Stainless Steel

Characteristics and properties

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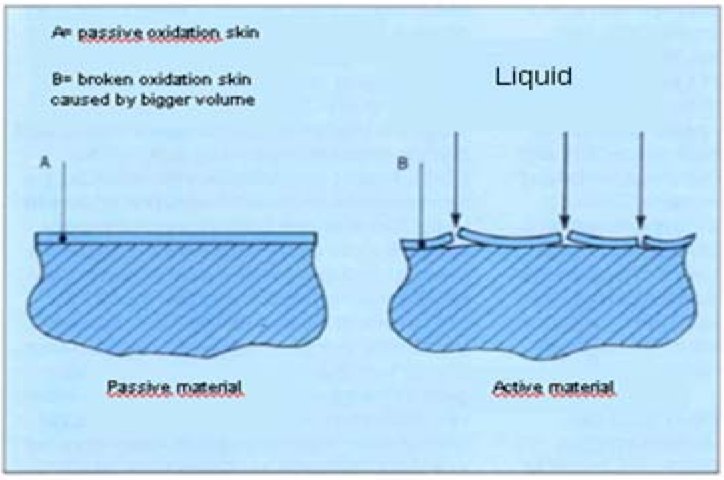
Introduction
Stainless steel is often indicated with the term rust-free steel. This is, however, a less happy expression, because also stainless steel has limits with regard to corrosion. In normal conditions stainless steel does not react with the environment and should therefore be called a passive metal. Passive means that the metal is in a stable thermo-dynamic balance through which the metal remains like it is. When this is not the case, the passivity disappears totally or locally, with corrosion as a consequence. Corrosion is also defined as deterioration of the metal through a chemical and electrochemical reaction with a medium which is in contact with the metal.

Corrosion
Iron (Fe) is an element that is often present in the earth's crust in the form of iron ore or iron oxide; a compound of iron and oxygen. Iron oxide is a stable compound, that can be broken only by addition of energy. This happens, for example, in a blast furnace where with carbon in the form of cokes a reaction takes place:

$2FeO+C+energy \rightarrow Fe+CO_2$

In this way fluent rough iron arises, it gathers on the bottom of the blast furnace and is afterwards drawn off. Rough iron contains almost 4% of carbon during the formation of steel, afterwards the content of carbon is brought back to maximum 2%. Steel is, therefore, an alloy of iron and a controlled quantity of carbon. Through extra amalgamation with a relative little quantity of elements - like nickel



Schematical impression of passive and active metal

(Ni), chrome (Cr), vanadium (V) and molybdenum (Mo) - the mechanical properties can be improved. This article will not pursue the matter further.

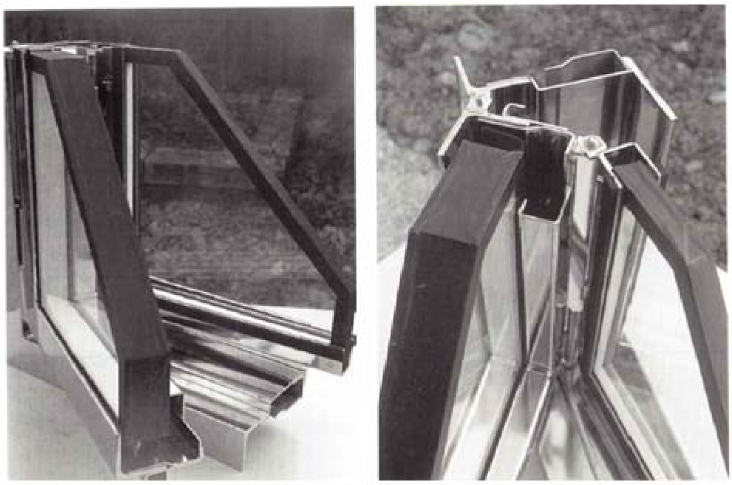
All not amalgamated or little amalgamated types of steel have in common that they react with oxygen in presence of an electrolyte. (An electrolyte is a substance, like water, whose

One American Square Tower, London. In this project stainless steel is used as curtain wall at the top of the building (AISI 316), for the fixing of the granite (AISI 304) and the snap-in-construction (AISI 316) molecules can divide totally or partially in ions and so be able to be lead into an electrical current). This has as consequence that the surface starts to oxidize and a product of corrosion or rust originates. Corrosion is the chemical transformation of iron into iron oxide, for example:

$2FeO+O_{2-} \rightarrow FeO$+ energy

It has been observed that also other reactions can happen, so that for example also Fe_2O_3 and Fe_3O_4 can be formed, but this is not further important here.
To discourage rust formation, the surface can be given a treatment like coating (painting), galvanizing (zinc covering) and greasing. Such covering layers prevent the electrolyte coming in contact with steel and that rust formation happens. However, as soon as a hole origins in the protective layer, local corrosion

begins if an electrolyte is present.
However, corrosion can also be prevented by alloying steel, through which it becomes rust resistant. In principle this is reached only by addition of the chrome element.


Window with windowframe of stainless steel (AISI 316Ti) for the residence of king Fahd of Saudi-Arabia

Types of alloys

Influence of chrome alloy

During oxidation of steel the formed oxide coating (rust layer) takes a bigger volume than the mother material. The oxide product dilates, presses itself into parts and does not form anymore a unity with the underlying mother material: it is porous.
This phenomenon does not occur, for example, with aluminum and chrome, so that corrosion products stay intact on these materials. A chromed handlebar is a good example of this: thanks to the perfect fitting oxide coating on the underlying chrome, the handlebar continues shining nicely. Aluminum and chrome passivate themselves when they come into contact with the air. Iron does not do this because the iron oxide coating causes porosity through its bigger volume and this makes it difficult for the electrolyte to continuously reach the mother material. Because of this, an iron or steel object in the end will rust, so that it eventually completely disappears and returns to its original form. Also rusting of a steel bolt is the consequence of dilatation of the oxide coating.
Alloying steel with the chrome element changes this unfavorable property. When the chrome content in iron becomes 12-13%, the passivity becomes so good, that the alloy does not rust in water and air under normal circumstances. This happens because a thin and resistant oxide layer forms on the surface of steel, which takes the same volume as the underlying metal. Steel becomes perfectly sealed. It is important, though, that oxygen is always present to form and keep this chrome oxide coating intact. This layer has to be perfect, so that no corrosion origins in the pores. In the oxidizing environments such coating origins very quickly on a clean metallic surface. If the surface is dirty or contains for example residues of welding slag, the formation of this oxide coating is significantly prevented and the risk of corrosion rapidly increases. Addition of molybdenum, as well as chrome, provides for extra improvement of the corrosion resistance.


Banisters of stainless steel. The balusters exist out of two fixed flat bars welded at the innside.

If the oxide coating is damaged chemically or mechanically and the conditions are so that the coating not
can be repaired (self-healing-effect), local corrosion will come forth, while the remaining surface will be intact. In reducing environments the metal mostly cannot construct a protective oxide coating, because oxygen which is very needed, is withdrawn. A present oxide coating can even dissociate (fall apart), through which the metal behaves active and so dissolve. From this it follows how relative the concept rust free is.

Chrome steel

The main element of stainless steel is chrome and the minimum required quantity is 12%. The fact that stainless steel can resist to corrosion, is due to a simple passivation because of this relatively high level of chrome content. In general, the resistance to corrosion increases when the content of chrome increases. Besides this, it also increases the resistance to oxidation at high temperatures. Addition of chrome does not cause any change in the structure of ferritic iron; therefore, it is often spoken about ferritic stainless steel. The physical properties are also almost identical to ferritic steel. If there is enough carbon, it is also possible to temper chrome steel like carbon steel through which also the tensile strength increases.
Several stainless steel types have chrome as the only alloy element, but most of the qualities also contain significant quantities of other alloy elements. Their aim is to increase corrosion robustness and/or to change the structure. Incidentally it is also possible to increase the mechanical strength through this. Broadly speaking, chrome steel looks a lot like normal construction steel but with the big difference that it has become passive and that it will stay like this if the corrosion load does not become too big. Due to the little resistance to corrosion the applications are also rather limited. Besides the simple usage for kitchen utensils and home applications it is also gaining more importance in coachwork, because the mechanical values are good and, moreover, it is easy to maintain. In chemical environments, however, the limits of stainless steel will be easily experienced and therefore at the time chrome nickel steel was introduced.

Chrome nickel steel 18/8

The resistance to corrosion increases proportionally to the increase of the chrome content. In quality 18/8 the alloy contains more or less 18% of chrome and 8% of nickel. Following the American Iron and Steel Association this alloy is often indicated with AISI304.
Nickel (Ni) influences the structure and the mechanical properties of stainless steel. If the nickel content is high enough, stainless steel gets an austenitic structure. For convenience we can than speak about austenitic stainless steel. Compared to the pure chrome steels this leads to significant variations of the mechanical properties, to better workability and toughness, to higher temperature strength, improved weldability and a change in the physical properties like, for example, that it does not become magnetic.
In some environments the corrosion resistance becomes higher due to the presence of nickel.
The fields of application of this alloy are much wider than for chrome steel due to its unique and often much better properties. It is possible to think about installations in the food- and dairy industry and in the mild chemical processes.

Chrome nickel molybdenum steel

The element molybdenum (Mo) increases the passivity of stainless steel. A significant improvement of the corrosion performances of chrome nickel steels appear already with the presence of two percent of molybdenum (Mo). In this way, we get chrome nickel molybdenum steels also called AISI316.
Molybdenum has the same effect on the structure as chrome has and mostly it increases the corrosion resistance both of ferritic and austenitic stainless steel. In some countries this

Europagebouw – Haarlem – The Netherlands
Two stainless steel sheets are covering two concrete pollars

stainless steels containing molybdenum are also called ‘acid-free’, because these qualities have such a striking corrosion resistance to aggressive watery sulphur compounds.
Over the last years, there has been a tendency to increase the content of molybdenum even more, so that super rust-proof steels arise. This is an interesting development because the corrosion resistance of these steel types is impressively good in aggressive seawater. Also the increasing demand for the so called duplex structures (ferritic/austenitic structure) is a development which cannot be thought away anymore, because here we are facing a unique combination of relative high level mechanical properties and a high corrosion resistance.

Stainless steel types

Specific characteristics, like the possibility of becoming harder and the magnetism, depend on the molecule structure. Depending on the structure it is possible to divide stainless steel in four groups (table 1):

- ferritic stainless steel;
- martensitic stainless steel;
- austenitic/ferritic stainless steel (duplex);
- austenitic stainless steel.

Various alloy elements have influence on the characteristics of stainless steel. The most important elements are characterized below.

Natrium (N) : Natrium increases the strength of austenitic stainless steels and influences the structure in the same way as nickel. Until a certain level, it can even replace nickel as long as the structure is austenitic.

Copper (Cu): copper improves the resistance to corrosion in certain acids. Sometimes, addition of copper makes it possible to apply a heat treatment, with which the mechanical properties are improved.

Titanium (Ti) and *Niobium* (Nb): stabilize stainless steels because these elements bind carbon. The affinity of carbon with titanium and niobium is higher than the affinity with chrome. Because of this, the chance of inter-crystalline corrosion decreases.

Manganese (Mn): stimulates the deformation characteristics of stainless steel at high temperatures and besides this improves the mechanical characteristics. Manganese is an austenite former and therefore can be used as a substitute of nickel, as it is the case with AISI200 stainless steels.

Phosphorus (P) and *Sulfur* (S): in principle are always undesired elements and will always have to be avoided for their polluting effect.

For an overview of the chemical composition of the often occurring types of stainless steels refer to table 2. The mechanical values are reported in table 3.

All the values in the tables are indicators which give an average value of the different regulations.

Table 1: Relation between structure, composition, hardability and magnetism of stainless steel groups

RVS type	%C	%Cr	%Ni	hardable	magnetic
ferritic	0.08 0.10 0.25	12-14 16-19 24-28	- - -	No No No	Yes Yes Yes
martensitic	0.09 0.17	12-14 16-18	- 1,25-2,5	Yes Yes	Yes Yes
ferritic – austenitic	0,10	24-27	4,5-7	No	Yes
austenitic	0,10	16-26	7-26	No	No

Table 2: Chemical composition of different types of stainless steel

AISI type	C% max	Si% max	Mn% max	Cr	Mo	Ni	other
304	0,08	0,75	2,0	18-20	-	8-11	-
304L	0,03	0,75	2,0	18-20	-	8-13	-
310	0,15	0,75	2,0	24-26	-	19-22	-
316	0,06	0,75	2,0	16-18	2-3	11-14	-
316L	0,03	0,75	2,0	16-18	2-3	10-15	-
316Ti	0,08	0,75	2,0	16-18	2-3	10-14	Ti=5xC
321	0,08	0,75	2,0	17-20	-	9-13	Ti=5xC
410	0,15	1,0	1,0	11,5-13	-	-	-
430	0,12	1,0	1,0	16-18	-	-	-
630	0,04	0,6	0,28	16	-	4,25	3Cu, 3Cb 0,27Ta

Table 3: Mechanical properties of different types op stainless steel

AISI type	0,2% yield strength	Tensile strength	Elonga-tion	Constric-tion	Impact value
304	185	500-700	50	60	85
304L	175	450-700	50	60	85
316	205	500-700	45	60	85
316L	195	450-700	45	60	85
321	205	500-750	40	50	85
410	300 or 450*	550-750	20 of 18*	- 55	85 or 70
630	1000	1100	1-15	-	-

* depends of heat treatment

Table 4: Equivalents of different types of stainless steel

AISI USA	DIN D.	AFNOR Fr.	JIS JAPAN	SIS SW	BS UK
304	1.4301	Z5CN1809	SUS 304	2332	304S15
304L	1.4306	Z2CN1810	SUS 304L	2352	304S12
316	1.4401	Z6CND1711	SUS 316	2347	316S16
316L	1.4404	Z2CND1712	SUS 316L	2348	316S12
316Ti	1.4571	Z6CNDT1712	-	2350	320S17
321	1.4541	Z6CNT1810	SUS 321	2337	321S31
410	1.4006	Z12C13	SUS 410	2302	410S21
630	1.4542	Z6CNU1704	SUS 630	-	-

Terms like AISI 304 and AISI 316 stem from the American norm. In many industrialized countries there are local norms; so, Germany has the Raw Material Numbers that are often used in our country too. *Table 4* gives the various equivalents for some of the often used stainless steel types. Here it applies too that, broadly speaking, in general the types fit in one with the other. This rough similarity, in practice, leads to a satisfactory interchange.

As can be seen from *tables 2-4*, besides 304 and 316, there are also types 304L and 316L. It is wrongly thought that the addition of L is related to the weldability. This is a misunderstanding because it is only related to a low carbon content (low carbon), as can be seen in *table 2*.

Awning shop – Alphen a/d Rijn – The Netherlands. The curragated parts are of stainless steel

Corrosion

Under certain circumstances also stainless steel can be attacked by both internal and external influences. External corrosion arises through the corroding load of water and oxygen. Internal corrosion derives from the undesired formation of chrome carbides in the material.

Corrosion in water

The aggressiveness of water can change considerably according to its chemical composition.

Under normal circumstances, and this article limits itself to them, three different types of corrosion arise in stainless steel: pit-, split-and stress-corrosion. The chloride percentage of water is the most important factor. Besides this, the stream speed plays a role, especially low velocities or even standstills have to be prevented in order to avoid sediments. The welded joints also ought to be cleaned well in order to stimulate the formation of a 'good' oxide hide.
- *Distilled and de-ionised water* contain a very low content of dissolved salts. These kinds of water will not have corrosion as consequence under 100 °C. At higher temperatures, especially when there is a high oxygen content in the water, the chance of stress corrosion will increase in not smouldered AISI 304 stainless steels.
-*Potable water* usually does not cause problems, however limits have to be set to the content of chloride. Potable water, for hygienic reasons, has a chloride content of about 100-200 mg/l. Water transport lines, for both cold and warm water, are generally made of an AISI 304 quality without molybdenum, when the content of chloride is lower than about 200 g/l. When the content of chloride is between 200 and 500 mg/l, AISI 316 quality is advisable.

With higher chloride content and temperatures, special types of stainless steel are a 'must'. The choice of the materials than depends on the content of chloride, the water stream speed, the design details and the possibility of cleaning the welds carefully.
- *Sewage* has a low temperature and the content of chloride varies normally between 50 and 300 mg/l. Generally an AISI 304-type (i.e. without molybdenum) satisfies in an excellent way. In some situations an AISI 316 type can be taken, because, for example, a pipe can be changed with a lot of difficulties.
- *Fresh- and sub-soil water* can have a very large variety in the quantity of pollutants. In Sweden for example the chloride content of lakes varies between 10-200 mg. Pumped sub-soil water has a relatively high content of chloride.
- *Swimming pool water* generally has a high content of chloride and chlorine. Since the AISI 304 kinds loose colour, usually types containing molybdenum are chosen. This is also valid for the filtration, chlorinating, and heating apparatuses and the relative pipe systems.
Brackish water, a mixture of fresh- and seawater, has a variable content of chloride. In practice values oscillating between 2.000 – 10.000 mg/l are measured. Stainless steel without molybdenum should never be used in such an environment. The type AISI 316 is satisfactory, when the temperature remains lower than 70°C.
Seawater has a very high content of chloride and therefore stainless steel can only be applied in the sea under certain conditions. Amongst others the stream speed should be high enough; there may not be cracks and the temperature has to remain lower than about 50°C. High percentages of chrome and molybdenum will make the stainless steel more suitable for this environment.

Corrosion in oxygen
Atmospheric corrosion arises if stainless steel is set up in the open air. The corrosion medium is, in this case, water with a high concentration of oxygen, a relative low temperature and a high concentration of air pollution. Factors like sunlight and wind hereby play a role. A difference is made between sea-, industrial, rural and urban environment.
Research and practical experience demonstrated stainless steel having a very good resistance to atmospheric corrosion. Regarding the loss of colour, following guidelines should be followed. A seawater environment requires a quality containing at least 2% molybdenum, whereas for other environments AISI 304 can be sufficient. In a rural environment sometimes chrome steel (type 3Cr12) is enough. It is also important to make the surface smooth enough in order to prevent undesirable corrosion effects. In a seriously polluted atmosphere the surface will not always remain shiny and therefore the stainless steel should be regularly cleaned.

Internal corrosion
Carbon has always the tendency to form chromecarbides (CrC) with the present chrome. Because chrome is bound, passive pieces of metal arise locally and this has pit-corrosion as consequence. Chrome carbides easily arise under heat constraint, for example through welding.
This can be prevented by glowing the material after a thermic load, so that all the carbides will dissolve again in the mother material. By thermally shocking, the dissolved situation will stabilize and no problems of pit corrosion should be expected. In practice, however, this does not seem to be so easy, because glowing is not always possible. For this reason qualities of stainless steel have been developed which are not, or hardly are, sensitive to the origination of chrome carbides, i.e. AISI304L/316L and AISI316Ti/321.
In qualities AISI 304L and 316L the content of carbon is so low (=< 0.03) that the chrome carbides cannot or hardly can originate. It is, however, important that all products containing carbon will be kept away from this stainless steel, mainly while welding. The carbon content is namely so unnaturally low that the material has an urge to absorb it. Qualities AISI321/316Ti have some titanium added, in order to bind this carbon (stabilize). Titanium alloys quicker with chrome than carbon so that it is not chrome carbides which originate, but titanium carbides. These are scattered very finely over the material and are not disturbing for stainless steel. The addition of a little nobium has the same effect as titanium.

Welding
The different types of stainless steel have different properties in connection with welding. In any case, it is necessary to perfectly clean the surfaces before welding in order to obtain a good corrosion resistance after the welding. If welding is not performed under influence of a sufficiently inert gas, the surface

has to be treated afterwards, for example by staining, grinding or brushing.

Ferritic stainless steel
The present types of ferritic stainless steel have a low C/Cr-relation. Because of this the structure of the material remains completely ferritic at all temperatures. Through the very low components of carbon and nitrogen and the presence of stabilizing elements, there is no risk of origination of chromium carbides. Welded sheets, thinner than 3 mm, do not need a heat treatment, whereas with thicker sheets this is advisable because of the better toughness of the material and the possibility of processing it.
With all the ferritic qualities, it is advisable to keep the thermal load as low as possible during welding. The welding material can be both ferritic and austenitic. Austenitic welding materials give a weld which is tough; this is especially an advantage with thick weld joints.

Austenitic stainless steel
Austenitic stainless steel can generally be welded easily, and it is not necessary to pre- heat the metals which have to be welded or to give them a heat treatment after welding. The highest alloyed types have a certain risk of cracking of the weld (heat cracks). Such qualities have, therefore, to be welded with a minimum of heat-contribution. If welding is done manifold times one after the other, each single weld has to have enough opportunity to cool down. The sensitivity to heat cracks diminuishes, if there are some percentages of ferrite in the weld. Therefore, weld materials containing ferrite are often used.

Design suggestions
In many cases, the corrosion damage is due to an unsuitable or even wrong design, which can be prevented by recognizing the corrosion risks already on the drawing table. When welding stainless steel constructions, it is very important that no pores and cracks are formed and that the welding metal penetrates completely in the welding cavity. Oxidized areas, which arise from welding, cause a low corrosion resistance; it is, therefore, important that similar oxides are eliminated after welding.
In principle, only two types deserve consideration for application in the construction field:
- ferritic stainless steel;
- austenitic stainless steel.

Even if ferritic stainless steel meets the needs of many internal applications, this quality is more and more loosing importance on behalf of the slightly more expensive austenitic stainless steel. The most important reason is that the designer has more certainty that no corrosion will arise, especially when the material has an architectonic function. Ferritic stainless steel has indeed better mechanical properties, but this advantage disappears in such an application.
Austenitic stainless steel for construction can be divided in two main types, namely with and without molybdenum, respectively AISI 304L and 316L. In the majority of cases, 304L is more than satisfactory, with exception of applications in the toilet units. In normal circumstances, AISI 304 suites the external use unless an influence from seawater is to be expected. In that case, 316L is the best choice. In practice, it seems that for this reason the AISI 316L is almost always applied in open air in order to prevent unnecessary risks.
The addition of molybdenum 316L is a little bit more expensive than the 304L. The increasing pollution of the atmosphere makes that higher demands are more and more set to the corrosion resistance of stainless steel, because of which the use of AISI 316L will gain more and more ground.