology of the pits can vary; some pits can be quite shallow while some penetrate deep into the material. They can also undermine the surface with attack that appears small but spreads out beneath the surface. Therefore, the full extent of pitting corrosion can be difficult to judge by just visual inspection as it may be concealed.

Crevice corrosion

As its name implies, this type of corrosion occurs in crevices and confined spaces. Crevices can be caused by component design or joints such as flanges and threaded connections, but also under deposits formed on the surface during service. As the oxygen content is limited inside a tight crevice the passive layer is weakened and just as for pitting dissolved metal ions in the crevice will lower the pH and allow chloride ions to migrate into the crevice. Eventually the passive layer breaks down and the aggressive environment facilitates the corrosion attack.

Figure 6:3 shows an example of crevice corrosion on a stainless steel valve flange. Compared to pitting, crevice corrosion results in larger but shallower attack and can occur in environments that normally do not cause pitting on free surfaces.

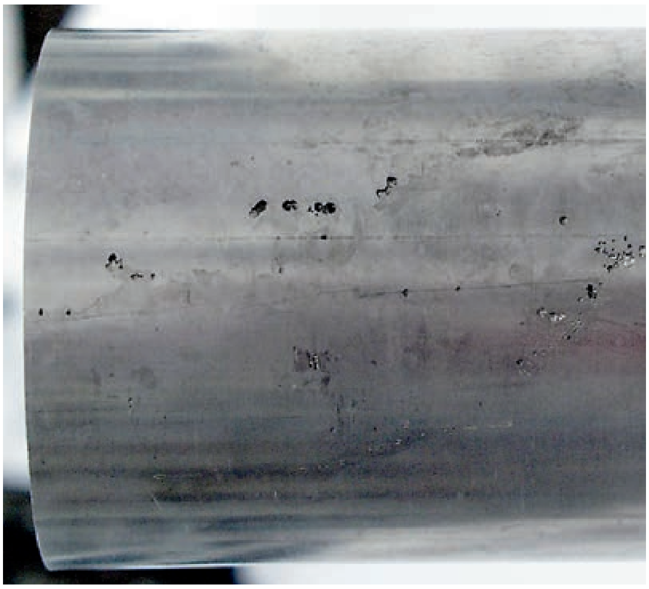


Figure 6:2. Pitting corrosion on the outside of a tube.

Figure 6:3. Crevice corrosion under the sealing on a flange exposed to chlorinated seawater.

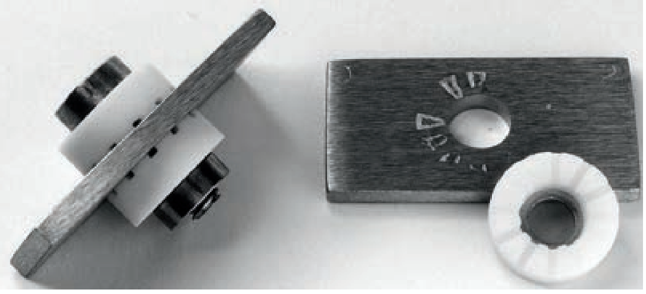


Figure 6:4. Crevice formers used in the ASTM G48 Method F test.

Resistance to pitting and crevice corrosion

It is well known that increasing the chromium content and adding molybdenum and nitrogen as alloying elements increase the resistance to pitting and crevice corrosion of stainless steels. The

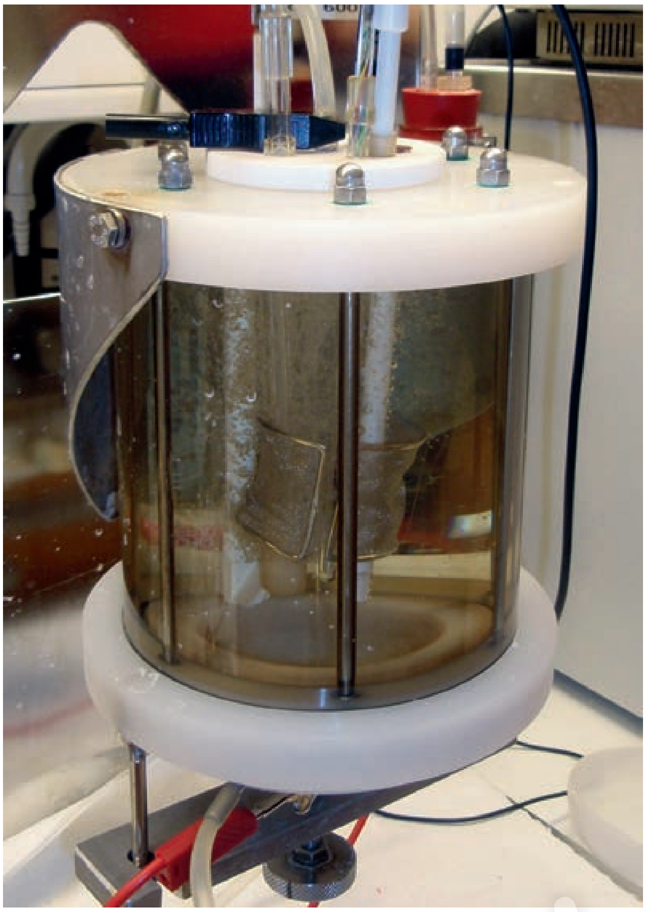


Figure 6:5. ASTM G150 test performed in the flush port Avesta Cell.

Pitting resistance equivalent (PRE) and typical CPT and CCT values for some stainless steel grades

Table 6:1

Outokumpu grade	PRE	ASTM G48 Method E CPT [°C]	ASTM G48 Method F CCT [°C]	ASTM G150 CPT^2 [°C]
DUPLEX				
FDX 25™	25	10	n.t.	14^3
LDX 2101®	26	15	<0	17±3
2304	26	25	<0	25±3
EDX 2304™	28	30	5	36±3
FDX 27™	27	30	n.t.	27^3
LDX 2404®	33	35	15	43±2
2205	35	40	20	52±3
2507	43	65	35	84±2
AUSTENITIC				
4301/4307	18	10	<0	$<10^1$
4401/4404	24	20	<0	20±2
4436/4432	26	25	<0	27±3
4438	28	n.t.	<0	33±3
904L	34	40	10	62±3
254 SMO®	43	65	35	87±3
4529	45	60	35	>90
4565	46	90	40	>90
654 SMO®	56	>b.p.	60	>90

[1] The standard specifies that values below 10°C are not valid for ranking
[2] test surface ground to 320 mesh
[3] limited amount of test results
n.t. = not tested
b.p. = boiling point

No ferritic grade is included in the table. These grades have PRE values varying from 11 to 25, but the local corrosion resistance is too low for determination according to the methods mentioned.

Different products and different surface finishes may show CPT and CCT values that differ from the above.

Pitting Resistance Equivalent (PRE), often also given as PREN to indicate the influence of nitrogen in the steel, can be used in order to rank and compare stainless steels in terms of their resistance to pitting corrosion. It takes into account the effect of the most important alloying elements. One frequently used equation for stainless steels is:

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

Other formulas exist that includes addition of alloying elements such as manganese, tungsten, sulphur and carbon. In Table 6:1 the PRE values, calculated with the formula above, are listed for some stainless steels. It is important to remember that the calculated PRE only gives an indication of the resistance of stainless steels and gives no information on their behaviour in real service environments. Therefore, it should only be used for roughly comparing the pitting corrosion resistance of different grades of stainless steels. Experimental ranking of individual grades can be performed by using accelerated laboratory tests which are described in ISO, ASTM and national standards.

ASTM G48 methods E and F use the highly oxidising environment of acidified ferric chloride solution (6% $FeCl_3$ + 1% HCl) where specimens are exposed for a period of 24 hours. Method E determines the critical pitting temperature (CPT) while method F uses PTFE crevice formers (see Figure 6:4) to determine the critical crevice temperature (CCT). The tests are performed at increasing temperature in 5 °C steps until pitting or crevice corrosion is detected. In Table 6:1 typical CPT and CCT values are presented. The results show that CCT values are considerably lower than CPT values for the same steel grade although the test solution and the test duration is the same. This illustrates the fact that crevice corrosion occurs more readily than pitting corrosion, i.e. even under conditions that do not cause pitting.

ASTM G150, as well as ISO 17864, evaluates the CPT using a solution of 1M NaCl and an applied potential of +700 mV_{SCE}. By using the flush port Avesta Cell shown in Figure 6:5, crevice corrosion is avoided at the contact between the specimen and the specimen holder. The temperature is increased from initial 0 °C at a rate of 1 °C/min and the CPT is defined as the temperature where the current density exceeds 100 $\mu A/cm^2$. Typical ASTM G150 CPT values for some stainless steels are presented in Table 6:1.

It is important to remember that it is not possible to compare CPT values measured using the two different test methods. Also, CPT and CCT values from these standard test methods cannot be used for predicting whether or not pitting or crevice corrosion will occur under specific service conditions, only for ranking.

Instead, engineering diagrams based on laboratory tests and field tests, as well as practical experience are important tools for material selection. Figure 6:6 shows an example of an engineering diagram for pitting and crevice corrosion of some high alloyed stainless steels. It indicates the temperature limits of use in slightly chlorinated (< 1 mg/l) and naturally aerated water with varying chloride content. It is crucial to remember that other environmental factors

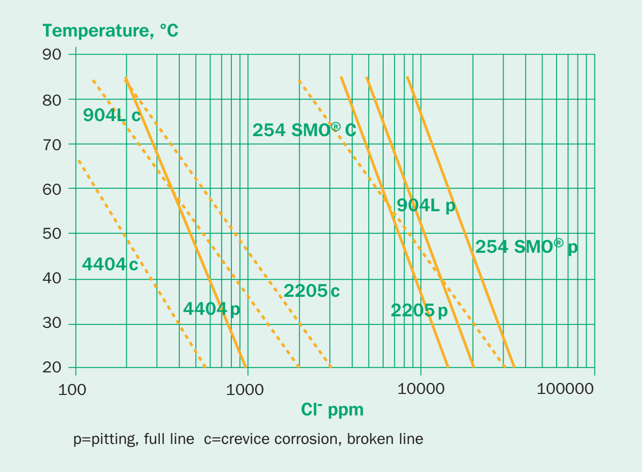


Figure 6:6. Engineering diagram indicating the maximum temperatures and chloride concentrations allowed for some stainless steels in slightly chlorinated (< 1 ppm) water.

such as pH, oxygen content, microbial activity, degree of chlorination and whether or not the water is flowing or stagnant can influence the resistance of the material. Also material factors such as surface finish and the presence of weld oxides and weld defects can have an effect. In the case of crevice corrosion the position of the lines in Figure 6:6 is dependent on the severity of the crevice geometry.

Avoiding pitting and crevice corrosion

There are a number of measures that can be taken in order to avoid pitting and crevice corrosion on stainless steel. These include:

- Select a highly alloyed stainless steel grade. As shown with the PRE formula, the resistance to pitting and crevice corrosion increases with increasing content of chromium and by adding molybdenum and nitrogen.
- Lower the chloride content of the corrosive environment.
- Increase the pH, as a higher pH reduces the risk for pitting and crevice corrosion.
- Decrease the content of, or remove, oxygen and other oxidising species from the environment.
- Use a favourable design that avoids tight crevices, stagnant conditions and formation of deposits.
- Employ good fabrication practices that produce smooth and clean surfaces and ensure that weld oxides are removed.

Uniform corrosion

Uniform corrosion occurs when the passive layer is destroyed on the whole, or a large part, of the surface as shown in Figure 6:7. Thus the anodic and cathodic reactions occur on the same surface at constantly changing locations much like corrosion on carbon steel. The result is more or less uniform removal of metal from the unprotected surface. Uniform corrosion can occur on stainless steels in acids or hot alkaline solutions. Generally the aggressiveness of the environment increases with increasing temperature, while the effect of concentration is variable.

In an environment with constant temperature and chemical composition, uniform corrosion occurs at rather a constant rate. This means that in contrast to pitting and crevice corrosion, a corrosion rate can be measured. The corrosion rate is often expressed as loss of thickness over time, e.g. mm/year. Stainless steel is normally considered to be resistant to uniform corrosion in a specific environment if the corrosion rate does not exceed 0.1 mm/year. The effect of temperature and concentration can be presented as iso-corrosion diagrams where the individual lines represent a corrosion rate of 0.1 mm/year for a specific grade. Figure 6:8 shows such an iso-corrosion diagram for sulphuric acid.

Figure 6:7. Uniform corrosion on the outside of a steam tube exposed to sulphuric acid.

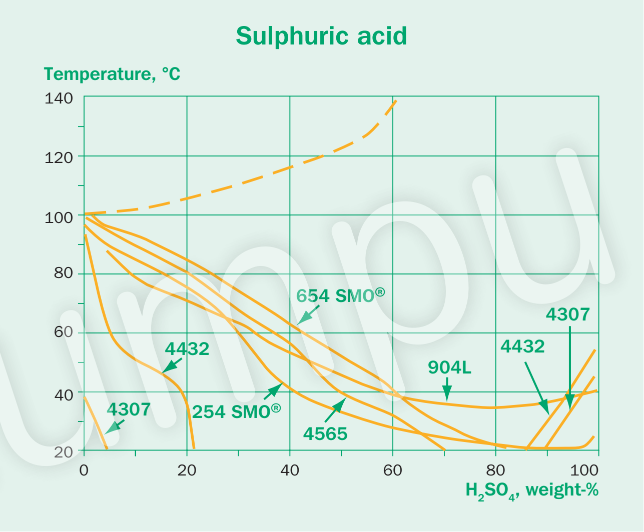


Figure 6:8. Iso-corrosion diagram, 0.1 mm/year, for austenitic stainless steels in pure sulphuric acid.

In oxidising acids such as nitric acid, stainless steels are generally able to maintain their passive layer and are thus not susceptible to uniform corrosion. However, in strongly oxidizing environments such as hot concentrated nitric acid and chromic acid, the passive layer can become unstable and oxidised to more soluble species by so-called transpassive corrosion. The resistance to uniform corrosion generally increases with increasing levels of chromium, nickel and molybdenum, but in these strongly oxidising environments molybdenum has proved to be detrimental to the corrosion resistance.

Strongly reducing acids such as hydrochloric acid and hydrofluoric acid readily break down the passive layer of stainless steels with little chance of repassivating. This means that the use of most stainless steels is limited to dilute solutions of these acids.

Sulphuric acid is an example in which corrosion does not necessarily increase with increasing concentration. This acid is reducing at low and intermediate concentrations, but oxidising when concentrated. Furthermore, the degree of ionisation reaches a maximum at intermediate concentrations. As a result, sulphuric acid is most

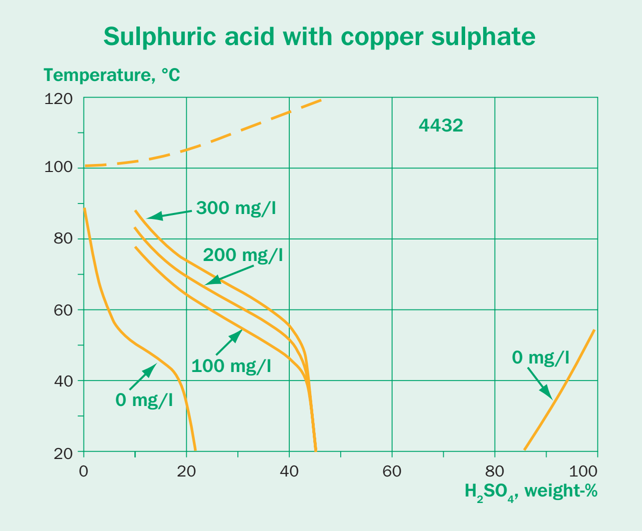


Figure 6:9. Iso-corrosion diagram, 0.1 mm/year, for steel 4432 in sulphuric acid with additions of copper sulphate.

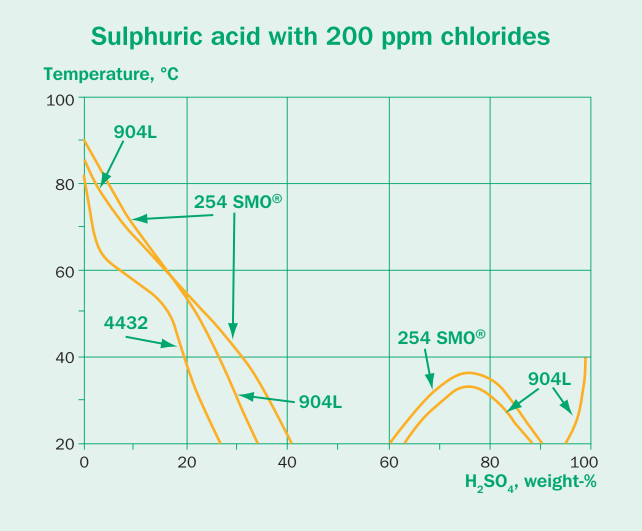


Figure 6:10. Iso-corrosion diagram, 0.1 mm/year, for austenitic stainless steels in sulphuric acid with an addition of 200 ppm chlorides.

Figure 6:11. Stress corrosion cracking in a stainless steel tube.

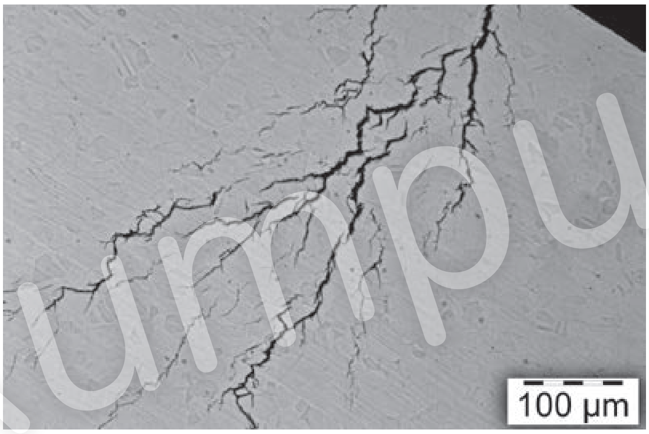


Figure 6:12. Micrograph of stress corrosion cracking.

corrosive to stainless steel in concentrations between 30 and 80 weight-% and less aggressive at low and high concentrations, Figure 6:8. Molybdenum and copper alloying improve the corrosion resistance, especially in the intermediate concentration range, as exemplified by grade 904L in Figure 6:8.

Impurities can have a dramatic effect on the corrosivity of acid solutions. Reducing agents, such as hydrogen sulphide or sulphur dioxide, may increase the uniform corrosion rate. On the contrary to the case of pitting and crevice corrosion, oxidising impurities such as ferric and cupric ions, nitric acid, and dissolved oxygen, can promote passivation and reduce the corrosivity as shown in Figure 6:9. The presence of halide ions, such as chlorides and fluorides, may also affect the corrosivity, Figure 6:10. Even small amounts of halides may increase the corrosion rate of stainless steels in both organic and inorganic acids, as exemplified by comparing Figures 6:8 and 6:10.

Uniform corrosion is considered easier to predict compared to localized corrosion. Moreover, while pitting and crevice corrosion should, if possible, be avoided completely, some degree of metal loss due to uniform contamination can often be tolerated. Exceptions are applications where contamination is unacceptable, e.g. for hygienic reasons in equipment for food handling.

Environmentally assisted cracking

Environmentally assisted cracking is a phenomenon that is caused by the combined action of mechanical stress and corrosive environment. It is not unique for stainless steel; many other alloys are also susceptible in different media, e.g. brass alloys in ammonia environments and carbon and low alloy steels in alkaline solutions. Once initiated, crack propagation can be very rapid and result in critical failure. Environmentally assisted cracking can be caused by a number of environmental species including chlorides, hydrogen and hydroxides.

In order for cracking to occur the mechanical tensile stresses must exceed a critical level. The required stresses need not necessarily be applied stresses, but can be residual stresses from manufacturing operations, such as forming and welding.

Stress corrosion cracking

Like pitting and crevice corrosion, stress corrosion cracking (SCC) most frequently occurs in chloride-containing environments, but it can also occur in concentrated alkali solutions such as sodium hydroxide. Elevated temperatures (> 60 °C for chloride environments and > 100 °C for alkaline environments) are normally required for stress corrosion cracking to occur in stainless steel. Nevertheless, there are cases where cracking can occur at temperatures as low as 30 °C, e.g. in swimming pool atmospheres. A common cause of stress corrosion cracking is evaporation on hot stainless steel surfaces. In this manner liquids with low chloride content that normally would be considered harmless, can cause chloride concentrations high enough to cause stress corrosion cracking. One such example is under thermal insulation on piping. Figures 6:11 and 6:12 depict some typical stress corrosion cracks.

Stress corrosion cracking caused by chlorides, is typically transgranular, i.e. occurs across the grains. Standard austenitic grades, such as 4307 and 4404, are generally sensitive to chloride induced stress corrosion cracking. High contents of nickel and molybdenum increase the resistance of austenitic stainless steels. Thus, high alloyed austenitic grades 904L, 254 SMO® and 654 SMO® show excellent resistance to chloride induced stress corrosion cracking. Stainless steels with a duplex microstructure generally have high resistance to stress corrosion cracking, as have ferritic grades.

Intergranular stress corrosion cracking, where cracking occurs along grain boundaries, can occur in high purity water at high temperatures (200–300 °C) with relatively high oxygen content (~ 0.2 ppm). This have been a concern in nuclear boiling water reactors (BWR), and mainly in sensitised steels where carbides have precipitated along the grain boundaries.

Sulphide stress cracking (SSC)

Sulphide stress cracking (SSC) is the cracking of a material under the combined action of mechanical tensile stress and corrosion in the presence of water and hydrogen sulphide (H_2S), and it is a form of hydrogen-induced cracking. Sulphide stress cracking is of particular importance in the oil and gas industry, as natural gas and crude oil can contain considerable amounts of hydrogen sulphide (often referred to as sour service).

To assess the corrosivity of process fluids containing hydrogen sulphide the partial pressure of hydrogen sulphide has to be considered, together with pH, temperature, chloride, carbon dioxide and oxygen contents. Susceptibility to hydrogen embrittlement is most severe at, or below, ambient temperature, whereas chloride induced stress corrosion cracking is most severe at high temperatures. Consequently, the combined risk of cracking due to hydrogen sulphide and chlorides tends to be most severe for austenitic and especially duplex stainless steel grades in the range 80–100 °C.

A standard, ISO 15156-3, for material requirements in hydrogen sulphide containing environments in oil and gas production has been developed. This standard provides guidance on the application limit and qualification procedure for cracking resistant alloys.

Hydrogen induced stress cracking (HISC)

Another hydrogen embrittlement failure mode that can be of concern in the oil and gas industry is hydrogen induced stress cracking (HISC), where hydrogen is introduced when the material is under cathodic protection in seawater. The hydrogen is a result of the increased cathodic reaction, hydrogen ion reduction, on the stainless steel surface. Even high alloyed stainless steels can be subjected to full cathodic protection in offshore applications as these steels typically are connected to carbon steel and other low alloyed steels already under protection.

The ferritic phase in stainless steels is generally more susceptible to hydrogen embrittlement than austenitic phase. This means that ferritic, martensitic and duplex stainless steels may suffer hydrogen induced stress cracking at ambient or low temperatures.

In the case of duplex stainless steels, failures have usually involved materials with an unfavourable microstructure (e.g. large grain size, intermetallic phases and high ferrite content) in combination with unusually high mechanical stresses. A guideline (DNV RP F-112) has been published with recommendations regarding the design of duplex stainless steel subsea equipment under cathodic protection, which specifies material requirements as well as best practice for design.

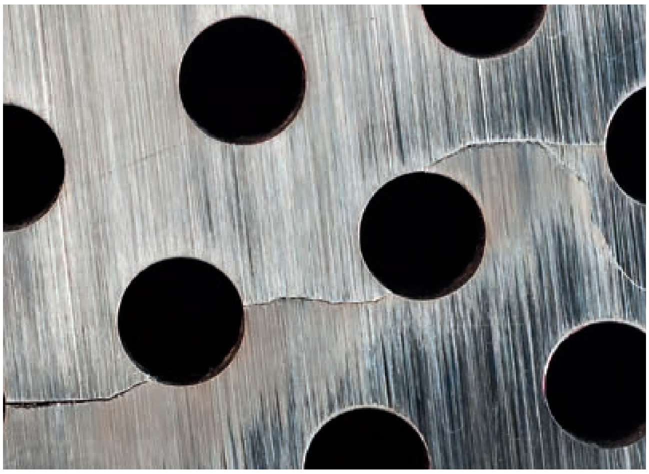


Figure 6:13. Corrosion fatigue cracks in a paper machine suction roll shell.

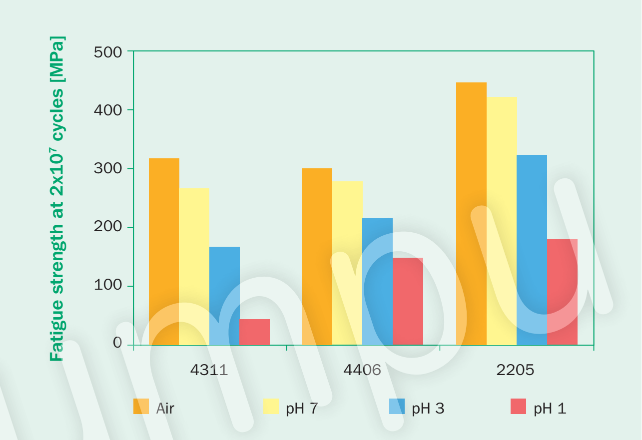


Figure 6:14. Effect of environment on fatigue strength for some stainless steels. Fatigue strength at 40 °C and rotating bending stress at 100Hz. Tested in air and 3 % NaCl at various pH.

Corrosion fatigue

A material that is subjected to a cyclic load can fail owing to fatigue, at loads far below the ultimate tensile strength; see chapter on Mechanical properties. If the material is simultaneously exposed to a corrosive environment, failure may occur at even lower load levels and after shorter periods of time. This failure by a combination of cyclic load and corrosive environment is known as corrosion fatigue, Figure 6:13.

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 determine the service life. At lower frequencies, the corrosive action is more pronounced and an aggressive environment may also cause corrosion attack that can act as a stress concentrator and thus contribute to a shorter life.s

Corrosion fatigue cracks are usually less branched than stress corrosion cracks (Figure 6:13), although both forms of corrosion cause brittle failures. Corrosion fatigue can occur at ambient temperature and in environments that could be considered harmless with regard to other forms of corrosion. As with stress corrosion cracking residual stresses from manufacturing processes can adversely affect resistance to corrosion fatigue.

Increasing the mechanical strength of stainless also increases their resistance to corrosion fatigue. Thus, duplex stainless steels, with their higher strength, are often superior to conventional austenitic stainless steel grades.

As can be seen from Figure 6:14, a lower pH, i.e. a more aggressive condition, gives lower fatigue strength. Comparison of the two austenitic steels shows that the higher alloyed grade, 4406, that has the higher corrosion resistance also has higher corrosion fatigue strength than 4311. The high strength duplex grade 2205 has higher corrosion fatigue strength than both austenitic grades.

Atmospheric corrosion

In contrast to other forms of corrosion, atmospheric corrosion is not a unique form of corrosion, but a collective term to describe the corrosion on metal surfaces in the atmosphere. The atmosphere may be indoor or outdoor, and many different corrosion forms may be involved. As with many other forms of corrosion of stainless steels halides, and mainly chlorides, are often involved in atmospheric corrosion as they are abundant in our environment. Chlorides can be found in coastal and marine environments and also in road environments owing to the use of de-icing salts.

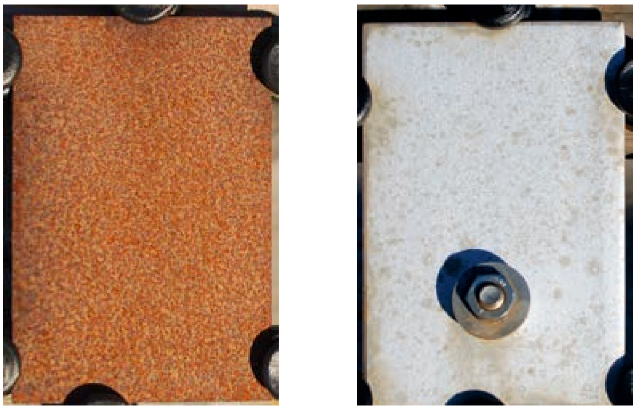
Stainless steel that is exposed to an aggressive atmospheric environment is primarily affected by staining, sometimes referred to as tea staining. However, not all discoloration is necessarily the result of corrosion. It can also be discoloration from dirt or extraneous rust caused by e.g. iron particles on the stainless steel surface. However, if the chloride level is high enough, stainless steel can in time also be attacked by localised corrosion such as pitting and crevice corrosion.

According to ISO 9223 the corrosivity of the environment is classified C1 to CX, where C1 is the least corrosive and CX the most aggressive as shown in Table 6:2. The corrosivity classes are a good tool for selecting materials that suffer uniform corrosion under atmospheric conditions, such as carbon steel or zinc. However, stainless steels with their passive layer exhibit a totally different corrosion mechanism. Therefore, it is not easy to transfer the corrosivity classes in ISO 9223 to stainless steels, and thus they are not the best tool for selecting stainless steels for atmospheric conditions. However, the higher the corrosion class, the higher alloyed stainless steel needs to be used, with the range going from ferritic grades up to superaustenitic and superduplex grades as shown in Table 6:2. Figure 6:15 shows the effect of alloying level for stainless steel samples exposed for one year at a marine test site on west coast of Sweden.

As a conductive electrolyte is needed for atmospheric corrosion, temperature, relative humidity and other weather conditions will affect the corrosion process. Polluting gases and other contaminates can dissolve into and affect the electrolyte. Sulphur dioxide (SO$_2$) is considered as the most important corrosive gas. While the concentration of sulphur dioxide has decreased in many developed countries, the emissions in other locations are still quite high and even increasing.

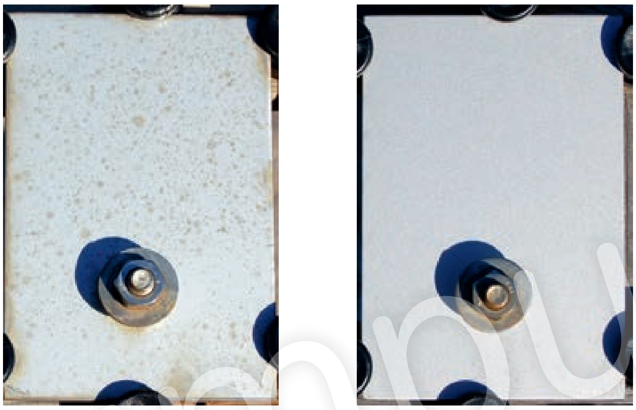
How the stainless steel is exposed to the atmosphere is also of great importance. In areas with rainfall sheltered conditions prevent rinsing, thus increasing the corrosivity. However, in dry areas with no or very little rainfall sheltering will protect from aggressive pollutants and thus decrease the corrosivity. Figure 6:16 shows an atmospheric test station where the samples are fully exposed.

The surface condition and surface roughness are factors that



Carbon steel.

Grade 4307 with a 2B surface finish.



Grade 4432 with a 2B surface finish.

Grade 2205 with a 2E surface finish.

Grade 254 SMO® with a 2E surface finish.

Figure 6:15. Carbon steel and stainless steel samples exposed for one year at Bohus Malmön on the west coast of Sweden. The corrosion category was measured to C4 for carbon steel.

Figure 6:16. One way to investigate the performance of different stainless steel grades in a specific type of atmosphere is to expose samples at an atmospheric test station at that specific location.

Examples of typical environments for ISO 9223 corrosivity classes with typical used stainless steel grades

Table 6:2

Corrosivity category	Corrosivity	Examples indoor	Examples outdoor	Typically used stainless steel grades
C1	Very low	Offices, schools and museums.	Dry or cold zone: Central Arctic/ Antarctica and certain deserts.	4016, 4521, 4307, 4372, LDX 2101®
C2	Low	Unheated storage facilities and sport halls.	Temperate zone: rural areas and small towns. Dry or cold zone: deserts and subarctic areas.	4016, 4521, 4307, 4372, LDX 2101®
C3	Medium	Food processing plants, laundries, breweries and dairies.	Temperate zone: urban areas and coastal areas with low deposition of chlorides. Subtropical and tropical zone: areas with low pollution.	4521, 4301, 4404,LDX 2101®, 2304
C4	High	Industrial processing plants and swimming pools.	Temperate zone: polluted urban areas, industrial areas, coastal areas without spray and exposure to de-icing salts. Subtropical and tropical zone: areas with medium pollution.	4404, 4438, 4439, 904L, 254 SMO®, 4565, 2304, 2205, 2507
C5	Very high	Mines, caverns for industrial purposes, and unventilated sheds in subtropical and tropical zones.	Temperate and subtropical zone: industrial areas, coastal areas and sheltered positions on coast line.	904L, 254 SMO®, 4565, 654 SMO®, 2205, 2507
CX	Extreme	Unventilated sheds in humid tropical zones with penetration of outdoor pollution.	Subtropical and tropical zone: extreme industrial areas, coastal and offshore areas.	254 SMO®, 4565, 654 SMO®, 2507

Note! For load bearing details in swimming pool buildings high alloyed austenitic grades must be used due to the risk of stress corrosion cracking, see EN1993-1 part 4.

can affect the performance of stainless steels. On a coarse surface dirt, particles and corrosive chemicals will be easily retained and thus increase the susceptibility to atmospheric corrosion. A smooth surface will facilitate rinse-off and thereby be less susceptible. Rinse-off is also facilitated if a ground or polished surface is vertically orientated. The lower the alloying levels of the stainless steel, the greater the impact of surface finish on the resistance to atmospheric corrosion.

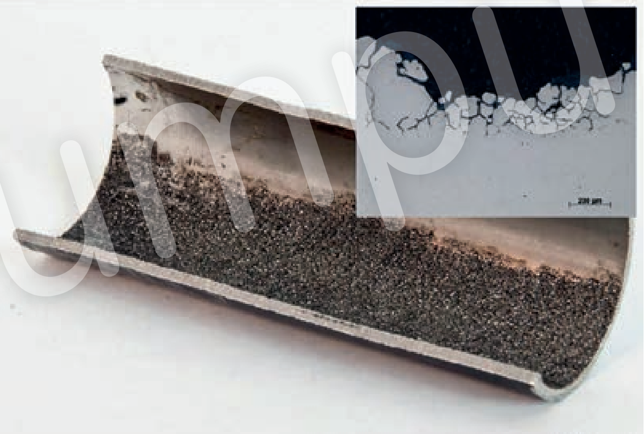


Figure 6:17. Intergranular corrosion attack on a stainless steel pipe. The micrograph shows a cross section of the attacked area.

Figure 6:18. Bicycle parking on Tenerife, Canary Islands, 100 m from the Atlantic Ocean. Galvanic corrosion on galvanized bolts.

Intergranular corrosion

Intergranular corrosion is the preferential corrosion of the grain boundary regions that can occur as a consequence of the precipitation of chromium carbides and intermetallic phases. This type of corrosion was previously a potential risk for stainless steel because of the high carbon content (0.05–0.15 %). Modern steel making methods, and especially the use of AOD (Argon Oxygen Decarburisation), have enabled lower carbon contents and thus intergranular corrosion is rarely a problem today.

Nevertheless, intergranular corrosion can occur if stainless steels are exposed to temperatures in the range 550-850 °C. Chromium carbides with very high chromium content can then be precipitated along the grain boundaries, causing the material nearby to be depleted of chromium and thus less corrosion resistant. A stainless steel which has been heat-treated in a way that produces such grain boundary precipitates and adjacent chromium depleted zones is said to be sensitised. Sensitisation can be a result of welding or of hot forming at an inappropriate temperature.

In a corrosive environment the chromium depleted areas may be attacked and the unfavourable anode-to-cathode surface area ratio accelerates the attack along the grain boundaries, Figure 6:17. Strong oxidising conditions are often needed to cause intergranular attack. However, sensitisation might also increase the sensitivity to other forms of corrosion, e.g. pitting, crevice corrosion and stress corrosion cracking.

Measures against intergranular corrosion by preventing carbide precipitation includes:

- Using low carbon stainless steel (< 0.05 %).
- Using steel that is stabilised with e.g. titanium or niobium (that bind the carbon as titanium- or niobium carbides so no chromium carbides are formed).

- Shortest possible holding time in the temperature range 550–850 °C.
- Solution annealing at 1000–1200 °C at which chromium carbides are dissolved, followed by rapid cooling in water or air.

Galvanic corrosion

Galvanic corrosion can take place if two dissimilar metals are electrically connected and exposed to a corrosive environment, Figure 6:18. Usually, galvanic corrosion, or dissimilar metal corrosion, is not a problem for stainless steels but can affect other metals in contact with them.

In Table 6:3 an example of a galvanic series is given which shows the relative nobility of some metals. A metal with a high corrosion potential (E) is nobler than one with a lower corrosion potential.

The larger the difference in the galvanic series between two dissimilar metals, the greater the risk for galvanic corrosion occurring on the less noble metal. While corrosive attack increases on the less noble metal, it 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.

In their passive state, stainless steels are nobler than the majority of other metallic construction materials in most environments. Thus, galvanic coupling to metals such as carbon steel, galvanized steel, copper and brass can increase the corrosion rate on these metals. Galvanic corrosion between different stainless steel grades is generally not a problem, on condition that each grade remains passive in the particular environment.

If the surface of the less noble metal is small relative to the nobler metal, the corrosion rate can become very high. This is the case if carbon steel bolts are used to fasten stainless steel sheets, and can lead to severe galvanic corrosion on the carbon steels bolts. Similarly, defects in coating or paint on a less noble material can result in a small anodic area and high corrosion rates. Thus, it is preferable to coat or paint the nobler metal in a galvanic couple in order to reduce the risk of galvanic corrosion. Also, the conductivity of the electrolyte will influence the intensity as well as the location of a galvanic attack. A low conductivity will lead to reduced corrosion rate, but the attack can become concentrated to the area adjacent to the interface between the two metals.

Problems with galvanic corrosion can often be avoided by proper design and by electrically insulating dissimilar metals.

Example of galvanic series in seawater **Table 6:3**

	Materia	Corrosion potential, E [mV_{SCE}]
↑ Noble (cathodic)	Graphite Platinum Gold	200 to 300
	Hastelloy C	0 to 100
	4404 (passive) 4307 (passive) Titanium Inconlel 600	-100 to 0
	4016 (passive) 4006 (passive) Bronzes Copper	-300 to -200
	Tin Lead	-400 to -300
	4404 (active) 4307 (active)	-500 to -400
	4016 (active) 4006 (active)	-600 to -500
	Mild steel Cast iron	-800 to -600
Active (anodic)	Aluminium alloys Zinc	-1000 to -800
↓	Magnesium	-1750 to -1600

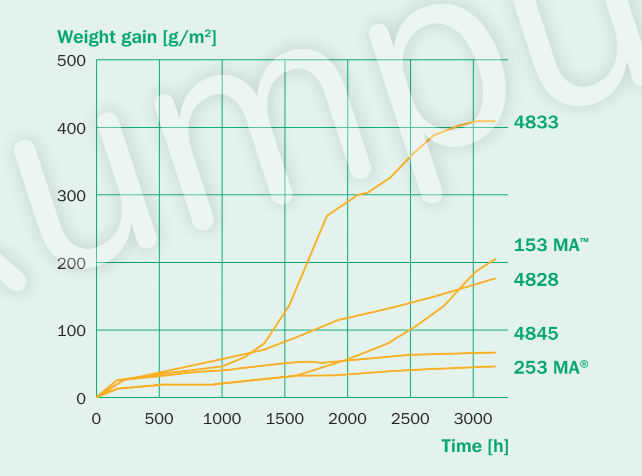


Figure 6:19. Oxide growth in air at 1000 °C, 165 hour cycles for some austenitic high temperature grades.

High Temperature Corrosion

In addition to the electrochemically-based aqueous corrosion stainless steels can suffer high temperature corrosion and oxidation. This can occur when a metal is exposed to a hot atmosphere containing oxygen, sulphur, halogens or other compounds able to react with the material. Some cases of high temperature corrosion can involve molten phases such as salts but not aqueous phases.

As for wet corrosion, stainless steel used for high temperature applications must rely on the formation of a protective oxide layer at the surface. The environment must be oxidizing in order to form a protective layer, consisting of oxides of one or several of the alloying elements. An environment is often termed oxidizing or reducing as meaning “with respect to iron”, since a so-called reducing atmosphere can oxidise elements such as aluminium and silicon and often even chromium.

Some common cases of high temperature corrosion will be described here: oxidation, sulphidation, carburization and nitridation. Other more complex cases such as corrosion in exhaust gases, molten salts and chloride/fluoride atmospheres are described in the Outokumpu Corrosion Handbook.

Oxidation

When stainless steels are exposed to an oxidising environment at elevated temperatures, an oxide layer is formed on the surface, acting as a barrier between the metal and the gas. A dense and adherent layer will retard further oxidation, whilst a layer with pores and cracks will be less protective. Chromium increases the oxidation resistance of stainless steels by the formation of a chromia (Cr_2O_3) scale on the surface. When the chromium content is increased from 0 to 27 %, the maximum service temperature increases from around 500 °C to 1150 °C. At temperatures above 1000 °C, aluminium oxides are more protective than chromium oxides. The amount of aluminium required for the formation of a protective layer will, however, make the alloy rather brittle and hence the fabrication difficult and costly. The addition of silicon will significantly increase the oxidation resistance but it will make the oxide layer more brittle so that it may spall off due to growth stresses in the scale, or thermal stresses from temperature changes. The sensitivity to temperature variations can be reduced by the additions of small amounts of so-called reactive elements such as yttrium, hafnium and rare earth metals (REM) such as cerium and lanthanum. Small REM additions will lead to the formation of a tougher and more adherent oxide layer, improving cyclic oxidation resistance, erosion-corrosion resistance and oxide spallation resistance, important properties when the component is subjected to temperature changes or mechanical deformation. Figures 6:19 and 6:20 illustrate the beneficial effect of such micro-alloying on the cyclic oxidation resistance.

The maximum service temperatures for some ferritic and austenitic high temperature stainless steels in dry air are given in Table 6:4.

Although oxides as a rule are beneficial, there are a few elements which tend to form liquid or gaseous oxides, leading to so-called catastrophic 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 (Cr_2O_3) scale. For this reason molybdenum, which forms low-melting-point oxides and oxide-oxide eutectics, should be avoided in material for service at temperatures above 750 °C. Similar behaviour is also reported for tungsten. The presence of vanadium and lead in the environment may also cause the formation of liquid oxides. Vanadium, which is a common contaminant in heavy fuel oils, can easily cause catastrophic oxidation due to its oxide, V_2O_5, which melts at 690 °C.

The presence of water vapour in the atmosphere reduces the resistance to oxidation and thus the maximum service temperature. The reduction can be 50–150 °C, depending on steam content and flow rate. All chromia-forming stainless steels are affected by water vapour in the atmosphere at rather low temperatures. An example is shown in Figure 6:21 where grade 4833 shows catastrophic breakaway oxidation in humid air after only 90 hours at 900 °C. In the presence of water vapour, evaporation of chromium species

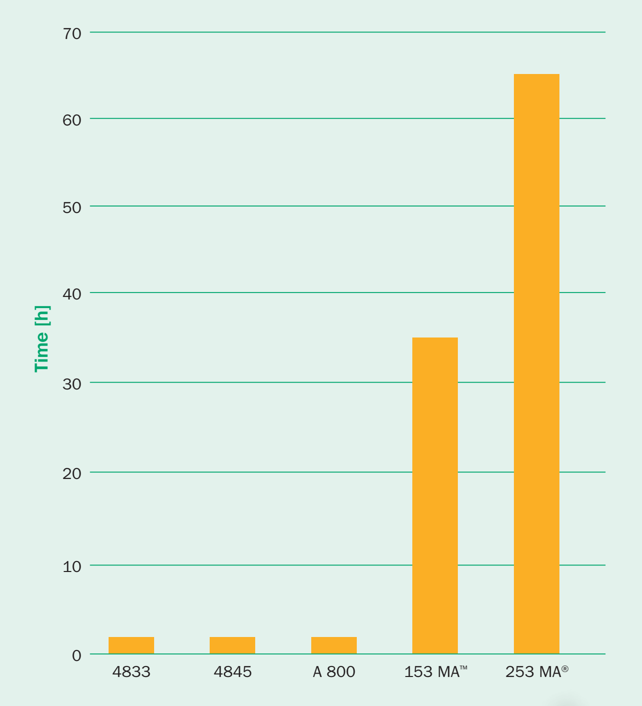


Figure 6:20. Time until oxide spallation exceeds oxide growth during one 2-hour cycle at 1150 °C. The higher the value the better oxide adherence.

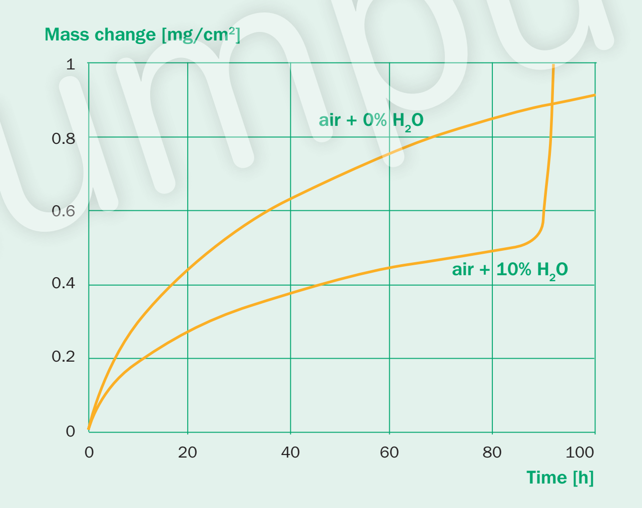


Figure 6:21. Mass change for 4833 during oxidation in air with and without 10 % H_2O at 900 °C.

Maximum service temperature in dry air for various stainless steels (for guidance only).

Table 6:4

	Steel designation			Typical chemical composition, % by wt.						Max. service temp.
	Outokumpu	EN	ASTM	C	N	Cr	Ni	Si	Others	°C
Ferritics	4713	1.4713	-	0.06		6.5		0.8	0.8Al	800
	4724	1.4724	-	0.07		12.5		1.0	0.9Al	850
	4736	1.4736	-	0.02		17.5			1.8Al, Ti	1000
	4742	1.4742	-	0.07		17.5		1.0	1.0Al	1000
	4762	1.4762	-	0.08		23.5		1.0	1.5Al	1150
Austenitics	4948	1.4948	304H	0.05		18.1	8.3			800
	4878	1.4878	321H	0.05		17.3	9.1		Ti	850
	153 MA™	1.4818	S30415	0.05	0.15	18.5	9.5	1.3	Ce	1050
	4833	1.4833	309S	0.06		22.3	12.6			1000
	4828	1.4828	-	0.04		20	12	2.0		1000
	253 MA®	1.4835	S30815	0.09	0.17	21	11	1.6	Ce	1150
	4845	1.4845	310S	0.05		25	20			1050
	4841	1.4841	314	0.07		24.5	19.5	2.0		1150

occurs and leads to chromium depletion in the matrix. Below a critical chromium concentration, the chromia scale does not re-form; instead a non-protective iron-rich oxide scale develops, resulting in catastrophic breakaway oxidation behaviour.

Sulphidation

Different sulphur compounds are often present as contaminants in flue gases and some process gases. Chemically, sulphidation is similar to oxidation. However, sulphides have a lower melting point than the corresponding oxide, so there is risk of forming molten corrosion products. Especially nickel can form low melting point nickel-sulphur compounds resulting in a rapid deterioration of the alloy. Moreover, the sulphide scales are generally much less protective than the corresponding oxide scales, leading to a faster corrosion rate. In order to avoid nickel-sulphur compounds, nickel-free materials, such as ferritic high temperature grades, should be selected in reducing sulphur environments.

In oxidizing sulphidizing environments, i.e. when a protective oxide layer can be formed, the corrosion resistance is determined by the protectiveness of this layer. When the oxide begins to crack, the gas will be able to penetrate through the protective layer and continue the attack. The maximum service temperature is lower than in air and determined by the balance between the protective oxidation and corrosion reaction. Under conditions where it is difficult to form a protective oxide layer (reducing environment), the corrosion resistance is considerably lower and directly dependent on the bulk chemical composition of the alloys. In these conditions steels with high chromium content and little or no nickel are superior.

Carburisation and nitridation

Carburisation of stainless steels can take place in carbon monoxide, carbon dioxide, methane and other hydrocarbon gases at high temperature. The degree of carburisation is governed by the levels of carbon and oxygen in the gas, the temperature and the steel composition. Excessive uptake of carbon or nitrogen has a detrimental effect on material properties. The precipitation of carbides and nitrides leads to embrittlement, a reduction in toughness and ductility, especially at room temperature. The resistance to carburization and nitridation is improved primarily by increasing the nickel content but also with increasing silicon and chromium content. Experience shows that it takes only minor amounts of oxygen in the gas (even in the form of carbon dioxide or steam) to produce a thin, tough oxide layer on steel grade 253 MA®, which provides good protection against pickup of both carbon and nitrogen. Figure 6:22 shows carburization of some stainless steels in carburizing atmospheres. Note the beneficial effect of silicon, apparent from a comparison of grade 4307 (18Cr, 9Ni) and SUS 302B (18Cr, 9Ni, 2.5Si). Also note the high level of carburization in grade 4404.

A special form of carburization is metal dusting, sometimes also called catastrophic carburization or carbon rot. This occurs at lower temperatures; typically between 450 °C and 700 °C in, for example, heat treating, refining and petrochemical processing. Attack is severe and leads to the disintegration of the material into carbon dust and metal, characterized by the formation of pits and holes in the material.

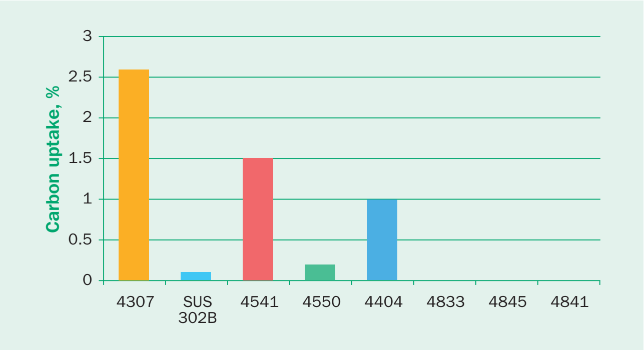


Figure 6:22. Carburization after 7340 hours at 910 °C in an atmosphere of 34 % H_2, 14 % CO, 12.4 % CH_4, 39.6 % N_2. Grade 4550 is an austenitic corrosion resisting grade with the following composition: max. 0.08 % C, 17-19 % Cr, 9-12 % Ni, Nb stabilised.

References

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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. For a detailed description of testing and definition of mechanical properties of metallic materials the reader is referred to listed standards in the reference list.

Engineering stress strain curves

The difference in the mechanical properties of various stainless steel grades is usually visualized through the stress strain curves from a tensile test, Figure 7:1. The engineering stress and strain are defined from the tensile test according to:

$$\textbf{Engineering stress; } s = \frac{F}{A_0} \qquad \textbf{Engineering strain; } e = \frac{L - L_0}{L_0} \qquad (1)$$

where **s** and **e** are engineering stress and strain respectively. **F** is the applied force to deform the specimen, $\mathbf{A_0}$ the cross section area and $\mathbf{L_0 / L}$ the gauge length (measuring length) before/after deformation respectively.

In Figure 7:1 two parts are defined; the elastic and the plastic region. In the elastic region an imposed strain is fully recovered upon unloading and occurs at low stresses and strains. In this region, the curve is linear with a slope that is given by the Young's elastic modulus E. The values of Young's elastic modulus are often in the range of 195-215 GPa for stainless steels.

In the plastic region, only the elastic part of the strain is recovered upon unloading. The 0.2 % proof strength $R_{p0.2}$ is evaluated as the engineering stress level that gives 0.2 % permanent engineering strain. The ultimate tensile strength R_m is the maximum engineering stress on the curve and is associated with the elongation A_g. A_g is sometimes called uniform elongation, since it defines the onset of necking/failure. Finally, the maximum strain or "strain to fracture" is called A_x where x represents the initial gauge length used. Table 7:1 gives some typical examples of gauge lengths used according to standards. Typically, A_5 is used for thick plate/bar while A_{50} or A_{80} is used for thin sheet metal. A_x is sensitive to the gauge length x and values cannot be compared unless the length is identical.

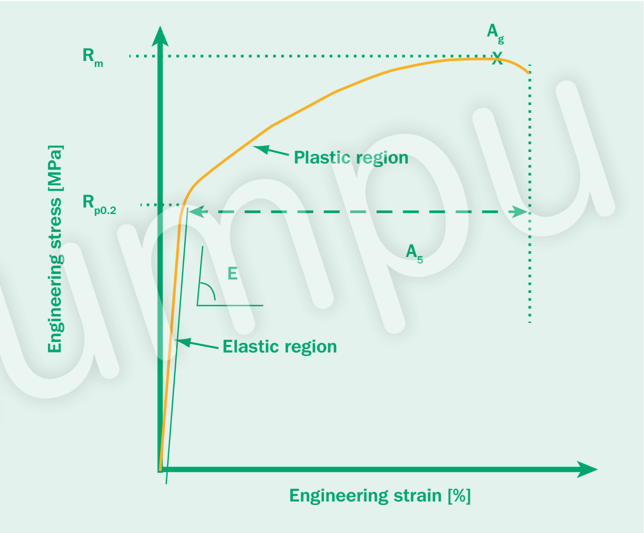


Figure 7:1. Some definitions from the stress strain curve.

Examples of gauge lengths

Table 7:1

Elongation measure	Gauge length flat specimen	Gauge length round specimen
A_5	$5.65 * \sqrt{A_0}$ mm	5 * D mm
A_{50}	50 mm	50 mm
A_{80}	80 mm	–

A_0 = cross section area, D = diameter

Sometimes an index t is added, such as A_{gt} or $R_{t0.2}$ indicating that the total strain (elastic plus plastic) has been used in the evaluation.

Austenitic stainless steel, e.g. 4301, has a low proof strength level and a very high elongation to fracture while duplex steel e.g. LDX 2101® has approximately twice the proof strength level with a lower elongation to fracture, as seen in Figure 7:2. The ferritic stainless steel 4509 has about the same or slightly higher proof strength than 4301 and elongation to fracture similar to LDX 2101®. Finally, it can be seen that the high performance austenitic stainless steel 254 SMO® has a higher strength than 4301 due to its higher alloying content, but still has a high elongation to fracture.

True stress strain curves

It is common to compensate the curves in Figures 7:1 and 7:2 for the change in specimen cross section area as the strain is increasing. To achieve this, the fact that plastic deformation occurs without volume change is utilized. The resulting upper curve in Figure 7:3 is called the “true” stress strain curve and the curves in Figure 7:2 are called “engineering” stress strain curves. The following equations show the relationship between engineering and true stress strain curves:

$$\textbf{True stress; } \sigma = \frac{F}{A} = s * (1 + e)$$
$$\textbf{True strain; } \varepsilon = \ln\left(\frac{L}{L_0}\right) = \ln(1 + e) \qquad \textbf{(2)}$$

where σ and ε are true stress and strain respectively and **A** is the actual cross section area after deformation. Figure 7:3 compares true and engineering stress strain curves for an austenitic stainless steel grade 4310. The end point of these curves is the ultimate tensile strength, beyond which it is not possible to determine the true stress strain curve.

The true stress strain curves are for example used to characterize the work hardening of steel, i.e. how much the stress increases with plastic strain. The amount of hardening depends on both the composition and the type of steel (austenitic, ferritic, duplex or martensitic). The commonly used work hardening exponent n is defined as

$$\sigma = K * \varepsilon^n \qquad \textbf{(3)}$$

where σ and ε are true stress and true strain respectively. The exponent **n** gives a simple measure of the tendency to work harden and **K** is the strength hardening coefficient.

Room temperature mechanical properties

In terms of mechanical properties, stainless steels show similar properties within each group: austenitic, ferritic, duplex and martensitic. Figure 7:2 shows examples of characteristic differences between these groups. Martensitic steel has been omitted in Figure 7:2 since the mechanical properties depend closely on the tempering condition. In soft annealed condition, the mechanical properties of martensitic steel are similar to ferritic steel and in quenched and tempered condition the strength is much higher than any steel in Figure 7:2 and with very small fracture elongation.

Tables 7:5 and 7:6 give typical mechanical properties at room temperature for a number of stainless steel grades in plate (P), sheet/coil (C) and bar/rod (R) form. To enable comparisons between grades the plate product form (P) has been chosen for the majority of steel grades. Data for other product forms can be found in Outokumpu data sheets.

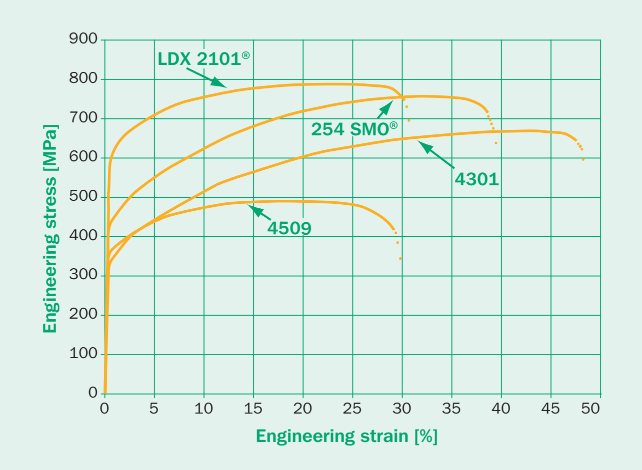


Figure 7:2. Stress strain curves for some stainless steels.

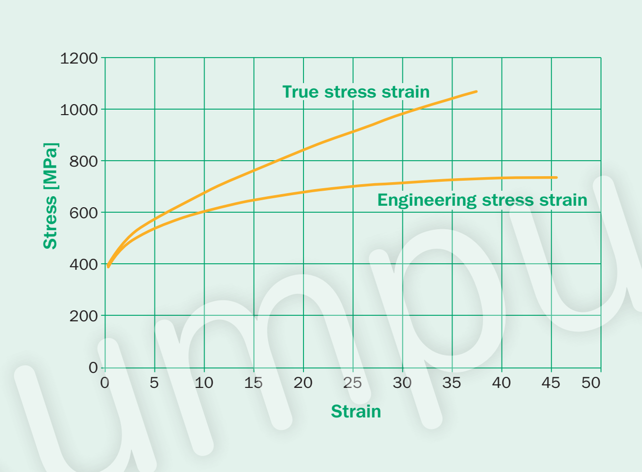


Figure 7:3. True and engineering stress strain curves for 4310.

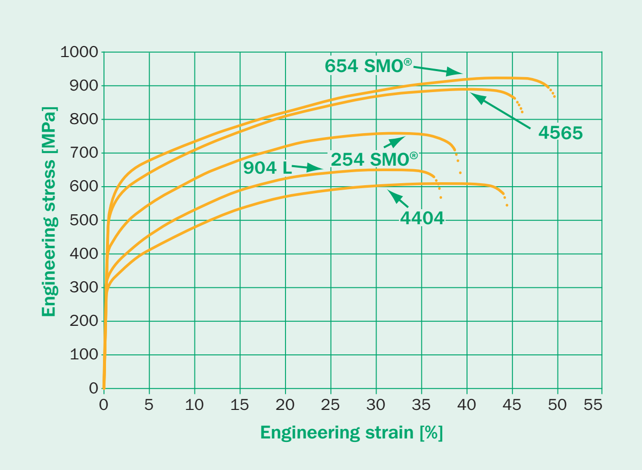


Figure 7:4. Stress strain curves of austenitic steels.

Austenitic grades

Austenitic stainless steels generally have a relatively low proof strength and are characterized by strong work hardening. The strength of the austenitic steels increases with increasing levels of carbon, nitrogen and, to a certain extent, also molybdenum. It should however be noted that carbon increases the risk of sensitization, which has a detrimental effect on corrosion resistance. Austenitic steels exhibit very high ductility; they have a high elongation to fracture and are very tough, also at low temperatures.

Some austenitic stainless steels with a low total content of alloying elements; e.g. 4301, 4310, 4318 and 4372 can be metastable and may form martensite either due to cooling below ambient temperature or through plastic deformation or a combination of both. This formation of martensite will cause a considerable increase in strength and will also influence the magnetic properties. The temperature below which deformation induced martensite will form is called the M_d temperature. A common equation for relating austenite stability and alloy composition is the M_{d30} temperature, discussed in chapter 3, Physical properties. This type of equation gives a good idea of the deformation behaviour of low alloyed austenitic stainless steels, but it must be noted that it is only approximate since interactions between the alloying elements are not taken into account.

For austenitic steels the work hardening exponent n in eq 3 is strain dependent. Often n-values are therefore estimated for a certain strain range, for example 10–15 %. n-values are between 0.4 and 0.6 for stable grades and for the metastable grades, i.e. those that form martensite at large deformations, the range 0.4 to 0.8 can be used. The higher values are applied at higher strains.

Basically all alloying elements affect the stress strain curves of stainless steel. This is demonstrated by Figure 7:4 where the engineering stress strain curves of austenitic stainless steel grades from low alloyed 4404 to very high alloyed 654 SMO® are compared. The more alloying elements, the higher the strength. An important alloying element that influences the strength is nitrogen as demonstrated by the differences between 4565 and 254 SMO® (with nitrogen contents of 0.45 and 0.20 % respectively) in Figure 7:4. Also the microstructure influences the stress strain curve, mostly through the grain size.

Ferritic grades

Ferritic stainless steels have relatively low proof 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. Figure 7:5 compares some ferritic grades with austenitic grades of similar corrosion resistance level. Ferritic steels have work hardening exponents n of about 0.2 for a strain range of 10–15 %.

Duplex grades

Duplex stainless steels have a high proof strength and the work hardening is limited. Modern duplex grades such as LDX 2101® are alloyed with nitrogen which results in a high strength. Increased ferrite content will, within limits, also increase the strength of duplex steels. The grain size and the lamellae distance between ferrite and austenite have a large influence on strength in duplex stainless steel. Figure 7:6 compares some duplex grades with austenitic grades of similar corrosion resistance. Duplex steels have work hardening exponents n of about 0.2 for a strain range of 10–15 %. With the recent development of the FDX-grades, the work hardening has been considerably improved.

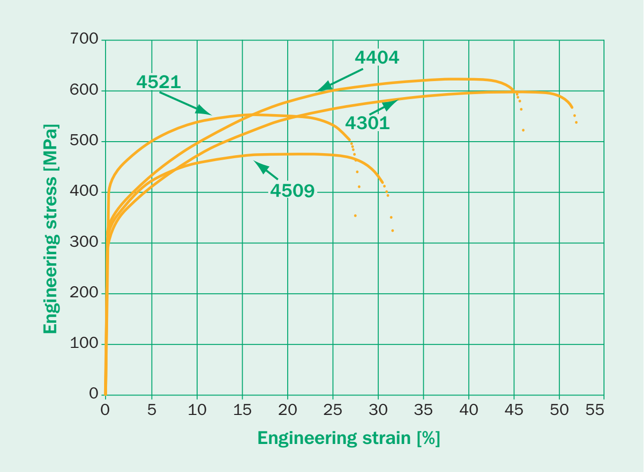


Figure 7:5. Stress strain curves of ferritic steel in comparison with austenitic steels of similar corrosion resistance level.

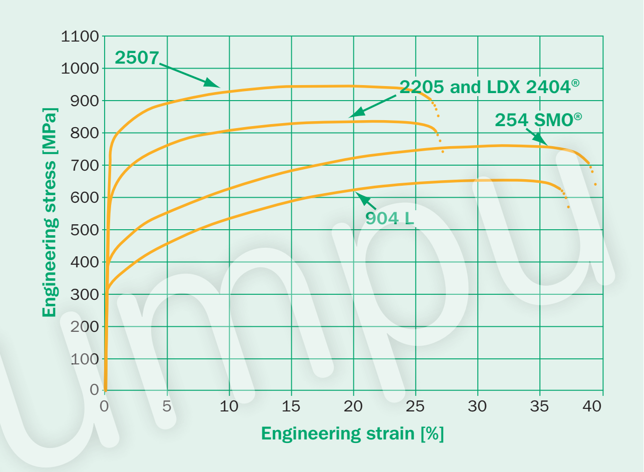


Figure 7:6. Stress strain curves of duplex steel in comparison with austenitic steels of similar corrosion resistance level.

Martensitic grades

Martensitic stainless steels are characterized by high strength in the quenched and tempered condition and are strongly affected by the heat treatment cycle. The steels are therefore usually used in a quenched and tempered condition. Details of heat treatments for martensitic steels can be found in the reference list. A martensitic grade can have a high ultimate tensile strength (above 1000 MPa) and a low elongation to fracture (less than 10 %) depending on the heat treatment conditions. In Table 7:5 hardness values for the soft annealed condition is given (HRB about 90). In quenched and tempered condition the hardness typically vary between HRC 40–60. Note that HRC is used for the quenched and tempered condition and is not comparable to HRB which is used for the soft annealed condition.

Effect of cold working

The mechanical properties of stainless steels are strongly affected by the degree of 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 an increased proof and ultimate tensile strength and at the same time a decrease in the elongation to fracture. Figure 7:7 shows the effect of cold working for an austenitic stainless steel.

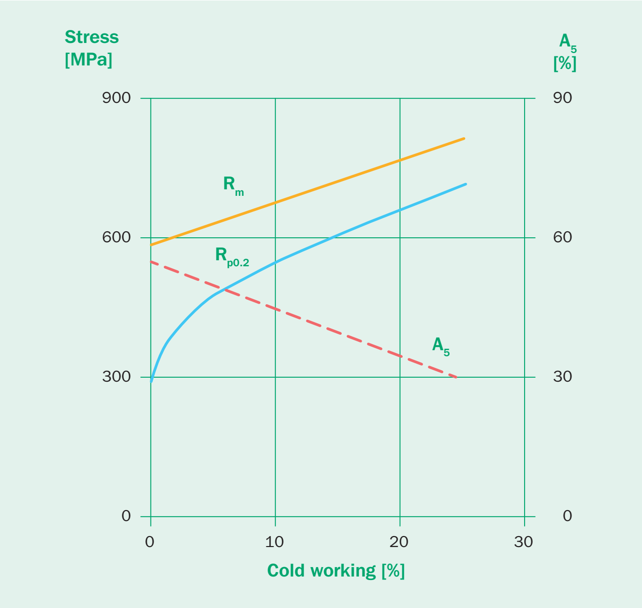


Figure 7:7. Effect of cold work on an austenitic stainless steel.

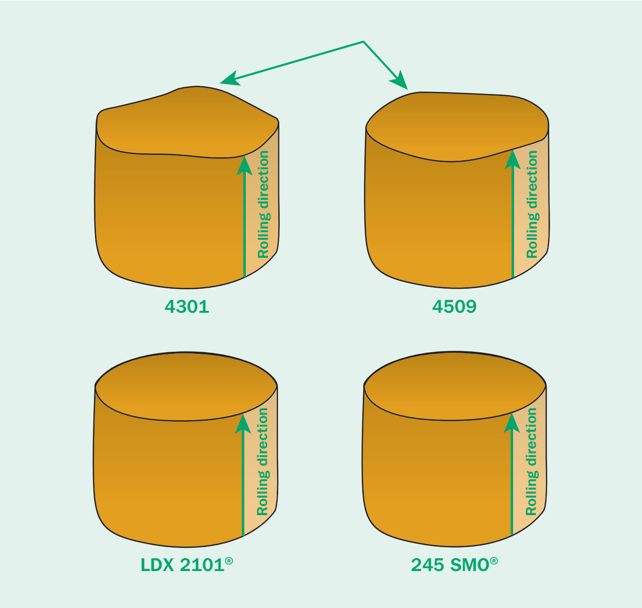


Figure 7:8. Earing (arrows) in deep drawn cup of the steel grades in Table 7:2

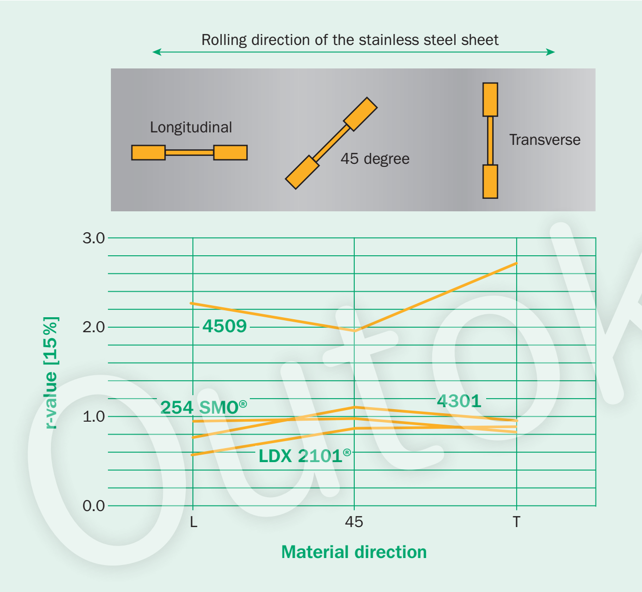


Figure 7:9. Typical r-values for some stainless steels. Top figure define the tensile testing directions L, 45 degree and T in equation 4.

Δr-values for some stainless steels (typical values for cold rolled coil and thickness of 0.8 mm)

Table 7:2

	Δr
4301	-0.6
4509	0.5
LDX 2101®	-0.03
254 SMO®	-0.11

Strength and elongation to fracture in longitudinal (L) and tranversal (T) direction for some stainless steels (typical values for cold rolled coil and thickness of 0.8 mm)

Table 7:3

	$R_{p0.2}$ (MPa)		R_m (MPa)		A_{50} (%)	
	L	T	L	T	L	T
4301	301	304	632	621	45	50
4509	329	343	477	473	31	31
LDX 2101®	624	625	837	829	31	28
254 SMO®	418	398	776	749	38	39

Anisotropy in stainless steels

All sheet metals that have been produced by a process of casting followed by one or more rolling stages commonly have different properties in different directions.

There are some practical manufacturing aspects of anisotropy during forming. When deep drawing cans for example, some materials have been known to display relatively significant earing, see Figure 7:8. This particular anisotropy is usually measured by the so-called **Δr**-value (planar anisotropy) calculated from r-values in different directions as

$$\Delta r = \frac{r_T - 2r_{45} + r_L}{2} \qquad (4)$$

The r-values are determined as the ratio between thickness and width strain in the tensile test. Figure 7:9 shows typical r-values for some stainless steel grades and the definition of L, T and 45 in eq 4. Table 7:2 gives the Δr-values for some stainless steels demonstrating that 4509 and 4301 have largest tendency for earing and LDX 2101® the least since Δr is close to zero.

The relative strength and fracture elongation along the rolling direction (L) and transverse to the rolling direction (T) may also vary as demonstrated in Table 7:3.

Minimum versus typical values

All standardized stainless steel grades have defined minimum strength and elongation values. These are the values the steel producer guarantees on the certificates and it is these values that designers use as a base for design of constructions such as bridges and pressure vessels. The actual values are, in other words, always higher. How much is a matter of statistical variance in the production as demonstrated in Figure 7:10. The typical values are either the statistical average value sometimes given in brochures, or the actual value for the specific sheet/plate as given in the certificate. In fact, the curve in Fig 7:10 demonstrate the range of values that can be on a certificate (240–310 MPa in this case).

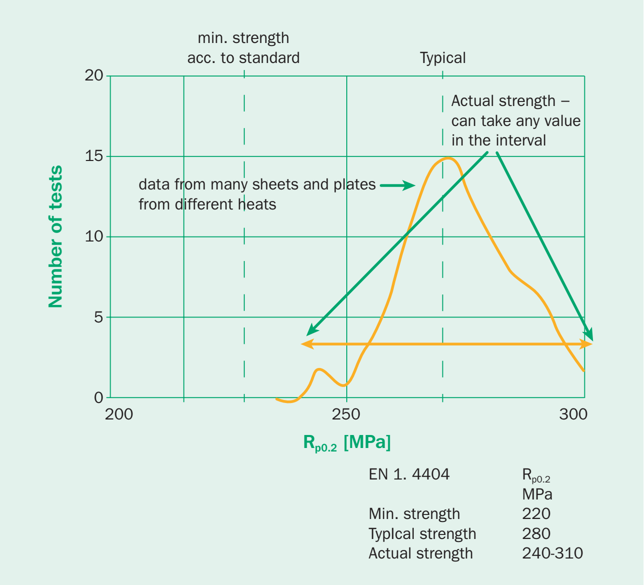


Figure 7:10. Typical statistical variance of proof stress for 4404.

Differences between product forms

The mechanical properties also vary between product forms. Typically, the strength increases with decreasing thickness, i.e. thick hot rolled plate has lower strength than thin cold rolled coil. For duplex grades this difference can be more than 100 MPa in $R_{p0.2}$, while for austenitic grades the difference is smaller (10–50 MPa in $R_{p0.2}$).

Toughness

The toughness of steel is the ability to absorb energy in the plastic range.

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 way of measuring toughness is through impact toughness (or impact energy measured in Joules), i.e. the toughness measured using rapid loading and typically the Charpy V method is used. Figure 7:11 shows typical Charpy V impact toughness ranges 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 (high toughness) and martensitic, ferritic (less toughness) and duplex steels (intermediate toughness).

The martensitic, ferritic and duplex steels are characterized by a transition in toughness, from tough to brittle behaviour at a certain temperature range; 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 duplex steels, 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 duplex steels are in the range 0 to –60 °C, with the ferritic steels in the upper part of this range.

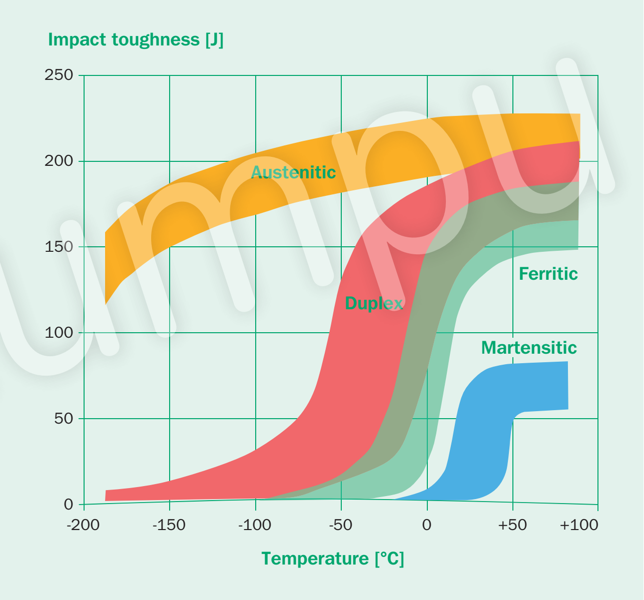


Figure 7:11. Impact toughness for different types of stainless steels. Charpy V method.

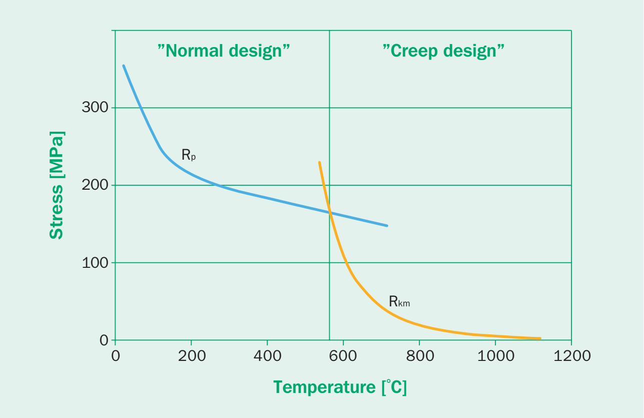


Figure 7:12. Elevated temperature strength of an austenitic stainless steel.

The austenitic steels do not exhibit a toughness transition as the other stainless steel types but have excellent toughness for a large temperature range, see Figure 7:11.

Another frequently used measure for impact testing is lateral expansion where the width of the fractured test specimen is measured. Fracture mechanics is sometimes used for a deeper understanding of toughness mechanisms.

Mechanical properties at cryogenic temperatures

Austenitic stainless steels have excellent toughness properties also at low temperatures and are usually the only material solution for very low (cryogenic) temperature applications. Ferritic, duplex and martensitic grades are commonly not suitable for low temperature applications due to the brittle behaviour at very low temperature.

High temperature mechanical properties

Creep is the time dependent slow plastic deformation of metals under a constant stress.

The high temperature strength of various steel grades is illustrated by the proof strength R_p and creep rupture strength at 10.000 or 100.000 hours R_{km}. Up to a temperature of about 550 °C a designer can utilize normal tensile testing data, such as R_p for design. Above 550 °C, creep is the dominant mechanical response and therefore creep data must be used in design, see Figure 7:12.

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 with high carbon content and stabilized by titanium or niobium. In terms of creep strength, the austenitic stainless steels are superior to ferritics (see Figure 7:13) and the other types of stainless steel.

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 is limited by the risk of embrittlement at temperatures above 250 °C. However, due to the good resistance of chromium steels to high temperature sulfidation 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 duplex steels behave in the same way as the ferritic steels but have higher strength at low temperatures. The upper service temperature limit is normally 250 °C due to the risk of embrittlement at higher temperatures.

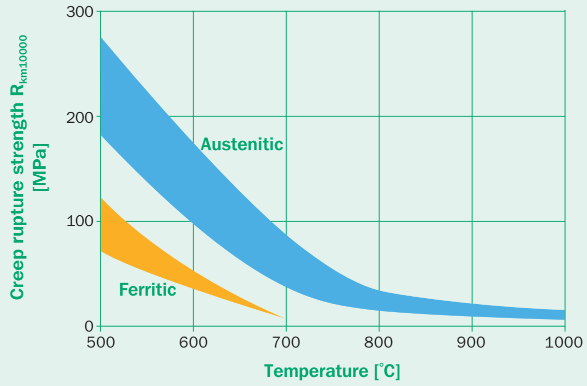


Figure 7:13. Creep rupture strength for austenitic and ferritic steels.

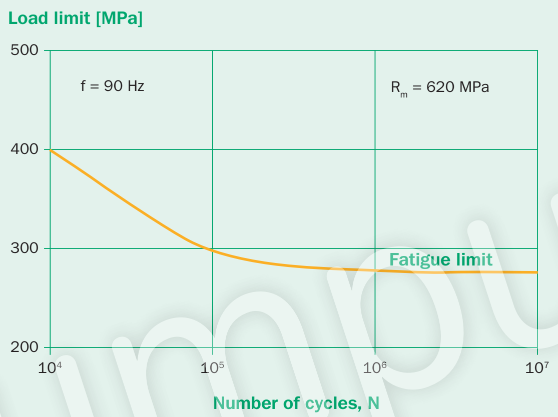


Figure 7:14. S-N curve (Wöhler curve) for the austenitic stainless steel 4404 in air.

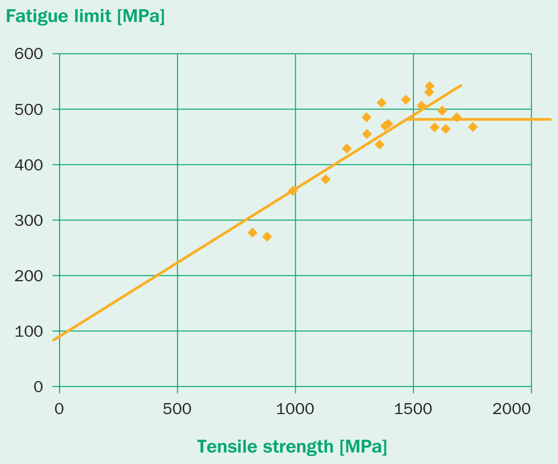


Figure 7:15. Fatigue limit for the austenitic stainless steel 4310, temper rolled to different strength levels.

Fatigue limit of stainless steel

Table 7:4

	LDX 2101®	2304	2205	2507	4404
$R_{p0.2}$ (MPa)	478	446	497	565	280
R_m (MPa)	696	689	767	802	578
Fatigue limit (MPa)	500	450	510	550	274

Fatigue strength

Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values are less than the ultimate tensile stress limit, and may also be below the proof strength limit of the material.

Fatigue occurs when a material is subjected to repeated loading and unloading. Microscopic cracks will begin to form if the loads are above a certain threshold. Eventually a crack will reach a critical size, and the structure will suddenly fracture due to rapid crack propagation. The shape of the structure will significantly affect the fatigue life; welds, square holes or sharp corners will lead to elevated local stresses where fatigue cracks can initiate (notch effect). Round holes and smooth transitions or fillets are therefore important to increase the fatigue strength of a structure.

The number of load cycles the material can withstand is dependent on the loading. The life time, i.e., the number of cycles to failure, increases with decreasing loading until a certain level is reached where the curve becomes horizontal, usually above 10^6 cycles (Figure 7:14). The material is said to last for an infinite number of cycles at this load level and it is commonly referred to as the fatigue limit or the endurance limit. The fatigue limit can be related to the proof strength and the ultimate tensile strength with quite good agreement as shown in Table 7:4 and Figure 7:15.

Of particular interest is how the fatigue properties respond to cold work (cold rolling or stretching). In Figure 7:15 the fatigue limit is related to the static strength for temper rolled/formed strips of 4310 in the 800 to 1700 MPa strength range.

Under combined cyclic loading and corrosive conditions, corrosion fatigue, the fatigue strength will generally decrease compared to cyclic loading at normal room temperature conditions. This is described further in chapter 6, Corrosion and corrosion properties

High temperature fatigue

The fatigue limit and fatigue strength will decrease with increasing temperature – often proportionally to the decrease in tensile strength. However, at elevated temperatures there are other fatigue types that are more common as life limiting factors.

Temperature gradients during start-ups, shut-downs, and major changes in service conditions can lead to generation of thermal and/or mechanical stresses and strains, which will lead to cracking and eventually failure of the temperature cycled components. Although the number of cycles is not very great, the strain range in each cycle can (at least locally) be large enough to cause failure in a limited number of cycles. This strain controlled fatigue type is often referred to as “low cycle fatigue, LCF”, while the common stress controlled fatigue is called “high cycle fatigue, HCF”. The boundary between LCF and HCF is somewhat loose, but generally defined as the loading level at which the plastic and elastic strain amplitudes in a cycle are equal, corresponding to cycle numbers between 10^3 and 10^5.

HCF at high temperatures is often isothermal and caused by rotation and/or vibration. LCF at high temperatures, on the other hand, often occurs in connection with temperature variations and is therefore also called “thermal fatigue” or “thermomechanical fatigue, TMF”.

Isothermal LCF failures may also occur at room temperature, but are less common than those caused by HCF.

Another type of HT fatigue is “thermal shock” due to rapid heating and/or cooling (e.g. quenching), where through thickness temperature gradients and “internal constraint” leads to the formation of surface craze cracking. This fatigue type is generally more severe for austenitic stainless steels, for which the thermal expansion is higher and the thermal conductivity lower than for ferritic stainless steels.

Hardness

Hardness is a measure of how resistant a material is to a permanent shape change when a force is applied. For metals, indentation hardness is typically used and measures the resistance of deformation due to a constant compression load from a sharp object normal to the metal surface. The test measures the critical dimensions of an indentation left by a loaded indenter. Common hardness scales are Rockwell (HRB), Vickers (HV) and Brinell (HB) and they differ primarily in the shape of the indenter and how the hardness is determined from the indentation shape. Tables 7:5 and 7:6 give typical hardness values for some Outokumpu stainless steel grades.

References

EN/ISO 6892-1 Metallic material. Tensile testing. Method of test at room temperature.

EN/ISO 6892-2 Metallic material. Tensile testing. Method of test at elevated temperature.

EN/ISO 148-1 Charpy pendulum impact test – Part 1: Test method.

EN/ISO 204 Metallic material. Uniaxial creep testing in tension. Method of test.

EN/ISO 12108 Metallic materials. Fatigue testing. Fatigue crack growth method.

EN/ ISO 6506-1 Metallic materials – Brinell hardness test –Part 1: Test method.

EN/ ISO 6507-1 Metallic materials – Vickers hardness test –Part 1: Test method.

EN/ ISO 6508-1 Metallic materials – Rockwell hardness test –Part 1: Test method.

Steel and its Heat Treatment – a handbook, Swerea IVF 12801, ISBN 987-91-86401-11-5.

Stainless Steels: Tables of Fabrication Parameters. Welding processes and filler materials – heat treatments – typical end uses, Euroinox Materials and Applications Series, ISBN 978-2-87997-047-9.

Mechanical properties for some stainless steel grades
Outokumpu typical values at room temperature

Table 7:5

Outokumpu steel name	International steel designation			Product	Outokumpu typical values				Hardness	
	EN	ASTM	UNS		$R_{p0.2}$ MPa	$R_{p1.0}$ MPa	R_m MPa	A_5 %	HB	HRB
FERRITIC GRADES										
4600	1.4600	–	–	H	435	460	545	25	87	-
4512	1.4512	409	–	C	255	275	425	33[4]	-	73
4003	1.4003	–	S40977	C	355	375	525	25[4]	-	80
4000	1.4000	410S	S41008	P	270	320	490	30	-	73
4589	1.4589	–	S42035	C	470	510	600	20[4]	-	87
4016	1.4016	430	S43000	C	365	390	520	26[4]	-	79
4511	1.4511	–	–	C	320	340	475	30[4]	-	76
4520	1.4520	–	–	C	265	285	430	34[4]	-	73
4510	1.4510	439	S43035	C	285	300	450	34[4]	-	74
4509	1.4509	–	S43940	C	310	330	480	31[4]	-	77
4607	1.4607	–	–	C	310	325	470	31[4]	-	76
4113	1.4113	434	S43400	C	390	420	550	24[4]	-	82
4513	1.4513	–	S43600	C	310	325	470	32[4]	-	76
4521	1.4521	444	S44400	C	350	370	525	31[4]	-	80
MARTENSITIC AND PRECIPITATION HARDENING GRADES										
4006[1]	1.4006	410	S41000	P	300	360	560	30	-	-
4005[1]	1.4005	416	S41600	R	350	450	550	20	-	-
4021[1]	1.4021	420	S42000	R	500	580	650	20	-	-
4031[1]	1.4031	420	S42000	C	*	*	*	*	-	-
4034[1]	1.4034	420	S42000	C	375	430	660	24[4]	-	89
4028[1]	1.4028	420	S42000	B	*	*	*	*	-	-
4313[2]	1.4313	–	S41500	P	700	770	850	20	-	-
4542[1]	1.4542	630	S17400	R	850	1050	1100	22	-	-
4116[1]	1.4116	–	–	C	390	430	640	23[4]	-	89
4110[1]	1.4110	–	–	C	410	460	690	24[4]	-	91
4568[1]	1.4568	631	S17700	R	210	240	700	50	-	-
4122[1]	1.4122	–	–	C	460	490	720	22[4]	-	93
4574	1.4574	632	S15700	C	320	340	860	25[4]	-	94
FERRITIC HIGH TEMPERATURE GRADES										
4713	1.4713	–	–	P	320	350	475	30	-	-
4724	1.4724	–	–	P	340	370	515	30	-	-
4736	1.4736	–	–	C	*	*	*	*	-	-
4742	1.4742	–	–	P	375	405	535	25	-	-
4762	1.4762	–	–	P	405	440	555	30	-	-
AUSTENITIC HIGH TEMPERATURE GRADES										
4948	1.4948	304H	S30409	P	290	330	600	55	-	-
4878	1.4878	321H	–	P	250	290	570	55	-	-
153 MA™	1.4818	–	S30415	P	340	380	660	55	-	-
4833	1.4833	309S	S30908	P	300	340	620	50	-	-
4828	1.4828	–	–	P	270	310	610	55	-	-
253 MA®	1.4835	–	S30815	P	370	410	700	50	-	-
4845	1.4845	310S	S31008	P	240	310	600	50	-	-
4841	1.4841	314	S31400	P	265	315	595	55	-	-

*to be established
[1] annealed condition
[2] quenched and tempered condition
[3] max value
[4] A80

P = Hot rolled plate Quarto
H = Hot rolled coil/sheet
C = Cold rolled coil/sheet
R = Rod

Mechanical properties for some stainless steel grades
Outokumpu typical values at room temperature

Table 7:6

Outokumpu steel name	International steel designation			Product	Outokumpu typical values				Hardness	
	EN	ASTM	UNS		$R_{p0.2}$ MPa	$R_{p1.0}$ MPa	R_m MPa	A_5 %	HB	HRB
DUPLEX GRADES										
LDX 2101®	1.4162	–	S32101	P	500		700	38	225	-
2304	1.4362	–	S32304	P	450		670	40	210	-
LDX 2404®	1.4662	–	S82441	P	520		750	33	230	-
2205	1.4462	–	S32205	P	510		750	35	230	-
4501	1.4501	–	S32760	P	580		830	35	-	-
2507	1.4410	–	S32750	P	580		830	35	250	-
AUSTENITIC GRADES										
4310	1.4310	301	S30100	C	300	325	770	56[1]	-	90
4618	1.4618	–	–	C	310	335	640	55[1]	-	81
4318	1.4318	301LN	S30153	C	360	400	750	50[1]	-	89
4376	1.4376	–	–	H	410	460	715	57	86	-
4372	1.4372	201	S20100	C	430	475	775	65	-	-
4301	1.4301	304	S30400	P	270	300	600	55	175[2]	-
4307	1.4307	304L	S30403	P	260	300	580	55	175[2]	-
4311	1.4311	304LN	S30453	P	310	350	640	55	185[2]	-
4541	1.4541	321	S32100	P	250	290	570	55	165[2]	-
4550	1.4550	347	S34700	P	260	290	595	45	-	-
4305	1.4305	303	S30300	P	275	–	585	35	-	-
4303	1.4303	305	S30500	C	260	280	570	56[1]	-	77
4306	1.4306	304L	S30403	P	240	270	580	55	160[2]	-
4567	1.4567	–	S30430	R	185	215	470	50	-	-
4640	1.4640	–	–	C	325	345	650	53[1]	-	-
4401	1.4401	316	S31600	P	260	300	570	55	170[2]	-
4404	1.4404	316L	S31603	P	260	300	570	55	170[2]	-
4427	1.4427	–	–	P	260	300	550	22	-	-
4436	1.4436	316	S31600	P	260	300	590	50	165[2]	-
4432	1.4432	316L	S31603	P	260	280	570	50	165[2]	-
4406	1.4406	316LN	S31653	P	300	330	620	50	-	-
4441	1.4441	–	–	C	320	355	630	46[1]	-	-
4429	1.4429	–	S31653	P	330	390	670	45	-	-
4571	1.4571	316Ti	S32100	P	260	300	570	50	170[2]	-
4435	1.4435	316L	–	P	260	300	570	55	-	-
3952	1.3952	–	–	P	330	380	670	50	-	-
HIGH PERFORMANCE AUSTENITIC GRADES										
4438	1.4438	317L	S31703	P	300	340	610	50	-	-
4439	1.4439	317LMN	S31726	P	310	350	640	50	-	-
725LN	1.4466	–	S31050	P	280	300	630	55	-	-
3964	1.3964	–	–	P	460	510	800	40	-	-
904L	1.4539	904L	N08904	P	260	285	600	50	155	-
254 SMO®	1.4547	–	S31254	P	320	350	680	50	160	-
4529	1.4529	–	N08926	P	320	340	700	50	180	-
4565	1.4565	–	S34565	P	440	480	825	55	200	-
654 SMO®	1.4652	–	S32654	P	460	490	860	60	200	-

[1] A80
[2] Hot rolled coil

P = Hot rolled plate Quarto
H = Hot rolled coil/sheet
C = Cold rolled coil/sheet
R = Rod

Physical properties

In terms of physical properties, stainless steels show appreciable differences between the various steel categories and may also be markedly different from carbon steels. Table 8:1 shows typical values for some physical properties of stainless steels.

Density

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.

Elastic modulus

The elastic modulus, or Young´s modulus, is a measure of the stiffness of the steel and is an important parameter in structural design (see also chapter 7, Mechanical properties). The true elastic modulus is not obtained from tensile testing, where there are a number of extraneous factors which influence the apparent modulus, but instead determined by, for example, ultrasound measurements.

The elastic modulus for stainless steels is typically ~200 GPa and shows only small variation with composition and microstructure. The elastic modulus decreases with increasing temperature, as is shown in Figure 8:1 for a typical austenitic grade.

Thermal properties

The two important physical properties that show greatest variation between the stainless steel types are thermal expansion and thermal conductivity. These thermal properties are a very important consideration in high temperature applications. Austenitic steels exhibit higher thermal expansion, typically 18×10^{-6}/°C, than ferritic grades, typically 11×10^{-6}/°C. Duplex grades show intermediate values while carbon steel is similar to the ferritic stainless steels. Thermal expansion can cause thermal stresses in applica-

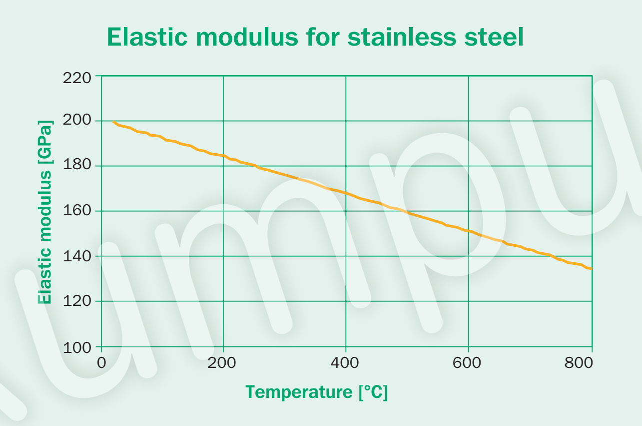


Figure 8:1. Elastic modulus of austenitic stainless steels as a function of temperatures.

Figure 8:2. Austenitic stainless façade which has buckled under intense sunlight. Unless this is desired as an architectural feature, a duplex or ferritic grade with lower thermal expansion may be preferred.

Typical physical properties for various stainless steel categories

Table 8:1

	Type of stainless steel			
Property	**Ferritic**	**Martensitic***	**Duplex**	**Austenitic**
Density (g/cm^3)	7.7	7.7	7.8	7.9–8.1
Elastic modulus (GPa or kN/mm^2)	220	215	200	190–200
Thermal expansion (× 10^{-6}/ °C) 200–400 °C	11	12	15	17–18
Thermal conductivity (W/m °C) 20 °C	30	30	12-15	15
Heat capacity (J/kg °C) 20 °C	460	460	500	500
Resistivity (µΩm) 20 °C	0.6	0.6	0.8	0.8
Ferromagnetism	Yes	Yes	Yes	No#

* in the hardened and tempered condition
# Some ferromagnetism is seen for austenitic grades if they contain a small amount of ferrite or martensite

tions with temperature fluctuations, heat treatment of complete structures and on welding. An example of the effect of thermal expansion is seen in Figure 8:2.

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 is ~30 W/m °C for martensitic and ferritic stainless steels, and about half that for austenitic and duplex grades. This can be compared with over 40 W/m °C for carbon steels. The variation in thermal conductivity for austenitic and duplex grades as a function of temperature is shown in Figure 8:3. A low thermal conductivity is important for retaining heat, for example in building components and food containers.

The specific heat capacity is the energy required to produce a specific temperature increase in the material. For stainless steel and carbon steels it is around 500 J/kg °C. The specific heat capacity has implications for heat input requirements in welding and in steelmaking.

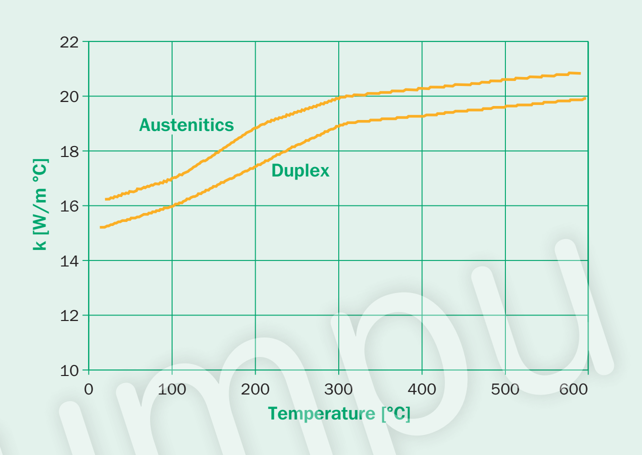


Figure 8:3. Thermal conductivity for austenitic and duplex stainless steels.

Electrical resistivity

The electrical resistivity of steels increases with the content of alloying elements and is thus higher for stainless steel than for carbon steels. The highest values of around 0.8 µΩm are seen for super-austenitic grades and the lowest for the leanest ferritic grades.

Magnetic properties

All ferritic, martensitic and duplex grades are ferromagnetic, while stable austenitic grades are not magnetisable. Small amounts of ferrite or martensite in an austenitic structure can have an appreciable effect on the magnetic properties and so must be avoided in applications where this is critical, for example cyclotrons and submarines.

References

EN 10088-1, Stainless steels – Part 1: List of stainless steels.

Material selection

Selecting the right stainless steel grade for a specific application is vitally important in order to achieve a sustainable solution. Cost aspects must also be taken into consideration. There are several stages when material selection needs to be made:

- new applications and equipment
- new processes and process changes
- exchange of material due to poor performance of existing material
- exchange of existing material to minimize cost

To make an appropriate material selection it is important to get a full picture of the service conditions so as to be able to specify the demands for the application. Aspects to consider could be material related, e.g.:

- corrosion resistance
- mechanical strength
- fabricability
- physical properties
- surface aspects (e.g. appearance and cleanability)

Other aspects to consider could be
- possibilities for weight reduction
- availability
- cost
- Life Cycle Cost (LCC)
- recyclability
- legislations, standards and approvals
- previous experience

Corrosion engineering utilizes corrosion data for the environment in which the material is to be exposed. Important criteria include temperature, concentration of main species and impurities, pH etc. Field testing in, or laboratory testing to simulate, the environment is often required in order to identify which grades that would be suitable.

Designing load bearing structural applications, such as bridges, pressure vessels and structural automotive components is mostly done by applying the mechanical strength data provided in national and international standards and design codes. Fabricability, of special grades in particular, is crucial for material selection.

outokumpu
stainless steel & high performance alloys

Duplex
Stainless Steel

Steel grades

Outokumpu	EN	UNS	ISO
LDX 2101®	1.4162	S32101	4162-321-01-E
2304	1.4362	S32304	4362-323-04-I
LDX 2404®	1.4662	S82441	4662-824-41-X
2205	1.4462	S32205/S31803	4462-318-03-I
4501	1.4501	S32760	4501-327-60-I
2507	1.4410	S32750	4410-327-50-E

Applications

- Pulp and paper industry
- Desalination plants
- Flue-gas cleaning
- Cargo tanks and pipe systems in chemical tankers
- Seawater systems
- Firewalls and blast walls on offshore platforms
- Bridges
- Components for structural design
- Storage tanks
- Pressure vessels
- Heat exchangers
- Water heaters
- Rotors, impellers and shafts
- Reinforcing bars for concrete structures

Characteristic properties

- Good to very good resistance to uniform corrosion
- Good to very good resistance to pitting and crevice corrosion
- High resistance to stress corrosion cracking and corrosion fatigue
- High mechanical strength
- Good abrasion and erosion resistance
- Good fatigue resistance
- High energy absorption
- Low thermal expansion
- Good weldability

General characteristics

Ferritic-austenitic stainless steel also referred to as duplex stainless steels, combine many of the beneficial properties of ferritic and austenitic steels. Due to the high content of chromium and nitrogen, and often also molybdenum, these steels offer good resistance to localised and uniform corrosion. The duplex micro-

Chemical composition

Table 1

	Outokumpu Steel name	International steel No				Chemical composition, % by wt. Typical values					
		EN	ASTM	UNS	ISO	C	N	Cr	Ni	Mo	Others
Duplex	LDX 2101®	1.4162	–	S32101	4162-321-01-E	0.03	0.22	21.5	1.5	0.3	5Mn Cu
	2304[1]	1.4362	–	S32304	4362-323-04-I	0.02	0.10	23.0	4.8	0.3	Cu
	LDX 2404®	1.4662	–	S82441	4662-824-41-X	0.02	0.27	24.0	3.6	1.6	3Mn Cu
	2205	1.4462	–	S32205[2]	4462-318-03-I	0.02	0.17	22.0	5.7	3.1	
	4501	1.4501	–	S32760	4501-327-60-I	0.02	0.27	25.4	6.9	3.8	W Cu
	2507	1.4410	–	S32750	4410-327-50-E	0.02	0.27	25.0	7.0	4.0	
Austenitic	4307	1.4307	304L	S30403	4307-304-03-I	0.02		18.1	8.1		
	4404	1.4404	316L	S31603	4404-316-03-I	0.02		17.2	10.1	2.1	
	904L	1.4539	904L	N08904	4539-089-04-I	0.01		20.0	25.0	4.3	1.5Cu
	254 SMO®	1.4547	–	S31254	4547-312-54-I	0.01	0.20	20.0	18.0	6.1	Cu

[1] also available as EDX 2304™ with modified composition for enhanced properties. [2] also available as S31803.

Duplex Stainless Steel - 1

Figure 9:1. Outokumpu Duplex Stainless Steel, example of data sheet.

Corrosion Handbook
Tenth Edition, 2009

OUTO
KUMPU

Figure 9:2. Outokumpu Corrosion Handbook, 10th edition, 2009.

Equipment to be used at elevated temperatures (>550 °C) is designed using creep and oxidation data, and previous experience is important when selecting material. In many applications the material is consumed after a period of time. Improvement in design is therefore important to prolong the expected life time. Experience and references play a more important role in this field than in wet corrosion and load bearing applications. Creep data and a track record of success and proven references are essential.

To facilitate material selection there are several different tools available from Outokumpu: material data sheets, Outokumpu Corrosion Handbook, Outokumpu Welding Handbook, segment and application brochures etc. Figures 9:1-9:3 show some examples.

Many of these can be downloaded from the Outokumpu Internet site at www.outokumpu.com. At this site there are also some other useful tools available e.g. corrosion tables, calculation tools for storage tanks and pressure vessels etc.

Technical support and assistance for customers can also be provided by Outokumpu's R&D departments via the sales offices. For such support it is necessary to provide detailed information regarding service conditions or other aspects that needs to be considered.

Table 9:1 gives a general overview of the main properties of the different stainless steel categories. It is important to realize that the properties for different steel grades within one steel group vary.

Figure 9:3. Outokumpu Welding Handbook, 1st edition 2010.

Main properties of the different stainless steel types

Table 9:1

Steel type		Wet corrosion resistance				Mechanical strength		HT properties		Fabricability				Physical properties				
		Uniform corrosion	Pitting/crevice corrosion	Stress corrosion cracking	Intergranular corrosion	Strength	Wear resistance	Oxidation/Corrosion	Strength	Machinability	Strech forming	Deep drawing	Weldability	Thermal expansion	Thermal conductivity	Thermal capacity	Electric resistivity	Magnetizable
Ferritic	Cr	B-M	B-M	H	B-M	M	M	H	L	H	L	H	L-M	L	M	M	M	Y
	HT grades	-	-	-	-	M	M	H	L	H	L	H	L-M	L	M	M	M	Y
Martensitic		B	B	H	B	H	H	-	-	L-M	L	-	L	L	M	M	M	Y
Duplex	Lean duplex	M	M	H	H	H	H	-	-	H	L-M	L	M	M	L	M	M	Y
	Duplex	H	H	H	H	H	H	-	-	L	L-M	L	M	M	L	M	M	Y
	Superduplex	H	H	H	H	H	H	-	-	L	L	L	M	M	L	M	M	Y
Austenitic	Cr-Mn	B	B	B	B	M-H*	M	B	M	M	H	M-H	H	-	L	-	M	N
	Cr-Ni	B	B	B	H	M-H*	M	M-H	M	M	H	M-H	H	H	L	M	M	N
	Cr-Ni-Mo	M	M	B	H	M-H*	M	B-M	M-H	M	H	M-H	H	H	L	M	M	N
	High performance	H	H	H	H	M-H	M-H	-	-	L	M-H	M-H	M	H	L	M	M	N
	HT grades	-	-	-	-	M	M	H	H	M	H	-	M	H	L	M	M	N

B = basic, L = low, M = medium, H = high, Y = yes, N = no, H* = temper rolled (work hardened)

Alternative stainless steel grades for different corrosion classes

Table 9:2

Corrosion class	Ferritic alternative	Martensitic alternative	Duplex alternative	Austenitic alternative
Basic	4003, 4512, ...	4006, 4005, 4021, ...		
	4016, ...	4313, 4542, ...		4618, 4372
	4509, 4510, ...	4122, 4376		4301/4307, 4541, 4306 ...
Medium	4521		LDX 2101®, 2304	4401/4404, 4571
				4436/4432 ...
High				4438, 4439
			LDX 2404®, 2205	725LN, 904L
			2507, 4501	254 SMO®, 4529, 4565
				654 SMO®

Corrosion resistance

Regarding wet corrosion resistance, one way to simplify and get a rough overview of alternative stainless steel grades is to divide the grades into three different "corrosion classes". These classes could represent "basic", "medium" and "high" corrosion resistance, as illustrated in Table 9:2 and discussed in more detail in the following section.

It is, however, important to remember that the corrosion resistance range within one class can be rather large. It is also important to remember that the final material choice must be based on the actual application and service conditions.

More detailed information regarding corrosion types and corrosion resistance is available in the Outokumpu Corrosion Handbook.

Basic resistance

Ferritic grades

The ferritic microstructure of these grades makes them magnetic and improves resistance to stress corrosion cracking. Ferritic grades are generally good for deep drawing but have a limited stretch forming capability compared to austenitic stainless steels.

The low alloyed ferritic stainless steels 4003 and 4512 have higher corrosion resistance compared to carbon steel and can therefore replace painted or galvanized carbon steel in many applications. Grade 4003 is typically used in structural applications replacing carbon steel, while the most common application for grade 4512 are automotive exhaust applications. The non-stabilised ferritic grade 4016, with slightly higher corrosion resistance, is typically used in domestic appliances. Dual stabilized grade 4509, as well as the stabilized grade 4510, has corrosion resistance close to that of austenitic grade 4301/4307 and offers properties suitable for general use.

The stabilized ferritic grades 4512, 4509 and 4510 have good weldability, whereas the non-stabilized grade 4016 is less suited for welding in thicker gauges. The non-stabilised grade 4003 has good weldability comparable to that of structural carbon steel.

Some typical applications for these ferritic grades are washing machines, counter tops, refrigerators, dish-washers, cooker hoods, tableware and restaurant equipment, architectural use (mainly indoor, Figure 9:4), transport industry e.g. exhaust systems in automotive and structural hollow sections in heavy transport.

Martensitic grades

The martensitic grades 4006 and 4005 are usually not used in applications where corrosion resistance is needed. However, there are martensitic grades like 4313 and 4542 that have slightly better corrosion resistance. Martensitic grades are often used in applications where high strength and wear resistance is demanded, in e.g. shafts, knifes and for wear and press plates.

Austenitic grades

The "Cr-Mn" grade 4372 where some of the nickel is replaced by manganese may give a cost benefit over 4301/4307 type of grades, but this grade have slightly lower corrosion resistance. Sensitivity to delayed cracking may be observed after demanding forming processes.

Grades 4301/4307, i.e. type "Cr-Ni", "18-8" or 304/304L grades, are the most common stainless steels in service globally.

Figure 9:4. Ferritic stainless steels are often used in architectural and design applications where corrosion resistance is not an issue.

Figure 9:5. Domestic water heaters are often made of ferritic stainless steel. Photo: Courtesy of Kaukora.

These grades are well-known and versatile. Type 4307 grades are non-magnetic all-purpose stainless steels available in a wide range of surface finishes. They have good formability and good weldability, and are ductile even at low temperatures which are essential for cryogenic applications. They are however sensitive to stress corrosion cracking in certain environments. The availability of these types of grades is excellent.

Typical applications/areas are in the food industry, catering and kitchen equipment, process industries, building, architecture and transport.

Medium resistance

Ferritic grades

The dual stabilized ferritic grade 4521 has corrosion resistance almost on the level of type 4401/4404 but has better resistance to stress corrosion cracking. As for other ferritic grades, 4521 is magnetic and is suitable for deep drawing. Some typical applications/areas are domestic water heaters (Figure 9:5), water tubing and heat exchanger tubes.

Lean Duplex grades

Lean duplex grade LDX 2101® has higher corrosion resistance than type 4301/4307 and closer to that of type 4401/4404, with good resistance to stress corrosion cracking. LDX 2101® has excellent machinability, Figure 9:6, but is harder to form. Welding is more demanding than for type 4307. All duplex grades have a limitation in service temperatures and should normally only be used between -40 °C and 250–325 °C as they are more brittle at lower or higher temperatures.

The duplex grade 2304 has corrosion resistance at least on the level of type 4401/4404, but higher resistance to stress corrosion cracking. It has high mechanical strength and is harder to form than type 4404. The abrasion resistance is good. Welding is more demanding than for type 4404.

Some typical applications for these grades are large storage tanks, equipment in process industries, bridges, reinforcement bars and domestic water heaters.

Austenitic grades

Grades 4401/4404, i.e. type “Cr-Ni-Mo”, “17-11-2L” or 316/316L grades are the second most common stainless steel category in service globally. The corrosion resistance is higher compared to grades 4301/4307 due to the molybdenum addition. Grades 4436/4432 are of the same type but with slightly higher molybdenum content and thus somewhat higher corrosion resistance. Type 4404 and 4432 grades are non-magnetic all-purpose stainless steels available in a wide range of surface finishes. They have good formability and good weldability, and are ductile even at low temperatures which are essential for cryogenic applications. They are sensitive to stress corrosion cracking in certain environments. The availability of these types of grades is excellent.

Typical applications are e.g. food and drink industry, chemical and other process industries, building, architecture and transport. Figure 9:7 shows a time capsule in grade 4404.

High resistance

Duplex grades

Duplex grades with high corrosion resistance includes LDX 2404® and 2205.

These grades generally have better corrosion resistance than austenitic grades 4438 and 4439 and higher resistance to stress corrosion cracking. The grades have high mechanical strength, have good abrasion resistance but are harder to form than type 4404. Welding is more demanding than for type 4404.

Some typical applications are process industries, pulp & paper, oil & gas applications, desalination, chemical tankers (cargo tanks), pressure vessels and structural applications in harsh climates.

Superduplex grades

Superduplex grades 2507 and 4501 have high resistance to localised corrosion and good resistance to stress corrosion cracking. The corrosion resistance of these grades is very close to that of the superaustenitic grade 254 SMO®. These grades have very high mechanical strength and good abrasion resistance. Welding is more demanding than for type 4404.

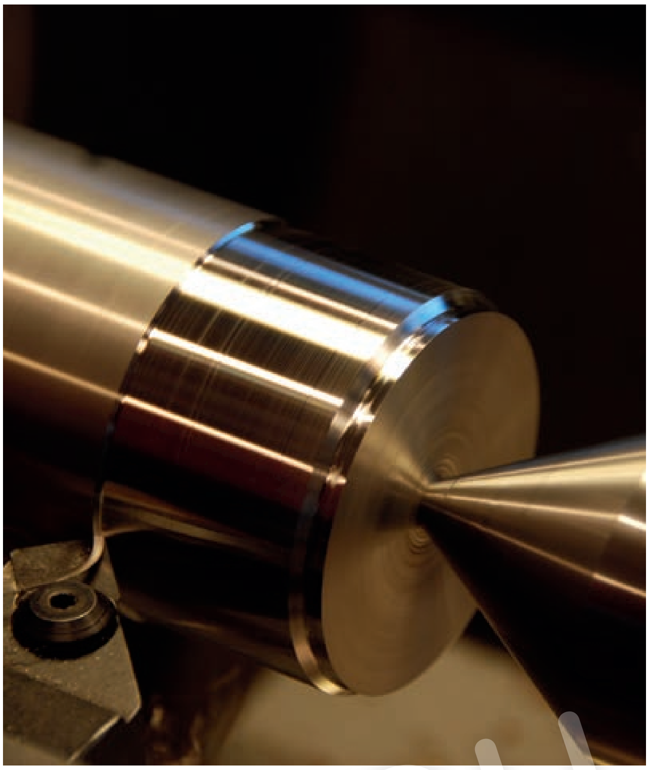


Figure 9:6. Duplex grade LDX 2101® shows excellent machinability.

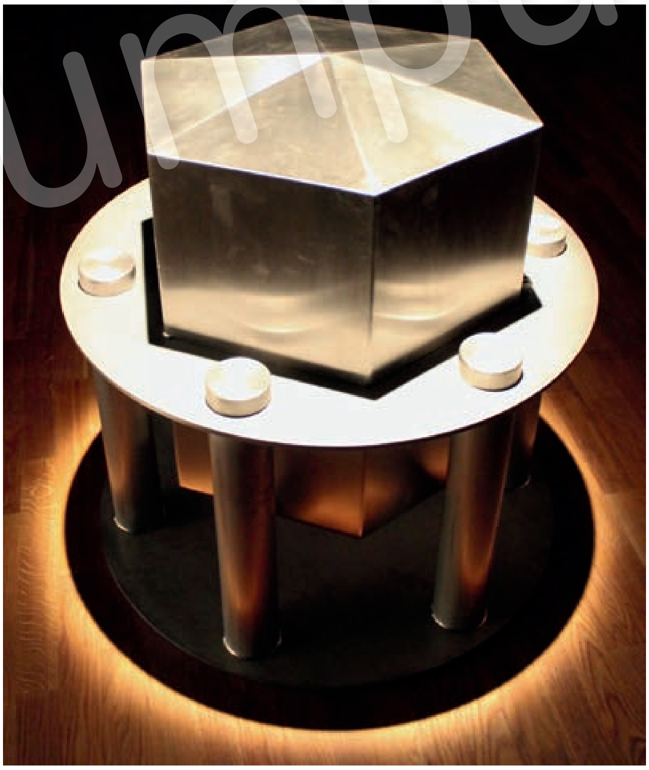


Figure 9:7. In this stainless steel time capsule photos from the aday.org project are stored for the future. The time capsule, which consist of an inner capsule of the superaustenitic stainless steel 654 SMO® where the items are stored, and an outer capsule in grade 4404, can be seen at the Falun Copper Mine in Falun, Sweden, inscribed on UNESCO's list of World Heritages. The capsule will be stored down in the mine for several hundreds of year.

Some typical applications are marine installations, oil & gas, flexible pipes, umbilicals and desalination.

Austenitic grades

This is a broad "corrosion class" where there are several austenitic grades with an appreciable span in corrosion resistance, but all higher than that of type 4404 or 4432 grades. The resistance of these grades is very much dependent on their chemical composition i.e. the higher alloy content the better corrosion resistance.

Examples of grades are 4438 and 4439 with higher molybdenum content than type 4432 grades. Grades 725 LN and 904L are even higher alloyed. 904L has good resistance to corrosion in sulphuric acid and good resistance to stress corrosion cracking. These grades have good formability and are ductile even at low temperatures.

Some typical applications are chemical industry, heat exchangers, vessels and flue gas cleaning.

Superaustenitic grades

Examples of superaustenitic grades are 254 SMO®, 4529 and 4565. These grades have high resistance to localised corrosion, to uniform corrosion in many acids, to stress corrosion cracking and to sulphide induced stress cracking, SSC. They have high mechanical strength especially grade 4565. Welding is more demanding than for type 4404.

Some typical applications are marine service, chemical industry, oil & gas applications, desalination, flue gas cleaning, plate heat exchangers and condenser tubing.

In this group we also find "the world's most stainless steel grade", 654 SMO®. This grade has superior resistance to localized corrosion, very good resistance in acids and high resistance to stress corrosion cracking. It has high mechanical strength but still very good ductility making it suitable also for demanding stretch forming operations.

654 SMO® can replace Ni-based alloys and titanium in many applications where very high resistance to corrosion is needed.

Some typical applications are chemical industry, oil & gas (Figure 9:8), desalination, flue gas cleaning, plate heat exchangers and condenser tubing.

High temperature service

Even if standard ferritic and austenitic stainless steels are sometimes used in high temperature applications, e.g. ferritic 4512 and 4510 for automotive exhaust systems, there are specially designed ferritic and austenitic high temperature grades. Outokumpu's high temperature steels are designed primarily for use in the temperature range ~500–1100 °C depending on steel grade. Figure 9:9 shows an exhaust manifold in grade 253 MA®. Environmental factors such as erosion/abrasion, thermal cycling, sulphur, carbon, chlorides, water vapour etc. in the gas reduce the maximum recommended service temperature.

Below are some comments regarding material selection in high temperature applications. However, the final material selection must always be based on actual application and service conditions.

Ferritic high temperature grades

In reducing sulphur-containing environments, nickel sulphides can form resulting in rapid deterioration of the metal. In order to avoid this, nickel-free materials such as ferritic high temperature grades should be selected.

Figure 9:8. Superautenitic and duplex stainless steels are common materials for different applications on oil platforms.

Figure 9:9. Exhaust manifold in high temperature grade 253 MA®.

Some typical applications for these types of grades are chemical industry (drums), power industry (coal burners) heat treatment boxes.

Austenitic high temperature grades

In oxidizing sulphidiszing environments grades 153 MA™ and 253 MA® are, due to their adherent protective oxide scales, better suited for service than materials with similar or higher nickel contents.

Under oxidising conditions with temperature variations (thermal cycling) 253 MA® shows better oxidation resistance than e.g. 4845. The presence of water vapour in the atmosphere reduces the resistance to oxidation and thus the maximum recommended service temperature. The reduction can be 50–150 °C depending on steam content and flow rate.

For all applications where good microstructural stability, in combination with high creep strength is essential 153 MA™ is suitable. The maximum service temperature (in dry air) is around 1000 °C. Use of this grade allows reduced section thickness or higher load capacity in comparison with other high temperature steel grades. 153 MA™ has also good oxidation resistance.

An excellent choice for high to very high temperatures (700–1100 °C) is 253 MA®, particularly for conditions involving erosion-corrosion in oxidizing and neutral environments. The excellent mechanical strength at high temperatures allows higher loads or thinner wall thickness than common high temperature steels like

4833 and 4845. 253 MA® provides better oxidation/corrosion resistance than 153 MA™. However 253 MA® has poorer microstructural stability than 153 MA™, especially at temperatures below 850 °C. In fatigue loading, when a component is subjected to varying load and temperature, grades 153 MA™ and 253 MA® show superior resistance. In Figure 9:10, results from thermo mechanical fatigue (TMF) testing are presented, showing that ageing has a beneficial effect on the fatigue life of 253 MA®, which forms nitrides during ageing, while the effect is detrimental for grade 4845 due to sigma phase precipitation.

Due to higher creep strength there is a potential for weight savings with grades 153 MA™ and 253 MA® in comparison to other stainless steel grades, e.g. at 900 °C the weight saved is 60% by choosing 253 MA® instead of 4828 or 4845 for a cylindrical application with internal pressure, see Figure 9:11.

Some typical application/areas for these types of grades are conveyor belts, bell furnaces, radiant tubes, boiler components, exhaust systems, manifolds and cyclones in the cement industry.

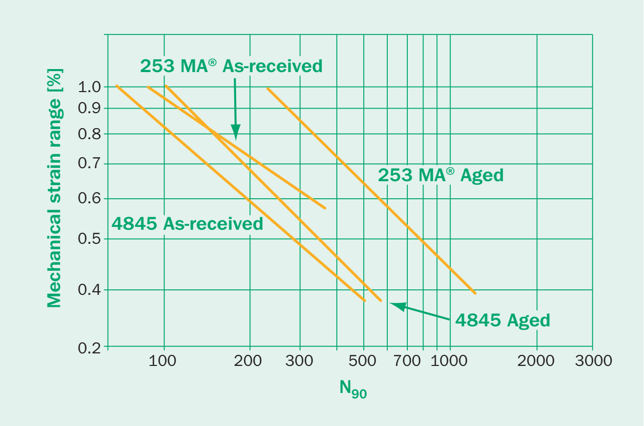


Figure 9:10. TMF tests show that ageing (800 °C, 2000 h) is beneficial for Outokumpu 253 MA®, but detrimental for 4845. N_{90} is the number of cycles to substantial fatigue crack initiation. The precipitation of nitrides in 253 MA® increases its fatigue life.

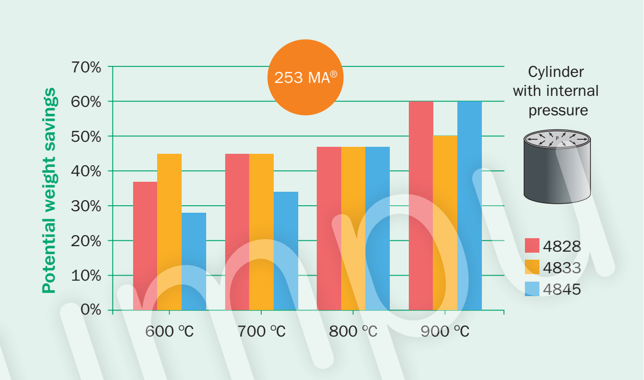


Figure 9:11. Potential weight savings with Outokumpu 253 MA® in comparison to other stainless steel grades. At 900 °C the weight saved is 60 % compared to austenitic 4828 and 4845.

Fabricability

In general the same fabrication techniques as for carbon steel can be used for stainless steel. However, there are some precautions for stainless steel fabrication in general, and some specific precautions for high performance grades. See also Chapter 10, Fabrication, for more detailed information regarding fabricability.

Machining

Grades 4301/4307 are considered more demanding to machine compared to carbon steel, so alternative stainless steel grades will usually not introduce further challenges.

Ferritic grades are often easier to machine compared to 4307, while the austenitic grades 4401/4404 and the ferritic grade 4521 are somewhat more demanding. The same applies for the duplex grades, the high alloyed austenitic grades and the high temperature grades. The step from 4404 to high alloyed austenitic is much larger than the step from 4307 to 4404. Machining becomes more demanding the higher the alloy content. One exception is, however, the lean duplex grade LDX 2101® which shows excellent machinability. Some Outokumpu steel grades are also available as PRODEC® variants with balanced sulphur content for improved machinability. See also chapter 2, Stainless steel categories and grades and chapter 10, Fabrication.

More information can be found in the Outokumpu Machining Guidelines.

Forming

Grades 4301/4307 have very good formability compared to most other stainless steel grades. The fracture elongation (A_5, A_{80},...) is a good indication of the formability.

Ferritic grades have lower bendability compared to 4307, but better formability for axi-symmetric forming (deep drawing). The formability is however lower if the component contains a lot of thinning (stretch forming or sharp bending). The austenitic grade 4401/4404, the high alloyed austenitic grades and the austenitic high temperature grades have formability fairly close to that of 4307. Figure 9:12 shows a heat exchanger plate in 654 SMO®, a product which requires good stretch formability.

Figure 9:12. The formability of e.g. grade 654 SMO® is excellent.

The duplex grades have similar formability to 4307 in deep drawing but lower in stretch forming operations. The recently developed FDX-grades have, however, close to the same formability in stretch forming operations. Typically, twice as high press forces are needed due to the higher strength. However, this may be reduced if thinner gauges can be used. Duplex grades have also higher springback. High performance tool material may be necessary due to larger tool wear.

Welding

Grades 4301/4307 are considered “easy” to weld and most welders have practical experience with these grades. Grades 4401/4404 have similar weldability as 4301/4307.

For ferritic steels special attention to heat input is needed to avoid ductility loss, grade 4016 is more sensitive than grades 4509 and 4521 which are Ti and Nb stabilized. Ferritic grades can be welded with austenitic fillers or without filler.

Duplex grades have good weldability in general, but some parameter modification compared to 4307 is needed, e.g. a larger joint angle (about +10°). Specially designed fillers should be used and heat input and interpass temperature control is important.

The high alloyed austenitic grades are more demanding to weld than 4307 and specially designed fillers should be used. Good control of welding parameters is needed.

Weld qualification must always be performed when changing from one grade to another.

More information regarding welding and post weld treatments is found in the Outokumpu Welding Handbook.

Physical properties

The thermal expansion is probably the most common physical property which needs to be taken into account in material selection. The ferritic and martensitic stainless steels have lower thermal expansion compared to carbon steel. The duplex grades have slightly higher thermal expansion than carbon steel, while the austenitic grades exhibit the highest thermal expansion. In applications where both corrosion resistance and low thermal expansion is needed, a duplex grade would be the best choice.

Surface aspects

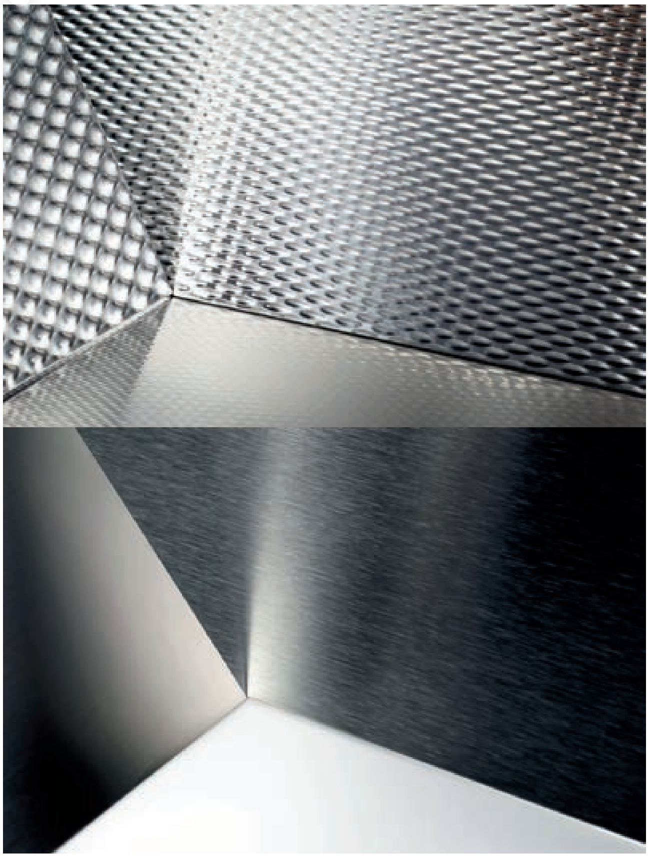
The surface finish is an essential parameter in most applications, for example in architecture or in the food and drink industry, while in other applications it is of minor interest e.g. where abrasion occur. Figures 9:14 and 9:15 show examples of some different surfaces available.

A smooth surface (e.g. low Ra value) is easier to keep clean since contaminants or bacteria stick more readily to a rougher surface. A smoother surface has also higher resistance to initiation of corrosion attack.

The standard austenitic grades like type 4307 or type 4404 are available in many different surface finishes while the other grades are available in more limited surface finishes.

See also chapter 5, Product forms.

Figure 9:13. All stainless steels have good weldability, but some grades are more demanding to weld.



Figures 9:14-9:15. Examples of different surfaces.

Figure 9:16. Proof strength (min. values for hot rolled coil acc. to EN 10088-2) for some austenitic and duplex grades in relation to their corrosion resistance (CPT acc. to ASTM G150). Grade EDX 2304™ has a balanced chemical composition to obtain optimal corrosion resistance and strength, but it still correspond to EN 1.4362 and UNS S32304.

Figure 9:17. White liquor tank in duplex LDX 2101®, where corrosion resistance and strength of this grade is utilized.

Possibilities for weight reduction

To use a stainless steel grade with high mechanical strength can in many cases be a cost effective solution. High strength means that it may be possible to down-gauge, using thinner material, which results in weight savings, less welding, lower transportation cost, and possibly lower total cost. Figure 9:16 shows the proof strength for some austenitic and duplex grades in relation to their corrosion resistance. As can be seen, for most austenitic grades there are duplex alternatives with the same corrosion resistance but with twice the strength. Figure 9:17 shows one application where the high strength of duplex grades can be utilised.

By changing from austenitic grade 4404 to duplex LDX 2404® weight savings up to 40 % can be achieved for the cylindrical shell of large storage tanks, depending on size and design code. Enhanced corrosion resistance is an additional bonus.

There are also austenitic grades, e.g. 4318 and 4372, with corrosion resistance in the region of 4307 but with enhanced strength compared to 4307 due to nitrogen alloying. Grades 4318 and 4372 have a minimum proof strength of 330 MPa as hot rolled coil.

Some austenitic grades, e.g. 4310, 4318, 4301 and 4401, may also be delivered in the temper rolled condition with proof strength varying from 500 MPa up to 2000 MPa depending on steel grade. However, when welding these temper rolled grades the material will soften, and the strength of the weld will be the same as for ordinary cold rolled material of that grade.

Material combinations to reduce cost

In certain applications where the environment may vary from one location to another, a combination of different stainless steels may give a cost benefit.

One example is in the desalination industry where the DualDuplex™ concept is sometimes used in multi stage flash (MFS) chambers. In these chambers the lower part is subjected to brine with high chloride content, while in the upper part conditions are less harsh for stainless steel. Several plants use duplex 2205 in a lower section and an upper section in lean duplex LDX 2101®.

In flanged pipe systems, the flanges are the most critical part due to the risk of crevice corrosion on the sealing surfaces. In such a system a stainless steel with higher resistance to crevice corrosion can be used as flange material. One example is welded pipes of 254 SMO® for seawater service where flanges of 654 SMO® are used. This can also be used for pipe systems with threaded connections where a higher alloy grade can be used for the threaded parts where the risk of crevice corrosion is high.

Differences in physical properties, e.g. thermal expansion, should be taken into account if different types of stainless steel grades are combined.

Life cycle cost, LCC

When calculating the cost of material for a specific application it is important to take the whole life cycle into consideration. Even if the material cost for a stainless steel is higher than for carbon steel this does not necessarily mean that the total cost during the life cycle will be higher.

The material cost plus the manufacturing cost gives the total investment cost. However, it is just as important to add also the total operation and maintenance cost during the entire life cycle, and to add the metal value when the component is scrapped. This together gives the total life cycle cost, Figure 9:18, which often shows that to use stainless steel as an alternative material gives the lowest total cost.

Recyclability

The production of stainless steel within Outokumpu is based on metal scrap as the main ingredient. All stainless steels are 100 % recyclable and this means that the value of scrapped stainless steel equipment can be high.

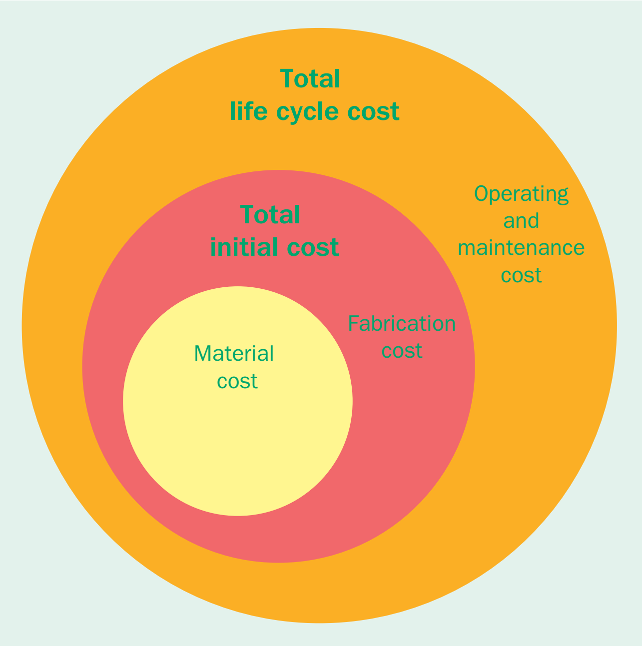


Figure 9:18. Total life cycle cost.

Legislations, standards and approvals

For some stainless steel equipment and applications, such as pressure vessels, there are legislations, design codes, standards and approvals that must be followed to ensure that necessary structural integrity and safety is provided. This can affect the material selection so the first step is to check that targeted material is included in relevant standard. Table 9:3 shows some of these standards.

Common design codes for stainless steel

Table 9:3

Standard	Concerns
Storage tanks	
EN 14015	Vertical, cylindrical, above ground, welded, steel tanks for the storage of liquids
API 650	Welded steel tanks for oil storage - Supplementery rules for austenitic and duplex stainless steels in Appendix S and X respectively
Pressure vessels	
EN 13445	Unfired pressure vessels
EN 13458-2C	Cryogenic vessels. Annex C Pressure strengthening of vessels from austenitic stainless steel
ASME VIII-1	Boiler and Pressure Vessel Code
ASME VIII-2	Boiler and Pressure Vessel Code
Industrial piping	
EN 13480	Metallic industrial piping
ASME B31.1	Process piping
Transportable tanks	
ADR	International carriage of dangerous goods by road (Accord européen... Dangereuses par Route)
RID	International carriage of dangerous goods by rail (Règlement... International... Dangereuses)
IMDG	International Maritime Dangerous Goods code
UN ST/SG/AC.10/1	Recommendations on the transport of dangerous goods (United Nations)
Steel structures	
EN 1993-1-4	Eurocode 3: Design of steel structures – Supplementary rules for stainless steel
DIBt Z-30.3-6	Allgemeine bauaufsichtliche Zulassung (German code)
AS/NZS 4673	Cold formed stainless steel structures (Australia and New Zealand code)
AEI/ASCE 8-02	Cold formed stainless steel structural members (US standard)

Previous experience

Previous experience of a certain stainless steel grade, negative or positive, is valuable information when making material selection. If a certain grade has failed, information of type of corrosion attack or other failure mechanisms, may give a hint of what grade(s) could perform better. Alternatively, if a certain grade performs very well, this may point to the possibility of using more cost-efficient alternatives.

Application examples

Taking into account the properties of the available stainless steel grades, Table 9:4 shows a rough overview of the different stainless steel types and their main application areas. There are of course application areas where other types of grades are also used even if they are not indicated as “frequently used” or “used in specific applications”.

References

Outokumpu Corrosion Handbook

Outokumpu Welding Handbook

Outokumpu data sheets

Segment and application brochures

www.outokumpu.com

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IMOA (www.imoa.info/)

ISSF (www.worldstainless.org)

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EN 14015, “Vertical, cylindrical, above ground, welded, steel tanks for the storage of liquids”.

API 650, “Welded steel tanks for oil storage - Supplementery rules for austenitic and duplex stainless steels in Appendix S and X respectively”.

EN 13445, “Unfired pressure vessels”.

EN 13458-2C, “Cryogenic vessels. Annex C Pressure strengthening of vessels from austenitic stainless Steel”.

ASME VIII-1, “Boiler and Pressure Vessel Code”.

ASME VIII-2, “Boiler and Pressure Vessel Code”.

EN 13480, “Metallic industrial piping”.

ASME B31.1, “Process piping”.

ADR, “International carriage of dangerous goods by road (Accord européen… Dangereuses par Route)”.

RID, “International carriage of dangerous goods by rail (Règlement… International… Dangereuses)”.

IMDG, “International Maritime Dangerous Goods code”.

UN ST/SG/AC.10/1, “Recommendations on the transport of dangerous goods (United Nations)”.

EN 1993-1-4, “Eurocode 3: Design of steel structures – Supplementary rules for stainless steel”.

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AS/NZS 4673, “Cold formed stainless steel structures (Australia and New Zealand code)”.

AEI/ASCE 8-02, “Cold formed stainless steel structural members (US standard)”.

Schematic overview of the different stainless steel types and some main application areas

Table 9:4

Steel type		Automotive exhaust systems	Automotive safety/structural components	Railway carriages	Freight trucks, container frames	Railroad and road tanks	Chemical tanker tanks	LNG tanks, cryogenic	Water heaters	Desalination	Waste water treatment	Kitchen utensiles, tableware, cutlery	Catering & appliances	Food processing	Chemical/petrochemical	Oil & Gas	Pulp & Paper	Power & heating	Incineration	Flue gas cleaning	Hydrometallurgy	Architecture wall panels	Bridges	Cement industry	Furnaces & fluidised beds	Large storage tanks	Plate heat exchangers	Biogas	Reinforcement bar	Pressplates for laminates & boards
Ferritic	Cr	X	-	-	X	-	-	-	X	-	-	X	X	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
	HT grades	-	-	-	-	-	-	-	-	-	-	-	-	-	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Martensitic		-	-	-	-	-	-	-	-	-	-	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X
Duplex	Lean duplex	-	X	X	-	X	O	-	X	X	X	-	-	X	X	X	X	-	-	-	X	-	X	-	-	X	-	-	X	-
	Duplex	-	X	-	-	-	X	-	X	X	X	-	-	X	X	X	X	-	-	X	X	-	X	-	-	X	-	-	X	-
	Superduplex	-	-	-	-	-	-	-	-	X	X	-	-	X	X	X	X	-	-	X	X	-	-	-	-	X	-	-	-	-
Austenitic	Cr-Mn	-	X	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-	O	-	-	-	-	-	-	-	-
	Cr-Ni	X	X	X	-	X	-	X	-	-	X	X	X	O	O	X	X	-	-	-	X	X	-	-	-	-	X	-	X	-
	Cr-Ni-Mo	-	-	-	-	X	X	X	-	-	X	-	X	X	X	X	X	-	-	-	X	X	X	-	-	X	X	X	X	-
	High performance	-	-	-	-	O	-	-	-	X	X	-	-	X	X	X	X	-	-	X	X	-	-	-	-	X	X	-	-	-
	HT grades	X	-	-	-	-	-	-	-	-	-	-	-	O	O	-	O	X	X	-	-	-	-	X	X	-	O	-	-	-

X = frequently used, depending on service conditions   O = used in specific applications   - = limited or no use/not relevant

Fabrication

Production of stainless steel equipment involves several different fabrication steps, cutting, forming, welding and machining. In this chapter some fabrication techniques are explained and discussed in relation to various types of stainless steels.

Welding

Welding methods can be divided into fusion welding methods, where the two edges or surfaces that are to be joined are heated and joined with or without a filler material, and pressure welding methods where two clean surfaces are brought into close contact to form a metallic bond between the two surfaces. The fusion welding methods are Manual Metal Arc (MMA), Metal Inert Gas (MIG), Metal Active Gas (MAG), Flux Cored Arc Welding (FCAW), Tungsten Inert Gas (TIG), Plasma Arc Welding (PAW), Submerged Arc Welding (SAW), Laser Beam Welding (LBW) and Laser hybrid welding. Pressure welding methods include Resistance Spot Welding, Seam Welding and High Frequency Welding. The microstructure in stainless steel welds is to a large extent dependent of the chemical composition. Constitutional diagrams such as the Shaeffler-De Long diagram (Figure 2:10 in chapter 2) can be used as a rough predictor of weld microstructure but the thermal history, particularly the cooling rate after welding, also has a major influence.

It is important to realise that weld microstructure is not to be seen as a material property. Technological properties such as mechanical strength, ductility/formability and corrosion resistance in different environments are instead the factors that should be taken into consideration for a fabricated welded construction. Other important aspects for a fabricator are productivity and the risk of unexpected defects/imperfections when welding new steels/product forms. For this reason, a welding procedure qualification should always be performed before a new material or process is introduced. In this way unexpected deviations can be identified and avoided in the final product. More information about welding of stainless steels can be found in the Outokumpu Welding Handbook.

Ferritic stainless steels

The main limitation of ferritic weldments compared to their austenitic counterparts is the lack of toughness in thicker sections. Sheet

Figure 10:1. Ferritic weldment. Weld metal right and HAZ left.

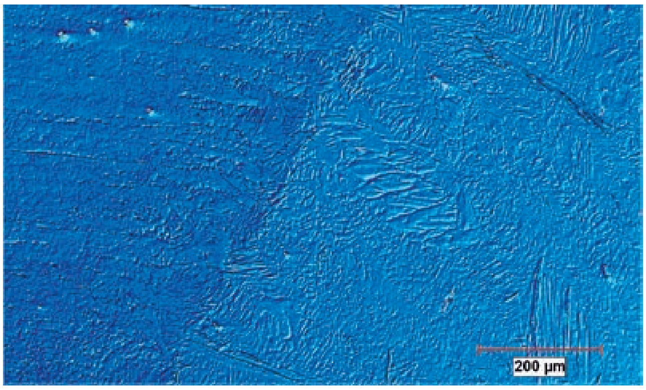

Figure 10:2. Martensitic weldment. Weld metal right and HAZ left.

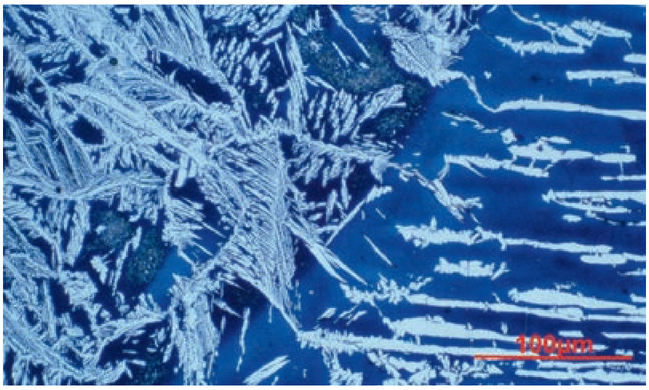

Figure 10:3. Duplex weldment. Weld metal left and HAZ right.

materials are typically used to ensure sufficient weldment toughness and ductility.

Weldment properties are strongly affected by welding parameters. Ferritic grades are preferred to be welded using minimum heat input to prevent excess grain growth in the HAZ. Moist electrodes and shielding gases that contain hydrogen or nitrogen should be avoided. Due to lower thermal expansion and higher thermal conductivity, distortion and buckling is lower during welding compared to austenitic or duplex stainless steel. Figure 10:1 shows an example of the microstructure in a ferritic weld.

Martensitic stainless steels

Being hardenable, martensitic stainless steels are more difficult to weld than the other types of stainless steel. Regardless of prior condition, welding produces a hard martensitic zone adjacent to the weld that is prone to cracking. The hardness increases with the carbon content in the steel and adds to the complexity in welding. The presence of hydrogen increases the risk of hydrogen-induced cold cracking.

Nevertheless, martensitic steels can be successfully welded provided the right precautions are taken to avoid cracking in the HAZ. Preheat and post-weld heat treatments (PWHT) are normally required to obtain reliable weldments. To get full strength of the welded joint, matching fillers should be used. If PWHT is not possible, austenitic or duplex fillers can be used for improved ductility.

Figure 10:2 shows an example of the microstructure in a martensitic weld.

Duplex stainless steels

The weldability and welding characteristics of duplex stainless steels are better than those of ferritic stainless steels, but generally not as good as those of austenitic steels. Modern duplex steels with significant nitrogen contents are readily weldable.

Weldment properties are strongly affected by welding parameters such as the heat input range, so appropriate procedures should be followed to obtain a correct weldment structure. Duplex stainless steels commonly solidify with a fully ferritic structure with austenite nucleation and growth during cooling. Filler metals are specially designed with higher nickel contents to produce a phase balance similar to that of the base material. Autogenous welding (without filler) is generally not recommended for duplex steels. The duplex microstructure is more sensitive to the effect of subsequent passes compared to e.g. standard austenitic grades. To reduce this effect on microstructure from previous passes, the interpass temperature should be maximized to 150 °C for standard/lean duplex and 100 °C for superduplex steels. Figure 10:3 shows an example of the microstructure in a duplex weld.

Austenitic stainless steels

Austenitic stainless steels have in general excellent weldability. The final weld metal structure normally contains a few per cent delta ferrite, which is a sign of a sound weld. The level of heat input for most common austenitic grades could be up to about 2.5 kJ/mm. If the welding is carried out on stabilized or fully austenitic grades, somewhat lower levels may be needed to avoid solidification cracks (≤1.5 kJ/mm). Austenitic steels have about 50% higher thermal expansion compared to ferritic and duplex steels. This means that larger deformation and higher shrinkage stresses may be a result from welding.

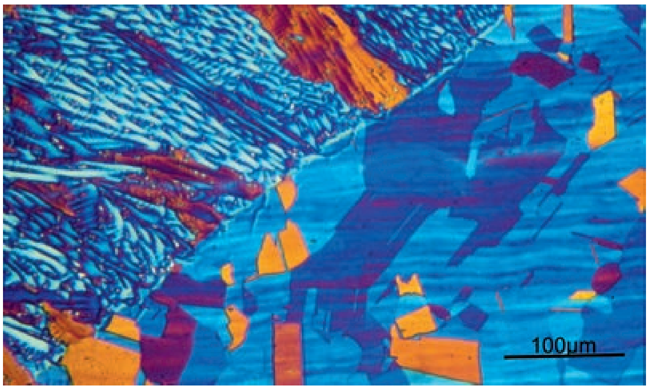

Figure 10:4. Austenitic weldment. Weld metal left and HAZ right.

For high alloy austenitic grades, pitting corrosion resistance can be reduced due to microsegregation, primarily of molybdenum, during solidification. Filler metals are thus, in most cases, overalloyed with chromium, nickel and molybdenum to enhance the corrosion resistance. For the highest alloyed austenitic grades Ni-base fillers are used.

The manganese-alloyed austenitic grades, Cr-Mn steels, offer the user relatively high strength to a moderate cost. These steels show lower weldability than the standard Cr-Ni grades mainly as they are more susceptible to hot cracking, i.e. cracks in the weld formed during solidification.

For some applications metastable austenitic steels are used in the cold-rolled condition in which they are temper rolled to very high strength levels. Welding will naturally have a softening effect in the weld zone and this fact should be taken into consideration at the design stage. Figure 10:4 shows an example of the microstructure in an austenitic weld.

Cutting

Cutting of stainless steel can involve shearing, punching, sawing and thermal cutting techniques like plasma or laser cutting. A general difference between cutting mild carbon steel and stainless steel is the need for higher cutting forces, but the same methods that are used for cutting carbon steel can be applied for cutting stainless steel. Ferritic stainless steels behave in cutting like carbon steels with similar strength level. To minimize burr height in punching and shearing the clearance, i.e. the distance between the punch and the die, should be kept below 10 % for austenitic stainless steel grades, while a somewhat larger clearance can be accepted for duplex. The major issue when shearing, punching and sawing is tool wear or chipping of the tool since this has a large impact on the quality of the edge. The amount of burr should be kept as small as possible and parameters that can have an influence are clearance, tool wear, cutting forces and cutting speed. For thermal cutting, parameters like shielding gas and energy input can have an effect on the amount of burr that is formed.

Machining

Machining processes include milling, turning, drilling and threading. Stainless steels are generally more challenging to machine than standard carbon steel and a general rule is that the higher alloying

Figure 10:5. Open die/close die bending.

Figure 10:6. Roll bending.

content the more difficult to machine. The ferritic grades are generally easier to machine compared to the standard austenitic grades.

Of the stainless steel grades, the free-machining grades are the most similar to carbon steel, as seen in Table 10:1. These grades have often increased amount of sulphur or selenium to facilitate chip breaking.

There are also machinability improved grades, still being within the specification of e.g. standard 4307 or 4404, where the machinability is enhanced by a special metallurgical treatment. These grades are within Outokumpu named as PRODEC® and have up to 40 % better machinability compared to standard grades.

Among the duplex grades LDX 2101® stands out as a duplex grade with good machinability and is in the same range as the machinability improved grades when using cemented carbide tools.

When machining stainless steels it is important to use tools and inserts that are designed for stainless steel and the tool supplier's recommendations should be followed in order to have optimal chip length and increased tool life. Outokumpu also provides starting recommendations for both High Speed Steel (HSS) tools and Cemented Carbide (CC) tools in the machining guidelines presented for a number of stainless steel grades.

Machinability index **Table 10:1**

Steel type		Machinability index
Carbon steel	Free-machining carbon manganese steel	1.0
Ferritic SS	Standard 1.4016 (430)	0.60
Martensitic SS	Free-machining 1.4005 (416)	0.95
	Standard 1.4006 (410)	0.50
Duplex SS	2205 (S32205)	0.50
Austenitic SS	Free-machining 1.4305 (303)	0.85
	Standard 1.4301 (304)	0.52

Ref. www.bssa.org.uk

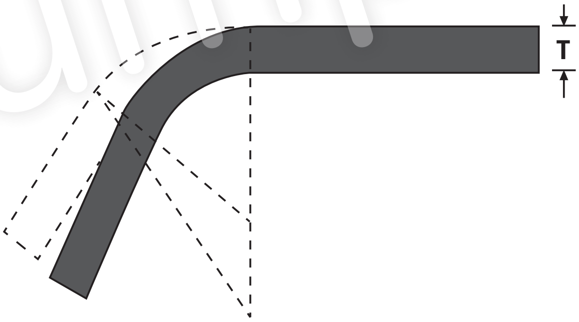

Figure 10:7. Springback.

Bending and roll bending

A bending operation can be an open die/closed die bending as illustrated in Figure 10:5, or a roll bending operation like in Figure 10:6. The major issue, especially for high strength steel is springback as shown in Figure 10:7. The amount of springback varies between different groups of steel and a change of grade and/or sheet thickness in roll bending often requires machine adjustments in order to achieve the right shape. In open die/closed die bending, the strategy is instead to over-bend the part. The formability in this type of bending is represented by the minimum allowed inner radius in the bend divided by the sheet thickness ratio. For austenitic and ferritic stainless steel this ratio is 1, while for duplex grades it is 2.

Spinning

The spinning method is used for cylindrical and symmetrical components. The method is particularly suited for production of relatively thin walled components and it is possible to obtain advanced shapes and sharp corners. Thinning of the sheet is possible and the method can be used on all stainless steel grades, but it is important to keep in mind that higher forces are needed for duplex grades. Machine power can be an issue for high strength material. Figure 10:8 shows a CNC-controlled spinning machine.

Roll forming

Roll forming is a method where a sheet passes through a series of roll stands that gradually shape the sheet into a profile or profile-shaped component. No thickness reduction is made during the forming. The method is suitable for all stainless steel grades, especially for high strength stainless steels like duplex or temper rolled austenitics. However, higher forces are required and the tendency to springback is more significant for duplex and high strength grades. Figure 10:9 shows a selection of roll formed profiles.

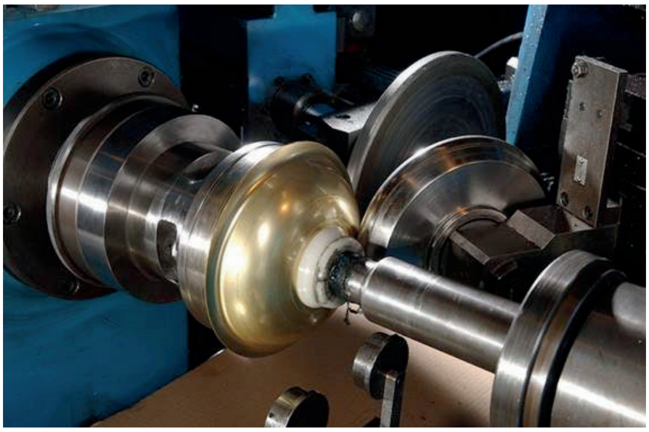

Figure 10:8. CNC-controlled spinning machine.
Courtesy of Hermanders AB, Töreboda, Sweden

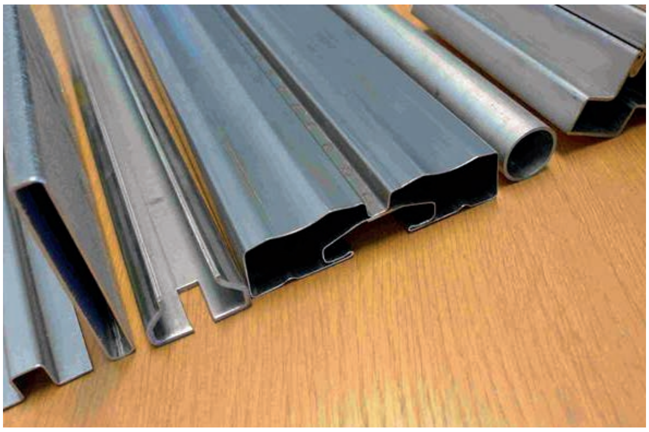

Figure 10:9. Roll formed profiles.

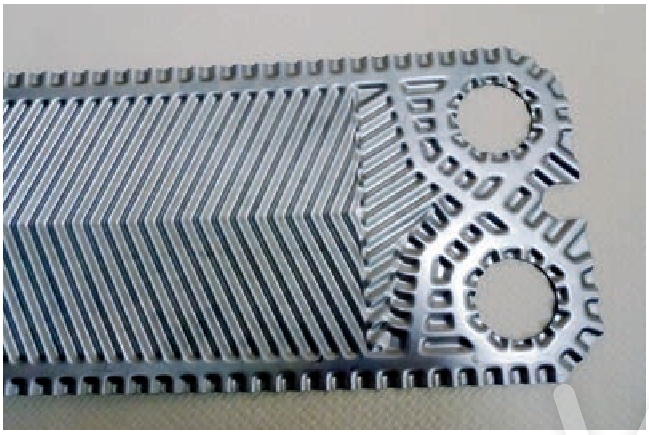

Figure 10:10. Heat exchanger plate.

Figure 10:11. Kitchen sink.

Press forming

The name press forming is a generic term for processes like deep drawing, stretch forming, ironing and hydroforming. The focus should be on choosing a robust forming process with safety margins for cracking and a shape accuracy within given tolerances. The tool surfaces and a correct lubrication are very important in deep drawing and stretch forming operations in order to obtain high surface quality of the formed parts.

The standard austenitic grades 4307 and 4404 have excellent formability compared to most other materials and they are well suited for applications where there is extensive thinning during forming, as in stretch forming operations. The higher alloyed austenitic grades like 904L, 254 SMO®, 4565 and 654 SMO® also have excellent formability in spite of the high alloying content, but 654 SMO® and 4565 have higher strength and requires higher press forces. Figure 10:10 shows a typical application where stretch forming is applied, a heat exchanger plate.

Ferritic steels have commonly better drawability properties in comparison to austenitic grades where the material is not subjected to thinning like in stretch forming. A phenomenon called ridging or roping may occur when deep drawing low alloyed ferritic grades but this can be avoided by using a Ti/Nb stabilized grade like 4509 or 4521. Ridging and roping will primarily lead to aesthetic rather than functional effects. Also austenitic grades are well suited for deep drawing if thinning is allowed. A good example of this is shown with the kitchen sink in Figure 10:11.

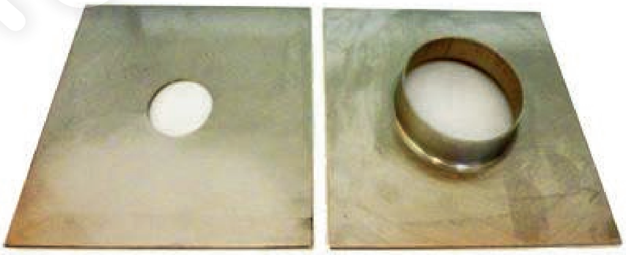

Figure 10:12. Stainless steel sheet before and after hole flanging.

The high strength of duplex grades can be a challenge and sets higher demands on machines, tools and lubrication performance. The higher springback might also be an issue for the shape accuracy. The remedy for these challenges is to utilize the strength and use thinner gauges.

Hole flanging

Hole flanging (Figure 10:12) is typically done to support tubular or rod connections and the flanges are sometimes threaded. The cut edges of the hole must be of good quality in order to avoid cracked edges and this sets high demands on tool performance, especially when punching holes. Burr should be positioned towards the tool during flanging to reduce the risk of edge cracking. Hole flanging should be avoided in areas where the component has been severely cold worked from previous forming operation since the formability in those areas may be more limited than in the less cold worked areas.

Grinding

Grinding involves metal removal in order to obtain a finer surface finish. A useful guideline when grinding stainless steel is that grinding with a very coarse grit (P 36) involves a risk of causing deep surface defects. Grit P60 or P80 is often a good starting point for many applications. Further grinding operation should take place in steps with a double value of the grit in each step, for example P80-P160-P320, until the desired surface finish has been reached.

Quality abrasives and tools suitable for the application should always be used and abrasives should always be changed before they are completely worn out. Worn out abrasives will smear the surface instead of removing metal. To avoid extraneous rust, the same tools used for carbon steels should not be used for stainless.

References

Outokumpu Welding Handbook.

Outokumpu Machining Handbook.

Outokumpu Machining Guidelines.

www.bssa.org.uk, article ”Influence of steel family (type) on machinability”.

Post fabrication treatment

For a variety of reasons some kind of treatment of stainless steels is often required after fabrication. The process environment or the application may demand a specific surface finish, a minimum of residual stresses, a desired microstructure or certain mechanical properties. To secure the corrosion properties of a stainless steel component, pickling of the welds and removal of weld spatter are often required. In applications where a high fatigue load is expected, annealing to relieve residual stresses might be necessary.

Most of the commonly encountered corrosion problems, in environments where the stainless steel grade normally performs well, can be traced to inadequate cleaning of the surface following fabrication. For best performance, it is essential to prevent or remove all fabrication-related defects.

A stainless steel surface should appear clean, smooth and faultless. This is obvious when the steel is used for such purposes as facades, Figure 11:1, or in applications with stringent hygienic requirements, but a smooth surface finish is also crucial to good corrosion resistance. Stainless steel is protected from corrosion by a thin, protective and invisible surface layer – the passive film - that consists mainly of chromium oxide. The oxygen content of the atmosphere or aerated aqueous solutions is normally sufficient to create and maintain this passive layer. However, surface defects and imperfections introduced during manufacturing operations may drastically disturb this self-healing process and reduce resistance to several types of local corrosion. This means that a final cleaning process will often be required to restore an acceptable surface quality with regards to hygiene and corrosion.

The extent and methods of treatment after manufacturing will be determined by the corrosivity of the environment, the inherent corrosion resistance of the steel grade, hygienic requirements and/or aesthetic considerations. Consideration must also be taken to local environmental regulations. Both chemical and mechanical cleaning methods are available. In some applications a heat treatment is carried out before the final cleaning in order to obtain the correct properties.

If for any reason cleaning and finishing are impossible to perform, there is usually a need for a more corrosion resistant grade than the environment itself would require in order to ensure that all parts in the structure actually obtain the required properties. However, a better approach is to use a fabrication process which minimizes the need for subsequent treatment. Good design, plan-

Figure 11:1. Stockholm Waterfront Building, Stockholm, Sweden. Façade made of z-profiles in duplex stainless steel grade 2205.

ning and methods of manufacture can reduce the need for finishing work, and thus costs, significantly.

Typical surface defects

Heat tint and oxide scale

High temperature oxidation, caused by processes such as annealing or welding, produces a thicker oxide layer with inferior protective properties compared with those of the original passive layer, Figure 11:2. It is therefore necessary to remove this layer and any underlying chromium depleted layer, in order to completely restore the corrosion resistance of the stainless steel.

Weld defects

Incomplete penetration, undercut, lack of fusion (Figure 11:3), pores, slag inclusions, weld spatter and arc strikes are typical examples of weld defects. These defects have negative impact on mechanical properties and resistance to local corrosion, and also make it difficult to maintain a clean surface. These defects must therefore be removed, normally by grinding, although sometimes repair welding is also necessary.

Iron contamination

Iron contamination is possible whenever stainless steel comes in contact with carbon steel. It is a common concern because almost all fabrication shops use carbon steel tools and fixtures that may transfer iron to the stainless steel, Figure 11:4. Iron contamination will corrode and form rust stains on the stainless steel surface in moist environments. The iron rust can also initiate corrosion of the stainless steel in borderline cases.

Rough surface

Uneven weld beads and grinding or sand blasting too heavily will result in rough surfaces. A rough surface collects deposits more easily, thereby increasing the risk for both corrosion and product contamination. Heavy grinding can also introduce tensile stresses, which increase the risk of stress corrosion cracking and pitting corrosion. There is a maximum allowed surface roughness (Ra value) for many applications, and manufacturing methods that result in rough surfaces should generally be avoided.

Organic contamination

Organic contaminants in the form of grease, oil, paint, footprints, glue residues and dirt can cause crevice corrosion in aggressive environments, render pickling ineffective, and pollute products handled in the equipment. Organic contaminants should be removed using a suitable chlorine/chloride-free pre-cleaning/degreasing agent. In less severe cases, a high pressure water jet can be used.

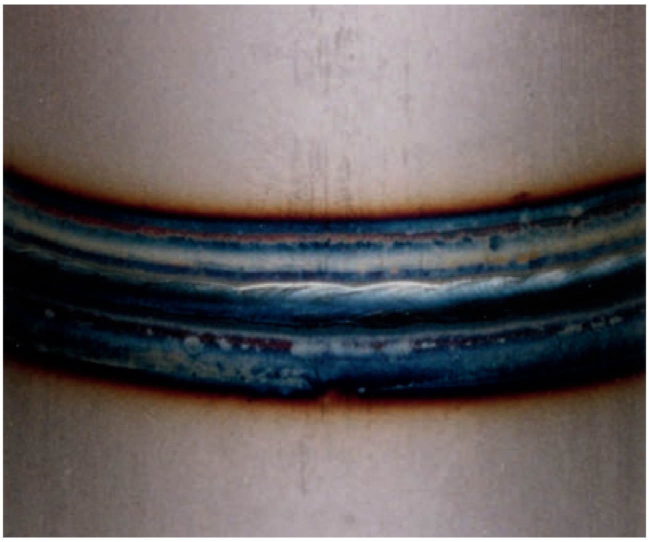

Figure 11:2. Weld with remaining weld oxide.

Figure 11:3. Lack of fusion in welds can cause corrosion attack.

Figure 11:4. Staining caused by iron contamination from mild steel brushing.

Cleaning procedures

Different chemical and mechanical methods, and sometimes a combination of both, can be used to remove different types of contamination. Generally, cleaning based on chemical methods can be expected to produce superior results, since most effective mechanical methods tend to produce a rougher surface, whilst chemical cleaning methods reduce the risk of surface contamination, Figures 11:5 and 11:6. However, local regulations regarding environmental and industrial safety as well as waste disposal problems may limit their applications.

Grinding and polishing

Coarse grit grinding removes deep defects like weld undercut and deep scratches. The grinding wheel or belt must be new or previously used only on stainless steel. Grinding should not heat the surface to such high temperatures that a yellow oxide layer forms. Coarse grinding should be followed by grinding with successively finer grit. If surface requirements are very exacting, polishing may be necessary as a final step.

Sand blasting

Sand and grit blasting can be used to remove high temperature oxides as well as iron contamination. However, care must be taken to ensure that the sand (preferably of olivine type) or grit is perfectly clean and not previously used for carbon steel. Sand blasting can easily embed contaminants like dirt or iron particles that can cause rust discolorations on the stainless steel.

Shot peening

Shot peening may remove oxide, but is primary used to give compressive surface stresses.

Brushing

For the removal of superficial heat tint, surface contamination and dirt, brushing using stainless steel or nylon brushes often provides a satisfactory result. These methods do not cause any serious roughening of the surface, but do not remove any chromium depleted layer beneath the oxide. They may leave a residual surface oxide which is not visible to the naked eye but can nevertheless impair corrosion resistance.

Degreasing

Organic contaminants like cutting oils, drawing lubricants, or crayon marks prevent the stainless steel surface from being wetted during chemical cleaning with acids. These contaminants must be removed with a non-chlorinated solvent prior to final use or before any chemical cleaning treatment.

Acid pickling

Pickling creates the most corrosion-resistant surface of all cleaning methods. It uses strong acids that remove oxide scale and the underlying chromium depleted layer. Pickling normally involves using an acid mixture containing nitric acid and hydrofluoric acid. These acid mixtures are hazardous and must therefore be handled with due care and disposed of correctly. Chloride-containing agents such as hydrochloric acid (HCl) must be avoided, since there is an obvious risk of pitting corrosion. Since pickling dissolves the stainless steel surface, it must be carefully controlled. It produces clean surfaces with a dull grey, matte finish that passivate spontaneously.

Pickling can be performed by immersing the stainless part in a bath or by spraying solution on the part while passing it through a spray box. Proprietary pickling products can also be applied locally in spray, gel or paste forms.

Passivation

Chemical passivation is rarely needed for improved corrosion resistance and is not required if the stainless steel has been properly pickled, resulting in a clean stainless steel surface. On the other hand, passivation is an effective way to ensure cleaning of stainless steel that has not been pickled to remove contaminants such as shop dirt or particles of iron from different fabrication operations, which otherwise could form rust or act as initiation sites for corrosion. Several passivation treatments may be used as described in ASTM A380 and ASTM A967. The choice of surface treatment for a certain application is often based on tradition rather than on insight. Although there are many passivation options available, the overwhelming choice is still nitric acid based solutions.

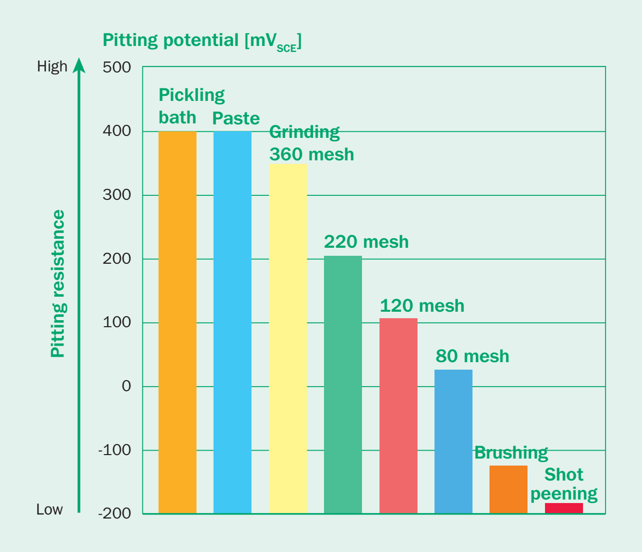

Figure 11:5. Effect of cleaning methods on corrosion resistance (pitting potential).

Figure 11:6. Appearance of different cleaning methods.

Figure 11:7. Solution annealing.

Electropolishing

Electropolishing is an electrochemical process that removes embedded iron, heat tint, and non-metallic inclusions. It smoothes the surface and leaves a shiny appearance. It is often used in appli-

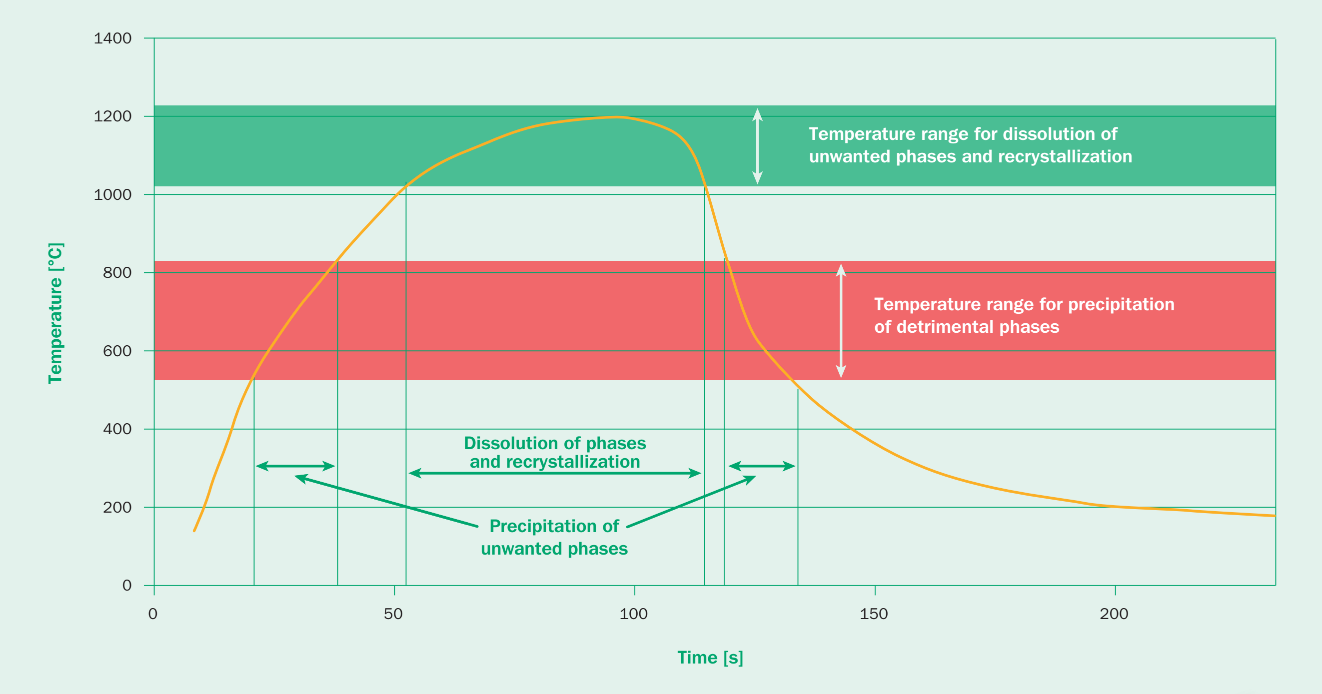

Figure 11:8. Example of a solution annealing cycle. The critical temperature ranges are strongly dependent on the steel grade.

cations where extreme cleanliness is important, for example in the pharmaceutical, semiconductor and dairy industries.

Heat treatment

Heat treatment is not without risk, as the material properties can easily deteriorate if it is done in an incorrect and uncontrolled way. The wrong combination of temperature/time/cooling rate can cause precipitation of detrimental phases, such as carbides, nitrides and sigma-phase. These may impair the mechanical properties, impact toughness and the corrosion resistance. In most cases, it is therefore usually safer to completely avoid heat treatment, but there are certain situations when it is justified.

The need of heat treatment is often driven by code or application requirements. The main reasons are restoration of microstructure to improve properties, relaxation of residual stresses to reduce risks of fatigue and stress corrosion cracking and improvement of dimensional stability.

Solution annealing

Solution annealing, Figures 11:7 and 11:8, softens material after cold working and dissolves secondary phases that can precipitate during hot working or welding. The term “full anneal” often means that the material is in its optimum metallurgical condition, with secondary phases completely dissolved and homogenized. This condition produces the best corrosion resistance and ductility. Because it is conducted at high temperatures, annealing in air produces a surface oxide scale that must be removed by descaling and pickling to restore the surface corrosion resistance.

The temperature is normally between 750 to 1200 °C depending on steel grade and the purpose of the annealing. Further details are given in the chapter 3, Physical metallurgy. The cooling should normally be as fast as possible; air cooling is normally fast enough but water quenching can be necessary for certain grades. Recommended solution annealing temperatures and cooling practice for individual grades are given in Outokumpu data sheets.

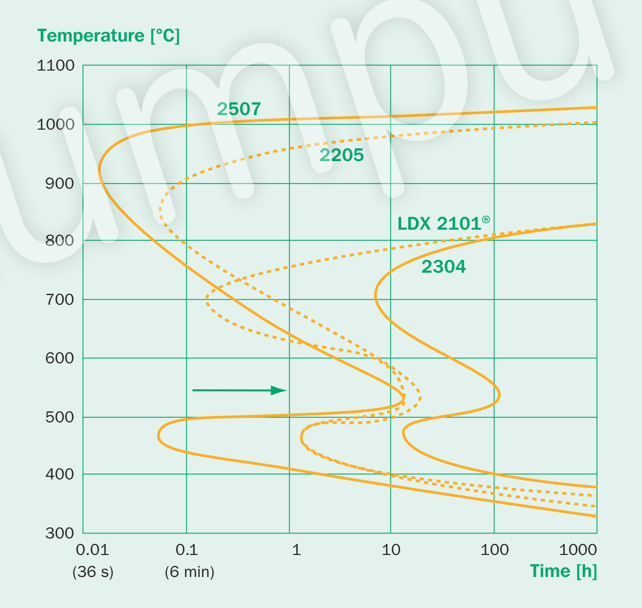

Figure 11:9. TTT (Time Temperature Transition) curves showing the narrow temperature range in which it is possible to carry out stress relieving of duplex stainless steel grades.

Stress relieving

Stress relief treatments reduce residual stresses that may develop during forming and welding, and lower the risk of distortion or stress corrosion cracking. Stress relief is performed at temperatures below those used for solution annealing, and may not always require the descaling and pickling needed after full annealing. There are several procedures (temperature/time intervals) to perform stress relieving, each with its pros and cons.

When selecting heat treatment, the steel grade’s susceptibility to precipitation of detrimental phases has to be considered, Figure

11:9. Furthermore, the shape of the work piece has to be taken into account, as large differences in thicknesses can give rise to new residual stresses during rapid cooling from high temperatures.

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Practical Guidelines for the Fabrication of High Performance Austenitic Stainless Steels, IMOA.

Erection and Installation of Stainless Steel Components, Euro Inox, 2006.

Fabrication and metallurgical experience in stainless steel process vessels exposed to corrosive aqueous environments, NIDI Technical Series No. 10026.

ASTM A380, “Standard Practice for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems”.

ASTM A967, “Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts”.

Handling and storage of stainless steel

Stainless steel products should be handled and stored in such a way that they are not damaged. The level of the demands depends both on the product and the intended future use. If the material is to undergo a fabrication sequence that includes both heat treatment and pickling, slight surface damage may be tolerated. On the other hand, if the stainless steel product will be directly installed, the demands of storage and handling are much more stringent.

A high standard of cleanliness, good order, and common sense regarding how various operations impact on the material, is usually enough to achieve appropriate handling conditions.

A clean, smooth and white surface provides the best corrosion resistance

As it is the surface which gives the material its corrosion resistance, one must always remember to protect the stainless steel surface. This includes taking care to avoid any mechanical damage. Scratches or other damage introduced in the fabrication shops are a common cause of passive film deterioration.

All kind of contamination should be avoided. Different types of contamination have different effects on the stainless steel. Carbon steel particles give rise to rust stain, Figures 12:1 and 12:2, paint, grease and oil can give rise to intergranular attack after welding or a heat treatment operation. Low melting metals such as copper, zinc, lead, aluminium and brass can give rise to cracks in weld or heat treated areas, so-called LME (Liquid Metal Embrittlement). The easiest way to avoid contamination is to keep stainless steel products separated from carbon steel and other metals.

Figure 12:1. Staining caused by a pair of tongs left on a stainless steel plate.

Figure 12:2. Staining caused by iron contamination from truck forks.

Store stainless steel indoors if possible

Storing indoors helps to protect the steel from external pollution. If indoor storage is not possible, the stainless steel should be covered. This is especially important if a wrapping which might absorb water and stain the surface, such as cardboard, has been used.

Use the packaging

The packaging should not be broken unnecessarily, it usually provides a good protection. It is often possible to save a lot of trouble and expense by taking advantage of the packaging, especially if the stainless steel surface is susceptible to damage e.g. a polished or ground surface.

The use of strippable plastic film coatings on the stainless steels can help to avoid surface contamination. If the stainless steel has a protective film cover, it should be left on as long as practically possible and removed just before handover. Special packaging measures may be needed for protecting stainless steel components in transit in order to protect the surface. For example, care is needed when components are being secured to pallets or vehicles for transport to avoid damage to surfaces from straps or strapping. Suitable protective materials, such as wood, should be placed between the stainless steel and the securing straps. If carbon steel strapping is to be used to secure items to pallets or in bundles, some form of wrapping or padding is required to prevent the strapping from damaging the edges or surface of the stainless steel components.

Figure 12:3. Example of careless loading. The bottom plates have lost their flatness.

Figure 12:4. Flat storage in wooden boxes.

Store flat or in racks

To maintain flatness and avoid permanent deformation, sheet should be stored in wooden boxes and should be covered to prevent airborne contamination, Figure 12:3 and 12:4. Plate should be stored vertically on racks in a covered dry location, to minimise contamination and avoid the possibility of footprints. Racks of carbon steel should be protected by wooden, rubber or plastic battens or sheaths to avoid carbon steel contamination of the stainless steel.

Extra precautions for pipes

The rules for storage of tubes and pipes are the same as for storage of sheet and plate but one should remember that it is much more difficult to clean the inside of a pipe than an open plate or sheet surface. Extra precautions are therefore needed to avoid inside contamination, especially for thin pipes with small diameter. One effective way to protect the pipe inside is to use end-plugs.

Maintenance of stainless steel

Cleaning/Restoration

Stainless steel does not remain stainless in all circumstances. Stainless steel products need to be cleaned to maintain a pristine appearance and preserve corrosion resistance. Stainless steel will not corrode under normal atmospheric conditions provided the correct grade has been selected and appropriate fabrication procedures and post treatment are followed. However, lack of cleaning can lead to accumulation of corrosive substances that surpass the corrosion resistance of the stainless steel grade selected. This may lead to staining and, in more severe cases, initiation of corrosion.

Advice is often sought concerning the frequency of cleaning of products made of stainless steel, and the answer is quite simple; clean the stainless steel surface when it is dirty in order to restore its original appearance. This may vary from one to four times per year for external applications or it may be once a day for an item in hygienic or aggressive applications.

Corrosion

Usually, discolorations is the first indication of incipient corrosion. In this case, it is no longer sufficient to remove visible stains by means of usual cleaners. In the tiny pits, which may hardly be perceptible to the unaided eye, corrosive media or corrosion products may be trapped, which will cause new stains to form. In such cases, it is advisable to use a cleaning agent which has a pickling and/or passivating effect. These kind of cleaning agents are often very aggressive and consequently health, safety and environmental precautions have to be taken. If the corrosion attack is more severe with deep pits or cracks, grinding and weld repair might be needed.

Weld repair

Repair welding may be necessary for filling pits or other defects which are too deep to just remove by grinding. Repair welding deserves as much or even more attention than the original structural welds.

Figure 13:1. Chrysler building in New York erected 1930. During the years, it has only been cleaned twice, with considerable surface deposits accumulation between the cleanings. During its second cleaning in 1995 a few panels near heating exhausts showed some pitting and had to be replaced otherwise in perfect condition.

All types of contamination have to be removed from the surface prior to weld repair. This can be done either by grinding to clean metal appears, or chemically with an appropriate cleaning agent. Cracks must be totally gouged out or removed and weld repairs can be carried out from both sides, if access is possible. Deep pits or localized corrosion can be welded with filler to restore the original thickness. If there is a larger area, which cannot be welded by build-up, it might be replaced with patch.

However, there is a clear risk that new stresses are introduced during weld repair, with subsequent failure as a consequence. Extra precautions are needed for stainless steel grades which are susceptible to form precipitates due to the heating cycle. A high heat input or too low cooling rate can result in degradation of both HAZ and weld deposit, so only one re-weld operation is advisable, even that with extreme care and control. The general recommendation for the most vulnerable materials is that any form of re-welding should preferably be avoided.

Sustainable stainless

Sustainability is about much more than just the environment. It takes into consideration the impact on environment, society, and economy (planet - people - profit).

Environment (Planet)

Stainless steel is the most recycled material in the world and 82% of the stainless steel in use is estimated to be recycled into new steel. When recycled, the stainless steel is not downgraded; the remelted recycled steel has just as good quality and properties as the original steel. Due to the attractiveness and high value of stainless steel scrap no subsidies are needed to uphold a working scrap market.

In principle, stainless steel can be recycled an infinite number of times. However, the 6 % annual increase in stainless steel production together with the durability of stainless steel products means that there is a scarcity of stainless steel scrap. This in turn means that although today's production is based mainly on recycled steel, virgin material in the form of alloying elements is still needed. Today approximately 60 % of the raw material used to make new stainless steel is recycled steel and for Outokumpu the recycled steel content is between 85 and 90 %.

Steel making, especially for alloyed steel, is undisputedly very energy consuming. However, the stainless steel industry has worked systematically on energy efficiency for many years and Outokumpu has decreased its direct CO_2 emission per ton of produced steel by 20 % the last 10 years. Also, since remelting scrap is more energy efficient than making steel out of virgin raw materials, the scrap input ratio of 60 % worldwide means a 33 % reduction of CO_2 emissions compared to producing the same amount of steel from virgin raw materials. This corresponds to more than 42 M tons of CO_2 annually.

The inert nature of stainless steel products offers many advantages during use. From an environmental point of view the passive layer that prevents metals release from the surface is of special interest. It means that stainless steel can be used in applications like roofing and water piping without risking metal leaching and contaminating the environment, e.g. the ground water.

Society (People)

Stainless steel has a long history of use in applications where cleanliness and high hygienic requirements are important, like medical equipment and food processing. Stainless steel does not affect the taste of food and drink and the surface is easy to clean and to disinfect. Stainless steel surfaces do not release metals or organic substances that could affect the indoor air quality in buildings negatively.

The reason behind the inert behaviour of stainless steel is the passive layer that also prevents the material from corroding. This means also that stainless steel does not behave like its alloying components. For example, nickel on its own can cause skin sensitization (allergy), while numerous tests have shown that nickel-containing stainless steel does not cause such allergic reactions.

The benefits to society by using stainless steel are numerous. Stainless steels have, for example, helped to make the process of desalination (i.e. producing potable water from seawater) economically viable. Thus many arid areas of the world can now enjoy the benefits that come from the availability of fresh water. Stainless steel is important for the development of new energy sources like solar power and the production of bioenergy, also for conventional energy sources e.g. in desulphurisation plants to reduce noxious emissions from fossil fuels.

Economy (Profit)

Choosing the right stainless steel grade for an application ensures that it will have low maintenance costs, a long life and be easily recycled at the end of that life. This makes stainless an economical choice in many applications from washing machines to process applications. The fire and corrosion resistance of stainless steel makes it a good choice in transportation, building or public works such as railways, subways, tunnels and bridges. These properties, together with stainless steels' mechanical behaviour, are of prime importance in these applications to ensure human beings are protected and maintenance costs are kept low.

High strength stainless steels provide extra benefits both in terms of economy and resource use, since less material can be used in constructions. High strength steels may absorb more energy in the case of collisions, which improves safety in vehicles and many other structural components and systems.

Stainless steel is durable which has a positive effect on the life cycle cost over the full lifetime.

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www.sustainablestainless.org

Stainless steel and CO_2. Facts and scientific observations (International Stainless Steel Forum)

www.outokumpu.com

Glossary

Below are explanations to some words used in this handbook and reference to in what chapter you can read more. (C4) = chapter 4.

1D surface finish
Surface finish designation according to EN 10088-2 of material that is hot rolled, heat treated, pickled, and free of scale. (C4, C5)

22Cr duplex
The duplex grade 2205 is sometimes referred to as 22Cr duplex as the chromium content is close to 22 %. (C2)

25Cr superduplex
The duplex grades 2507 and 4501 are sometimes referred to as 25Cr superduplex grades as the chromium content is close to 25 % in these grades. (C2)

2B surface finish
Surface finish designation according to EN 10088-2 and ASTM A480 of material that is cold rolled, heat treated, pickled and skin passed, where skin passing may be done by tension levelling. (C4, C5)

2BB surface finish
The Outokumpu designation of material that is cold rolled, heat treated, bright pickled and skin passed. (C5)

2D surface finish
Surface finish designation according to ASTM A480 of material that is cold rolled, heat treated pickled or descaled. (C4, C5)

2E surface finish
Surface finish designation according to EN 10088-2 of material that is cold rolled, heat treated and mechanically descaled. (C4, C5)

2H surface finish
Surface finish designation according to EN 10088-2 of cold rolled material that is work hardened to certain tensile levels. (C5)

2R surface finish
Surface finish designation according to EN 10088-2 of cold rolled material that is bright annealed, i.e. heat treated under inert gas atmosphere. (C4, C5)

6Mo superaustenitic
The austenitic grades 254 SMO® and 4529 are sometimes referred to as 6Mo superaustenitic grades as the Mo content is around 6 % in these grades. (C2)

7Mo superaustenitic
The austenitic grade 654 SMO® is sometimes referred to as 7Mo superaustenitic grade as the Mo content is around 7 %. (C2)

Activation
The changing of a passive surface of a metal to a chemically active state. (C6)

Active
(1) A state of a metal that is corroding without significant influence of reaction product. (C6)
(2) A lower or more negative electrode potential. (C6)

Anion
A negatively charged ion. An anion will migrate through the electrolyte toward the anode under the influence of a potential gradient. (C6)

Anisotropy, r-value
Determined as the ratio between thickness and width strain in the tensile test. (C7)

Annealing
Heat treatment that alters the microstructure of a material causing changes in properties such as strength, hardness, and ductility. (C5)

Anode
The electrode of an electrochemical cell at which oxidation occurs. (C6)

AOD
Argon Oxygen Decarburisation. A method to reduce the carbon content in the stainless steel melt. (C1, C4)

AP-line
Annealing and Pickling line. (C4)

Atmospheric corrosion
Corrosion of a metal by contact with substances present in the atmosphere, such as water, carbon dioxide, water vapor, and sulphur and chloride compounds. (C 6)

Austenite
One of the two major metallic phases in stainless steel, with a face-centred cubic structure. Austenite is promoted by higher levels of elements favoring austenite such as nickel and nitrogen. See also FCC. (C3)

Austenitic stainless steel
The austenitic grades are the largest group of stainless steels. They have good to excellent corrosion resistance, good formability and weldability. Their good impact strength at low temperatures is

often exploited in cryogenic applications. Cold working increases their strength. The austenitic microstructure makes the steel non-magnetic in the solution annealed condition. (C2)

Autogenous welding
Welding without adding filler metal. (C10)

BA surface finish
Surface finish designation according to ASTM A480 of material that is bright annealed, i.e. heat treated under inert gas atmosphere. (C4, C5)

BA-line
Bright Annealing line. Annealing line using hydrogen or hydrogen/nitrogen atmosphere to avoid oxidation during heat treatment. (C4)

Bar
Products supplied in straight lengths, never in coils, thus differentiating them from rod. Bars can be supplied in hot-rolled, and cold worked condition and have different geometries such as rounds, squares, hexagons and octagonal shape. (C5)

BCC
A Body-Centred Cubic structure, in which there is a central atom between the corner positions in the unit cell, Figure 3:6. (C3)

BCT
A Body-Centred Tetragonal structure with the same type of atomic positions as BCC but a unit cell in which only two of the lattice parameters are equal, Figure 3:6. (C3)

Billet
A semi-finished steel product with a square cross section up to 200 mm × 200 mm. (C5)

Blank
The starting sheet intended for forming. (C10)

Bloom
A cast semi-finished steel product with a smaller cross section than slabs, often rectangular, typically larger than 200 mm × 200 mm. (C5)

Bright annealing
Heat treatment of cold rolled stainless steel in an inert gas atmosphere often hydrogen or hydrogen/nitrogen which protects the steel from getting oxidised. (C4)

BWR
Nuclear Boiling Water Reactor. (C6)

C700
To write C700 is a way to describe that the material is work hardened (temper rolled) to a tensile strength of 700 MPa. (C5)

CAPL
Continuous Annealing and Pickling Line. (C4)

Carburization
A type of high temperature corrosion, in which the stainless steel reacts with e.g. CO or CO/CO$_2$ gas present in the environment. (C6)

Catastrophic 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 (Cr_2O_3) scale. For this reason molybdenum, which forms low-melting-point oxides and oxide-oxide eutectics, should be avoided in materials for service at temperatures above 750 °C. (C6)

Cathode
The electrode of an electrochemical cell at which reduction occurs. (C6)

Cathodic protection (CP)
A technique used to prevent the corrosion of metal by making it the cathode of an electrochemical cell. This can be achieved by connecting the metal to be protected to a less noble metal, i.e. a galvanic anode, which corrodes instead of the protected metal. Alternatively, imposed electrochemical polarization can be achieved by using an external DC power source. (C6)

Cation
A positively charged ion. A cation will migrate through the electrolyte toward the cathode under the influence of a potential gradient. (C6)

CCT
Critical Crevice corrosion Temperature. (C6)

Chi phase
A brittle intermetallic phase with a cubic structure. Chi phase occurs in the ternary Fe-Cr-Mo phase diagram. (C3)

Clearance
The distance between the punch and the die during e.g. punching. (C10)

Coil
Coil is a continuously hot or cold rolled sheet that is rolled to a ring shape (coil). (C5)

Cold rolling
Rolling of the stainless steel is done at room temperature. (C4)

Cold working
Cold working, also known as strain hardening or work hardening, is the strengthening of a metal by plastic deformation. (C5)

Corrosion
Corrosion is the gradual destruction of material by chemical reaction with its surrounding environment. (C6)

Corrosion fatigue
Fatigue under the combined action of mechanical loading and corrosive environment. (C6, C7)

Corrosion potential
The potential of a corroding surface in an electrolyte relative to a reference electrode under open-circuit conditions (also known as open-circuit potential). (C6)

Cottrell atmosphere
Cottrell atmosphere occur in body-centered cubic (BCC) materials and explains how dislocations are pinned in some metals by carbon or nitrogen interstitials. (C4)

CPP
Continuously Produced Plate. (C4, C5)

CPT
Critical Pitting corrosion Temperature. (C6)

Creep
The time dependent slow plastic deformation of metals under a constant stress. (C7)

Creep rupture strength, R_{km}
The stress level that leads to rupture after a specific time in the creep region. (C7)

Crevice corrosion
Localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the environment because of close proximity of the metal to the surface of another material. (C6)

Critical Crevice corrosion Temperature (CCT)
Lowest temperature at which stable propagating crevice corrosion occurs under specified test conditions. (C6)

Critical Pitting corrosion Temperature (CPT)
Lowest temperature at which stable propagating pitting corrosion occurs under specified test conditions. (C6)

Cr-steel
Ferritic stainless steels are sometimes referred to as Cr-steels due to the main alloying element chromium. (C2)

CTL-line
Cut-To-Length line. (C4)

CVC
Continual Varying Crown. (C4)

Delta ferrite
A non-magnetic form of ferrite, stable between 1403 °C and 1535 °C which is the melting temperature. (C10)

Density
The density of a stainless steel grade is its mass per unit volume, e.g. g/cm^3 or kg/dm^3. (C8)

Desulphurisation
Desulphurisation is a way to remove sulphur compounds from exhaust gasses that otherwise could form acidic compounds when released from the stack.

DFT
Density Functional Theory. DFT is a quantum mechanical method used to investigate the electronic structure of condensed phases by solving the Schrödinger equation. (C1)

DualDuplex™
A concept used in multi stage flash (MFS) chambers in desalination industry, where a higher alloyed duplex grade are used in the lower section and a lower alloyed duplex grade is used for the upper part where the environment is less aggressive. (C9)

Duplex stainless steel
A stainless steel with a ferritic-austenitic microstructure. The phase balance is approximately 50 % ferrite and 50 % austenite. The grades are magnetic due to the ferrite content. Due to their high strength, duplex grades can give cost effective solutions when thinner gauges can be used. Less material also gives more lightweight constructions. (C2)

EAF
Electric Arc Furnace. (C4)

Elastic modulus
The elastic modulus, or Young's modulus, is a measure of the stiffness of a stainless steel. (C7, C8)

Elastic/plastic deformation
In the elastic region an imposed strain is fully recovered upon unloading, while in the plastic region, only the elastic part of the strain is recovered. (C7)

Electric resistivity
The electrical resistivity quantifies how strong a stainless steel grade opposes the flow of electric current. (C8)

Electrolyte
A chemical substance containing free ions that makes it electrically conductive. (C6)

Engineering stress strain/true stress strain
The engineering stress strain curve is based on the original cross section area of the specimen, while the true stress strain curve compensates for the continuous decrease of the specimen cross section area during deformation. (C7)

Environmentally Assisted Cracking (EAC)
Brittle fracture of a normally ductile material in which the corrosive effect of the environment is a contributing factor. (C6)

Equiaxed microstructure
A structure in which the grains have approximately the same dimension in all directions. (C4)

Eutectic
Mixture of two or more compounds with a lower melting point than any of the compounds themselves. (C6)

Fatigue
The progressive and localized structural damage that occurs when a material is subjected to cyclic loading. (C7)

Fatigue life
The number of cycles to fracture in cyclic loading. (C7)

FCC
A Face-Centred Cubic structure in which there is an atom in the centre of face of the unit cell, Figure 3:6. (C3)

Ferrite
One of the two major metallic phases in stainless steel, with a body centred cubic structure. Ferrite is promoted by higher levels of elements favoring ferrite such as chromium and molybdenum. See also BCC. (C3)

Ferritic stainless steel
A stainless steel with a ferritic microstructure that makes the steel magnetic. These steels contain no or very small amounts of Ni which makes these steels more price stable compared to grades with high Ni content as Ni often demonstrates high price volatility. (C2)

Ferrochrome, FeCr
Important alloying element for stainless steel production. (C4)

Ferromagnetism
Ferromagnetism is the basic mechanism by which certain materials (such as stainless steels) form permanent magnets, or are attracted to magnets. (C8)

Free-machining grades
Grades with increased amount of sulphur or selenium to facilitate chip breaking. (C10)

Galvanic corrosion
Also denoted bimetallic corrosion or dissimilar metal corrosion. Refers to corrosion when two dissimilar materials with a conductive contact are connected in a corrosive electrolyte. (C6)

Hardness
A measure of how resistant a material is to a permanent shape change when a force is applied normal to the surface. (C7)

HAZ
Heat Affected Zone. The area around the weld bead that is unavoidably heated during welding. (C10, C13)

Heat capacity
The heat capacity specifies the amount of heat required to change the temperature of specific mass of stainless steel by a given amount. (C8)

Heat input
The amount of heat added when welding, expressed as KJ/mm. (C10)

HIC
Hydrogen Induced Cracking. (C10)

High temperature mechanical properties
The mechanical properties at temperatures above which creep is dominating. (C7)

HISC
Hydrogen Induced Stress Cracking. (C6)

Hot cracking
Cracks formed in the weld during solidification. (C10)

Hot rolling
Rolling of the stainless steel is done at a temperature above the recrystallization temperature of the material. (C4)

Hydrogen embrittlement
A loss of ductility of a metal resulting from absorption of hydrogen. Hydrogen penetrates into e.g. the grain boundaries and cause cracking. (C6, C10)

Hydrogen induced cracking, HIC
Hydrogen penetrates into e.g. the grain boundaries and cause cracking. (C10)

Hydrogen induced stress cracking, HISC
Cracking that results from the presence of hydrogen, eg. from cathodic protection, in a metal in combination with tensile stress. (C6)

Ingot
A semi-finished steel product obtained by casting the melt into fixed size moulds. (C5)

Intergranular corrosion
Preferential corrosion attack along the grain boundaries, or immediately adjacent to grain boundaries, while the bulk of the grains remain largely unaffected.(C6)

Interpass temperature
The recommended temperature of the material between the weld passes. Can be specified as a minimum or maximum temperature. (C10)

KTH
The Royal Institute of Technology, Stockholm, Sweden. (C1)

Laves phase
A brittle intermetallic phase with a hexagonal structure. It exists in the Fe-Mo phase diagram with a nominal composition Fe_2Mo, and also occurs in higher systems. (C3)

LCC
Life Cycle Cost. (C9)

Lean duplex
The duplex grades LDX 2101® and 2304 are sometimes referred to as lean duplex grades due to their “lean” chemical composition. (C2)

Life Cycle Cost, LCC
The life cycle cost is the total cost of an application during its entire life, including material cost, fabrication cost, operating and maintenance cost, including the value of the material when scrapped. (C9)

Liquidus
The temperature below which a solid phase starts to form from the melt. (C3)

LME
Liquid Metal Embrittlement. (C12)

LNG
Liquid Natural Gas. (C9)

Localized corrosion
Corrosion, such pitting and crevice corrosion, which results in attack at specific sites while other parts of the metal may remain totally unaffected. (C6)

Lüders band
Lüders bands, also known as “slip bands” or “stretcher-strain marks,” are localized bands of plastic deformation in metals experiencing tensile stresses, common to low-carbon steels and ferritic stainless steels. (C4, C5)

Martensite
A body-centred tetragonal metallic structure which can be formed from unstable austenite on quenching. See also BCT. (C3)

Martensitic stainless steel
A stainless steel with a martensitic microstructure that makes the steel magnetic and contributes to high strength. (C2)

Maximum strain to fracture, A_x
The fracture strain measured with initial measuring length x. (C7)

M_{d30}
The temperature at which 30 % deformation (strictly speaking a true strain of 0.3) causes the formation of 50 % martensite from an austenitic structure. (C3, C7)

Metal dusting
A special form of carburization, also called catastrophic carburization. (C 6)

Metal leaching
In this handbook metal leaching is defined as metal ions from the construction material leaching and contaminating the environment. (C14)

Microstructure
The microstructure of stainless steel is either ferritic, martensitic, ferritic-austenitic or austenitic. Ferritic grades have a body-centred cubic structure while martensitic grades have a body-centred tetragonal structure and austenitic grades have a face centred cubic structure. See also BCC, BCT and FCC. (C2)

Mixed acid
Pickling bath often containing a mixture of nitric acid (HNO_3) and hydrofluoric acid (HF). (C4)

Mother plate
The original plate from which several smaller plates are cut. (C4)

M_s
The temperature below which the transformation from austenite to martensite starts. (C3)

Nitridation
A type of high temperature corrosion, in which the stainless steel reacts with nitrogen compounds in the environment. (C6)

No.1 surface finish
Surface finish designation according to ASTM A480 of material that is hot rolled, heat treated, pickled, and free of scale. (C4, C5)

Noble
A higher or more positive electrode potential. Noble metals include gold and platinum. (C6)

Oxidation
(1) Loss of electrons in a chemical reaction.
(2) Corrosion of a metal that is exposed to an oxidizing gas at elevated temperatures. The stainless steel reacts with O_2, H_2O, CO_2 and forms an oxide on the stainless steel surface. (C6)

Passivation
(1) A reduction of the anodic reaction rate of an electrode involved in corrosion e.g. due to the presence of a passive film. (C6)

(2) Chemical treatment to improve the passive layer on stainless steel. Normally not needed if the steel has been properly pickled. (C11)

Passive
A state of a metal in which a surface reaction product causes a marked decrease in the corrosion rate relative to that in the absence of the product. A passive metal usually exhibits a higher electrode potential than one which is undergoing active dissolution. (C6)

Passive layer
The chromium oxide layer on the stainless steel surface that protects the steel from being attacked by corrosion. (C14)

pH
pH is a measure of the acidity of a solution. Pure water has a pH close to 7. Solutions with a lower pH than 7 are said to be acidic, and solutions with a higher pH are said to be alkaline. (C6)

Pickling
Removal of surface oxides by chemical treatment in a pickling bath often consisting of a mixed-acid bath containing nitric (HNO_3) and hydrofluoric acid (HF). (C4, C5, C11)

Pitting (corrosion)
Localized corrosion of a metal surface that is confined to a small area and takes the form of cavities called pits. (C6)

Pitting potential
The potential above which pits are initiated and start to grow. A high value of the pitting potential usually means a higher local corrosion resistance. (C11)

Pitting Resistance Equivalent (PRE, PREN)
Number developed to reflect and predict the pitting corrosion resistance of stainless steels based on chemical composition. Several formulas exist, but we use:
PRE = % Cr + 3.3 x %Mo + 16 x % N
(C6)

Plastic/elastic deformation
In the elastic region an imposed strain is fully recovered upon unloading, while in the plastic region, only the elastic part of the strain is recovered. (C7)

Plate
Flat product thicker than 3 mm (EN 10079) or 4.76 mm (ASTM A480). (C5)

ppm (parts per million)
For water solutions 1 ppm = 1 mg/l = 0.0001 % (C6)

PRE/PREN
Pitting Resistance Equivalent. (C6)

Precipitation hardening
Hardening by a special mechanism involving the formation of precipitates within the microsytructure. (C2)

PRODEC®
PRODEC® (PRODuction EConomy) is Outokumpu's trademark for some grades with improved machinability. (C2, C9, C10)

Proof strength, $R_{p0.2}$
The engineering stress level that gives 0.2 % permanent engineering strain after loading up to $R_{p0.2}$. This is defined as the start of plastic deformation for stainless steel. The proof strength at 1 % ($R_{p1.0}$) is also commonly used for the austenitic grades. (C7)

Quarto plate
Plate produced in a reversing hot rolling mill is generally known as "quarto plate". (C4, C5)

RAP-line
Rolling, Annealing and Pickling line. (C4)

Recrystallization
Heat treatment to soften the steel, previously hardened by cold work, and to control the grain structure in the final product. (C 5)

Reduction
Gain of electrons in a chemical reaction. (C6)

REM
Rare Earth Metal. Important alloying addition in Outokumpu's heat resisting MA-grades. (C6)

Ridging
The phenomenon known as ridging and roping is observed as raised ridge-like or rope-like features running parallel to the rolling direction on the surface of low alloyed ferritic stainless steel sheet after e.g. deep drawing. Ridging and roping will primarily lead to aesthetic rather than functional effects.

Rod
Hot rolled long product having a nominal size generally 5 mm or above and wound into irregular coils. (C5)

Roping
The phenomenon known as roping or ridging is observed as raised rope-like or ridge-like features running parallel to the rolling direction on the surface of low alloyed ferritic stainless steel sheet after e.g. deep drawing. Roping and ridging will primarily lead to aesthetic rather than functional effects.

Roughing mill
A rolling mill where the slab is rolled to reduce its thickness to prepare the slab for further rolling in the Steckel mill. (C4)

RSJ
Rolled Steel Joists used in building construction projects. (C5)

SAF
Submerged Arc Furnace. (C4)

Sand blasting
Sand blasting is a process to remove surface deposits by applying fine sand particles to the surface at a high pressure. (C11)

Scale
When thick oxide layer formed in e.g. furnace atmospheres, breaks down and spalls off due to growth stresses, the material "scales". (C1)

SCC
Stress Corrosion Cracking. (C6)

SEN
Submerged Entry Nozzle. (C4)

Sheet
Flat product with a thickness of maximum 3 mm (EN 10079) or 4.76 mm (ASTM A480). (C5)

Shot peening
Shot peening is a cold working process used to produce a compressive residual stress layer and modify mechanical properties of metals. It entails impacting a surface with shot (round metallic, glass or ceramic particles) with force sufficient to create plastic deformation.

SHRP
Steckel Hot Rolled Plate. (C5)

Sigma phase
A hard, brittle, nonmagnetic intermetallic phase with a tetragonal structure. Sigma phase exists in the Fe-Cr and Fe-Mo binary phase diagrams and in higher systems. (C1, C3)

Skin-pass
Rolling operation to smoothen the surface, improve the flatness and to increase the yield strength. Skin-passing gives a 2B surface. (C5)

Slab
A semi-finished steel product obtained by rolling or forging ingots or by casting a melt in a continuous caster and cut the strand into suitable lengths. (C5)

Slitting
A way to cut a coil into several narrow coils suitable for the end-users following production steps. (C4)

Slug
The left over scrap after cutting. (C10)

Solidus
The temperature below which there is no molten phase present. (C3)

Sour service
Environment with natural gas and crude oil containing considerable amounts of hydrogen sulphide (H_2S). (C6)

Spallation
Spallation is a state where the oxide formed on the stainless steel surface breaks and spalls off. (C6)

SPM
Skin Pass Mill. (C4)

SSC
Sulphide Stress Cracking. (C6, C9)

Stabilisation
Alloying with strong carbide-formers such as titanium and niobium to bind carbon and suppress the risk of forming chromium carbides, which can seriously degrade stainless steel properties. (C3)

Stainless steel
An iron-base alloy with at least 10.5 % chromium that forms a corrosion resistant passive layer on the steel surface. See e.g. ASTM A941 "Standard Terminology Relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys". (C2)

Steckel mill
Steckel rolling is a hot rolling operation where the strip is rolled back and forth between two coiler furnaces and the strip is reduced in thickness in each pass between the coilers. (C4)

Strain hardening
Strain hardening, also known as work hardening or cold working, is the strengthening of a metal by plastic deformation. (C5)

Stress Corrosion Cracking (SCC)
Cracking of a material produced by the combined action of corrosion and tensile stress (residual or applied). (C6)

Strip
Cold or hot rolled flat product often delivered as a coil. (C5)

Sulphidation
A type of high temperature corrosion, in which the stainless steel reacts with sulphur compounds in the environment. (C6)

Sulphide Stress Cracking (SSC)
Cracking of metal involving corrosion and tensile stress (residual or applied) in the presence of water and hydrogen sulphide (H_2S). (C6, C9)

Surface roughness
The surface roughness is often expressed by the Ra value (µm). A low Ra value indicates a smooth surface. (C9)

Temper rolling
Rolling operation to cold work the steel for increased strength. (C5)

Tension levelling
A rolling operation to straighten the sheet and smoothen the surface. (C5)

Thermal conductivity
The thermal conductivity is the property of a material to conduct heat. (C8)

Thermal expansion
Thermal expansion is the tendency of the stainless steel to change in length in response to a change in temperature. (C8)

ThermoCalc
Thermodynamic database system used in development of stainless steel for calculating phase equilibria. (C1, C3)

Toughness
The ability to absorb energy in the plastic range. (C7)

TR surface finish
Surface finish designation according to ASTM A480 of cold rolled (Temper Rolled) material that is work hardened to certain tensile levels. (C5)

True stress strain/engineering stress strain
The engineering stress strain curve is based on the original cross section area of the specimen, while the true stress strain curve compensates for the continuous decrease of the specimen cross section area during deformation. (C7)

TTT curve
Time Temperature Transformation curve shows the kinetics of precipitation or other phase transformations as a function of temperature. (C3, C11)

Ultimate tensile strength, R_m
The largest stress on the tensile testing curve characterizing the maximum obtainable engineering stress and is associated with the uniform elongation A_g. (C7)

Uniform corrosion
Also termed general corrosion. Uniform corrosion is characterized by corrosive attack proceeding evenly over the entire surface area, or a large fraction of the total area, with general thinning of the material as a result. (C6)

Uniform elongation, A_g
The limit of uniform elongation where necking starts. (C7)

Wet corrosion
Also designated aqueous corrosion. Corrosion in liquids, usually water based, or moist environments. (C6)

Wire
Product of constant full cross section along its length, obtained by cold drawing rod through a reducing die or passing under pressure between rollers and rewinding the drawn product. (C5)

Widmanstätten austenite
Elongated lamellae of austenite formed within ferrite grains; seen particularly in duplex stainless steel welds. (C3)

VOD
Vacuum Oxygen Decarburization. A method to reduce the carbon content in the stainless steel melt. (C4)

Work hardening
Strengthening of the steel by plastic deformation. (C2, C5)

Work hardening, n
The increase of stress with strain in the plastic region of the stress strain curve. (C7)

Young’s modulus of elasticity, E
The Young’s modulus, or elastic modulus, is a measure of the stiffness of a stainless steel. It is the slope of the stress strain curve in the elastic region. (C7, C8)

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Own notes

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Working towards forever.

We work with our customers and partners to create long lasting solutions for the tools of modern life and the world’s most critical problems: clean energy, clean water and efficient infrastructure. Because we believe in a world that lasts forever.

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high performance stainless steel

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