POLITECNICO DI MILANO

DIPARTIMENTO DI MECCANICA

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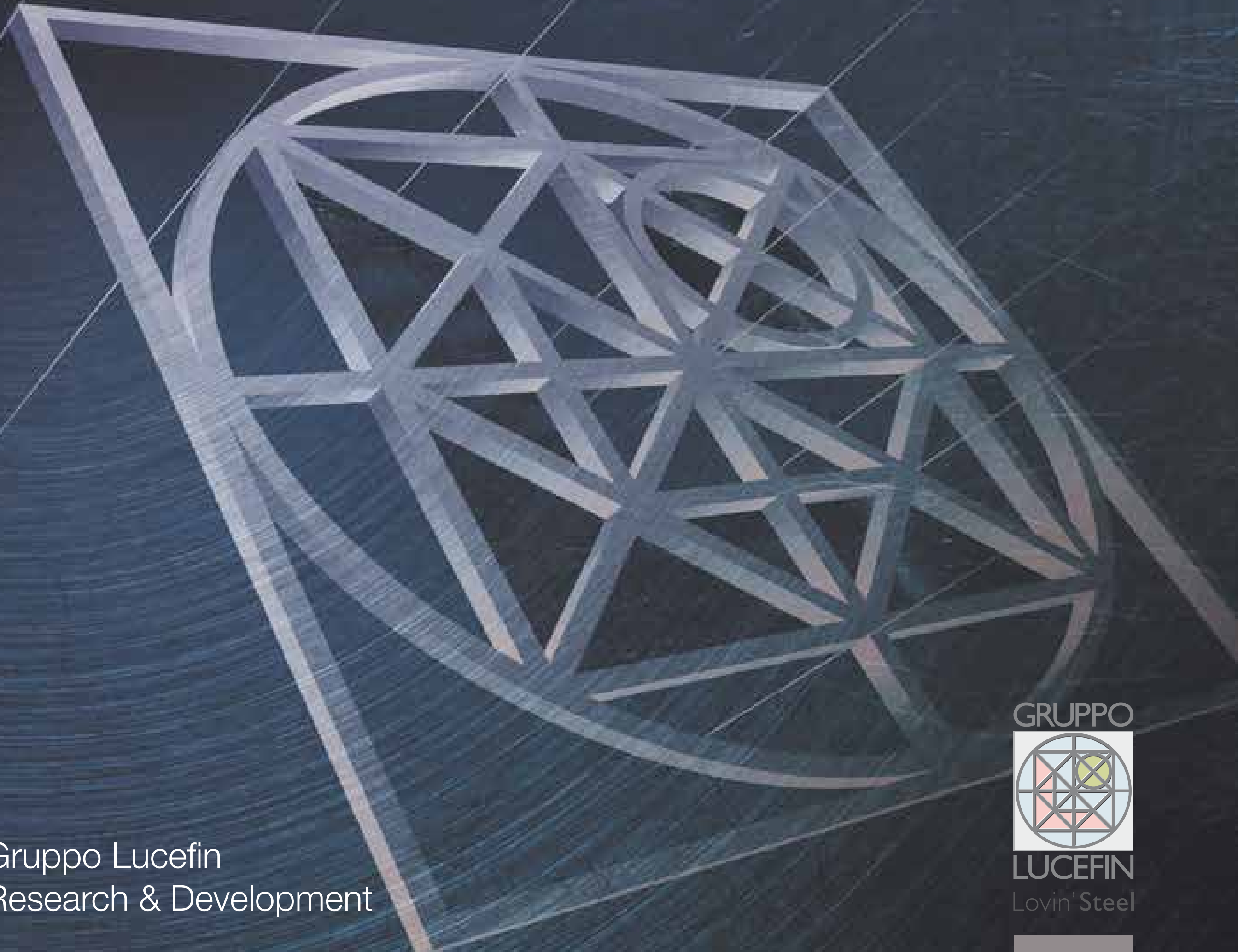
Stainless steels



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1. WHAT ARE STAINLESS STEELS?

Stainless steel is an iron-based alloy with a significant chromium content; in many cases, together with chromium, other special chemical elements are intentionally added, such as nickel and molybdenum. The main characteristics of this family of steels is resistance to wet corrosion, or electrochemical corrosion, in aggressive environments such as fresh water, sea water, contaminated water based solutions, acid and base environments, industrial environments, etc. Another important characteristic of this category of steel is the resistance to oxidation at high temperatures, or chemical corrosion, as typically occurs in hot process gases. The typical fields of application for stainless steel are those in the chemical industry, oil industry, foodstuffs and paper manufacturing, the pharmaceutical, biomedical and transport sectors, in off-shore structures, household appliances, and the construction and urban furnishing sectors.

In accordance with the European standard EN 10088, steel is classed as stainless when its chemical composition has a minimum chromium content of 10.5%. However, it should be noted that in virtually all types of stainless steel available on the market, the chromium content is much greater than this value, normally ranging, in the most common cases, from 13% to 18%: this is due to the fact that in practice, a chromium content of at least 12% is needed to obtain satisfactory resistance to corrosion in water based solutions.

The presence of chromium alloy ensures the possibility of creating a very thin layer of oxide (also known as passive film) on the steel surface, mainly made up of chromium oxides and hydroxides Cr_2O_3 and $Cr(OH)_3$: this film is insoluble, compact and adheres well to the substrate thereby protecting the material on which it is formed. The passive film does not only comprise chromium oxides and hydroxides: tests performed using XPS[1] techniques have also revealed the presence of iron and molybdenum (again in the form of oxides and hydroxides) and have shown how nickel tends to accumulate in the interface between the passive film and steel substrate (note the schematic in figure 1).

The film of chromium oxide/hydroxide is extremely thin – just a few nanometres – and transparent to luminous radiation, and therefore gives stainless steel its typical grey-silver metal finish, as clearly seen in cooking utensils, pans, cutlery and metal watch straps.

All the above properties are the consequence of the rapid reaction of the chromium alloy with oxygen in the atmosphere. Oxidation of stainless steel, also known as passivation, occurs naturally and spontaneously in neutral oxidating environments, such as in contact with air. Otherwise, as normally occurs in the processes for manufacturing semi-finished articles, it is induced artificially by the immersion of the semi-finished product

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[1] *XPS is the acronym for X-ray Photoelectron Spectroscopy. The sample is exposed to a flow of photons, emitted by the X-ray: the interaction of the photons with the material to be investigated lead to the emission of electrons each of which has a specific kinetic energy that depends on the binding energy of the chemical element from which it was emitted. By measuring this kinetic energy of the emitted electrons, it is possible to calculate the binding energies and then the type of chemical elements present in the test material. This technique is also known as ESCA, i.e. Electron Spectroscopy for Chemical Analysis.*

in a solution diluted with nitric acid. In this case the protective and stable chromium oxide/hydroxide film that is formed acts as a sealant and creates a barrier between the material and the external environment.

In consideration of the above process, in a certain sense the term "stainless" is not appropriate. Steel is, in fact, highly "oxidisable" and as it is in a stable oxide/hydroxide state, it is also highly resistant to corrosion and aggression from the surrounding environment.

The passive film of chromium oxide/hydroxide also has another important property: when scuffed, scratched or mechanically damaged, it spontaneously forms again on the surface of the component, thus immediately restoring protection against any corrosive action (figure 2).

As well as the considerations of general corrosion, the presence of chromium also ensures optimal resistance to localised forms of corrosion such as pitting and crevice.

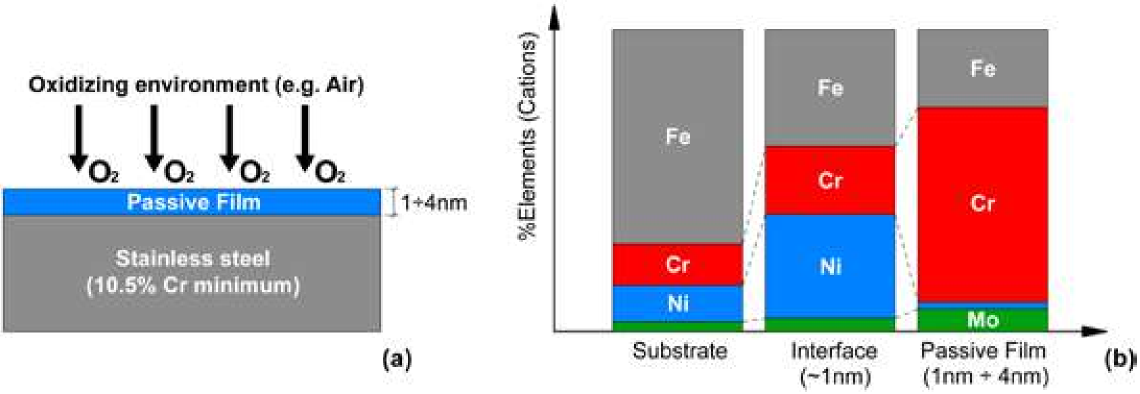

Figure 1 – (a) Mechanism of stainless steel passivation in contact with the atmosphere and (b) schematic of trends of elements present in the passive film, in the interface and in the substrate of a stainless steel grade 18%Cr-14,3%Ni-2,5%Mo [from Olefjord and Elfstrom 1982].

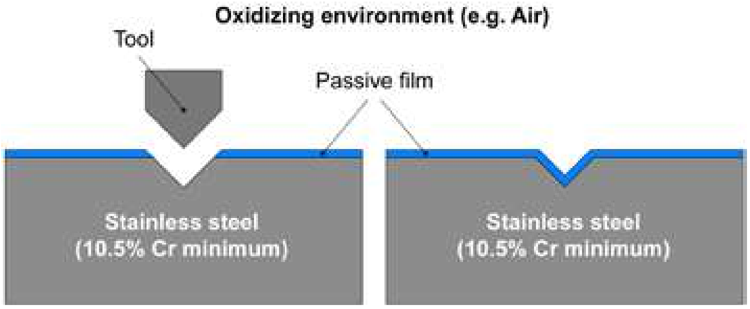

Figure 2 – Mechanical removal of the passive layer and subsequent re-passivation of stainless steels [from Baddoo 1995].

Lastly, given that the chromium oxides that form on the surface of stainless steels are highly stable at temperatures above ambient values, the material is therefore highly resistant to oxidation and corrosion when subject to heat.

Thus in very general terms, it can be concluded that the greater the quantity of chromium in the alloy, the greater the resistance of stainless steel to corrosion. This applies both in conditions of wet corrosion and under the effect of heat oxidation. For this purpose, figure 3 illustrates the trend in the speed of corrosion of iron alloys with various chromium contents, in the presence of water based solutions diluted with nitric acid and sulphuric acid and in conditions of oxidation under heat in air at a temperature of 1000°C.

Note that in the presence of nitric acid, i.e. an oxidising acid that can cause passivation of the chromium, the steel's resistance to corrosion increases in proportion to the increase in chromium content, whereas in the presence of a reducing acid such as sulphuric acid, the speed of corrosion follows a similar trend in reverse.

An additional effect of the chromium is that of improving resistance to creep in stainless steels, which for this reason are widely used at temperatures higher than ambient values, in conditions where deterioration is predominantly caused by creep.

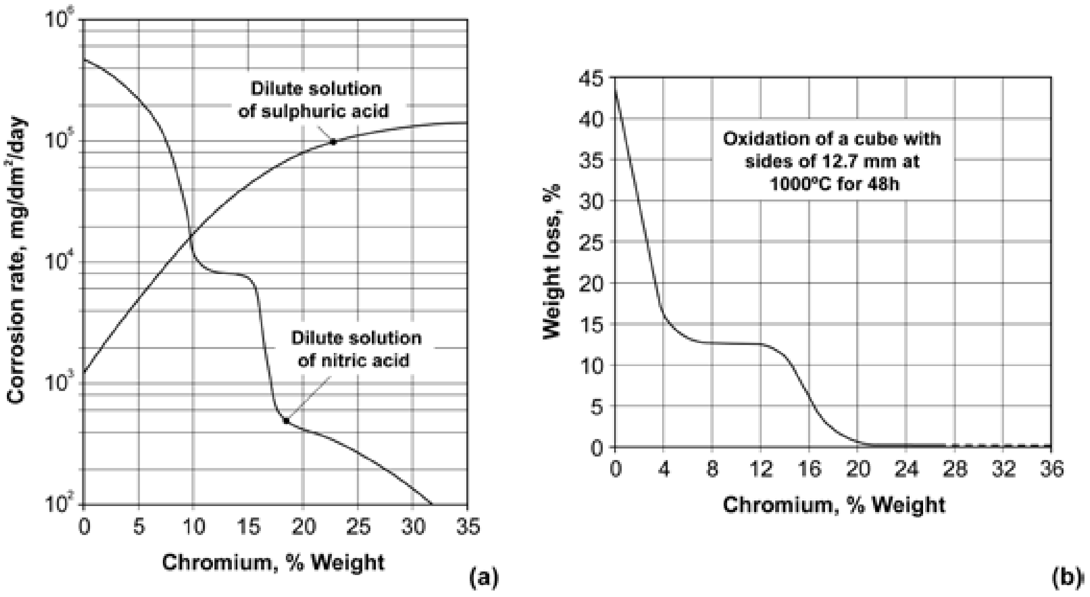

Figure 3 – Speed of corrosion, in terms of weight loss of chromium-iron alloys (a) in water based solutions diluted with nitric acid and sulphuric acid and (b) in conditions of oxidation under heat in air at temperatures of 1000°C [from Verhoeven 2007].

2. STAINLESS STEEL TREE STRUCTURE

Before dealing in detail with the relevant metallurgical and mechanical characteristics, the main types of stainless steel available on the market can be summarised in a simple tree view (see figure 4).

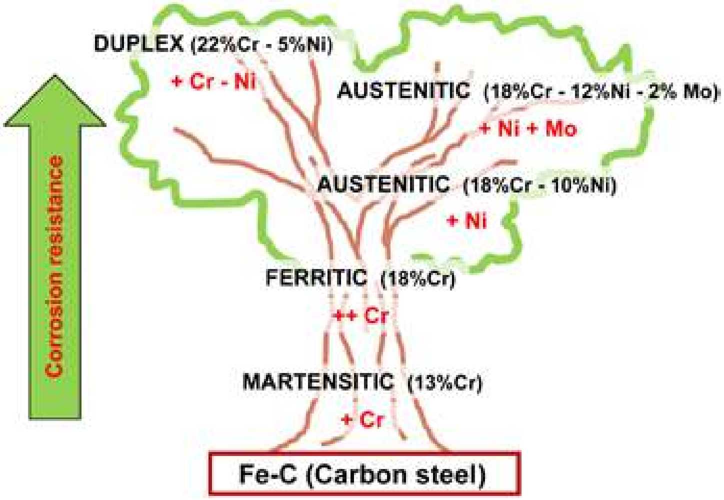

Figure 4 – Schematic of the evolution of stainless steels starting from plain carbon steels: the stainless steel tree structure.

To begin with we consider a common heat-treatable plain steel, such as steel grade C30: to make this steel stainless it is sufficient to add a set content of chromium (~13%) to obtain an initial possible version of stainless steel. This is grade X30Cr13.

A steel with this type of chemical composition can undergo heat treatment (in fact this is a heat-treatable steel) and, after tempering and quenching (hardening), it takes on a tempered martensitic structure at ambient temperature. It also offers the benefit of offering good resistance to corrosion, combined with good mechanical resistance.

With the aim of further increasing corrosion resistance of stainless steel as proposed above, a larger quantity of chromium needs to be added, while the presence of carbon should be reduced. In this case the steel grade obtained will be X6Cr17, with a ferritic structure at ambient temperature, due to the significant presence of chromium, with notable ferrite forming properties. The level of corrosion resistance of the new steel will be greater than that of the X30Cr13 steel; on the contrary the mechanical resistance of the X6Cr17 will be much more limited as no hardening heat treatment will be possible.

To obtain a steel with even greater corrosion resistance than the two grades described above, the addition of nickel and molybdenum will be necessary, and possibly a further increase in chromium content.

In this case, there are two alternative procedures:

starting with the X6Cr17, nickel could be added to obtain stainless steel grade X5CrNi18-10 or both nickel and molybdenum to obtain the grade X5CrNiMo17-12-2: this will thus obtain an austenitic structure at ambient temperature, due to the austenite stabilising properties of nickel that predominate over the ferrite forming strength of the chromium.

alternatively, again starting with X6Cr17, smaller quantities of nickel can be added, along with greater quantities of chromium, with a set percentage of molybdenum, to obtain the stainless steel grade X2CrNiMoN22-5-3: this solution obtains a mixed (or two-phase) structure of ferrite and austenite.

The four steel grades described above, belonging to various levels of the tree structure of stainless steels illustrated in figure 4, also represent the four main families of stainless steels currently used; these families, all defined on the basis of their microstructure at ambient temperature, are:

martensitic stainless steel (such as X30Cr13),

ferritic stainless steel (such as X6Cr17),

austenitic stainless steel (such as X5CrNi18-10 and X5CrNiMo17-12-2),

austen-ferritic, two-phase or duplex stainless steel (such as X2CrNiMoN22-5-3).

A fifth category can be added to these four, i.e. the family of stainless steels by precipitation hardening: this is not defined by the metallurgical structure of the steel at ambient temperature but rather, as per tradition, by the heat treatment/strengthening mechanism used to produce it (precipitation hardening).

3. METALLURGY OF STAINLESS STEELS

As described in the previous chapter, the four main families of stainless steels are classified on the basis of the microstructure they have at ambient temperature, in other words:
- martensitic stainless steels (with a martensitic microstructure)
- ferritic stainless steels (with a ferritic microstructure)
- austenitic stainless steels (with an austenitic microstructure)
- austen-ferritic stainless steels (with a mixed austenitic and ferritic microstructure)

To understand how it is possible to obtain such diverse microstructures, a thorough analysis is needed of the effect of the alloy elements on the phase diagram of stainless steels: only a careful examination of these phase diagrams will enable a full understanding of how such different structures and properties can be obtained within the same family of materials.

On analysis of the phase diagrams, it must always be taken into account that these diagrams are only valid in balanced conditions, i.e. only when the specified alloy is cooled very gradually in consecutive stages of equilibrium from the melting temperature to the ambient temperature.

3.1 Iron-chromium

The first phase diagram to be considered has to be the Fe-Cr diagram, as it is the very element of chromium that characterises the family of stainless steels, and which gives all types their excellent levels of corrosion resistance. For this purpose, refer to figure 5.

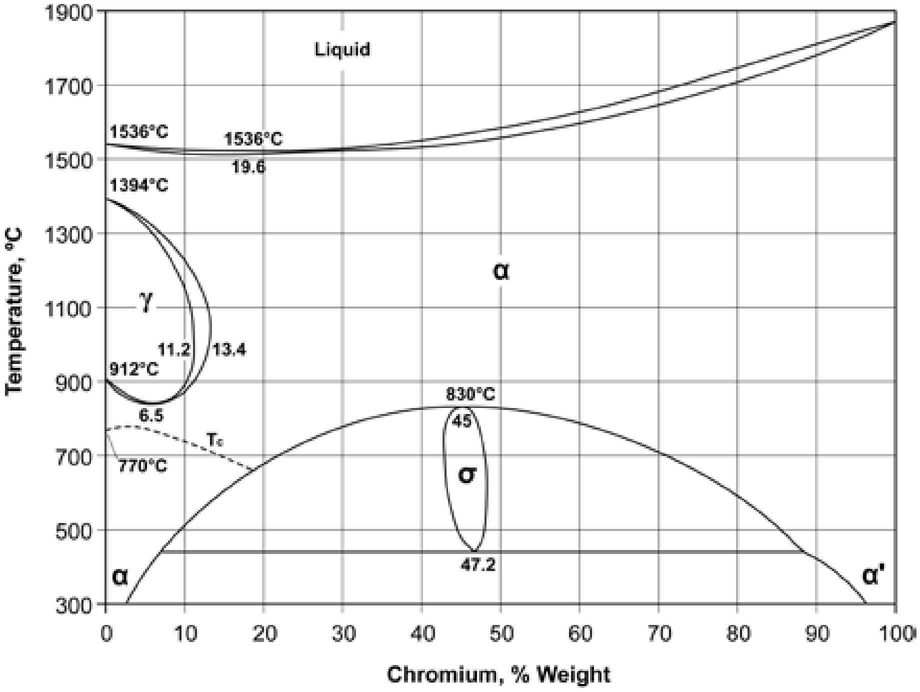

Figure 5 – Fe-Cr phase diagram [from ASM-H.3 1992].

As chromium is a ferrite forming element, i.e. it aids the expansion of the field of phase α, the Fe-Cr phase diagram highlights the presence of a closed γ field, with upper and lower limits corresponding respectively to 11.2% and 13.4%: this means that if the chromium content exceeds 13.4% the iron-chromium alloy will have a lattice α with a stable ferritic structure[2] starting from the temperature of alloy solidification through to the ambient temperature. On the contrary, if the chromium content is lower than 13.4%, the standard transformation $\gamma \rightarrow \alpha$ will occur, typical of the Fe-C phase diagram.

While closure of the field γ is caused by the addition of ferrite forming elements such as chromium, aluminium, vanadium, silicon, molybdenum, titanium, niobium or tungsten, the austenitising elements such as nickel, manganese, carbon or nitrogen contribute to expanding the field γ and shifting the limit threshold to the right.

All these factors are critical because, as seen in figure 6, on addition of carbon, nitrogen or nickel to the iron-chromium alloy, the existence field of phase γ expands significantly. This therefore can obtain a stable phase γ at high temperatures (900°C-1000°C) even with chromium contents of more than 13.4%.

These two specific characteristics of the Fe-Cr phase diagram enable an explanation of the existence of two important stainless steel families.

On the one hand, if the chromium content is around 16%-17% and the carbon level is very low (less than 0.1%), there are no structural transformations and the steel structure will be ferritic (the grade of ferritic stainless steels); on the other hand, when the chromium content is around 13% and the carbon level is around 0.2%-0.3%, the alloy undergoes a transformation $\gamma \rightarrow \alpha$ and may achieve the status of martensitic stainless steel.

Another notable characteristics of the Fe-Cr phase diagram is the presence of the phase σ, i.e. an intermetallic compound between the iron and chromium with a tetragonal structure (with a variable chromium content, ranging approximately between 40% and 50%) which is deposited on the grain boundary, achieving optimal levels of hardness and brittleness of the steel. As phase σ is high in chromium content, it tends to significantly worsen corrosion resistance of stainless steels (removing the same element that gives steel its resistance to corrosion): its presence should therefore be avoided at all costs, taking care not to expose the material to temperatures in the range 550°C-850°C for time intervals of 100-1,000 hours. Bear in mind that the specified temperature range (550°C-850°C) applies exclusively to alloys made up of iron and chromium; if other alloy elements are present, such as molybdenum, phase σ may also occur at temperatures up to 980°C. At times the phenomena following formation of phase σ are also termed "embrittlement at 800°C".

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[2] *When speaking of stainless steels, the phase α, corresponding to the ferritic structure, is often alternatively referred to as phase δ. The distinction (α and δ) between the two names used to define the same structure (ferrite), is completely conventional: usually the body-centred cubic phase is known as δ if found at a high temperature, while α is used when referring to ambient temperature.*

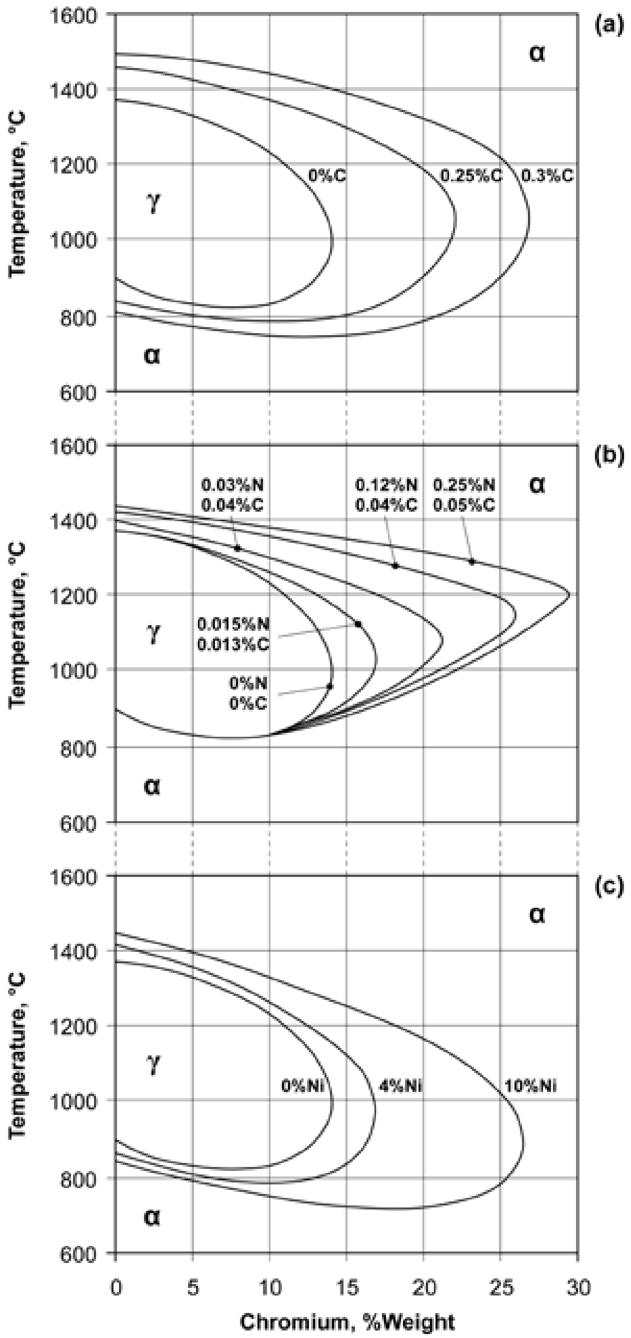

Figure 6 – Effect of adding (a) carbon, (b) nitrogen and (c) nickel on the expansion of the existence field of phase γ in the Fe-Cr phase diagram [from Lacombe et al. 1993].

On the same Fe-Cr phase diagram, there exists phase α': this phase forms at temperatures ranging from approximately 350°C to 550°C for hold times of varying lengths[3]. The most critical condition occurs at 475°C, after some tens of minutes, and is hence known as "embrittlement at 475°C".

Phase α' forms within ferrite grains and has a body-centred cubic structure: it is a phase rich in iron and chromium, in line with the steel α matrix, with sub-microscopic dimensions. To all effects and purposes, phase α' is a decomposition/transformation of the ferrite structure, not identifiable by means of standard metallographic analysis or by X-rays, due to the sub-microscopic dimensions and lattice parameters identical to those in phase α[4].

Phase α' tends to lead to a progressive embrittlement of the steel on increase of the hold time at the critical temperatures, as well as the decline in corrosion resistance properties of the alloy. The phenomenon occurs on alloys with a chromium content of more than 14% with kinetics that increase in proportion to the increase of alloy elements.

3.2 Iron-Nickel

We will now look into the effect of nickel (Fe-Ni phase diagram), i.e. the other alloy element always present in the chemical composition of the two remaining stainless steel families (austenitic stainless steel and austen-ferritic stainless steels).

The nickel affords ductility to the material and extremely high strength, also at cryogenic temperatures; it contributes to the increase in corrosion resistance of stainless steels not so much because it improves stability of the passive film (which is the case of chromium) but rather because it aids repassivation of the steel[5] and increases corrosion resistance in reducing environments. Just as in the case of chromium, nickel gives stainless steel optimal resistance to oxidation under heat and to creep.

While the effect of chromium is to close the field of phase γ, the action of nickel is to open the field γ up to the ambient temperature and then at the same time close the field α: note this process in the Fe-Ni phase diagram shown in figure 7.

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[3] The formation of phase α' is obtained, according to most authors, by spinodal decomposition, in other words by decomposition of an unstable phase (the original α phase) which gives rise to two separate solid solutions with the same crystalline structure but a different chemical composition (phase α' is the new modified phase α); however a minority maintain that the phase α' forms by nucleation and accretion from phase α.

[4] Note that the symbol α' is also currently attributed to martensite obtained by cold plastic deformation of austenitic stainless steel following transformation from austenite (see more details below). As the two phases (α'-martensite and α'-ferrite from spinodal decomposition) must not be confused, we have opted in this document to use the term "embrittlement at 475°C" rather than the term α'.

[5] If the passive film is subject to mechanical scratches or worse, if it is chemically damaged, the presence of nickel aids the film to "reheal", restoring the original corrosion resistance of the material.

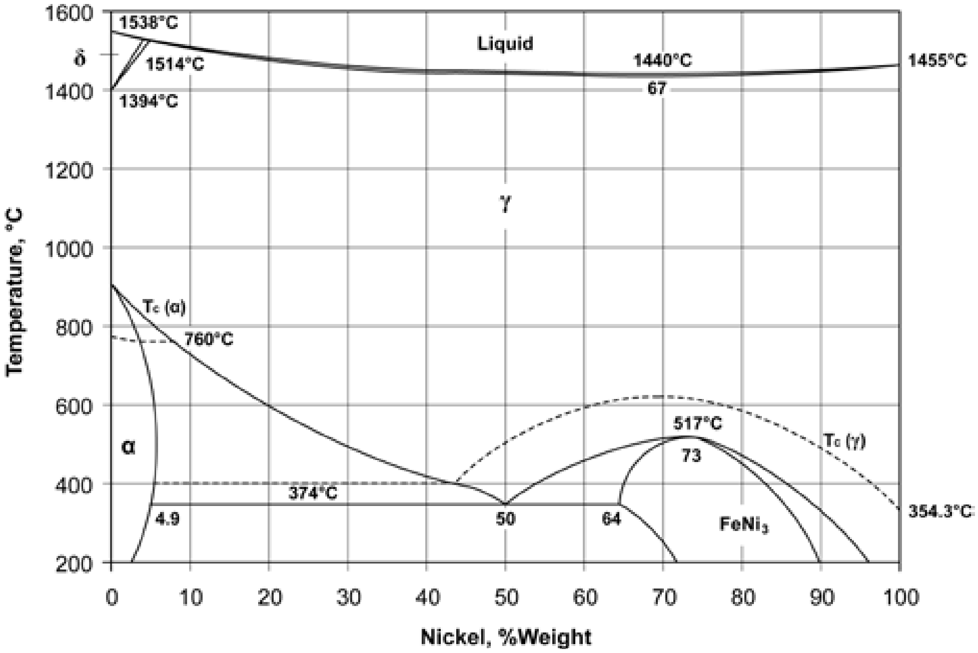


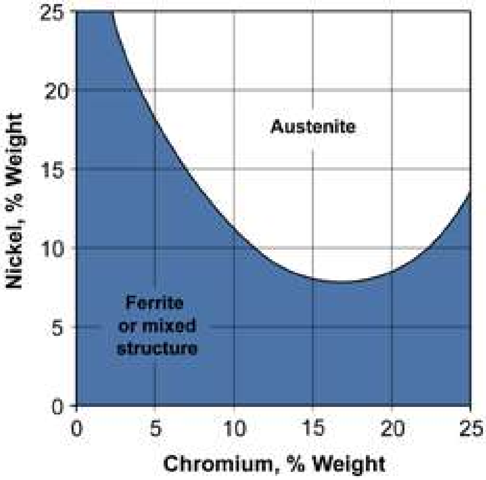
Figure 7 – Fe-Ni phase diagram [from ASM-H.3 1992].

The possibility of having an open field γ (i.e. with a stable γ phase) starting from the solidification temperature through to the ambient temperature, will obtain a completely austenitic structure. The phenomenon is possible as the addition of nickel tends to shift the critical points of transformation γ→α at very low temperatures: on cooling, the structure is not subject to any transformation, remaining austenitic also at ambient temperature. The Fe-Ni phase diagram also shows the existence of the phase Ni_3Fe, which however is of little practical interest with regard to stainless steels.

While in simple Fe-Ni alloys, around 30% of nickel is needed to have only phase γ at ambient temperature, if around 17% of chromium is added, 8% of nickel is sufficient to obtain a stable austenitic structure: this would explain the existence of austenitic stainless steels with 17%-18% chromium and 10%-12% nickel (see figure 8).

3.3 Iron-Chromium-Nickel

For a better understanding of the phenomena described above, it is worth considering the Fe-Cr-Ni ternary diagram, undoubtedly more significant when describing alloys containing higher percentages of the three alloy elements. However, in consideration of the practical difficulty in plotting ternary diagrams (which in other words would have a three dimensional structure), it is more customary to use a representation in the form of binary sections in which the percentage of one of the three alloy elements is plotted. With regard to this, refer to the Cr-Ni binary section of the Fe-Cr-Ni ternary diagram, with an iron content of 70% (figure 9), useful when both chromium and nickel are present in the alloy[6].



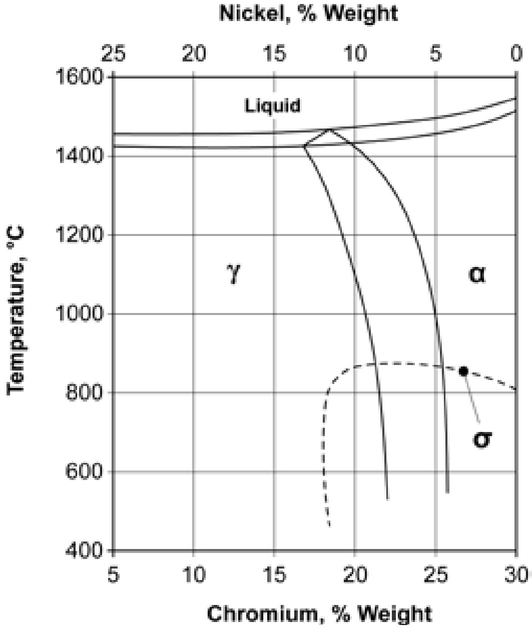


Figure 8 – Effect of nickel on the formation of an austenitic structure in relation to the chromium content in alloys: steels of various chemical compositions with C=0.1% soluble in water from 1100°C [from Peckner and Bernstein 1977].

Figure 9 – Cr-Ni binary section in Fe-Cr-Ni ternary diagram (with Fe = 70%) [from Lippold and Kotecki 2005].

The ternary section shown in figure 9 again highlights the absence of critical points in transformation γ→α. It also explains, in relation to the chromium and nickel contents in the alloy, the existence of exclusively austenitic structures (austenitic stainless steels) or of two-phase austenite and ferrite structures (austen-ferritic or duplex stainless steels): hypothesising a chromium content of 17%-18% and nickel of 10%-12% an austenitic structure is obtained, while a chromium content of 22%-25% and nickel at 4%-8% an austen-ferritic structure is obtained.

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[6] *To be more precise, note that austenitic chromium-nickel or chromium-nickel-molybdenum stainless steels do not have a completely austenitic structure. On examination of the ternary diagrams, the presence of a small percentage of is always shown (up to 5%): this is normally an advantage as it reduces the steel's susceptibility to the formation of hot cracks during welding.*

3.4 Other alloy elements

As well as chromium and nickel, stainless steels also contain other chemical elements that modify both the metallurgical characteristics and the mechanical properties and corrosion resistance of the steel, creating additional and specific properties.

Given all stainless steels are steel, carbon is always present.

Carbon, an austenitising element like nickel, gives steel hardness and mechanical resistance. As carbon has a close affinity with chromium, in stainless steels there is always the tendency to form chromium carbides, such as $Cr_{23}C_6$, particularly detrimental to stainless steel, as it impoverishes the same chemical element that guarantees corrosion resistance. The phenomena of chromium carbide formation occurs at temperatures above ambient values, normally within the range of 450°C to 900°C.

Chromium carbides usually deposit on the grain boundary and leading to a localised, i.e. within the boundary of the grain itself, depletion of chromium: a consequence of this process is that the chemical composition of the metal mass falls below the passivation threshold (10.5% chromium) giving rise to intergranular corrosion, also in only slightly aggressive environments[7]. The entity of corrosion depends both on the quantity of carbide precipitation and the lesser or greater ability of the chromium to spread in the steel lattice: in the crystalline structure of the steel, this causes short or long range depletion of the chromium with differing effects in terms of material deterioration[8] (see figure 10).

Given the great importance of the issue of chromium carbides, we shall deal with this in more detail below. For now it is sufficient to note that, with the exception of the case in which high mechanical properties are required (such as the case of martensitic stainless steels), this problem is avoided by minimising the carbon content or attempting to neutralise the effect of the latter, by combining it with other chemical elements.

After chromium, nickel and carbon, the fourth significant chemical element in stainless steels is molybdenum, another ferritising element.

When added to the alloy, this element significantly increases resistance to corrosion, with particular regard to the phenomena of localised attack, such as the case of pitting and crevice corrosion. Molybdenum also aids heat resistance of stainless steels at least up to medium temperatures; however, at temperatures over 800°C, it tends to form liquid oxides (MoO_3) leading to catastrophic phenomena of selective oxidation.

There is then another series of alloy elements often present in stainless steels, but these are of less importance with respect to those above. They are manganese, titanium, niobium, sulphur, nitrogen and copper.

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[7] *The mechanism of deterioration generated by the presence of phase σ is also very similar to what occurs with the formation of chromium carbides, leading to localised depletion of chromium and intergranular corrosion.*

[8] *In ferritic stainless steels, the diffusivity of chromium is high, while the depletion of chromium caused by the formation of carbides is long range, starting from the grain boundary; on the contrary in the case of austenitic stainless steels (low chromium diffusivity) chromium depletion remains short range. As a consequence, possible phenomena of intergranular corrosion are much more marked in austenitic stainless steels compared to ferritic stainless steels.*

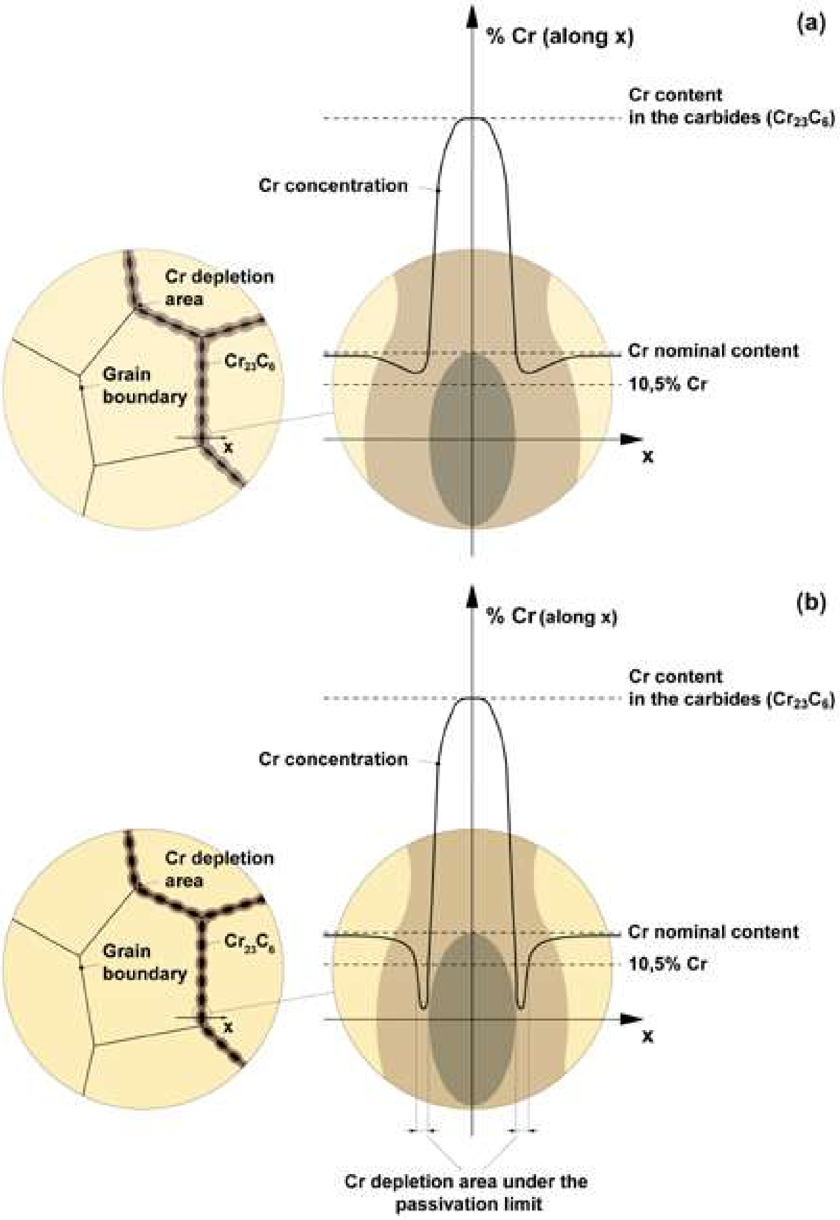

Figure 10 – Trends in chromium concentrations at a grain boundary where chromium carbide precipitation occurs: a) in the case of ferritic stainless steel (high diffusivity of chromium); b) in the case of austenitic stainless steel (low diffusivity of chromium).

Manganese is normally present in stainless steels at percentages lower than 2% as it is used in the steel production phase as a strong de-oxidant[9]; at values greater than 2% it is used as a replacement for nickel due to its austenitising properties. The presence of significant percentages of manganese (>2%) improves the work hardening properties of stainless steel, but reduces its corrosion resistance.

Titanium and niobium are both ferritising elements, and in the case of stainless steels, are known as stabilising elements. These two elements are added in chemical analysis as they have a great affinity with carbon and can form carbides or carbonitrides of titanium or niobium such as MC or $M_x(NC)_y$ (with M=Ti or Nb): this prevents the carbon from alloying with chromium , thus forming chromium carbides and reducing the steel's resistance to corrosion[10].

To improve workability on machine tools (machinability) sulphur can be added to the stainless steels: sulphur forms manganese and/or chromium sulphides that contribute to the breakability of chips during roughing and finishing of the part. However the presence of sulphur has a series of negative implications: it reduces corrosion resistance and the strength/resilience of stainless steel, as well as its plastic deformability under heat and weldability.

Nitrogen, a highly austenitising element, is added to some grades of stainless steel (austenitic and austen-ferritic) both to increase mechanical strength and to improve localised resistance to corrosion.

Lastly, copper, another austenitising element, is added in small percentages (maximum 1%) to improve ductility (cold plastic deformability) of austenitic stainless steels. However, the presence of copper slightly reduces corrosion resistance, as well as weldability and plastic deformability under heat.

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[9] *Silicon is also used in a similar way, as a strong de-oxidant of the metal steel bath.*

[10] *As an alternative to titanium and niobium, tantalum may also be added, also known as columbium, with similar stabilising effects.*

3.5 Schaeffler diagrams and De Long diagrams

Given the great variety of alloy elements that can be found in the chemical composition of stainless steels, it is always important to consider the overall ferritising or austenitising effect of each, to enable a specific definition of the structure of the steel at ambient temperature.

To solve this problem, the use of a more intuitive instrument is needed in place of a phase diagram.

For this purpose, a structure diagram has been drawn up, originally by Schaeffler and subsequently modified by other researchers, which enables the identification, after rapid solidification, of the metallurgical structure of stainless steels at ambient temperatures starting from the alloy elements present in the chemical composition. Although the diagram lacks the solid thermodynamic foundations typical of equilibrium diagrams, it is still very useful for a great number of practical applications (refer to figure 11).

On the X-axis, the Schaeffler diagram shows a summary of the ferritising elements (known as equivalent chromium, Cr_{eq}) while the Y-axis summarises the austenitising elements (known as equivalent nickel, Ni_{eq}). In both cases, each element is weighed with its specific coefficient, set at 1 for the ferritising effect of chromium and for the austenitising effect of nickel.

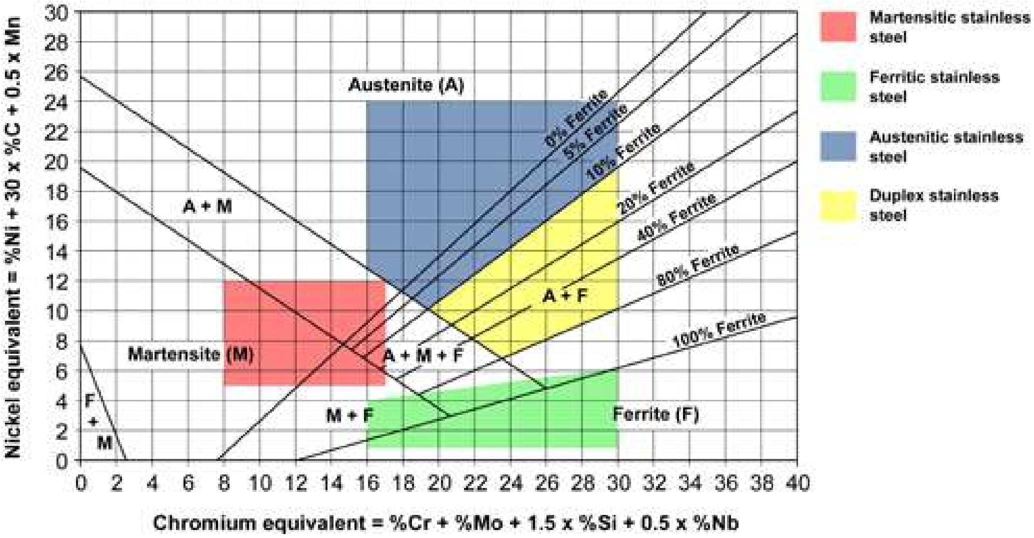

Figure 11 – Schaeffler structural diagram [from Krauss 2005]; highlighting the existence fields of the for main families of stainless steel.

The Schaeffler diagram is divided into four zones that correspond to the four typical microstructures of the above four categories of stainless steel (martensite, ferrite, austenite and austen-ferrite): note the chemical composition of the steel, which enables the identification of the microstructure at ambient temperature and the relative material category.

As can be observed, the Schaeffler diagram does not mention nitrogen among the alloy elements: to remedy this problem, in the 1970s the diagram was amended by De Long, within the austenitic and austen-ferritic fields (figure 12). The need for a more complete diagram with respect to that of Schaeffler arises from the possibility of adding controlled percentages of nitrogen to the alloy during the manufacturing phase: this applies above all to the austenitic and austen-ferritic families of stainless steel, with the aim of increasing hardness and resistance.

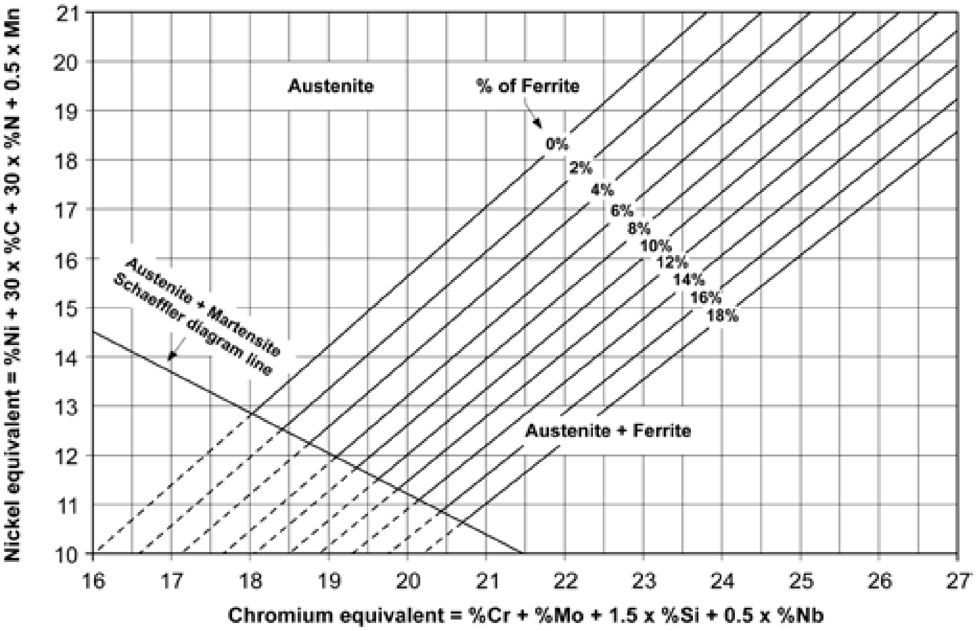

Figure 12 – De Long structural diagram [from Krauss 2005].

Lastly it is worth re-iterating previous observations that both the Schaeffler and the De Long diagrams referred to welding beads, i.e. for alloys cooled rapidly from the melting temperature: these can therefore only provide reliable results in these specific conditions.

However in many cases the two diagrams are used, even if only as a guideline, to evaluate the structures of semi-finished parts in the annealed or soluble state (castings, laminates, forged, drawn etc.)[11].

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[11] *It is worth noting that the Schaeffler diagram must never be used to define the microstructural specifications of steel based on its chemical composition. Although quantity-based data can also be obtained, it mustalways be taken into account that the microstructuresand semi-finished products in stainless steel are always highly influenced by the heat treatment applied, as well as the presence of local irregularities in the chemical composition, obviously in addition to the values of Req and Nieq.*

4. STAINLESS STEEL REFERENCE STANDARDS

On a European scale, the reference standard for stainless steels is EN 10088, parts 1 to 5 (in Italy this is implemented with the pre-fix UNI-EN): this standard lists the various types of stainless steel, the relative chemical compositions, the physical and mechanical properties, and heat treatments, also specifying the technical conditions for the supply of flat semi-finished and long semi-finished products.

As well as the European standard, another useful standard is still used, though now "old fashioned", which are the AISI (American Iron and Steel Institute) standards, the last edition of which dates back to the 1990s: this standard, as in the case of all US standards, refers to a method of designation in which each type of stainless steel has a specific progressive number within a specific grade (or class). The AISI standards was then taken over by the ASTM (American Society for Testing and Materials) which quotes its reference in its own standards packages[12].

The AISI standard divides stainless steels into set grades; the most common are the following:

- 200 series: chromium-manganese austenitic stainless steels
- 300 series: chromium-nickel austenitic stainless steels
- 400 series: chromium martensitic and ferritic stainless steels
- 600 series: precipitation hardening stainless steels

While with the normal precautions specific to the case, an approximate correspondence can nevertheless be established between the European standard symbols and the AISI symbols used. As regards the main types of stainless steel (as outlined above), the corresponding AISI types are as follows[13]:

- martensitic stainless steel type X30Cr13 corresponds approximately to type AISI 420,
- ferritic stainless steel type X6Cr17 corresponds approximately to type AISI 430,
- austenitic stainless steel types X5CrNi18-10 and X5CrNiMo17-12-2 correspond approximately to types AISI 304 and AISI 316.

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[12] *This is the case, for example, of the standard ASTM A240/A240M entitled "Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications" or the standard ASTM A473 entitled "Standard Specification for Stainless Steel Forgings" which state, together with the UNS designation (Unified Numbering System), the equivalent AISI designation, if this exists.*

[13] *In this document, as regards the section on equivalents between the standards, it was decided to use the term "corresponding approximately to" or "similar to" to avoid misleading information and the reader's presumption that the corresponding designations are identical to one another.*

5. NOTES ON THE MARKET OF STAINLESS STEELS

Although the production of stainless steels represents just a fraction of the overall production of steel (approx. 2% of all semi-finished products) it nevertheless is of significant importance, both in terms of the high unit value of the marketed product (with a market share of around 15%) and in terms of the fact that the use of stainless steel, in certain specific applications, is an absolute necessity.

Approximately three quarters of the world production of stainless steel is for flat semi-finished articles (sheets, strips, etc.); only one quarter derives from long semi-finished products (bars, rods, wires, profiles etc.).

As a consequence of the market shares described above, the sector for the production of long semi-finished products has a much more flexible response to market demands (with more types and formats available) with respect to the case of flat semi-finished products which tends to be more standardised.

A basic and guideline schematic on how the various families of stainless steel are used is illustrated in figure 13, which makes a distinction between flat and long semi-finished products.

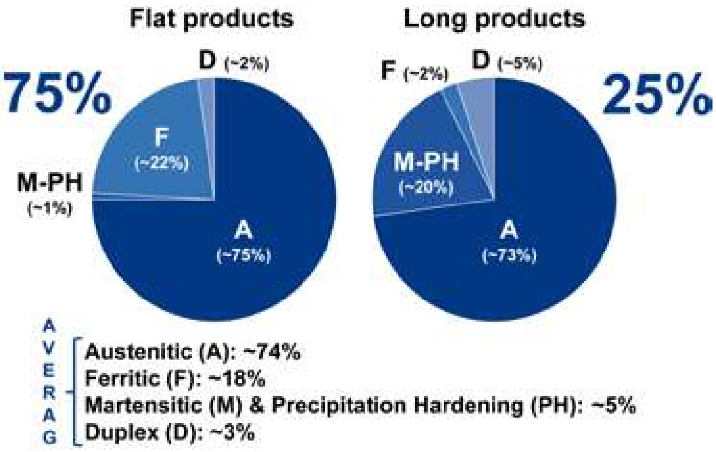


Figure 13 – Guideline schematic of world production/use of stainless steels, divided by flat and long semi-finished products.

Among the types of stainless steel most used, the lion’s share is certainly taken by the austenitic stainless steel grades, which cover the most substantial applications (flat and long semi-finished products), and consequently this type represents the most significant portion of world stainless steel production. Less used, but no less important, are the ferritic and martensitic stainless steels. The more “niche” type applications regard the austen-ferritic and precipitation hardening stainless steels.

The main intended uses of stainless steels are summarised in table 1.

SECTOR AND/OR APPLICATIONS	%
Petrochemical and energy (iOn-shore and off-shore plants, oil extraction and production industries, resource and natural gas transport systems, undersea equipment, geothermic, solar and photovoltaic plants, etc.)	12 – 14
Process industries (chemical, petrochemical and pharmaceutical industries, transformation and production of semi-finished products and components industries, food industries, pulp and paper industries, water treatment and desalination plants, etc.)	18 – 20
Transport (Cars, bicycles and motorcycles, heavy goods vehicles, trains, ships and boats etc.)	12 – 14
Building, architecture and urban furnishing (Architectural monuments and structures, facades and roofs, flues and chimneys, handrails and railings, escalators and elevators, water distribution pipes, etc.)	16 – 18
Appliances and household items (Pots, cutlery, washing machines, dishwashers, sinks, taps and general cooking utensils etc.)	34 – 36
Other	~ 3

Table 1 – Main fields of application of stainless steel

Bear in mind that approximately 55% of the stainless steel produced (flat and long semi-finished products) is normally used for the manufacture of durable goods and components – industrial plants, construction and transport – while 45% is used for consumables, above all household appliances and goods.
These two markets differ significantly: while in the first case the final user looks mainly to the metallurgical characteristics of stainless steel used, comparing performance and costs with other materials such as coated steel, aluminium alloys, plastic materials etc., in the case of consumables, the technical specifications pass to second place with respect to the cost of the product and current market conditions.

6. MARTENSITIC STAINLESS STEELS

6.1 Metallurgy

As can be observed in the Schaeffler diagram, the martensitic family of stainless steels is characterised by limited chromium content (normally between 11.5% and 18%) and carbon contents among the highest of the stainless steels most commonly used (generally between 0.1% and 1%).

Chromium, a highly ferritising element, and carbon, an austenitising element, are balanced so that the steel has an austenitic structure at high temperature and a martensitic structure at ambient temperatures after tempering.

It must be pointed out that the presence of a high content of carbon, required to ensure a good level of hardness and mechanical resistance for the steel, also tends to aid the formation of chromium carbides. Consequently martensitic stainless steels are, among all types, the least resistant to corrosion; their field of application in fact is limited to only slightly aggressive environments.

The chemical composition of some of the main types of martensitic stainless steels and relative designation according to EN 10088 are shown in table 2.

Figure 14 illustrates the "metallurgical" logic that has led to the creation of the main types of martensitic stainless steels, starting with X30Cr13 (similar to AISI 420B), the progenitor of this family, and still today widely used in the knife sector.

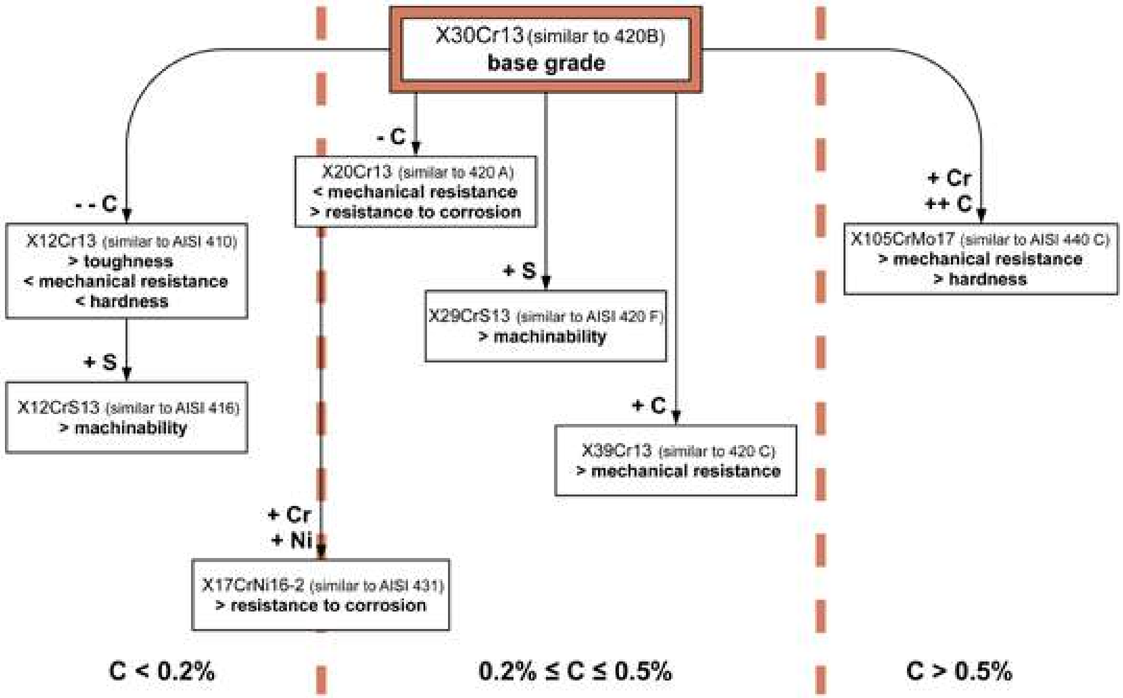


Figure 14 – Schematic of the main types of martensitic stainless steels, starting from X30Cr13 (similar to AISI 420B), progenitor of this family.

EN Designation	%C	%Si	%Mn	%P	%S	%Cr	Other	AISI approximate correspondence
X12Cr13 (1.4006)	0,08-0,15	≤1,00	≤1,50	≤0,040	≤0,015	11,5-13,5	1	AISI 410
X12CrS13 (1.4005)	0,08-0,15	≤1,00	≤1,50	≤0,040	0,15-0,35	12,0-14,0	2	AISI 416
X20Cr13 (1.4021)	0,16-0,25	≤1,00	≤1,50	≤0,040	≤0,015	12,0-14,0	---	AISI 420 (420A*)
X30Cr13 (1.4028)	0,26-0,35	≤1,00	≤1,50	≤0,040	≤0,015	12,0-14,0	---	AISI 420 (420B*)
X39Cr13 (1.4031)	0,36-0,42	≤1,00	≤1,00	≤0,040	≤0,015	12,5-14,5	---	AISI 420 (420C*)
X29CrS13 (1.4029)	0,25-0,32	≤1,00	≤1,50	≤0,040	0,15-0,25	12,0-13,5	3	AISI 420F
X17CrNi16-2 (1.4057)	0,12-0,22	≤1,00	≤1,50	≤0,040	≤0,015	15,0-17,0	4	AISI 431
X105CrMo17 (1.4125)	0,95-1,20	≤1,00	≤1,00	≤0,040	≤0,015	16,0-18,0	5	AISI 440C
X3CrNiMo13-4 (1.4313)	≤0,050	≤0,70	≤1,50	≤0,040	≤0,015	12,0-14,0	6	---
X4CrNiMo16-5-1 (1.44185)	≤0,060	≤0,70	≤1,50	≤0,040	≤0,015	15,0-17,0	7	---

*The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 420B)

Notes:

1: %Ni ≤ 0,75
2: %Mo ≤ 0,60
3: %Mo ≤ 0,60
4: 1,50 ≤ %Ni ≤ 2,50
5: 0,40 ≤ %Mo ≤ 0,80
6: 3,50 ≤ %Ni ≤ 4,50; 0,30 ≤ %Mo ≤ 0,70; %N ³ 0,020
7: 4,00 ≤ %Ni ≤ 6,00; 0,80 ≤ %Mo ≤ 1,50; %N ³ 0,020

Table 2 – Chemical composition of some of the main types of martensitic stainless steels [from EN 10088].

The phase diagrams that can be used as a reference to further understand the metallurgy of martensitic stainless steels are illustrated in figure 15 and figure 16: these envisage the existence of critical points, i.e. the possibility of transformation $\gamma \rightarrow \alpha$, in a similar manner to that which occurs on the classic Fe-C phase diagram. For example, this is what happens when the carbon content is around 0.3%, such as in the case of X30Cr13 (similar to AISI 420B) or when it is around 1% such as in the case of X105CrMo17 (similar to AISI 440C).

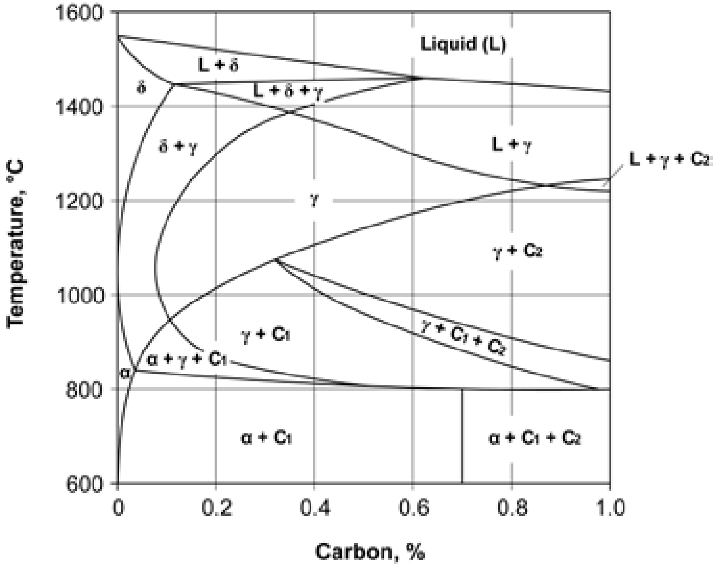


Figure 15 – Binary section Fe-C of Fe-Cr-C ternary diagram with Cr = 13%; C_1 carbides type $(Cr,Fe)_{23}C_6$, C_2 carbides type $(Cr,Fe)_7C_3$ [from Lippold and Kotecki 2005].

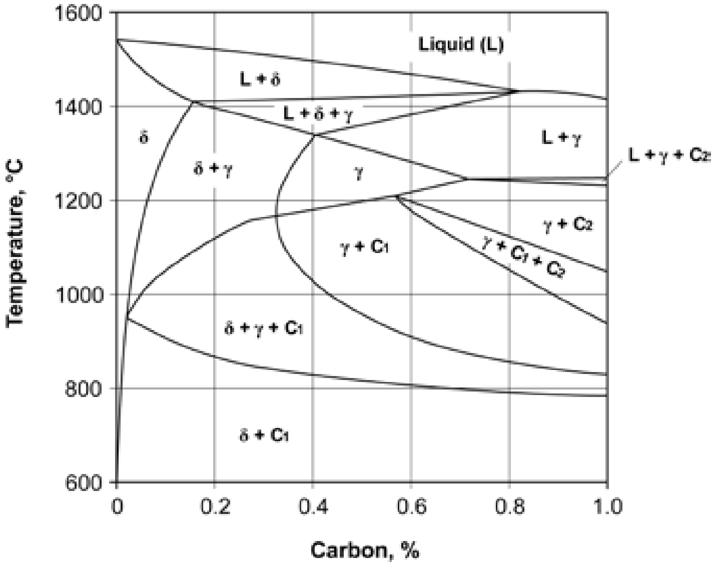


Figure 16 – Binary section Fe-C of Fe-Cr-C ternary diagram with Cr = 17%; C_1 carbides type $(Cr,Fe)_{23}C_6$, C_2 carbides type $(Cr,Fe)_7C_3$ [from Lippold and Kotecki 2005].

Therefore when the steel is heated to temperatures above the critical points, the original microstructure transforms completely into austenite plus carbides, to then become martensite plus carbides under the effect of cooling the steel in oil or in air.

Note that the addition of carbon (or nitrogen or nickel) aids expansion of the field of existence of phase γ thereby obtaining a martensitic structure after tempering, also in the case of chromium contents well above 13.4%, the threshold envisaged by the Fe-Cr diagram (refer back to figure 5).

Given the existence of critical points, it is therefore possible to trace the isothermal transformation curves (TTT) and anisothermal curves (CCT) of the austenite: these curves are shown in figure 17 for a martensitic stainless steel grade. As already indicated previously, the presence of stable carbides, both at high and low temperatures, can be explained due to the high carbon content, which aids formation of the carbides.

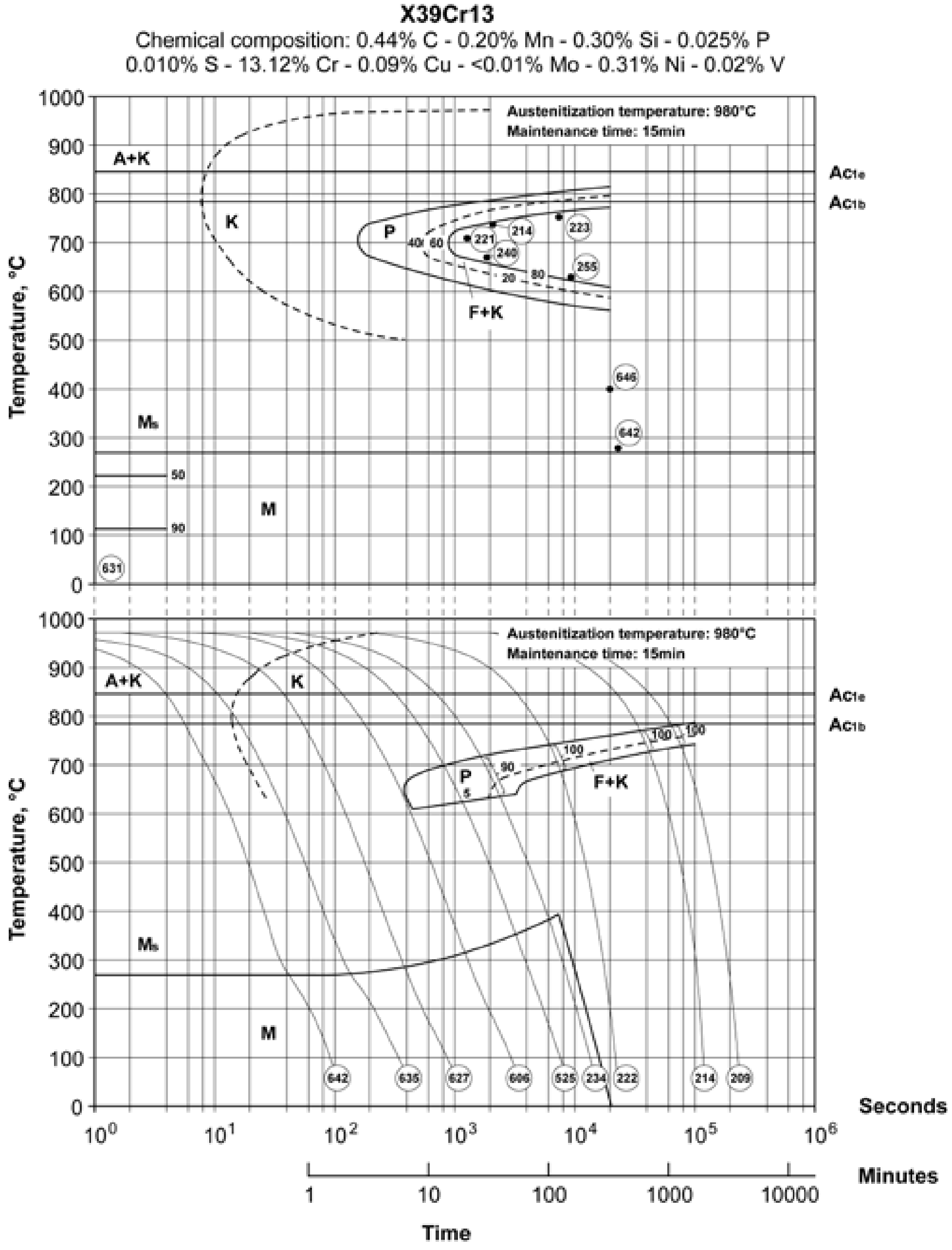
Also note, given the great quantity of alloy elements present, that the TTT curves and CCT curves shift significantly to the right and downwards, with respect to the temperature-time axes: this greatly aids the hardenability of the steel (martensitic stainless steels are in fact self-hardening steels) but at the same time this may lead to the presence of residual austenite (above all for the types with high carbon content) and the formation of quench cracks.

6.2 Heat treatments

Before using semi-finished products in martensitic stainless steel, they must undergo heat treatment to obtain a structure adequately workable for the machine tools. For this purpose, as in the case of traditional special steels for construction, an annealing process could be performed (complete or isothermal annealing). However, in practice a sub-critical annealing process is used on martensitic stainless steels, i.e. a heat treatment at temperatures from 730°C – 830°C for several hours, followed by gradual cooling in the furnace or air: this obtains a globular pearlite structure characterised by a matrix of phase α with globular carbides.

During execution of the heat treatments on martensitic stainless steels, special attention must always be paid to the phenomena of surface decarburisation and that of chromium oxidation under heat, due to the oxygen present in the treatment atmosphere. To remedy this situation, in many cases, users resort to treatment processes in furnaces with a controlled neutral or reducing atmosphere (nitrogen or nitrogen/hydrogen atmosphere).

The technological process that obtains a component in martensitic stainless steel (such as a power drive shaft for applications in the marine sector) envisages the use of an annealed semi-finished piece; all necessary roughing operations are performed on this part using machine tools to bring it to dimensions close to those of the finished piece, minus an adequate machine allowance.



A + K	Austenite and carbides	**RA**	Retained Austenite
K	Carbides	**F**	Ferrite
P	Pearlite	**F + K**	Non lamellar eutectoid
O	Vickers Hardness, HV	**Ac_{1b}**	= 790°C
M	Martensite	**Ac_{1e}**	= 850°C
B	Bainite	**M_s**	= 280°C

Figure 17 – Isothermal transformation curves (TTT) and anisothermal transformation curves (CCT) for martensitic stainless steel type X39Cr13 (similar to AISI 420C) [from Wever et al. 1954/56/58].

The semi-finished part, roughed by machine tools, then undergoes the hardening treatment: this gives it the mechanical properties and characteristics of resistance to corrosion, aimed at ensuring optimal behaviour during operation. Lastly the mechanical finishing processes are performed on the machine tools to obtain a semi-finished part with the dimensions and tolerances as required on the finished piece.

A schematic of the technological process required to obtain a component in martensitic stainless steel is shown in figure 18.

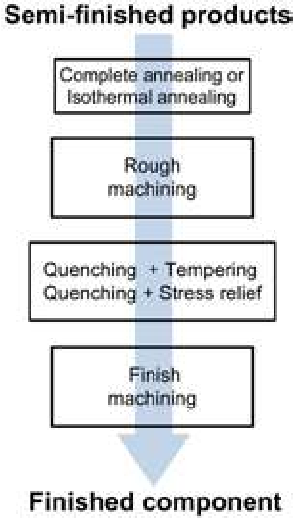


Figure 18 – Technological process required to obtain a component in martensitic stainless steel.

With regard to the hardening heat treatment of martensitic stainless steels, a number of important factors must be taken into account.

The heating phase during tempering must be managed with care. Martensitic stainless steels, as in the case of all stainless steels, feature very low conductivity: to avoid permanent deformation of parts, or even worse breakage, the heating phase must be controlled (such as stepped heating, with pre-heating to between 550°C and 800°C), especially in the case of large size parts and/or parts with complex geometry.

As regards the subsequent austenitisation phase, a higher temperature must be envisaged with respect to those usually used for common heat-treatable steels: martensitic stainless steels are in fact heated and held at temperatures ranging from 950° C – 1100° C[14]. As well as to obtain an austenitic structure, these high temperatures are necessary to aid, as far as possible, solubilisation of any carbides present, thus creating the carbon in a solid solution for hardening of the martensite during the subsequent tempering phase (see figure 19).

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[14] *On increase of the carbon (and chromium) content, there is a proportional increase in the steel austenitisation temperature.*

However, there is an optimal temperature for austenitisation, over which phenomena occur such as grain enlargement, which then predominate the process with a consequent reduction in resistance properties of the steel (see figure 20).

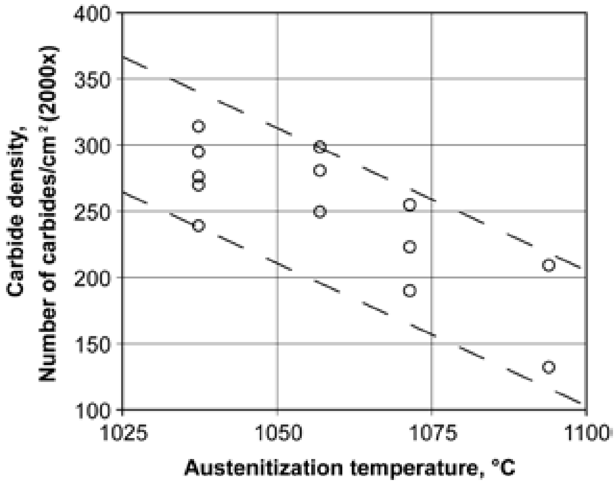

Figure 19 – Effect of the austenitisation temperature on the density of chromium carbides present after tempering on a martensitic stainless steel with 0.65%C - 12.8% Cr - 0.4%Si - 0.65%Mn [from Verhoeven 2007].

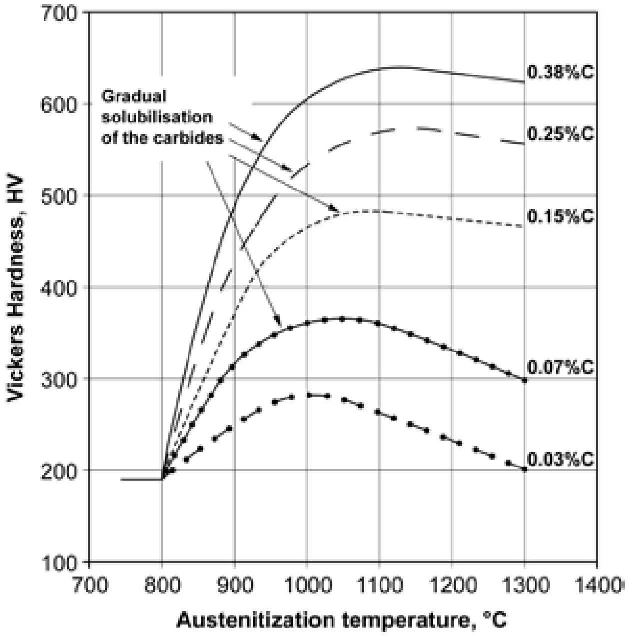

Figure 20 – Effect of the austenitisation temperature on the hardness of a martensitic stainless steel at 13%Cr with increasing carbon content (quenched in oil and then stress relieved at 200°C) [from Lacombe et al. 1993].

The austenitisation temperature of martensitic stainless steels however must not be increased as required: this would increase the risk of enlarging the crystalline grain and the probability of obtaining residual austenite at ambient temperatures, above all in the case of steels with high carbon content (see figure 21).

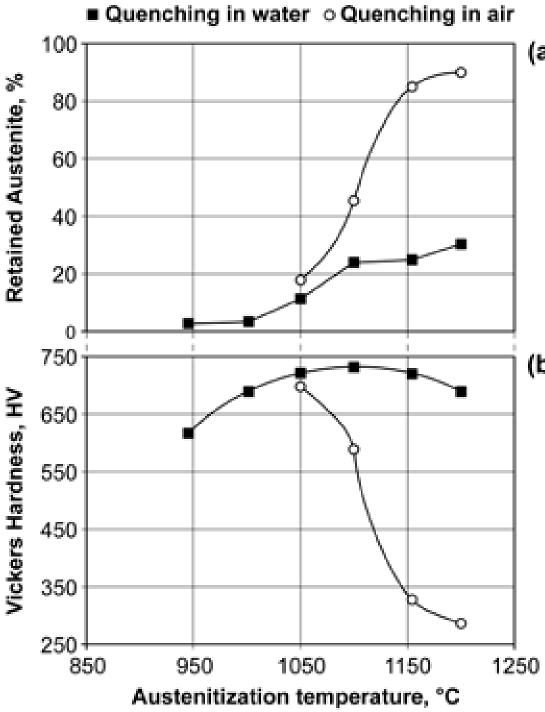

Figure 21 – Effect of the austenitisation temperature and tempering method on the hardness and % of residual austenite in a martensitic stainless steel with 0.4%C - 16% Cr - 0.9%Mo - 0.5%Ni [from Lacombe et al. 1993].

Due to their particular chemical composition, martensitic stainless steels, as previously noted, are self-tempering steels, and even harden by simple air cooling; however very often oil cooling may be envisaged (oil tempering), especially in the case of large to medium size parts, to achieve a uniform microstructure and increase uniformity of response along the resistant section of the component.

The tempering phase, always necessary after hardening treatment, also has a number of special features. Tempering, as mentioned for special construction steels, is performed to reduce brittleness of the fully quenched martensite and to reduce residual tension generated in the part during the tempering treatment. In the case of martensitic stainless steels, tempering is performed at low temperatures (below 400°C) or at high temperatures (over 640°C). Great care is taken to prevent the tempering process from taking place within the temperature range of 450°C to 600°C: this interval is considered critical as it reduces resistance to brittle fractures (a type of temper brittleness) and significantly reduces corrosion resistance (see figure 22).

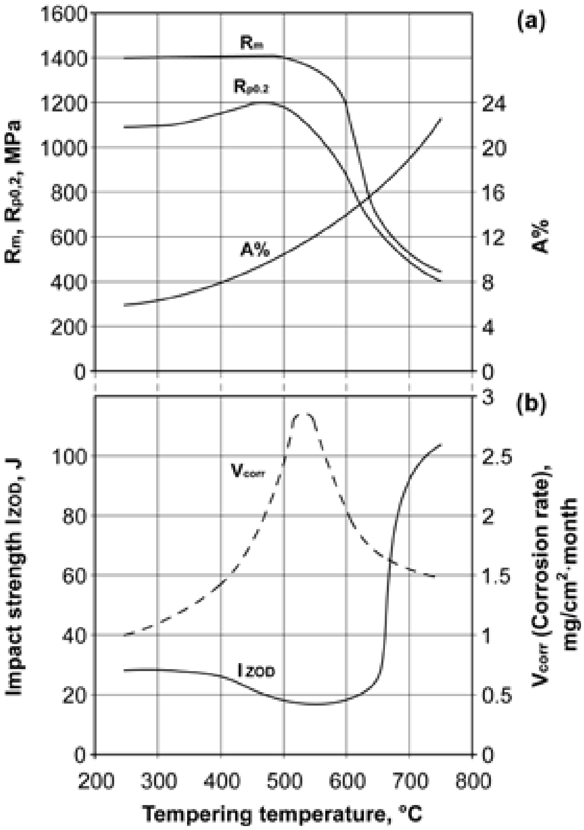

Figure 22 – Effect of tempering temperature on mechanical properties and corrosion resistance of a martensitic stainless steel type X20Cr13 (similar to AISI 420A) [from Sedriks 1996].

By tempering martensitic stainless steels at temperatures below 400°C (in these cases it is known as stress relieving) maximum hardness is obtained, along with the highest values of tensile strength and resistance to corrosion. Even though a certain brittleness remains in the martensitic structure not fully tempered, stress relief is the method envisaged by standards, normally performed on an industrial level on small size components in martensitic stainless steel.

Alternatively tempering can be performed at temperatures over 640°C (up to even a maximum of 750°C): this second case will obtain further strength and resistance to fracturing of the steel (with respect to the case of stress relief at temperatures below 400°C), combined however with a more limited hardness and reduced resistance to corrosion.

The heat treatment methods for some of the most common martensitic stainless steels are summarised table 3.

EN Designation	Annealing Subcritical annealing	Cooling in	Austenitization	Quenching in	Stress Relieving	AISI approximate correspondence
X12Cr13 (1.4006)	820°C-900°C 730°C-790°C	furnace calm air	930°C-1010°C	oil, air	600°C-750°C 150°C-400°C	AISI 410
X12CrS13 (1.4005)	820°C-900°C 730°C-790°C	furnace calm air	930°C-1010°C	oil, air	600°C-750°C 150°C-400°C	AISI 416
X20Cr13 (1.4021)	840°C-900°C 730°C-790°C	furnace calm air	950°C-1050°C	oil, air	600°C-750°C 150°C-400°C	AISI 420 (420A*)
X30Cr13 (1.4028)	840°C-900°C 730°C-790°C	furnace calm air	950°C-1050°C	oil, air	600°C-700°C 150°C-400°C	AISI 420 (420B*)
X39Cr13 (1.4031)	840°C-900°C 730°C-790°C	furnace calm air	950°C-1050°C	oil, air	600°C-700°C 150°C-400°C	AISI 420 (420C*)
X29CrS13 (1.4029)	840°C-900°C 730°C-790°C	furnace calm air	950°C-1050°C	oil, air	600°C-700°C 150°C-400°C	AISI 420F
X17CrNi16-2 (1.4057)	840°C-900°C 680°C-790°C	furnace calm air	950°C-1050°C	oil, air	600°C-700°C 150°C-400°C	AISI 431
X105CrMo17 (1.4125)	840°C-900°C 730°C-770°C	furnace calm air	1010°C-1070°C	oil, air	150°C-400°C	AISI 440C
X3CrNiMo13-4 (1.4313)	hot forming**	air	950°C-1050°C	oil, air	600°C-700°C	---
X4CrNiMo16-5-1 (1.4418)	hot forming**	air	950°C-1050°C	oil, air	600°C-700°C	---

*The designation indicated does not refer to the AISI standard; it is often referred to as the “type” (for example type 420B).
**These steels are cooled in air after hot plastic deformation and can be used as such or can be quenched and tempered.

Table 3 – Guideline characteristics of heat treatment on some of the main types of martensitic stainless steels.

6.3 Physical and mechanical properties

The physical properties of martensitic stainless steels are very similar to those of the common heat-treatable steels, sharing the same martensitic tempered microstructure (see table 4).

The mechanical properties of martensitic stainless steels depend on the heat treatment applied. While in the annealed state, hardness values of around 160-250 HB are obtained, when in the hardened state most martensitic stainless steels have a unit resistance under traction R_m of between 700 MPa and 1700 MPa depending on the chemical composition and tempering conditions; the fatigue limit in air remains around the value $0.45 \cdot R_m$.

Table 5 shows the mechanical properties obtainable for each type of martensitic stainless steel according to the different heat treatment applied.

Brittle fracture also strongly depends on the chemical composition and heat treatment conditions of the steel. In proportion to the increase in carbon content, phosphorous, and the average size of the crystalline grain (i.e. to the increase in austenitisation temperature), the strength of the steel is reduced, while the transition temperature increases.

Figure 23 illustrates the trend of the transition curves for a number of commonly used martensitic stainless steels: note the behaviour virtually identical to that of special heat-treatable steels used frequently in industrial applications.

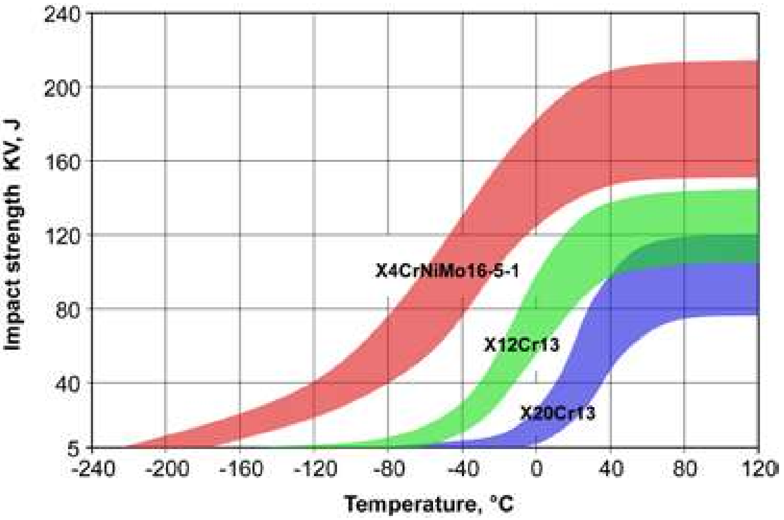

Figure 23 – transition curves for a number of commonly used martensitic stainless steels after quenching and tempering at 650°C.

EN Designation	Mass volume [kg/dm^3]	Specific heat at 20°C [J·kg^{-1}·K^{-1}]	Electrical resistance at 20°C [W·mm^2·m^{-1}]	Thermal conductivity [W·m^{-1}·K^{-1}]	Linear thermal expansion [10^{-6}·K^{-1}]		Modulo elastico [GPa]		AISI approximate correspondence
					from 20°C to 100°C	from 20°C to 200°C	to 20°C	to 200°C	
X12Cr13 (1.4006)	7,7	460	0,60	30	10,5	11,0	215	205	AISI 410
X12CrS13 (1.4005)	7,7	460	0,60	30	10,5	11,0	215	205	AISI 416
X20Cr13 (1.4021)	7,7	460	0,60	30	10,5	11,0	215	205	AISI 420 (420A*)
X30Cr13 (1.4028)	7,7	460	0,65	30	10,5	11,0	215	205	AISI 420 (420B*)
X39Cr13 (1.4031)	7,7	460	0,55	30	10,5	11,0	215	205	AISI 420 (420C*)
X29CrS13 (1.4029)	7,7	460	0,55	30	10,5	---	215	205	AISI 420F
X17CrNi16-2 (1.4057)	7,7	430	0,70	25	10,0	10,5	215	205	AISI 431
X105CrMo17 (1.4125)	7,7	460	0,80	15	10,4	10,8	215	205	AISI 440C
X3CrNiMo13-4 (1.4313)	7,7	430	0,60	25	10,5	10,9	200	185	---
X4CrNiMo16-5-1 (1.4418)	7,7	430	0,80	15	10,3	10,8	200	185	---

*The designation indicated does not refer to the AISI standard; it is often referred to as the “type” (for example type 420B)

Table 4 – Guideline physical properties of some of the main types of martensitic stainless steels [from EN 10088].

EN Designation	Metallurgical condition	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	Hardness	AISI approximate correspondence
X12Cr13 (1.4006) X12CrS13 (1.4005)#	A	300-400	500-600	18-28	160-200 HB	AISI 410 AISI 416
	A + CD**	450-900	650-1000	12-18	---	
	Q T 200°C	1000-1250	1350-1500	11-16	42-46 HRC	
	Q T 350°C	950-1150	1250-1400	11-17	40-44 HRC	
	Q T 650°C	550-700	650-850	18-24	16-24 HRC	
X20Cr13 (1.4021) X17CrNi16-2 (1.4057)	A	350-450	550-700	16-26	220-260 HB	AISI 420 (420A*) AISI 431
	A + CD**	500-900	700-1100	12-18	---	
	Q T 200°C	1050-1300	1350-1550	11-16	42-46 HRC	
	Q T 350°C	1000-1200	1250-1450	11-17	40-44 HRC	
	Q T 650°C	600-800	750-950	16-20	21-25 HRC	
X30Cr13 (1.4028) X39Cr13 (1.4031) X29CrS13 (1.4029)#	A	350-450	550-700	14-24	180-220 HB	AISI 420 (420B*) AISI 420 (420C*) AISI 420F
	A + CD**	600-1000	700-1200	10-16	---	
	Q T 200°C	1250-1400	1550-1750	10-15	48-52 HRC	
	Q T 350°C	1200-1350	1450-1650	10-16	45-49 HRC	
	Q T 650°C	650-900	800-1050	14-18	22-28 HRC	
X105CrMo17 (1.4125)	A	400-550	650-800	12-20	230-270 HB	AISI 440C
	A + CD**	600-900	750-1100	8-14	---	
	Q T 200°C	1650-1900	1900-2100	4-8	56-60 HRC	
	Q T 350°C	1600-1750	1750-1900	4-8	54-58 HRC	
X3CrNiMo13-4 (1.4313)	Hot formed Q T 650°C	550-750	650-900	18-24	16-24 HRC	---
X4CrNiMo16-5-1 (1.4418)		650-850	750-1000	16-22	24-32 HRC	

*The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 420B).
A: Annealed
A + CD: Annealed and Cold Drawn
Q T: Quenched and Tempered at the indicated temperature
**The values of the mechanical features in the condition A + CD are variable as they very much depend on the hardening conditions
The types with sulphur have a slightly lower elongation to failure that the equivalent types without sulphur.

Table 5 – Guideline mechanical properties of some of the main types of martensitic stainless steels.

6.4 Types and applications

The semi-finished products in martensitic stainless steel commercially available are either annealed or pre-hardened, predominantly in the form of long products (bars and rods); only in some cases flat semi-finished products are manufactured (strips and sheets), especially for the sector of cutting blades.

The martensitic stainless steels most commonly used in industrial sectors are X30Cr13 (similar to AISI420B[15]) and X12Cr13 (similar to AISI 410): among the two, the first will guarantee hardness with a higher carbon content, while the second features increased strength.

These two steels are widely used where high mechanical resistance and wear resistance is required. Corrosion resistance is good, especially in rural environments, fresh water not contaminated by chlorides, in contact with foodgrade substances, or with weak acids (such as organic acids), with petrol products (crude and intermediate) and with oxidating saline solutions (chromates, permanganates, etc.).

These are frequently used for the production of table knives, industrial cutting knives, surgical instruments, rasors, scissors, callipers, machine gun barrels, brake disks for motor vehicles; they are also used in the sector of moulds for plastic materials and for springs.

Another specific use of this steel grade is for the manufacture of power drive shafts in mildly aggressive environments, steam turbine blades or compressor blades, con rods, bushings for pumps and compressors, filters, bathroom fittings, hardware, handles, coins and medals.

Type X29CrS13 (similar to AISI420F) and type X12CrS13 (similar to AISI 416) are the same as the two steel types described above (X30Cr13 and X12Cr13) but with improved machinability due to the significant presence of sulphur (approx. 0.2%). This means that strength is limited, and above all weldability will prove to be very difficult. Furthermore, resistance to corrosion is slightly lower than that of the same steel types without sulphur.

Type X17CrNi16-2 (similar to AISI 431[16]) is must more resistant to corrosion with respect to those described above, due to the increased chromium content in the alloy: it also offers increased strength due to the presence of nickel (not present in types X30Cr13 and X12Cr13).

The steel type X17CrNi16-2 is used in particular for shafts on marine engines, propeller shafts, pump parts, hydraulic machinery shafts, valves, turbine blades and wear-resistant components in reforming oil plants.

Worth noting here is also type X105CrMo17 (similar to AISI 440C[17]): this steel, due to the significant content

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[15] *AISI standards divide type 420 into three sub-groups, of low, medium and high carbon content. Type 420A with an average carbon content of 0.2%, type 420B with an average carbon content of 0.3% and type 420C with an average carbon content of 0.4%: on increase of the carbon content, there is a proportional increase in hardness at the same time sensitivity to carbide formation.*

[16] *In fact the AISI standard envisages two martensitic stainless steels with nickel contents ranging between 1.25% and 2.5%: AISI 414 and AISI 431. AISI 414 envisages a carbon content of approximately 0.15% while in the case of AISI 431 it is approximately 0.20%. In the case of EN 10088, the type X17CrNi16-2 envisages a carbon content ranging from 0.12% to 0.22%.*

[17] *Also in this case the AISI standard envisages a low carbon type (AISI 440A with %C 0.60-0.75), medium carbon (AISI 440B with %C 0.75-0.95%) and high carbon content (AISI 440C with %C 0.95-1.20%)*

of chromium and carbon, offers good resistance to corrosion (comparable with that of type X12Cr13) and, after hardening, ensures excellent durability and resistance to wear; on the contrary fracture toughness is reduced.

This is used to parts resistant to wear, oxidation or to wear and corrosion, such as the production of chains working at high temperatures, special ball bearings and surgical instruments for special applications.

Lastly, the types X3CrNiMo13-4 and X4CrNiMo16-5-1, known also as “super-martensitic”, which represent two examples of martensitic stainless steel with a low content of carbon with nickel and molybdenum: these materials, at the end of the manufacturing process (for example downline of hot rolling) offer good mechanical resistance and high strength, even without heat treatment.

Tubular products manufactured using these steels are used in the chemical and oil sector as fluid carriers or as structural elements or, also, for the construction of heat exchangers. These offer optimal resistance to attack in environments rich in H_2S e CO_2, where they can be used without the addition of corrosion inhibitors.

7. FERRITIC STAINLESS STEELS

7.1 Metallurgy

When the chromium content in an alloy reaches values of 17% (or greater) and, at the same time, the presence of carbon is reduced (content below 0.1%), the ferritising effect of the chromium is no longer compensated for by the austenitising action of the carbon and, as envisaged in the Schaeffler diagram, the structure of the stainless steel will be ferritic at ambient temperatures: this is precisely what occurs on steel type X6Cr17 (similar to AISI 430), the progenitor of ferritic stainless steels.

Commercially available ferritic stainless steels however are not limited to just this chemical composition, there are in fact various types, roughly divided into three families, according to the relative chromium content in the alloy.

Figure 24 illustrates the "metallurgic" logic that led to the creation of the main types of ferritic stainless steels present on the market, starting from type X6Cr17, the progenitor of this family; on the other hand, table 6 shows the chemical composition of some of the main types of ferritic stainless steels and the relative designation in accordance with the standard EN 10088.

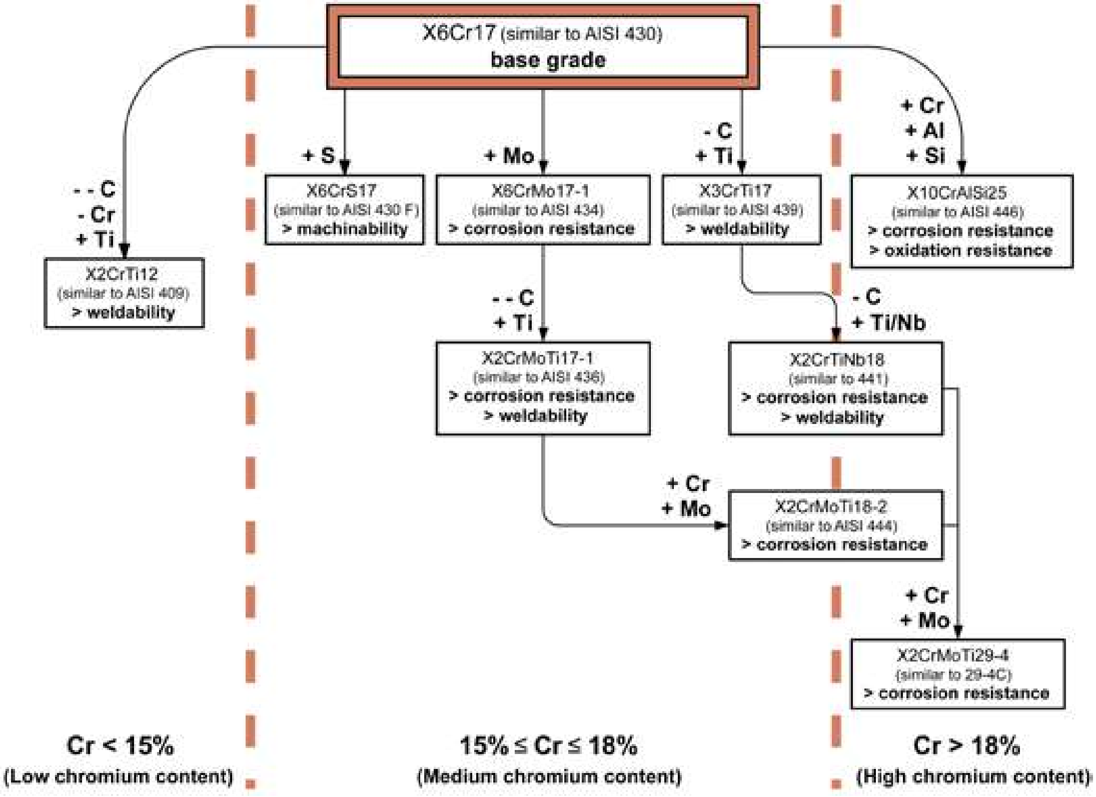

Figure 24 – Schematic of the main types of ferritic stainless steels, starting from X6Cr17 (similar to AISI 430), progenitor of this family.

EN Designation	%C	%Si	%Mn	%P	%S	%Cr	%Mo	Other	AISI approximate correspondence
X2CrTi12 (1.4512)	≤0,03	≤1,00	≤1,00	≤0,040	≤0,015	10,5-12,5	---	1	AISI 409
X6Cr17 (1.4016)	≤0,08	≤1,00	≤1,00	≤0,040	≤0,015	16,0-18,0	---	---	AISI 430
X6CrMoS17 (1.4105)	≤0,08	≤1,50	≤1,50	≤0,040	0,15-0,35	16,0-18,0	0,20-0,60	---	AISI 430F
X3CrTi17 (1.4510)	≤0,05	≤1,00	≤1,00	≤0,040	≤0,015	16,0-18,0	---	2	AISI 439 (430Ti*)
X6CrMo17-1 (1.4113)	≤0,08	≤1,00	≤1,00	≤0,040	≤0,015	16,0-18,0	0,90-1,40	---	AISI 434
X2CrMoTi17-1 (1.44513)	≤0,025	≤1,00	≤1,00	≤0,040	≤0,015	16,0-18,0	0,80-1,40	3	AISI 436
X2CrMoTi18-2 (1.4521)	≤0,025	≤1,00	≤1,00	≤0,040	≤0,015	17,0-20,0	1,80-2,50	4	AISI 444
X2CrTiNb18 (1.4509)	≤0,03	≤1,00	≤1,00	≤0,040	≤0,015	17,5-18,5	---	5	441*
X10CrAlSi25 (1.4762)	≤0,12	0,70-1,40	≤1,00	≤0,040	≤0,015	23,0-26,0	---	6	AISI 446
X2CrMoTi29-4 (1.4592)	≤0,025	≤1,00	≤1,00	≤0,030	≤0,010	28,0-30,0	3,50-4,20	7	29-4C*

* The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 441).
1: $\%Ti = [6 x (C + N)] - 0{,}65$
2: $\%Ti = [4 x (C + N)+0{,}15] - 0{,}80$
3: $0{,}30 \leq \%Ti \leq 0{,}60$; $\%N \leq 0{,}020$
4: $\%Ti = [4 x (C + N)+0{,}15] - 0{,}80$; $\%N \leq 0{,}030$
5: $0{,}10 \leq \%Ti \leq 0{,}60$; $[3 x C +0{,}30] \leq \%Nb \leq 1{,}00$
6: $1{,}20 \leq \%Al \leq 1{,}70$; $1{,}20 \leq \%Si \leq 1{,}70$
7: $\%Ti = [4 x (C + N)+0{,}15] - 0{,}80$; $\%N \leq 0{,}045$

Table 6 – Chemical composition of some of the main types of ferritic stainless steels [from EN 10088].

The first family, to which the aforementioned type X6Cr17 belongs, has a chromium content ranging from 15.5% to 18%: this family is the most numerous in terms of the quantity of alloy types present on the market. There are a further two families, one characterised by chromium content ranging from 11.5% to 14.5% (ferritic stainless steels with low chromium content) and the other with a chromium content of more than 18% (known also as "superferritic" stainless steels).

In all three of the above families - with low, medium and high carbon chromium content - other alloy elements may also be present: these include aluminium and silica, aimed at stabilising the ferritic structure and improving resistance to oxidation under heat, molybdenum, necessary to improve corrosion resistance, titanium and niobium, to prevent precipitation of the harmful chromium carbides.

For a more comprehensive understanding of the structure of a general ferritic stainless steel with a high chromium content and very low carbon content, it is necessary to take into account the reference phase diagram. For this purpose, note how the original Fe-Cr diagram (already illustrated in figure 5) is modified, due to the presence of carbon at a percentage of around 0.05% (figure 25).

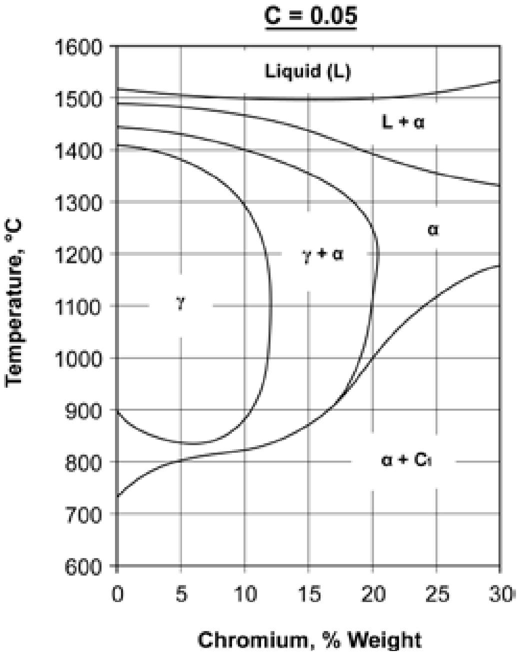

Figure 25 – Fe-Cr binary section of Fe-Cr-C ternary diagram for a steel containing 0.05% carbon; C_1 carbides type $(Cr,Fe)_{23}C_6$ [from McGuire 2008].

In the case of ferritic stainless steel type X6Cr17 initial solidification is noted in phase α followed by a two-phase transformation type $\gamma+\alpha$; subsequently, from temperatures of around 900°-950°C through to ambient temperature[18], the steel returns to a single phase state α with a ferrite grain structure.

Therefore if we attempt to temper this steel, for example by heating it to around 800°C to then cool it in water, no particular change in structure would occur and, after cooling, there would be no significant increase in resistance. In fact in the temperature range 20°-900°C there are no critical points to enable austenite → martensite transformation: this means that it would not be possible to apply the classic tempering heat treatment to increase the tensile strength of the steel (as otherwise is possible in the case of martensitic stainless steels).

Above 900°-950°C, as observed above, there is a two phase field of ferrite and austenite[19]: this is typical of non stabilised ferritic stainless steels with chromium content of 16%-17% .

On the one hand, the presence of small percentages of austenite at high temperatures is positive, in that it avoids excessive enlargement of the crystalline grain during annealing heat treatments.

Nevertheless, on the other hand the existence of austenite at high temperatures should be taken into due consideration due to another additional problem: if rapid cooling is performed immediately after heating at such high temperatures, the austenite could be transformed into martensite, causing problems of intergranular brittleness in the steel.

However, when the ferritic stainless steel contains stabilising elements, such as titanium and niobium, and/or a high content of chromium (more than 18%) or molybdenum (1-2%), its microstructure will be completely ferritic, starting from the melting temperature through to ambient temperature: this significantly improves weldability of these steels with respect to non-stabilised traditional types.

An additional metallurgical problem typical in stainless steels, including ferritic, is related to the precipitation of chromium carbides, type $Cr_{23}C_6$: as is known, this occurs due to the high level of affinity between the chromium and carbon, and can lead to the phenomena of intergranular corrosion in this material.

As the solubility of carbon in the body-centred cubic lattice is significantly limited, the precipitation of chromium carbides in ferritic stainless steels is practically impossible to eliminate. On the other hand, due to the high diffusivity of chromium in the lattice of phase α, the chromium gradients in the vicinity of the ferritic grain boundary are much less pronounced with respect to what occurs in austenitic stainless steels (refer also back to figure 10, and case “a” in particular): as a consequence the problems of intergranular corrosion in ferritic stainless steels, under the effect of carbide precipitation on the grain boundary, are less marked with respect to the same phenomena in austenitic stainless steels.

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[18] *The temperature at which the transition occurs, from a two phase structure $\gamma+\alpha$ to a single phase structure α depends on the chromium content in the alloy. The value specified at 900°-950°C is representative of a steel with chromium content of around 17%. If the chromium content is greater, the temperature would increase proportionally, and vice versa in the case of lower chromium contents.*

[19] *However, the entity of austenite present at high temperatures in non stabilised ferritic stainless steels is still limited: values remain at a maximum of 20%.*

To eliminate the problem of chromium carbides, it is often necessary to return to the source, i.e. the phase of processing steel in its liquid state: here stabilising elements are added, such as titanium and niobium, in an attempt to minimise the carbon content in the chemical composition of steel. Also, as explained further in the section below, the semi-finished products should also undergo a complete annealing heat treatment before being used.

Again in relation to the phenomena of deterioration due to temperatures, two further problems should be noted in relation to ferritic stainless steels: the formation of phase σ and embrittlement at 475°C.

Due to the harmful effects in terms of corrosion resistance and strength, the problem of the formation of phase σ (Fe-Cr phase) needs to be taken in due consideration exclusively as regards steels with high contents of chromium and molybdenum (superferritic); in these steels, the presence of molybdenum also contributes to additional harmful phases, such as χ and the Laves phase (in both cases, this regards Fe-Cr-Mo phases).

To eliminate any secondary phases present (σ, χ, Laves) the steel should be heated to temperatures of around 1050°C, followed by rapid cooling of the semi-finished product in water: this enables the chromium compounds to be solubilised, thereby preventing re-formation of the latter during cooling.

A typical example of the diagrams that illustrate the formation of carbides and secondary phases on variations in temperature and the time of exposure of the iron-chromium alloy is shown in figure 26.

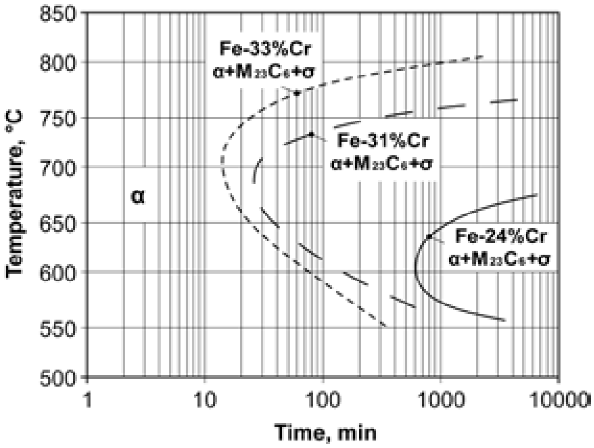

Figure 26 – Time-temperature diagram representing the formation of chromium carbides and phase σ in different Fe-Cr alloys [from Vander Voort 1991].

Embrittlement at 475°C is obviously a far more significant problem with respect to the formation of phase σ: in fact it affects a wider spectrum of ferritic stainless steels, with the only exception of those with a very low carbon content (Cr < 14%).

Also in this case, to be able to describe the phenomenon, time-temperature diagrams can be used, such as that shown in figure 27 or diagrams that illustrate the decline in strength in proportion to the embrittlement temperature according to variations in the exposure time (see figure 28).

The harmful effect of embrittlement at 475°C is eliminated by annealing at a temperature of around 550°-600°C for intervals however that do not lead to the formation of carbides/phase σ; subsequent cooling must be in air or water.

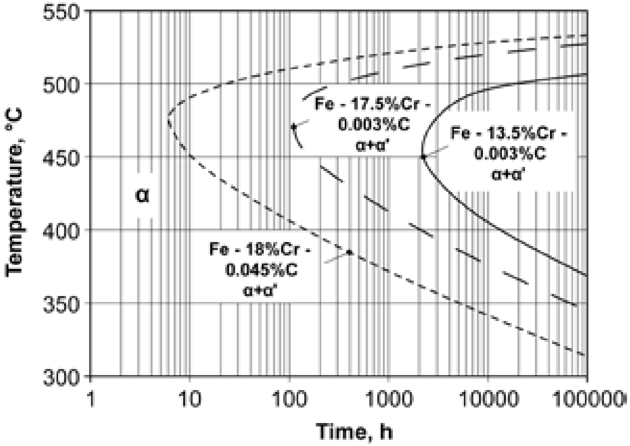

Figure 27 – Time-temperature diagram representing embrittlement at 475°C (spinodal decomposition of phase α in different Fe-Cr alloys [from Grobner 1973].

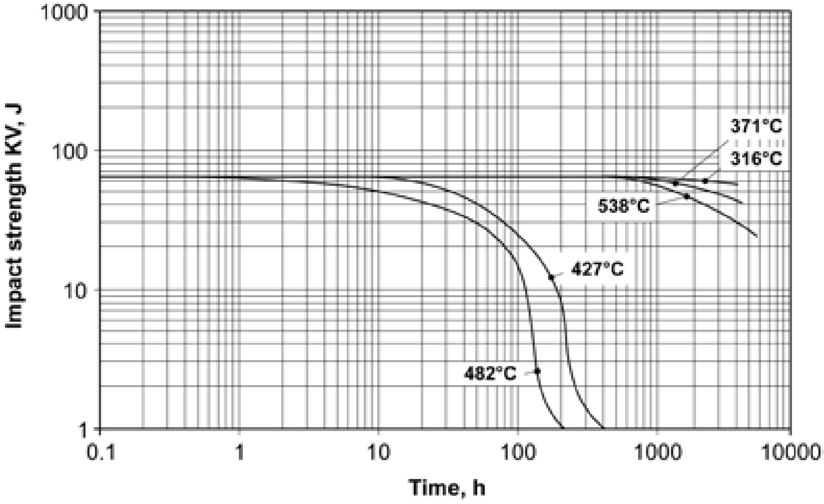

Figure 28 – Trends of strength of ferritic stainless steels with 18% chromium, aged at 316°C, 371°C, 427°C, 482°C e 538°C for progressively increasing time intervals [from Grobner 1973].

7.2 Heat treatments

The only heat treatment possible for the family of ferritic stainless steels is complete annealing or simply annealing: its role is to optimise corrosion resistance of the steel, aiding a uniform distribution of the chromium in the crystalline structure of the semi-finished part[20].

Annealing of ferritic stainless steels is performed at different temperatures depending on the chemical composition of the steel treated. Great care is taken in selecting the temperature and hold time, as this family of materials is particularly sensitive to the phenomena of crystalline grain enlargement. Table 7 shows the heat treatment methods to be adopted for the most common types of ferritic stainless steels.

Cooling after annealing is always performed in air for for thin, flat semi-finished parts or for long, small diameter parts; in water for parts with larger sections; otherwise water cooling is compulsory for compositions with a higher content of chromium, to avoid the phenomena of embrittlement at 475°C.

Annealing of ferritic stainless steels also has another important characteristic. If the material to be treated is in the hardened state, the heat treatment would also serve to re-crystallise the microstructure, i.e. to reform new crystalline grains, starting from the original grains that have extended under the effect of cold plastic deformation. In general, these newly formed grains are finer that the original hot formed grains in the semi-finished part. This is normally referred to as recrystallisation annealing (figure 29).

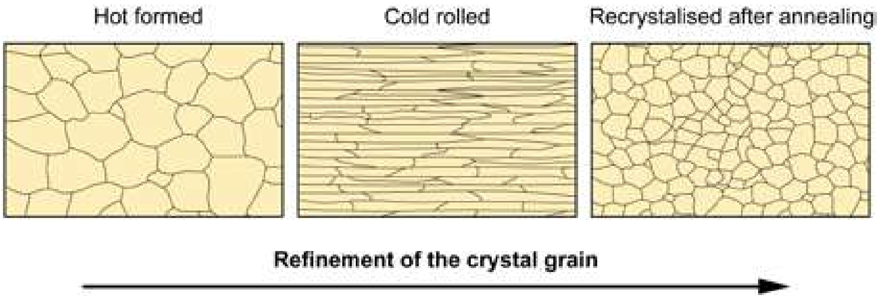

Figure 29 – Effect of recrystallisation annealing on ferritic stainless steels.

Lastly, it must be noted that the semi-finished parts to undergo heat treatment must be cleaned thoroughly to remove all oils, grease or carbon residue; otherwise there is the risk of the phenomena of surface carburisation, a common occurrence in steels with a very low carbon content.

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[20] *The temperatures for ferritic stainless steel annealing do not constitute a risk of solubilisation of any chromium carbides present. Nevertheless, annealing is carried out because, through the diffusion mechanisms, it aids redistribution of the chromium in the metal matrix of the steel. Therefore, even in the vicinity of the carbides, the chromium content will be restored to levels above the passivation threshold, thereby avoiding the typical problems of intergranular corrosion.*

EN Designation	Annealing	Cooling in	AISI approximate correspondence
X2CrTi12 (1.4512)	770°C-850°C	air or water	AISI 409
X6Cr17 (1.4016)	770°C-850°C	air or water	AISI 430
X6CrMoS17 (1.4105)	770°C-850°C	air or water	AISI 430F
X3CrTi17 (1.4510)	770°C-850°C	air or water	AISI 439 (430Ti*)
X6CrMo17-1 (1.4113)	770°C-850°C	air or water	AISI 434
X2CrMoTi17-1 (1.4513)	800°C-880°C	air or water	AISI 436
X2CrMoTi18-2 (1.4521)	800°C-880°C	air or water	AISI 444
X2CrTiNb18 (1.4509)	850°C-930°C	air or water	441*
X10CrAlSi25 (1.4762)	800°C-880°C	air or water	AISI 446
X2CrMoTi29-4 (1.4592)	900°C-1000°C	air or water	29-4C*

* The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 441).
The treatment duration depends on the dimension of the components and, usually, does not exceed 1 continuous hour.

Table 7 – Guideline characteristics of annealing heat treatment on some of the main types of ferritic stainless steels.

7.3 Physical and mechanical properties

The physical characteristics of some of the most common types of ferritic stainless steels are shown in table 8. An important physical property of ferritic stainless steels, given their special microstructure, is the magnetically soft behaviour, which is enhanced after the annealing heat treatment with prolonged hold intervals (see figure 30).

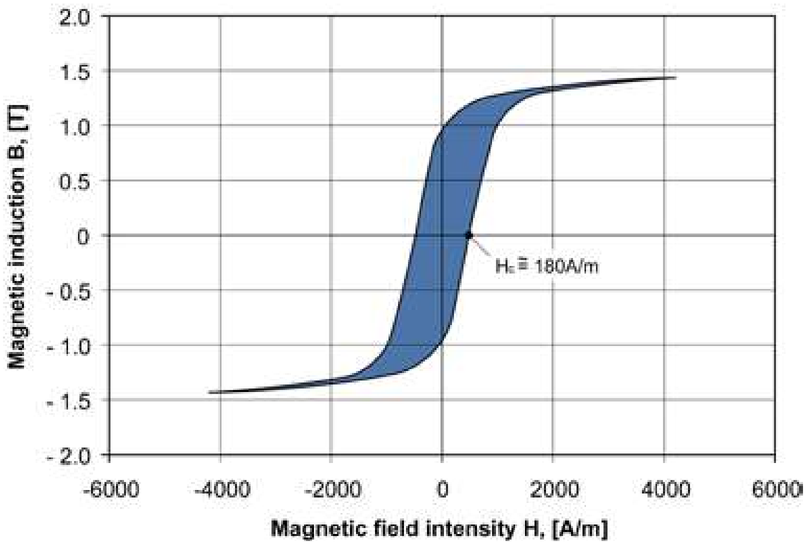

Figure 30 – Hysteresis curve up to 4200 A/m of a ferritic stainless steel type X6Cr17 (similar to AISI 430) [from Oxley et al. 2009].

The resistance properties of ferritic stainless steels are not particularly significant; in fact these steels are made up of uniform ferrite grains and are used in an annealed state. The unitary value of tensile strength R_m ranges between 450 MPa and 600 MPa, according to the chemical composition, with hardness values of 150-220 HB.

Table 9 show the typical mechanical properties for some types of ferritic stainless steels.

As already mentioned, ferritic stainless steels cannot be hardened by means of a quenching heat treatment: the only way to increase mechanical resistance is by means of cold plastic deformation processes, such as cold drawing or rolling, which harden the steel: in this case the unitary value of tensile strength can reach up to 900-1000 MPa (figure 31).

The strength of ferritic stainless steels is highly variable which therefore leads to difficulties in establishing a reference: in general it can be said that the transition temperature increases (and therefore the behaviour worsens) in proportion to the increase of chromium content in the alloy (refer to figure 32).

EN Designation	Mass volume [kg/dm^3]	Specific heat at 20°C [$J \cdot kg^{-1} \cdot K^{-1}$]	Electrical resistance at 20°C [$W \cdot mm^2 \cdot m^{-1}$]	Thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]	Linear thermal expansion [$10^{-6} \cdot K^{-1}$]		Modulus of elasticity [GPa]		AISI approximate correspondence
					from 20°C to 100°C	from 20°C to 200°C	to 20°C	to 200°C	
X2CrTi12 (1.4512)	7,7	460	0,60	25	10,5	11,0	220	210	AISI 409
X6Cr17 (1.4016)	7,7	460	0,60	25	10,0	10,0	220	210	AISI 430
X6CrMoS17 (1.4105)	7,7	460	0,70	25	10,0	10,5	220	210	AISI 430F
X3CrTi17 (1.4510)	7,7	460	0,60	25	10,0	10,0	220	210	AISI 439 (430Ti*)
X6CrMo17-1 (1.4113)	7,7	460	0,70	25	10,0	10,5	220	210	AISI 434
X2CrMoTi17-1 (1.4513)	7,7	460	0,70	25	10,0	10,5	220	210	AISI 436
X2CrMoTi18-2 (1.4521)	7,7	430	0,80	23	10,4	10,8	220	210	AISI 444
X2CrTiNb18 (1.4509)	7,7	460	0,60	26	10,0	10,0	220	210	441*
X10CrAlSi25 (1.4762)	7,7	500	1,10	17	---	10,5	220	210	AISI 446
X2CrMoTi29-4 (1.4592)	7,7	440	0,67	17	11,5	---	220	210	29-4C*

* The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 441).

Table 8 – Guideline physical properties of some of the main types of ferritic stainless steels [from EN 10088].

EN Designation	Metallurgic condition	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	Hardness	AISI approximate correspondence
X2CrTi12 (1.4512)	A	250-350	400-500	27-32	140-180 HB	AISI 409
X6Cr17 (1.4016)	A A + CD**	300-400 550-850	450-550 650-950	25-30 5-18	150-200 HB ---	AISI 430
X6CrMoS17 (1.4105)	A A + CD**	250-350 400-700	450-550 600-850	20-25 5-15	150-200 HB ---	AISI 430F
X3CrTi17 (1.4510)	A A + CD**	250-350 500-800	450-550 600-900	25-30 5-20	150-200 HB ---	AISI 439 (430Ti*)
X6CrMo17-1 (1.4113)	A	300-400	480-580	22-28	150-200 HB	AISI 434
X2CrMoTi17-1 (1.4513)	A	250-350	420-520	25-30	140-180 HB	AISI 436
X2CrMoTi18-2 (1.4521)	A	350-450	480-580	25-30	160-220 HB	AISI 444
X2CrTiNb18 (1.4509)	A	250-350	450-550	20-25	150-200 HB	441*
X10CrAlSi25 (1.4762)	A	350-450	550-650	12-18	170-230 HB	AISI 446
X2CrMoTi29-4 (1.4592)	A	450-550	560-660	22-27	150-200 HB	29-4C*

* The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 441).
A Annealed
A + CD: Annealed and Cold Drawn
** The values of the mechanical features in the condition A + CD are variable as they very much depend on the hardening conditions

Table 9 – Guideline mechanical properties of some of the main types of ferritic stainless steels.

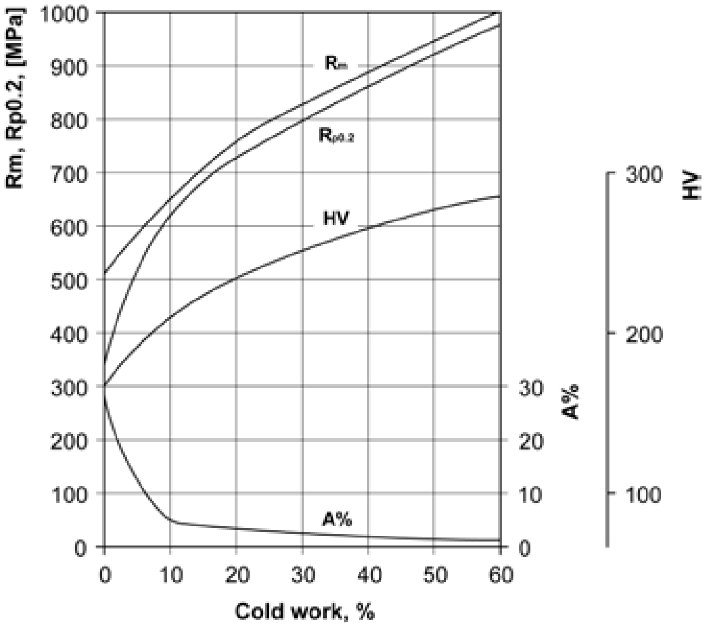

Figure 31 – Effect of hardening on mechanical properties of a ferritic stainless steel type X6Cr17 (similar to AISI 430) [from Lacombe et al. 1993].

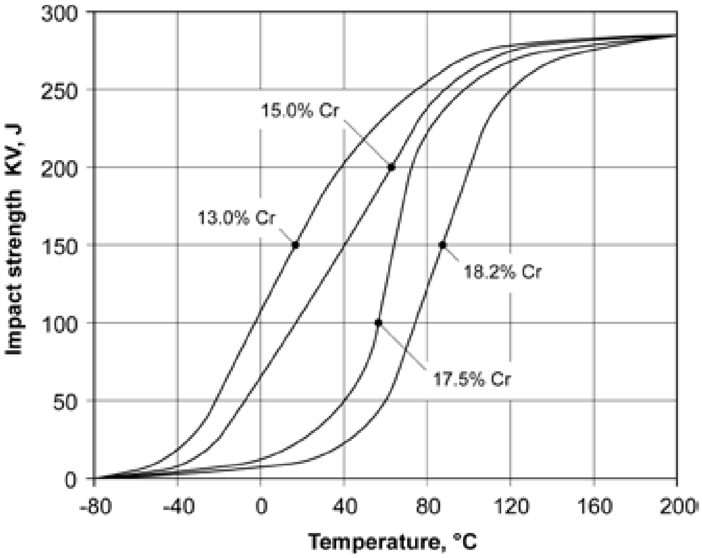

Figure 32 – Effect of chromium content on transition curves of iron-chromium alloys (the carbon content is ~ 0.01) [from Sedriks 1996].

In addition to the chromium content, the resistance to brittle fractures also depends on the combined effect of other metallurgical parameters. The transition temperature increases with the increase in contents of interstitial elements (carbon and nitrogen) and decreases under the effect of a reduction in the average size of the crystalline grain; the thickness of the semi-finished part also has an interesting effect on the brittle fractures of the ferritic stainless steels (see figure 33).

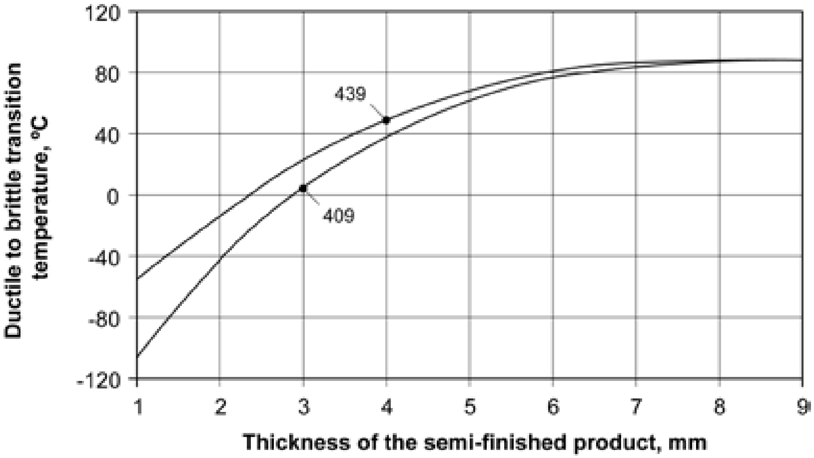

Figure 33 – Effect of thickness of semi-finished part on the transition temperature of two ferritic stainless steels [from Sedriks 1996].

7.4 Types and applications

Semi-finished parts in ferritic stainless steels are available on the market in the annealed state, mainly in the form of sheet steel, strips or sheets; a more limited percentage is also available as long products, such as bars and rods.

The ferritic stainless steels most commonly used in the industrial environment are grades X6Cr17 (similar to AISI 430) and X2CrTi12 (similar to AISI 409).

Steel grade X6Cr17 is a traditional ferritic stainless steel, easily cold plastically deformable and workable by machine tools.

X6Cr17 is mainly produced in the form of steel sheet or strips to be cold formed or pressed, in pipes or extruded bats; it has a good resistance to corrosion, certainly superior to martensitic grades, especially in the presence of nitric acid (up to 90% in water-based solutions in cold conditions, and up to 10% in heat). As regards the above, steel grade X6Cr17 (similar to AISI 430) is used for machine parts in the industry for the production and transformation of nitric acid (tanks, condensers, pipelines, coils, etc.); it is also widely used for cracking and reforming plants in the oil sector, for the production of low cost cutlery, household appliances, decorative elements and furnishing accessories for interiors, coverings for bar counters and tables, and kitchen extractor hoods. It is also used in a number of applications in the cheese/milk dairy sector and for manufacture of train carriages and buses. Ferritic stainless steel grade X6Cr17 is also used in components operating at temperatures up to 750°-800°C due to its optimal resistance to oxidation under heat.

Grade X6CrMoS17 (similar to AISI 430F) is the same as X6Cr17, but with improved machinability due to the presence of sulphur in the alloy: this steel is used to produce bars and rods (long semi-finished products) mainly used in the sector of solenoid valves[21] and metal hardware obtained by metal cutting.

The other widely used ferritic stainless steel is X2CrTi12 (similar to AISI 409). This offers less corrosion resistance with respect to the traditional X6Cr17 but increased cold plastic deformability and improved weldability due to the stabilisation of titanium; it also has a lower cost than the X6Cr17.

X2CrTi12 is widely used in the automotive sector for the manufacture of exhausts, catalytic converters and exhaust pipes for cars, lorries and motorcycles: this field of application represents the single most important market for a specific type of stainless steel.

To resolve issues related to material weldability, while conserving the corrosion resistance typical of the transitional grade X6Cr17, the grade X3CrTi17 has been developed, stabilised with titanium and with a carbon content of around 0.025% (similar to AISI 439, also known as 430Ti).

X3CrTi17 is used in similar applications to that of the ferritic stainless steel X6Cr17, at least in all cases where welding is required to make the component. One typical application is in the sector of household appliances: washing machine drums are produced from a strip in X6Cr17 if made by mechanical joining (stapling), or from a strip in X3CrTi17 if produced by welding.

With the aim of increasing corrosion resistance of the traditional X6Cr17, above all in relation to the phenomena of local deterioration, other chemical compositions have also been developed.

In aggressive environments, the ferritic stainless steel X6CrMo17-1 (similar to AISI 434) can be used, in which the presence of molybdenum improves resistance to corrosion due to pitting, or stabilised types X2CrTiNb18 with 18% chromium (known also as 441) and X2CrMoTi17-1 (similar to AISI 436) with the addition of molybdenum.

As well as for exhaust systems in the automotive sector, these steels are also used for internal cladding of buildings, on escalators, lifts and conveyor belts, for drinking water pipelines or as supports for photovoltaic cells.

Ferritic stainless steel grades X2CrMoTi18-2 (similar to AISI 444) and X2CrMoTi29-4 (also known as 29-4C) represent a further improvement in terms of corrosion resistance, due to the addition of high percentages of chromium and molybdenum: these are widely used for heat exchangers, boilers and hot water storage tanks.

Lastly, the ferritic stainless steel X10CrAlSi25, with a high content of chromium and added silicon and aluminium (more correctly a heat-resistant steel, as defined by the standard EN 10088): this alloy is very

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[21] *In the sector of solenoid valves ferritic stainless steels have been developed with specific chemical compositions containing a percentage of silicon (1-1.5%): this has the specific aim of making the material magnetically soft to improve the action of the mobile core in the solenoid valve itself.*

resistant to heats up to 1100°C, both in oxidating and reducing environments and also offers optimal behaviour in sulphurous environments (diesel oil combustion products, sulphur oxides, etc.) in which austenitic stainless steels would offer only poor performance due to the high content of nickel. This type is widely used for the production of ovens and boilers, floors and mufflers, annealing enclosures, crucibles, hydrogeneration plant parts (also with oils rich in sulphur) and superheater pipelines.

8. AUSTENITIC STAINLESS STEELS

8.1 Metallurgy

If the chromium content is increased to at least 17-18% and at the same time nickel is added to a percentage of 8% to 9%, the steel will have an austenitic structure at ambient temperature: this is due to the significant austenitising effect of the nickel that predominates over the ferritising action of the chromium (with regard to this, refer back to the diagram in figure 8 and the Schaeffler diagram in figure 11). As in the other cases, the carbon content is fixed a very low values ($C = 0.02\text{-}0.06\%$) to limit the formation of chromium carbides as far as possible.

The combination of chromium and nickel in the alloy obtains a stainless steel with an austenitic structure, i.e. with a face-centred cubic lattice, highly resistant to atmospheric corrosion and water-based solutions[22]: this is grade X5CrNi18-10 (similar to AISI 304) progenitor of the family of austenitic chromium-nickel stainless steels.

Added corrosion resistance can be achieved by increasing the nickel content up to 11-12% or adding molybdenum to values of 2-3%: this obtains another widely used stainless steel, i.e. the X5CrNiMo17-12-2 (similar to AISI 316), progenitor of the second family of austenitic stainless steels, i.e. chromium-nickel-molybdenum[23].

There is then a third possibility of obtaining an austenitic stainless steel: this is by replacing the nickel part with manganese[24], the element which otherwise would only act as a deoxidant in the alloy. This solution was developed in the 1950s, with the aim of limiting production costs; the progenitor of the family of austenitic stainless steels with chromium-manganese-nickel is the X12CrMnNiN17-7-5 (similar to AISI 201). Austenitic stainless steels with manganese – which here are not taken into consideration – did not have the distribution that was hoped for, perhaps due to the limited resistance to corrosion in contact with water-based solutions, more similar to the behaviour of a ferritic stainless steel type X6Cr17 or that of an austenitic stainless steel with chromium-nickel type X5CrNi18-10.

Figure 34 illustrates the "metallurgical" logic, which led to the creation of two main types of austenitic stainless steels available on the market: one is chromium-nickel stainless steels such as X5CrNi18-10 and the other is the chromium-nickel-molybdenum such as X5CrNi17-12-2 and their respective by-products.

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[22] *In air and water-based solutions, even partially contaminated by chlorides (generally up to 500ppm of ions Cl^-) the corrosion resistance of austenitic stainless steel X5CrNi18-10 is superior with respect to martensitic and ferritic types such as X30Cr13 and X6Cr17.*

[23] *The austenitic chromium-nickel-molybdenum stainless steel X5CrNiMo17-12-2 (similar to AISI 316) is suitable for applications in contact with sea water ($Cl^- \cong 20{,}000ppm = 2\%$) or with water-based solutions strongly contaminated by chlorides.*

[24] *The alternative to manganese with respect to nickel is based on the austenitising effect that both elements show if added to Fe-C alloys: as the austenitising effect of the manganese is equal to half that of nickel, around 2% of Mn needs to be added for each 1% of replaced Ni.*

A further distinction divides these two families into "austenitic" if the nickel content is less than or equal to 20% and "super-austenitic" if greater.

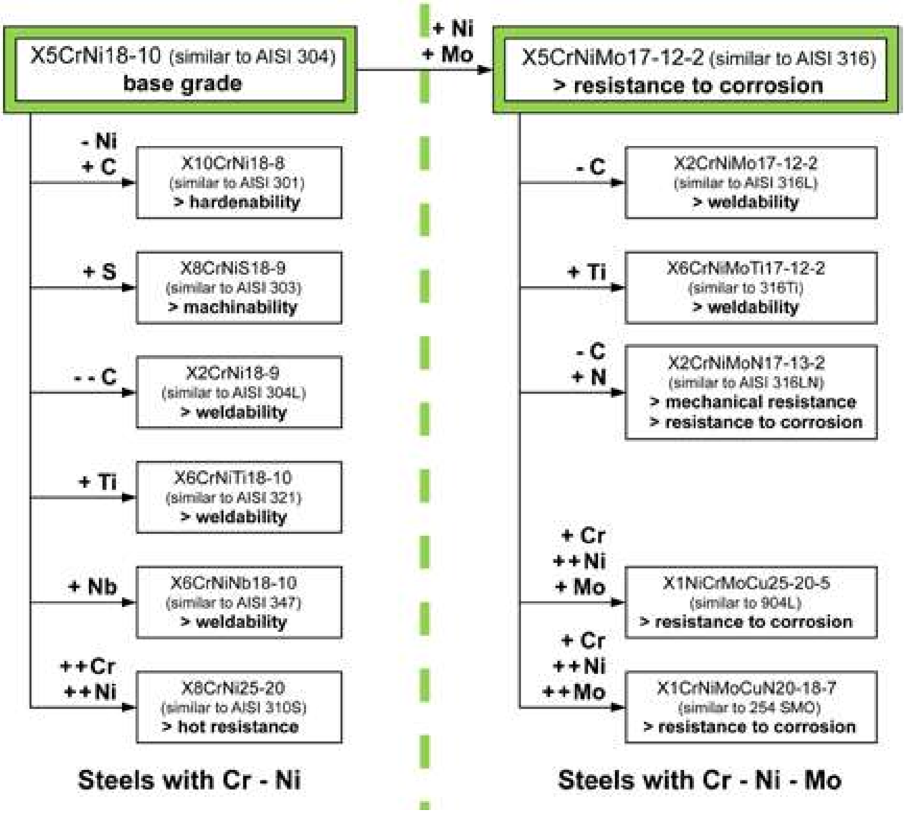

Figure 34 – Schematic of main types of austenitic chromium-nickel and chromium-nickel-molybdenum starting from X5CrNi18-10 and X5CrNiMo17-12-2.

Table 10 shows the chemical composition of some of the most commonly used austenitic stainless steels and relative designation according to the standard EN 10088.

As in the previous cases, also in the case of austenitic stainless steels it is important to refer to a phase diagram for a full understanding of the metallurgical problems of these alloys: figure 35 shows the simplified phase diagram of a steel with 18% chromium and 8% nickel on variation in carbon content.

An undoubtedly significant aspect of the phase diagram of austenitic stainless steels is the absence of critical points, i.e. no transformation $\gamma \rightarrow \alpha$, as can clearly noted on figure 35 following cooling of an alloy with very low carbon content (C = 0.05%). After initial solidification at very high temperatures in phase $\gamma + \delta$, the stainless steel becomes completely austenitic (phase γ) and remains in this state through to ambient temperature, without the inevitable chromium carbides.

EN symbolic designation	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	Other	AISI approximate correspondence
X10CrNi18-8 (1.4310)	0,05-0,15	≤2,00	≤2,00	≤0,045	≤0,015	16,0-19,0	6,0-9,5	≤0,80	1	AISI 301
X8CrNiS18-9 (1.4305)	≤0,10	≤1,00	≤2,00	≤0,045	0,15-0,35	17,0-19,0	8,0-10,0	---	1, 2	AISI 303
X5CrNi18-10 (1.4301)	≤0,07	≤1,00	≤2,00	≤0,045	≤0,015	17,5-19,5	8,0-10,5	---	1	AISI 304
X2CrNi18-9 (1.4307)	≤0,03	≤1,00	≤2,00	≤0,045	≤0,015	17,5-19,5	8,0-10,5	---	1	AISI 304L
X6CrNiTi18-10 (1.4541)	≤0,08	≤1,00	≤2,00	≤0,045	≤0,015	17,0-19,0	9,0-12,0	---	3	AISI 321
X6CrNiNb18-10 (1.4550)	≤0,08	≤1,00	≤2,00	≤0,045	≤0,015	17,0-19,0	9,0-12,0	---	4	AISI 347
X8CrNi25-21 (1.4845)	≤0,10	≤1,50	≤2,00	≤0,045	≤0,015	24,0-26,0	19,0-22,0	---	1	AISI 310S
X5CrNiMo17-12-2 (1.4401)	≤0,07	≤1,00	≤2,00	≤0,045	≤0,015	16,5-18,5	10,0-13,0	2,00-2,50	1	AISI 316
X2CrNiMo17-12-2 (1.4404)	≤0,03	≤1,00	≤2,00	≤0,045	≤0,015	16,5-18,5	10,0-13,0	2,00-2,50	1	AISI 316L
X2CrNiMoN17-13-3 (1.4429)	≤0,03	≤1,00	≤2,00	≤0,045	≤0,015	16,5-18,5	11,0-14,0	2,50-3,00	5	AISI 316LN
X6CrNiMoTi17-12-2 (1.4571)	≤0,08	≤1,00	≤2,00	≤0,045	≤0,015	16,5-18,5	10,5-13,5	2,00-2,50	3	316Ti*
X1NiCrMoCu25-20-5 (1.4539)	≤0,02	≤0,70	≤2,00	≤0,030	≤0,010	19,0-21,0	24,0-26,0	4,00-5,00	6	904 L*
X1CrNiMoCuN20-18-7 (1.4547)	≤0,02	≤0,70	≤1,00	≤0,030	≤0,010	19,5-20,5	17,5-18,5	6,00-7,00	7	254 SMO*

* The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 904 L).

1: %N ≤ 0,11
2: %Cu ≤ 1,0
3: %Ti = 5 x C - 0,70
4: %Nb = 10 x C - 1,00
5: %N = 0,12 - 0,22
6: %N ≤ 0,15; %Cu = 1,20 - 2,00
7: %N = 0,18 - 0,25; %Cu = 0,50 - 1,00

Table 10 – Chemical composition of some of the main types of austenitic stainless steels [from EN 10088].

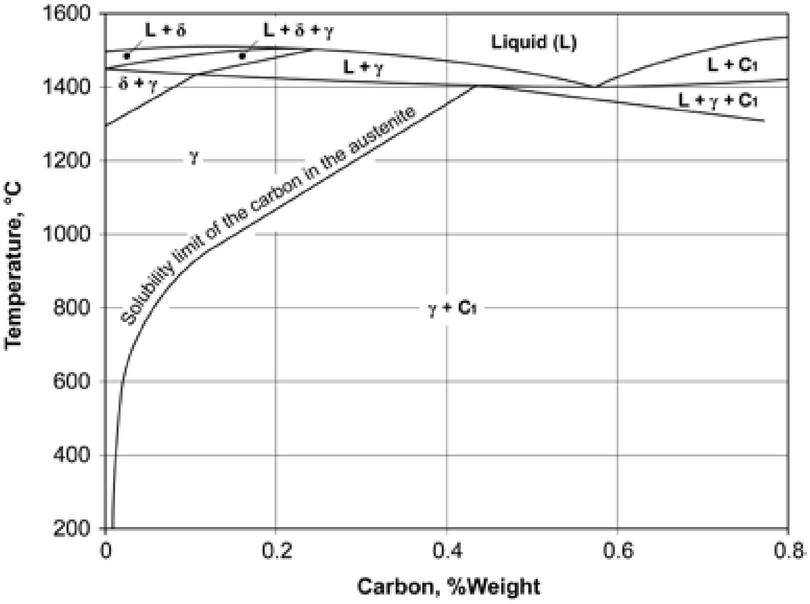

Figure 35 – Fe-C binary section of Fe-Cr-Ni-C quaternary diagram with Cr =18% and Ni = 8%; C_1 carbides type $(Cr,Fe)_{23}C_6$ [from Sedriks 1996].

The presence of various austenitising elements, such as carbon, nitrogen, nickel and manganese, have in fact shifted the temperature of austenite transformation into martensite to well below the ambient temperature: this explains the impossibility of performing heat treatments, such as quenching, which can increase the mechanical resistance of austenitic stainless steels.

Another very important aspect, again shown in the diagram of figure 35, is the extremely limited solubility of the carbon in phase γ[25]: even if the carbon content is kept at very low values (in the case of these steels this is normally %C = 0.04-0.06%), the presence of chromium carbides type $(Cr,Fe)_{23}C_6$ at ambient temperature is virtually certain.

The phenomena of carbide precipitation, also known as "sensitisation", is quite complex. It occurs at temperatures between 450°C and 900°C and at highly variable exposure times: the most critical conditions are found at around 700°C for time intervals of just a few minutes.

Sensitisation of austenitic stainless steels leads to a decline of chromium in the immediate vicinity of areas where the carbides form, i.e. on the boundaries of the crystalline grains: consequently, the chromium content of the grain boundaries is below the passivation limit of the steel, leading to local deterioration in corrosion resistance and the phenomena of inter-crystalline corrosion, even in only slightly aggressive environments (refer also back to figure 10, case "b").

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[25] *In the case of an austenitic stainless steel with 18% chromium and 8% nickel, the limit of carbon solubility in phase γ is equal to approx. 0.03%.*

To remedy the problem of chromium carbides, various interventions have been developed: these are based on the modification to the chemical composition of the steel and appropriate heat treatments.

An initial method of solving this problem is to add titanium or niobium at the time of manufacture: titanium and niobium in fact aid the formation of very stable carbides, thereby preventing the carbon from engaging with the chromium to form chromium carbides (the mechanism of intervention of titanium and niobium is the same as that described in the case of ferritic stainless steels).

In light of these metallurgical considerations, "stabilised" austenitic stainless steels have been developed, such as X6CrNiTi18-10 (similar to AISI 321), X6CrNiNb18-10 (similar to AISI 347) or X6CrNiMoTi17-12-2 (similar to AISI 316Ti): in brief, these are steels identical to X5CrNi18-10 and X5CrNiMo17-12-2 but with the addition of titanium or niobium[26]. As better explained in the section on heat treatments, the semi-finished products in these types of steel, before being used in operation, should undergo a "stabilisation" heat treatment in order to form the carbides of the stabilising elements (Ti and Nb).

A second method of intervention, in many ways simpler than the first, consists in minimising the carbon content of the steel down to values of around 0.02-0.03%. As a consequence the time required for incubation and the formation of chromium carbides changes from a few minutes to several hours, which practically renders sensitisation of the material negligible.

For a clearer idea of this concept, it is helpful to refer to the isothermal diagram shown in figure 36, specifically drawn up to establish (note the temperature) the minimum time for carbide precipitation: the curves shown on the diagram are also known as "C curves".

As can be seen, the time required to sensitise the steel depends, as well as on the exposure temperature, on the carbon content in the alloy: for example, if the carbon content is 0.08%, the time for carbide precipitation is around one minute, while this can extend to several hours if carbon is reduced to 0.02%.

On the basis of the "C curves" austenitic steels with low carbon content have been developed, such as X2CrNi18-9 (similar to AISI 304L[27]) or X2CrNiMo17-12-2 (similar to AISI 316L) which are virtually insensitive to the phenomena of chromium carbide precipitation.

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[26] *The analogy between traditional and stabilised stainless steels is not only formal: there is also very little different in terms of corrosion resistance. The only difference lies in the presence of stabilising elements, which in fact inhibit the formation of chromium carbides.*

[27] *The L series in the AISI standards indicates the presence of a very low carbon content, normally C = 0.03%. L stands for low carbon.*

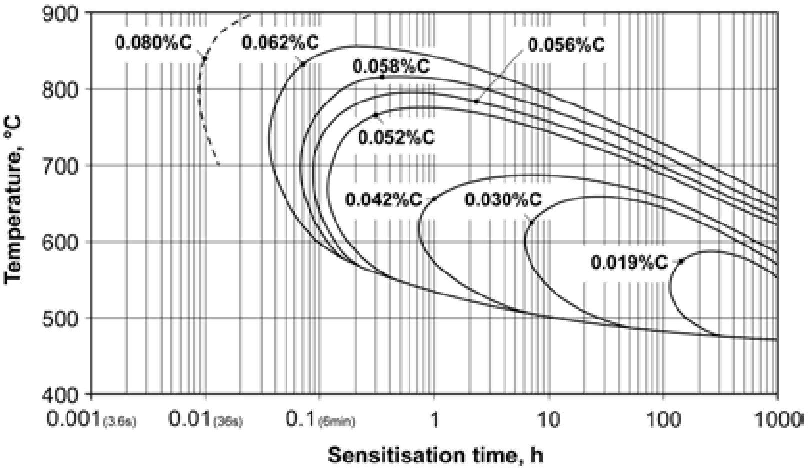

Figure 36 – Time-temperature diagram ("C curve") showing precipitation of chromium carbides on variation of the carbon content, for austenitic stainless steels with 18% chromium and 9% nickel [from McGuire 2008].

Lastly it is worth remembering that there is always another option to avoid the occurrence of inter-granular corrosion. If there are founded reasons to believe that chromium carbide precipitation has occurred in one or more areas of the component, a solubilisation heat treatment can still be performed, at 1040°-1050°C[28]: this would "dissolve", i.e. solubilise, any carbides present, but this will be dealt with in more detail in the next section.

Again with reference to austenitic stainless steels, there are also metallurgical problems related to the hold times of the material at high temperatures.

As the chromium or chromium-molybdenum contents in these alloys is significant, the possible formation of phase σ, phase χ or the Laves phase must be taken into account: this occurs due to prolonged holding times (more than 100 hours) at temperatures between 550°C and 900°C (see figure 37).

However note that the problem of precipitation of phases rich in chromium or chromium-molybdenum is often secondary to the phenomena of chromium carbide precipitation, which as noted above, occurs at the same temperatures but for much shorter time intervals.

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[28] The option of solubilisation also depends on the dimensions of the semi-finished part or component to be treated. Small parts are easily managed while in the case of plant parts or large welded structures, the option of a final heat treatment after all processes is virtually impossible. In these cases the stabilised or low carbon steels should be used.

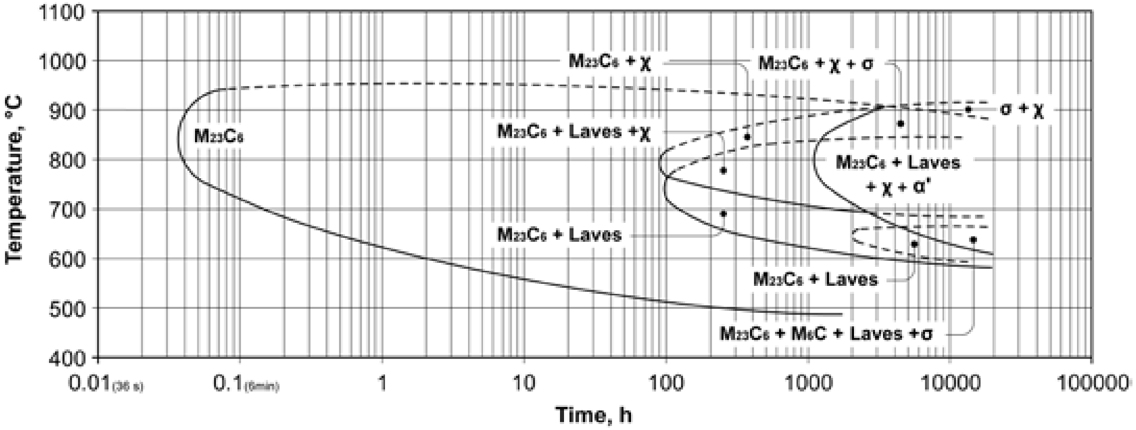

Figure 37 – Time-temperature diagram showing precipitation of phases σ, χ and the Laves phase, and of chromium carbides in an austenitic stainless steel type X5CrNiMo17-12-2 [from Khatak and Baldev 2002].

In austenitic stainless steels other alloy elements are sometimes added, the most common being sulphur, nitrogen and copper.

Sulphur serves to improve machinability of the material under the effect of the formation of iron sulphides and iron-chromium sulphides (as occurs on martensitic and ferritic stainless steels).

It is a different case for nitrogen and copper. While nitrogen is added due to the strongly austenitising capacity and at the same time to improve corrosion resistance and mechanical strength, copper is used because it tends to improve cold plastic deformability of stainless steels.

Lastly, on careful examination of the Schaeffler diagram[29] it can be noted how in the case of the common austenitic stainless steels (X5CrNi18-10 and X5CrNiMo17-12-2) at ambient temperature the microstructure may even show a small percentage of ferrite (usually between 1% and 5%): this occurs if the material undergoes rapid cooling from the melting temperature, as in the case during welding operations[30]. Only by increasing the nickel content (from 12% upwards) and/or adding nitrogen (0.10%-0.25%) is it possible to obtain a completely austenitic structure: this is necessary when the final application requires such a structure, for example in the case of specific corrosive environments (strongly reducing acid solutions) or in nuclear applications (magnetic containment circuits operating at 0°-5°K) or due to specific problems of hot machining.

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[29] *A similar situation can also be seen on the phase diagram shown in figure 35 where initial solidification is evident, with a two phase structure of* $\gamma + \delta$ *which can remain in this state if the alloy is rapidly cooled to ambient temperature.*

[30] *The presence of small percentages of ferrite in austenitic stainless steels can, in some cases, also be a positive factor: it can aid material weldability as it reduces the occurrence of hot cracks in the melted area of the welding bead and limits enlargement of the crystalline grain during heat treatments.*

8.2 Heat treatments

Austenitic stainless steels, as noted above, do not need to be hardened for heat treatment as in practice their microstructure remains unchanged from the melting temperature through to ambient temperature.

The only feasible heat treatment is solubilisation, also known as negative quenching or austenitic quenching: this treatment is normally performed on semi-finished products and finished products in austenitic stainless steel, downline of the various manufacturing processes.

The treatment is performed at high temperatures (approximately in the range 1000°C to 1100°C), for a sufficient time to ensure homogenisation of the chemical composition of the steel: during the treatment, microstructural irregularities are also eliminated, and above all solubilisation of the chromium carbides is ensured.

Refer to Table 11 for more precise information on the treatment temperatures for the most common austenitic stainless steels.

Before the heat treatment, the parts must be cleaned to remove all residue from previous processes (oil, grease, etc.); in many cases solubilisation is performed in a controlled atmosphere (nitrogen or nitrogen + hydrogen) so that the steel can maintain its typical metal grey shine, avoiding oxidation in air or undesired carburisation effects.

To ensure successful solubilisation, austenitic stainless steels must be cooled rapidly in water, above all if they are particularly thick parts. Cooling must be rapid to avoid deterioration in the uniform composition of the austenite in the stage between 450°C and 900°C as well as to prevent separation of the carbides on the grain boundary, causing local deterioration of chromium[31]. In the case of thin parts, a high pressure flow of nitrogen can also be used, although cooling in water is still preferable[32].

On the other hand a special treatment is used on stabilised austenitic stainless steels. In fact in the case of types X6CrNiTi18-10, X6CrNiNb18-10, X6CrNiMoTi17-12-2 stabilisation must be performed after completing solubilisation.

The stabilisation treatment consists in maintaining the steel at temperatures between 850°C and 950°C for times ranging from 1 to 4 hours depending on the dimensions of the semi-finished part. During treatment, there is precipitation of the titanium and niobium carbides which, by fixing the carbon, prevent any from remaining, with the formation of harmful chromium carbides. The subsequent cooling is in air.

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[31] *Take into account that cooling in water does not produce any structural transformation or hardening of the material, as austenitic stainless steels have no critical points: also for this reason the treatment is also known as negative quenching as the hardness at the end of the process is normally less than the initial value.*

[32] *Even if less drastic than water, cooling in nitrogen (combined with treatment in controlled atmosphere) undoubtedly has the advantage of not causing oxidation of the part surface, so that it maintains a pleasant shine: the treatment, in British literature, is known as bright annealing.*

EN Designation	Solubilisation	Cooling	Stabilization	AISI approximate correspondence
X10CrNi18-8 (1.4310) X8CrNiS18-9 (1.4305) X5CrNi18-10 (1.4301) X2CrNi18-9 (1.4307)	1010°-1120°C	water, air	No	AISI 301 AISI 303 AISI 304 AISI 304L
X6CrNiTi18-10 (1.4541)	955°C-1065°C	water, air	850°C-950°C	AISI 321
X6CrNiNb18-10 (1.4550)	980°C-1065°C			AISI 347
X8CrNi25-21 (1.4845)		water	No	AISI 310S
X5CrNiMo17-12-2 (1.4401) X2CrNiMo17-12-2 (1.4404) X2CrNiMoN17-13-3 (1.4429)	1020°C-1120°C	water, air	No	AISI 316 AISI 316L AISI 316LN
X6CrNiMoTi17-12-2 (1.4571)	1020°C-1120°C	water, air	850°C-950°C	316Ti*
X1NiCrMoCu25-20-5 (1.4539)	1050°C-1150°C	water, air	No	904 L*
X1CrNiMoCuN20-18-7 (1.4547)	1140°C-1200°C	water, air	No	254 SMO*

*The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 904 L).

Table 11 – Guideline characteristics of heat treatments on some of the main types of austenitic stainless steels.

8.3 Physical and mechanical properties

The physical characteristics of some of the most common austenitic stainless steels are shown in table 12. It should be immediately noted how such characteristics are very particular and strictly depend on the face-centred cubic matrix of the austenite, which is very different from that of ferritic and martensitic stainless steel. The linear heat expansion of austenitic stainless steels, for example, is 50-60% greater than that of ferritic or martensitic stainless steels, as well as the thermal conductivity, which on the contrary is 40-50% lower. These particular properties must be taken into consideration in an industrial context: in the heating and cooling during thermal treatment, the dimensional variation of the stainless steel pieces will be much greater than in common steels, but heat exchange will be much more limited[33].

Again from a point of view of the physical characteristics, it should be noted how austenitic stainless steels have nonmagnetic behaviour, this characteristic makes them well suited to some military applications; finally, please note that as a result of cold plastic deformation operations, the semi-finished products tend to become slightly ferromagnetic.

The mechanical characteristics of austenitic stainless steels are rather limited, due to the high deformability of the austenite matrix. In an annealed condition, these steels provide a tensile strength R_m of 550-650 MPa and a yield stress $R_{p0.2}$ of 220-280 MPa; conversely, the austenitic microstructure has high ductility, with percentage values of elongation at break of 40-50% and hardness of 160-200 HB.

Table 13 reports the resistance properties of the main types of austenitic stainless steel.

The only way to increase the traction resistance of austenitic stainless steels is through hardening: by cold plastic deformation (rolling, drawing etc.) it is possible to obtain a tensile strength R_m of 1500-1800 MPa and yield stress $R_{p0.2}$ of 1300-1600 MPa, much greater values than those that would be obtained using a low carbon common steel (see Figure 38).

This significant increase of tensile characteristics (R_m can triple and $R_{p0.2}$ can increase up to six times compared to its annealed state!) is due to the great hardening capacity of the austenite and the effect of the structural transformation of austenite into martensite, triggered by the mechanical energy transferred to the steel during the cold deformation processes.

Austenitic stainless steels that can be hardened more easily will therefore be those with an unstable austenitic structure, or rather those that are more prone to transformation into martensitic due to mechanically induced deformations. This is typical of stainless steels with low nickel content, as is the case of X10CrNi18-8 (similar to AISI 301); however, steels with a high nitrogen and nickel content are more stable and therefore more difficult to harden, such as for example X8CrNi25-21 (similar to AISI 310S) or X2CrNiMoN17-13-3 (similar to AISI 316LN). To this regard see Figure 39.

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[33] *In the sector of quality cookware, the issue of the poor conductivity of austenitic stainless steels leads to the need to apply heat diffusing bases (usually in aluminium) to allow for the uniform distribution of heat during cooking.*

EN Designation	Mass volume [kg/dm^3]	Specific heat at 20°C [J·kg^{-1}·K^{-1}]	Electrical resistance at 20°C [W·mm^2·m^{-1}]	Thermal conductivity [W·m^{-1}·K^{-1}]	Linear thermal expansion [10^{-6}·K^{-1}]		Modulus of elasticity [GPa]		AISI approximate correspondence
					from 20°C to 100°C	from 20°C to 200°C	to 20°C	to 200°C	
X10CrNi18-8 (1.4310)	7,9	500	0,73	15	16,0	17,0	200	186	AISI 301
X8CrNiS18-9 (1.4305)	7,9	500	0,73	15	16,0	16,5	200	186	AISI 303
X5CrNi18-10 (1.4301)	7,9	500	0,73	15	16,0	16,5	200	186	AISI 304
X2CrNi18-9 (1.4307)	7,9	500	0,73	15	16,0	16,5	200	186	AISI 304L
X6CrNiTi18-10 (1.4541)	7,9	500	0,73	15	16,0	16,5	200	186	AISI 321
X6CrNiNb18-10 (1.4550)	7,9	500	0,73	15	16,0	16,5	200	186	AISI 347
X8CrNi25-21 (1.4845)	7,9	500	0,85	15	---	15,5	---	---	AISI 310S
X5CrNiMo17-12-2 (1.4401)	8,0	500	0,75	15	16,0	16,5	200	186	AISI 316
X2CrNiMo17-12-2 (1.4404)	8,0	500	0,75	15	16,0	16,5	200	186	AISI 316L
X2CrNiMoN17-13-3 (1.4429)	8,0	500	0,75	15	16,0	16,5	200	186	AISI 316LN
X6CrNiMoTi17-12-2 (1.4571)	8,0	500	0,75	15	16,5	17,5	200	186	316Ti*
X1NiCrMoCu25-20-5 (1.4539)	8,0	450	1,00	12	15,8	16,1	195	182	904 L*
X1CrNiMoCuN20-18-7 (1.4547)	8,0	500	0,85	14	16,5	17,0	195	182	254 SMO*

*The designation indicated does not refer to the AISI standard; it is often referred to as the "type" (for example type 904 L).

Table 12 – Physical characteristics indicative of some of the main types of austenitic stainless steels [from EN 10088].

EN Designation	Metallurgic condition	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	Hardness	AISI approximate correspondence
X10CrNi18-8 (1.4310)	Solubilised	250-300	600-750	40-50	170-220	AISI 301
X5CrNi18-10 (1.4301)	Solubilised	220-270	550-650	45-55	160-210	AISI 304
X8CrNiS18-9 (1.4305)	Solubilised	200-250	520-630	35-45	170-220	AISI 303
X2CrNi18-9 (1.4307)	Solubilised	200-250	520-630	45-55	160-210	AISI 304L
X6CrNiTi18-10 (1.4541) X6CrNiNb18-10 (1.4550)	Solubilised + Stabilized	230-280	550-650	40-50	170-220	AISI 321 AISI 347
X8CrNi25-21 (1.4845)	Solubilised	250-300	550-650	40-50	150-200	AISI 310S
X5CrNiMo17-12-2 (1.4401) X2CrNiMo17-12-2 (1.4404)	Solubilised	250-300	550-650	40-50	160-210	AISI 316 AISI 316L
X6CrNiMoTi17-12-2 (1.4571)	Solubilised + Stabilized	250-300	550-650	40-50	160-210	316Ti*
X2CrNiMoN17-13-3 (1.4429)	Solubilised	290-340	600-700	40-50	190-240	AISI 316LN
X1NiCrMoCu25-20-5 (1.4539)	Solubilised	230-280	550-650	35-45	170-220	904 L*
X1CrNiMoCuN20-18-7 (1.4547)	Solubilised	300-350	700-800	35-45	200-250	254 SMO*

*The designation indicated does not refer to the AISI standard; it is often referred to as the “type” (for example type 904 L).

Table 13 – Mechanical characteristics indicative of some of the main types of austenitic stainless steel.

Figure 38 – Effect of section reduction in drawing on the increase of the traction resistance of two austenitic stainless steels compared to a common carbon steel [from Atlas Speciality Metals 2003].

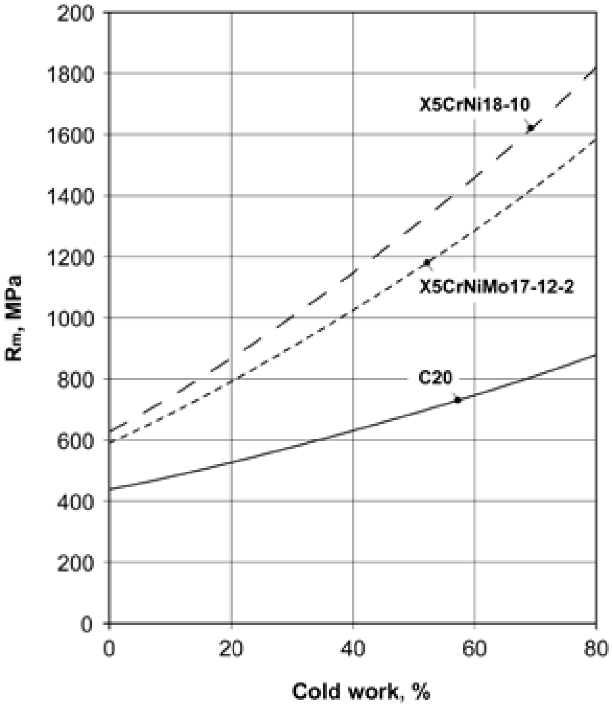
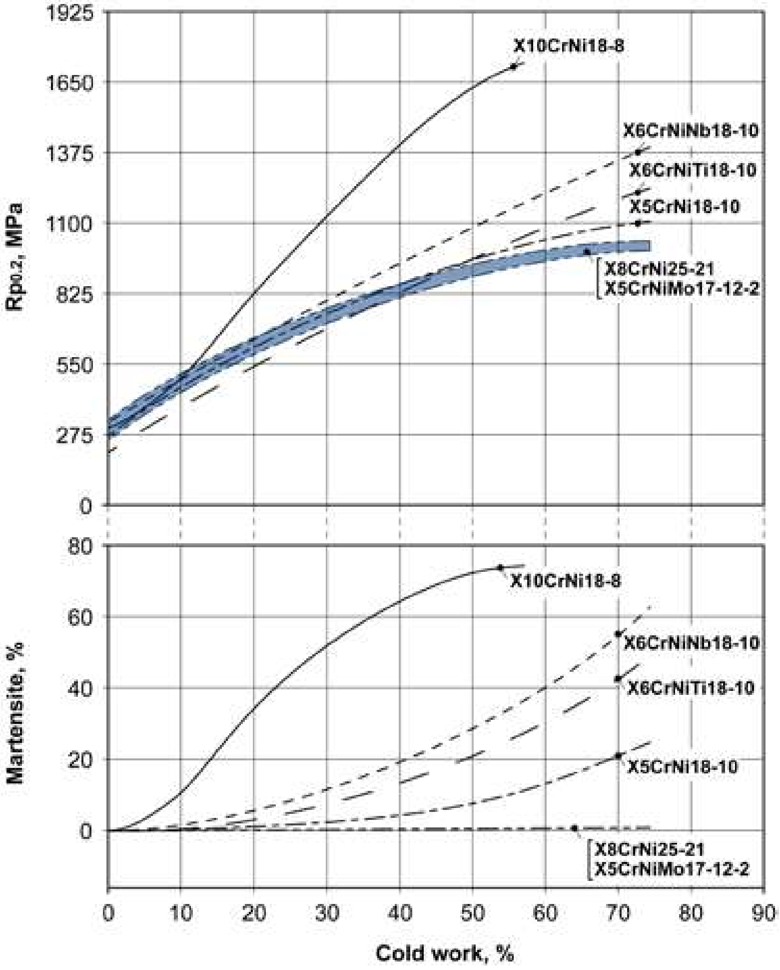


Figure 39 – Effect of section reduction during cold rolling on the increase of the yield strength $Rp_{0.2}$ and on the transformation of austenite into martensite for various austenitic stainless steels [from Llewellyn and Hudd 2003].



One very interesting mechanical characteristic of this family of materials is the high resistance to brittle fracture. Due to the special crystalline matrix, the resilience curve of austenitic stainless steels never shows the transition towards the brittle component, but remain tough up to temperatures close to absolute zero (see Figure 40): for these reasons, austenitic stainless steels are widely used in cryogenic applications.

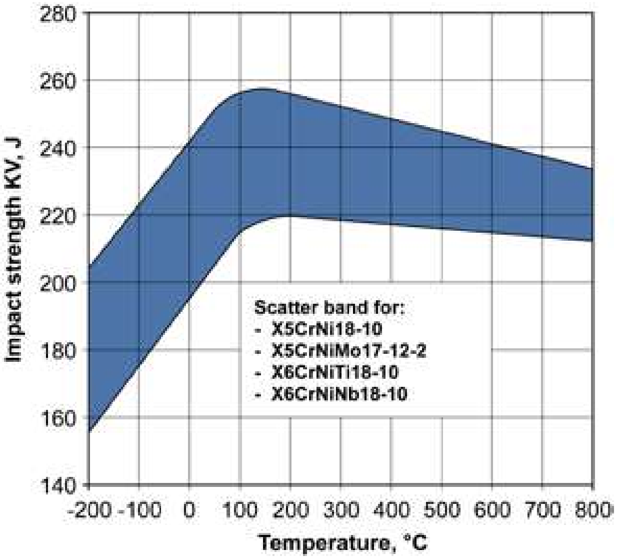


Figure 40 – Trend of Charpy V type resilience performed at various temperatures for different austenitic stainless steels [from Llewellyn and Hudd 2003].

8.4 Types and applications

The steel X5CrNi18-10 (similar to AISI 304) was the first of the austenitic stainless steels with chromium and nickel: it is the single most produced and used material among all the stainless steels.

This type of steel is widely used in many contexts (industrial, civil, military, etc.) with mechanical characteristics which are not particularly high but with a resistance to corrosion significantly greater than martensitic and ferritic types containing only chromium. Type X5CrNi18-10 can be easily cold deformed and welded using suitable electrodes.

It is widely used in various applications: boilers, pressure tanks, vessels, heat exchangers, fluid transport pipes, plumbing, elevators and signs. It is also used in building and urban furnishings, in domestic utensils (cookware, cutlery, appliances), in sinks and cabinets, as well as in the chemical, petrochemical, nuclear and pharmaceutical industries as well as for the production of milk, beer, canned food, paper and pulp, colorants and explosives. Due to its high toughness at low temperatures, it is also widely used in the cryogenics sector for the storage and transport of liquefied gases.

In closest relationship to the steel X5CrNi18-10, the types X6CrNiTi18-10 (similar to AISI 321) and X6CrNiNb18-10 (similar to AISI 347) are the stabilised versions with titanium and niobium. As these materials have a high resistance to corrosion comparable with that of X5CrNi18-10, they are used in the same applications, especially for the production of large sized and/or very thick items that are subjected to welding operations. It should be underlined how the stabilised types are not suitable for decorative applications as the presence of titanium or niobium carbide appearing on the surface does not allow an optimum surface finish.

With regards to X6CrNiTi18-10 and X6CrNiNb18-10, they demonstrate a greater mechanical resistance to heat than traditional X5CrNi18-10: in addition to traditional applications, they are also used for making exhaust manifolds, boiler bodies, chemical reactors, pressure vessels and pipes for armoured resistors.

X2CrNi18-9 (similar to AISI 304L) is actually the low carbon version of X5CrNi18-10: this composition is also used to solve issues of the precipitation of chromium carbides during welding and is a good alternative to the previously indicated stabilised types. Mechanical resistance, both at ambient temperature and in heat, is however lower than that of stabilised stainless steels; however, the surface finish is excellent. X2CrNi18-9 is widely used to perform overlay welding, for the construction of large-scale tanks, for very thick reactors, as well as in all applications where the aesthetic aspect of the stainless steel is very important.

The steel X10CrNi18-8 (similar to AISI 301) is the most used austenitic stainless steel in its hardened condition: it is used with the specific aim of obtaining high mechanical resistance after cold plastic deformation. It is commonly used for making chains for conveyor belts, springs, load bearing structures for the automotive sector and, sometimes, also for manufacturing knives. It is not suitable for drawing operations or deep moulding operations.

The type X8CrNiS18-9 (similar to AISI 303) is the version of X5CrNi18-10 with improved machinability: the presence of sulphur promotes its machinability for the machining tools; it is known for its deterioration of resistance to corrosion, with particular regard to localised attack phenomena. X8CrNiS18-9 is widely used as metal for very small parts and for the production of screws, nuts, pins and bushings.

Finally, there is the type X8CrNi25-20 (similar to AISI 310S), an austenitic stainless steel resistant to high temperature oxidation. It is used for components or parts of a plant that must withstand oxidising non sulphurous atmospheres at temperatures up to 1100°C. In the case of sulphurous or carbon oxidising atmospheres, the maximum operating temperatures are usually 1000°C; in reducing atmospheres, the use temperature is limited to 750°C. This material is used to make forges for salt baths, carburizing boxes, conduit for thermoelectric couples, muffles for patenting furnaces, distillation retorts and piping for cracking and reforming plants.

In the chromium-nickel-molybdenum stainless steel family, the first steel is the type X5CrNiMo17-12-2 (similar to AISI 316) containing 2-2.5% of molybdenum. It is the reference material for manufacturing components or parts of a plant operating in marine atmospheres or subject to significant corrosion issues: it is usually used when chromium-nickel stainless steels (such as X5CrNi18-10) are not able to meet the operating conditions. Produced in large quantities, it is an deformable and weldable steel and it has mechanical characteristics similar to those of the type X5CrNi18-10.

The stainless steel X5CrNiMo17-12-2 has high resistance to corrosion in seawater, in contact with process waters contaminated with halides (Cl^-, I^-, F^-), with acid condensates and with waste water; it has excellent behaviour in the presence of organic acids or alkaline solutions, also showing a small resistance in dilute sulphuric, hydrochloric or phosphoric acid solutions.

This steel is widely used in chemical and petrochemical plants and in off-shore structures, as well as in the food and pharmaceutical industry and the dyeing industry. Due to its nonmagnetic behaviour, it is used in some military applications, such as for example, for constructing the hulls of submarines.

To this regard, for the stabilised type containing titanium, X6CrNiMoTi17-12-2 (similar to AISI 316Ti), and the low carbon type, X2CrNiMo17-12-2 (similar to AISI 316L), similar considerations should apply to those already made for the stabilised and low carbon types of X5CrNi18-10: both steels are ideal in welding operations, avoiding having to perform an additional solution treatment to eliminate any chromium carbides formed.

To further increase resistance to corrosion, the stainless steels X1NiCrMoCu25-20-5 (similar to 904L) and X1CrNiMoCuN20-18-7 (similar to 254 SMO) are used, the second belongs to the so-called “super austenitic” family: it is one of the two special stainless steels used in particular applications.

The type X1NiCrMoCu25-20-5, due to its high nickel content, is very resistance to solutions of sulphuric and phosphoric acids (both dilute and concentrate) and is used in storage and transport systems.

The type X1CrNiMoCuN20-18-7 has very high resistance to attack from chlorides due to its high chromium and molybdenum content. It is used in desalination plants, in the chemical sector and in pulp bleaching systems where the use of bleaching substances is extensive.

9. AUSTENITIC-FERRETIC STAINLESS STEELS

9.1 Metallurgy

Austenitic-ferritic stainless steels (also called duplex or biphasic) owe their name to the presence of a mixed structure of austenite and ferrite at ambient temperature. This is the result of the combination of chromium and nickel suitably balanced in the chemical composition of the alloy: typically, duplex stainless steels have a chromium content between 22% and 25%, nickel content between 4% and 7%, with added molybdenum (3-4%) and nitrogen (0.1-0.25%) in many cases.

Table 14 shows the chemical composition of some of the most used austenitic-ferritic stainless steels and the relative designation according to the standard EN 10088. Please note that the trade name originally developed by Sandvik is most commonly used: it includes two pairs of numbers of which the first indicates the chromium content and the second the nickel content (for example 2205 indicates a biphasic stainless steel containing 22% chromium and 5% nickel).

The status diagram of duplex stainless steels (already reported in Figure 9) shows an initial solidification during the ferritic phase and only after the structure becomes biphasic they remain almost unchanged up to ambient temperature. At temperatures between 1050°C – 1150°C, an optimal ratio between the austenite and the ferrite is obtained (the two phases fluctuate between 40% and 60%), thus obtaining high mechanical characteristics and resistance to corrosion; in particular, biphasic stainless steels excel due to their significant resistance to stress corrosion cracking in solutions rich in chlorides.

Duplex stainless steels allow the combination of the specific properties of resistance to corrosion of the austenitic and ferritic stainless steels; however, they also share a number of specific problems, typical of both, such as the precipitation of chromium carbides and the presence of a harmful phase that forms at around 800°C as well as an embrittlement issue at 475°C.

The formation of carbides/nitrides and intermetal phases (σ, χ and Laves), even for short exposure periods between 550°C and 900°C, can cause slight reductions to the toughness of the material, as well as considerably worsen resistance to corrosion. Great attention must be placed on all those technological processes that involve thermal alteration with damage to the steel: this is the case of welding operations or during cooling after forging semi-finished products of medium-large dimensions.

Similar changes to toughness and resistance to corrosion occur at temperatures around 475°C due to the spinodal decomposition of the ferrite. The existence of this degradation phenomenon, together with the previous at around 800°C, limits the use of biphasic stainless steels in operation at temperatures no higher than 300 °C.

For an overall assessment of the two aforementioned problems, see Figure 41 which assesses the formation of deleterious phases with the variation of temperature and holding time for some types of biphasic stainless steels.

EN Designation	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	%N	Sandvik Denomination
X2CrNiN23-4 (1.4362)	≤0,03	≤1,00	≤2,00	≤0,035	≤0,015	22,0-24,0	3,50-5,50	0,10-0,60	0,05-0,20	2304
X2CrNiMoN22-5-3 (1.4462)	≤0,03	≤1,00	≤2,00	≤0,035	≤0,015	21,0-23,0	4,50-6,50	2,50-3,50	0,10-0,22	2205
X2CrNiMoN25-7-4 (1.4410)	≤0,03	≤1,00	≤2,00	≤0,035	≤0,015	24,0-26,0	6,00-8,00	3,00-4,50	0,24-0,35	2507

Table 14 – Chemical composition of some of the main types of austenitic-ferritic stainless steel (or duplex) [from EN 10088].

EN Designation	Solubilisation	Cooling	Sandvik Denomination
X2CrNiN23-4 (1.4362)	950°C-1050°C	water, air	2304
X2CrNiMoN22-5-3 (1.4462)	1020°C-1100°C	water	2205
X2CrNiMoN25-7-4 (1.4410)	1040°C-1120°C	water	2507

Table 15 – Characteristics indicative of annealing heat treatment of some of the main types of austenitic-ferritic stainless steel.

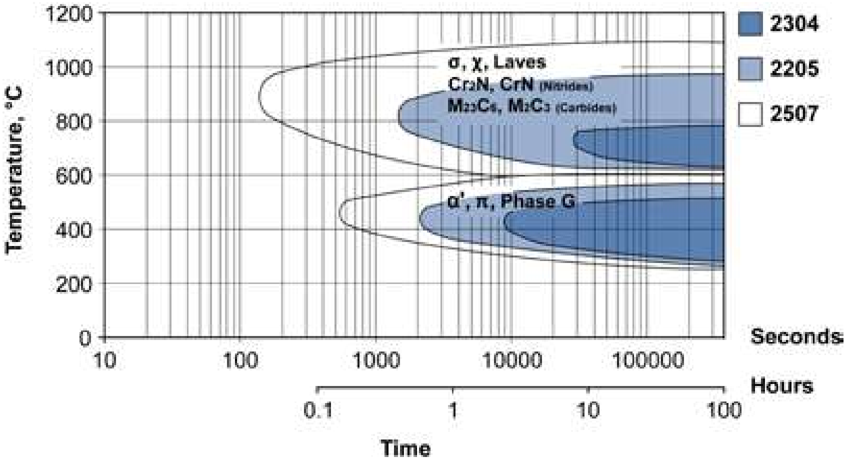


Figure 41 – Time-temperature diagram relative to the intervals of embrittlement at around 800°C and 475°C for three widely used duplex stainless steels.

9.2 Heat treatments

Semi-finished products made from biphasic stainless steels must always be subjected to an annealing treatment before being put into operation. This heat treatment is usually performed by holding the steel in the temperature interval of 1050-1150 °C; it is then rapidly cooled in water[34] to optimise the austenite-ferrite ratio (close to unity) and to encourage the resolution of unwanted phases possibly forming during manufacturing and transformation processes.

Table 15 indicates the heat treatment methods to be adopted for the most common types of biphasic stainless steel.

Also for these materials, both the annealing treatment and the subsequent cooling phase are often performed in a controlled atmosphere to avoid the surface oxidation of the semi-finished product.

9.3 Physical and mechanical properties

Table 16 shows the physical characteristics of some of the most common biphasic stainless steels.

It should be observed how most of the physical properties are all comparable with those of austenitic stainless steels (specific heat, conductivity, resistance and elastic modulus); the only exception is thermal expansion between austenitic and ferritic stainless steels. When it is exposed to magnetic fields, the duplex component is ferromagnetic, similar to what happens for ferritic stainless steels.

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[34] *Cooling in air can only be considered in the case of small sized pieces.*

EN Designation	Mass volume [kg/dm^3]	Specific heat at 20°C [J·kg^{-1}·K^{-1}]	Electrical resistance at 20°C [W·mm^2·m^{-1}]	Thermal conductivity [W·m^{-1}·K^{-1}]	Linear thermal expansion [10^{-6}·K^{-1}]		Modulus of elasticity [GPa]		Sandvik Denomination
					from 20°C to 100°C	from 20°C to 200°C	to 20°C	to 200°C	
X2CrNiN23-4 (1.4362)	7,8	500	0,80	15	13,0	13,5	200	186	2304
X2CrNiMoN22-5-3 (1.4462)	7,8	500	0,80	15	13,0	13,5	200	186	2205
X2CrNiMoN25-7-4 (1.4410)	7,8	500	0,80	15	13,0	13,5	200	186	2507

Table 16 – Physical characteristics indicative of some of the main types of austenitic-ferritic stainless steel (or duplex) [from EN 10088].

EN Designation	Metallurgic condition	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	Hardness	Sandvik Correspondence
X2CrNiN23-4 (1.4362)	Solubilizzato	420-480	650-750	25-35	200-250	2304
X2CrNiMoN22-5-3 (1.4462)	Solubilizzato	460-520	700-800	25-35	200-250	2205
X2CrNiMoN25-7-4 (1.4410)	Solubilizzato	520-580	750-850	25-35	230-280	2507

Table 17 – Mechanical characteristics indicative of some of the main types of austenitic-ferritic stainless steel (or duplex).

The particular microstructure of biphasic stainless steels allows high values to be obtained of both the yield stress $Rp_{0.2}$ (which is around double that of austenitic stainless steels) and the tensile strength R_m. Table 17 reports some mechanical characteristics indicated of the main types of biphasic stainless steels.

The high resistance properties of duplex steels, greatly higher than those of traditional austenitic and ferritic stainless steels, are very important during the design phase because they allow the resistance sections of the component to be greatly decreased.

Furthermore, biphasic stainless steels have an excellent behaviour in terms of resilience: their transition temperature is around -80°C. A qualitative comparison of the resilience characteristics of these steels compared to austenitic or ferritic stainless steels is presented in Figure 42.

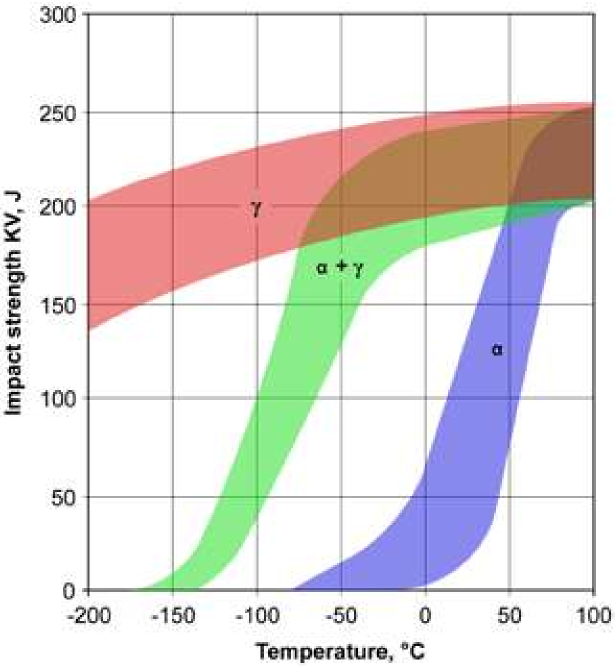

Figure 42 – Effect of the microstructure of the resilience of some families of stainless steels (γ = austenite; α+γ = ferrite and austenite; α = ferrite) [from Nicodemi 2002].

9.3 Types and applications

X2CrNiN23-4 (type 2304) was the first of the low alloy biphasic stainless steels: this steel was developed to economically compete with the traditional stainless steels X5CrNi18-10 and X5CrNiMo17-12-2 in the sectors where mechanical resistance and resistance to corrosion in chloride environments are essential. It is used in the production plants of nitric acid and for plants in contact with caustic substances (concentrations <30%), with organic acids or aqueous solutions rich in chlorides.

The steel X2CrNiMoN22-5-3 (type 2205) is definitely the most widespread of the biphasic stainless steels: it has a high mechanical resistance and excellent anti-corrosion characteristics, especially in marine environments where its behaviour is much superior than X5CrNiMo17-12-2. It is largely used in the petrochemical and chemical field, in environments contaminated by chlorides and in the presence of carbon dioxide CO_2 or hydrogen sulphide H_2S[35]; it is widely used in desalinisation plants and plants in contact with dilute and concentrate solutions of sulphuric, phosphoric, acetic and formic acid.

Finally, the steel X2CrNiMoN25-7-4 (type 2507): is the evolution of type 2205 and was created to ensure a further increase of the tensile properties and resistance to corrosion. It has quite a niche use compared to the previous type, however it is a possible alternative to the "super austenitic" stainless steels and titanium alloys; it is used in oil wells and in subsea pipelines where high resistance to corrosion and fatigue phenomena as well as erosive wear is required, in addition to traditional degradation caused by the marine environment.

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[35] *Sulphuric acid is also know as hydrogen sulphide.*

10. PRECIPITATION HARDENING STAINLESS STEELS

10.1 Metallurgy

Precipitation hardening (or PH) stainless steels were created with the aim of improving the mechanical behaviour of martensitic stainless steels (especially the fracture toughness), increasing the resistance to corrosion at the same time.

They are classified based on the microstructure that they have upon the initial annealing heat treatment: they are divided into martensitic, semi-austenitic and austenitic[36]. The hardening phase (after annealing) involves cooling the material through the finely dispersed precipitation of intermetallic compounds and interstitials in the crystalline matrix of the steel. For this purpose, alloy elements are added such as aluminium, copper, titanium and niobium which give rise to compounds of the type $Ni_3(Al, Ti)$, Ni_3Ti and NiAl or $Fe_2(Mo, Nb)$ or even carbonitrides type M(C, N) with M = Nb, Ti, Cr; however the copper does not form compounds but precipitates under the form of very small metal particles that strengthen the matrix of the steel.

Nickel is always present in precipitation hardened stainless steels, both to improve resistance to corrosion and to make the metal mass tough; it usually has very low carbon content ($C \leq 0.1\%$) and molybdenum is often added for anti-corrosion.

Table 18 reports the chemical composition of some of the main types of precipitation hardening stainless steels.

10.2 Heat treatments, physical and mechanical properties

At the state of supply, i.e. after the annealing treatment, semi-finished products in precipitation hardening stainless have a microstructure characterised by good cold plastic deformability and good machinability: the work piece is then subjected to the aging treatment to obtain mechanical properties aimed to withstand operating stresses.

Martensitic type precipitation hardening stainless steels, such as for example X5CrNiCuNb16-4 (also called 17-4 PH), are usually annealed at 1030°-1060°C and then cooled in air: a low carbon martensitic structure is obtained with low hardness and good deformability.

At the end of the operations of forming and chip removal, the semi-finished product is subjected to an aging treatment, performed at temperatures between 480°C and 630°C and for variable times from 1 to 4 hours[37].

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[36] *As will be better seen in the paragraph dedicated to heat treatment, martensitic and austenitic PH stainless steels maintain their microstructure until the hardening heat process, whereas semi-austensitic PH undergo a further heat teatment that induces the transformation of the initial microstructure into martensite.*

[37] *Annealing treatment is indicated with the letter A (Annealing) where as hardening treatment is indicated by the letter H (Hardening) followed by the aging temperature in degrees Fahrenheit. For example A + H925 indicates that the steel was annealed and aged at 495°C (925°F).*

EN Designation	Common name	%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo	Other	AISI approximate denomination
X5CrNiCuNb16-4 (1.4542)	17-4 PH	≤0,07	≤0,70	≤1,50	≤0,040	≤0,015	15,0 17,0	3,50 5,00	≤0,60	1	AISI 630
X7CrNiAl17-7 (1.4568)	17-7 PH	≤0,09	≤0,70	≤1,00	≤0,040	≤0,015	16,0 18,0	6,50 7,80	---	2	AISI 631
X5NiCrTiMoVB25-15-2 (1.4606)	A-286	≤0,08	≤1,00	1,00 2,00	≤0,025	≤0,015	13,0 16,0	24,00 27,00	1,00 1,50	3	AISI 600

1: %Cu = 3,00-5,00; %Nb = 5 x C – 0,45
2: %Al = 0,70 – 1,50
3: %B = 0,001 – 0,010; %Ti = 1,90 – 2,30; %V = 0,10 – 0,50; %Al ≤ 0,35

Table 18 – Chemical composition of some of the main types of precipitation hardening stainless steel [from EN 10088].

In this way it is possible to obtain a tensile strength R_m between 850 MPa and 1400 MPa with an elongation A% variable from 25% to 12% (see Figure 43); resilience at ambient temperature fluctuates between 40J (se R_m = 1400 MPa) and 100J (if R_m = 850 MPa).

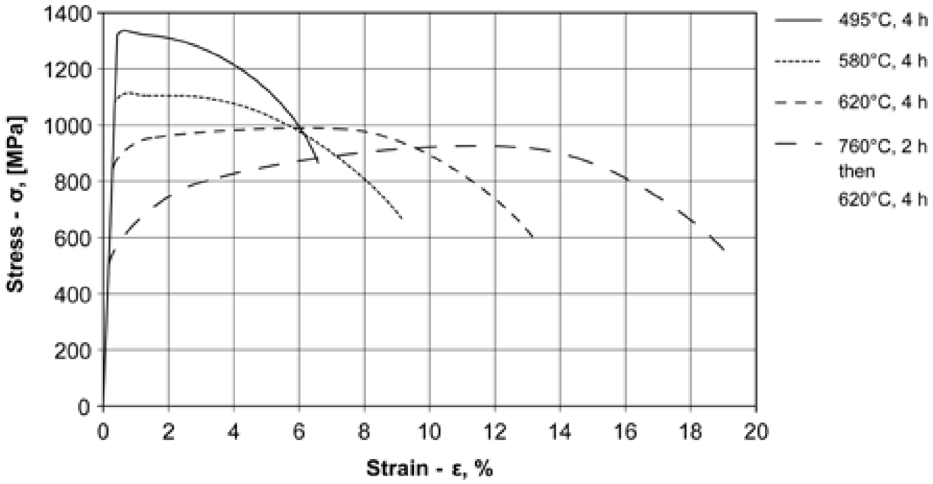

Figure 43 – Steel X5CrNiCuNb16-4 (also called 17-4 PH) annealed at 1050°C in air, then aged according to various methods: curves σ - ε [Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano, Milan].

Semi-austenitic precipitation hardening stainless steels, such as for example X7CrNiAl17-7 (also called 17-7 PH), have a predominantly austenitic structure after annealing[38] at ambient temperature: this makes the execution of high pressure cold plastic deformation operations such as rolling very thin plates or strips easier. Due to the special chemical composition, after annealing the austenitic structure is unstable and, following the cold plastic deformation operations and the action of suitable heat treatments, it is transformed into martensite[39]. The aging heat treatment will be performed on the martensitic structure obtained in this way, similarly to what happens in normal martensitic PH stainless steels.

A schematic of the possible technological processes which can be performed on a semi-austenitic precipitation hardening stainless steel type X7CrNiAl17-7 is shown in Figure 44. The mechanical characteristics fluctuate between 1300 MPa and 1700 MPa for the tensile strength R_m and between 1100 MPa and 1500 MPa for the yield stress $Rp_{0.2}$; the hardness is around 42-48 HRC.

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[38] *In semi-austenetic precipitation hardening stainless steels the structure always contains a certain amount of ferrite after annealing.*

[39] *The name "semiaustenitic" stainless steels derives from the instability at ambient temperature of the austenite present in such steels.*

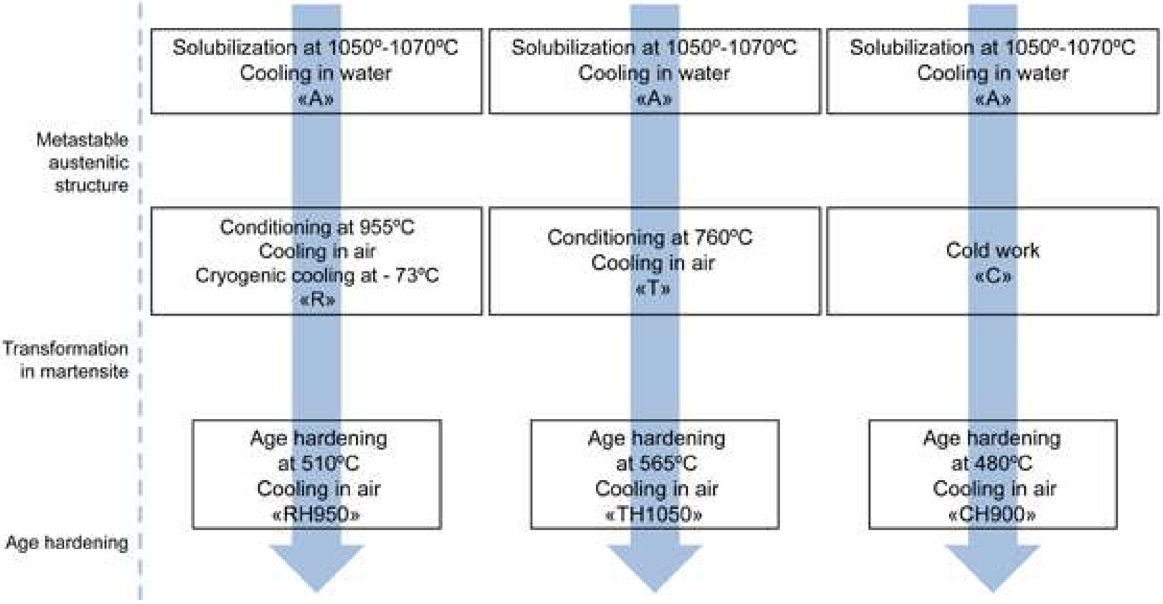

Figure 44 – Steel X7CrNiAl17-7 (also called 17-7PH): possible heat and thermo mechanical treatments necessary to cause precipitation hardening.

Finally, austenitic precipitation hardening stainless steels, such as X5NiCrTiMoVB25-15-2 (also called A-286[40]).

Due to the high nickel content, the structure of this steel is completely austenitic and is very stable even after cold plastic deformation. The annealing treatment is performed between 970°C and 1050°C with cooling in water or in oil; aging occurs between 650°C and 750°C.

Figure 45 shows the hardness trend of the steel X5NiCrTiMoVB25-15-2 after annealing, cold hardening for rolling and subsequent aging at variable temperatures.

The physical properties of some of the main types of precipitation hardening stainless steels are shown in Table 19.

10.4 Types and applications

Precipitation hardening stainless steels are generally present on the market under the form of long products in round or hexagonal bars, plates and sheets are less widespread.

They are used in the aeronautical and aerospace industries, in the naval field, in the chemical and petrochemical industry and in the energy sector for the production of components characterised by

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[40] *It should be noted that this steel is also called Incoloy A-286: Incoloy is the trade name that the American Special Metal Corporation assigns to Fe-Ni-Cr superalloys produced by them.*

high mechanical resistance and resistance to corrosion such as valves, shafts, bearings and turbine and compressor blades. They are also used in applications for load cells, sprockets, firearms, utensils, springs and surgical instruments.

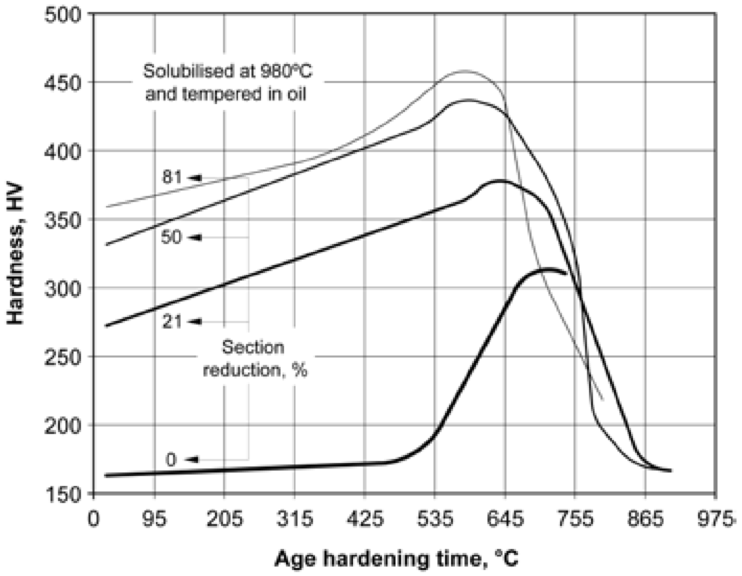

Figure 45 – Hardness trend according to the aging temperature for a steel X5NiCrTiMoVB25-15-2 (also called A-286) after annealing and quenching in oil and cold rolling at various levels of hardening [from McGuire 2008].

EN Designation	Common name	Mass volume [kg/dm^3]	Specific heat at 20°C [J·kg^{-1}·K^{-1}]	Electrical resistance at 20°C [W·mm^2·m^{-1}]	Thermal conductivity [W·m^{-1}·K^{-1}]	Linear thermal expansion [10^{-6}·K^{-1}]		Modulus of elasticity [GPa]		AISI approximate denomination AISI
						from 20°C to 100°C	from 20°C to 200°C	to 20°C	to 200°C	
X5CrNiCuNb16-4 (1.4542)	17-4 PH	7,8	500	0,71	16	10,9	---	200	185	AISI 630
X7CrNiAl17-7 (1.4568)	17-7 PH	7,8	500	0,80	16	13,0	13,5	200	185	AISI 631
X5NiCrTiMoVB25-15-2 (1.4606)	A-286	7,9	460	0,91	14	16,5	16,8	211	200	AISI 600

Table 19 – Physical characteristics indicative of some of the main types of austenitic-ferritic stainless steel (or duplex) [from EN 10088].

11. THE CORROSION OF STAINLESS STEEL

11.1 Introduction[41]

Stainless steels are mainly used because of their excellent resistance to corrosion and it is perhaps for this reason that corrosion is the most typical form of operating degradation. This problem therefore needs to be investigated further, because only through understanding the mechanisms of damage will it be possible to identify the proper criteria of choice and use of this family of materials.

Corrosion is a form of degradation caused by chemical and electrochemical reactions that take place at the interface between the surface of a material and the environment with which it is in contact: the result is a gradual decay of the functional features of the stainless steels occurring when the main constituents of the alloy (Fe, C, Cr, Ni, etc.) combine with the aggressive agents present in the environment, thus forming corrosion products.

The corrosion of stainless steels can cause several problems. In the case of piping and tanks, the degradation can give rise to punctures that lead to leakage of the fluids contained within; in structural elements corrosion can cause the reduction of the resistant part with the consequent loss of the component's load capacity. Other problems are also linked to the formation of corrosion products, which can lead to the alteration of the aesthetic features of the surfaces or the contamination of the processed substances (for example, in the case of foods, possible alteration to their organoleptic characteristics)[42].

The corrosion of stainless steels can be divided into two basic forms:

- electrochemical corrosion – also called wet corrosion – in which the metal alloy undergoes an oxidation reaction in the presence of an electrolyte (usually water); the oxidation reaction is coupled with a reduction reaction of the substances present in the environment (usually oxygen): the combination of the two reactions, anodic (oxidation) and cathodic (reduction), involve both chemical species (ions and molecules) and electrons;
- chemical corrosion (also called high temperature oxidation or dry corrosion) in which the metal alloy undergoes an oxidation reaction upon contact with a gaseous atmosphere (usually air); the phenomenon usually occurs at temperatures well above ambient temperature (>300°C) and the corrosion products are oxides and salts with low melting points.

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[41] *This paragraph and the two subsequent paragraphs were partially taken from the article by Boniardi M., Casaroli A., Tagliabue C., 'Fenomeni di danneggiamento dei materiali metallici dovuti all'esercizio (Failure Analysis)' (Phenomena of damage to metal materials caused by operation(Failure Analysis)), by Various Authors, Le Prove non Distruttive (Non-destructive testing), Vol. 1, Associazione Italiana di Metallurgia, Milan 2013.*

[42] *The reader should consider that the phenomenon of "corrosion" is not limited to just iron based alloys (common steel, special steel, stainless steel, cast iron, etc.) but regards several types of metal materials (alluminium, magnesium, copper, titanium, nickel and their alloys). Failure to resolve problems of environmental degradation of metal materials has significant financial impact: it has been estimated that, in the most industrialised countries, the damage incurred due to corrosion is equal to 4-5% of the GDP, both in the form of direct damage from restoring the corroded structures and in terms of indirect damage from lack of production.*

Most of the forms of degradation of stainless steels (~95%) are due to the action of electrochemical corrosion or wet corrosion, whereas only a very small percentage (~5%) of corrosion is relative to the problem of oxidation under heat.

11.2 Wet corrosion and electrochemical corrosion

Wet corrosion of stainless steels can be described using the electrochemical model: the mechanism that governs the phenomenon depends on the presence of an anodic process, i.e. the oxidation of metal/ metal alloy subject to corrosion, and a cathodic process or reduction of a chemical species present in the aggressive environment (in many cases this is a reduction of oxygen and development of hydrogen). In order for corrosion to occur, the anodic reaction (oxidation) and the cathodic reaction (reduction) must occur at the same time and at the same speed on the surfaces of the metal mass.

In order for the redox reactions to take place, an ionic conductor in a liquid state must be present, the so-called electrolyte, which allows the passage of a current between the anodic zone and the cathodic zone: in most of the corrosive processes, the electrolyte is water (fresh water, sea water, condensation of aqueous steam and atmospheric moisture).

To understand the problem further, refer to the diagram shown in figure 46, in which an iron plate is placed in contact with a copper plate and the drop of water is the electrolyte.

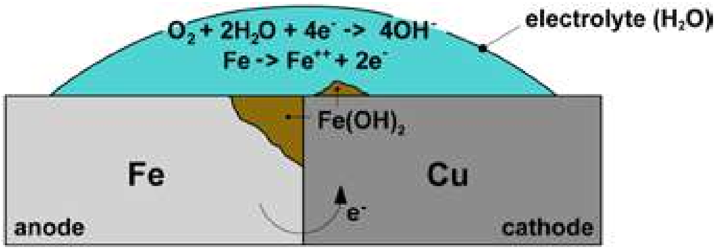

Figure 46 – Electrochemical diagram of the corrosive phenomenon of an iron plate in contact with a copper plate.

As the copper is a nobler metal than iron (copper has a greater electrochemical potential than iron), a potential difference is established between copper and iron, i.e. an electromotive force that allows the circulation of current. The analogy using the galvanic cell is clear[43]: the iron behaves as an anode and the copper as a cathode and the potential difference between the two metals allows the circulation of current. The oxidation reaction occurs to the anode (iron) and the reduction reaction of oxygen occurs to the cathode (copper) at the same time.

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[43] *For this reason the degradation phenomena caused by contact between dissimilar metals or metal alloys take the name of galvanic corrosion.*

The two reactions are:

$Fe \longrightarrow Fe^{+2} + 2e^-$ (anodic reaction of oxidation)

$\frac{1}{2} O_2 + H_2O + 2e^- \longrightarrow 2OH^-$ (cathodic reaction of reduction)

overall obtaining:

$\frac{1}{2} O_2 + H_2O + Fe \longrightarrow Fe(OH)_2$

In summary: the iron gradually transforms into solution under the form of Fe^{+2} ions, corroding due to the effect of the presence of the copper cathode where the reduction of oxygen occurs.

In the example shown previously, the anodic and cathodic zones are clearly distinct: the corrosive phenomenon occurs due to a galvanic coupling[44] that creates a potential difference "E" because of the different nature of the two metals involved.

However, it should not be believed that corrosion only occurs in these conditions: the case of degradation phenomena on metal alloys not in contact with dissimilar metals is much more common.

To understand the problem better the experience of Evans[45] should be considered, as shown in figure 47: his experiment is especially significant as it explains the phenomenon of corrosion of homogenous metal materials.

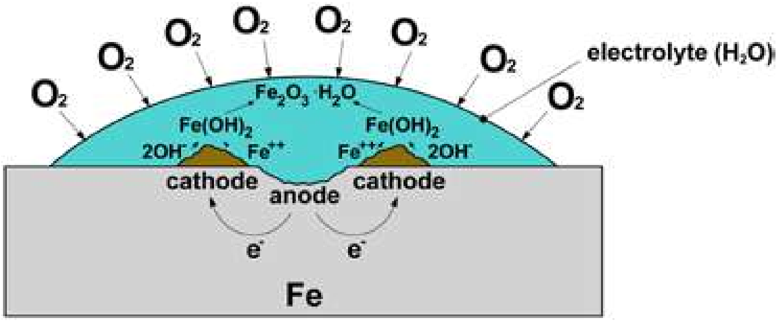

Figure 47 – Experience of Evans; phenomenon of electrochemical corrosion in a homogenous metal material [from Pedeferri 2010].

By taking an iron plate on which a deaerated drop of water is placed as the electrolyte, after a short time corrosion phenomena are only observed near the central area of the drop: this can be explained by considering the process of oxygen diffusion in the water drop, also called differential aeration corrosion.

Initially, the chemical composition of the drop is constant and the oxygen is totally absent: over time however, due to contact with air, diffusive phenomena will occur near to the external surfaces of the drop (which is the surface of exchange with the surrounding air) and a variation of the oxygen concentration will take place

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[44] *A particular form of corrosion is called galvanic corrosion and, as will be explained later, it occurs when stainless steel is placed in contact with a nobler metal (such as graphite) or with a less noble metal (such as aluminium).*

[45] *Ulick Richardson Evans (1889-1980) was one of the founding fathers of modern science who studied corrosion and the protection of metal materials.*

in the drop. The different concentration of O_2 in the drop will create an anodic zone, i.e. the zone lacking in oxygen in the centre of the drop, and a cathodic zone, i.e. the zone rich in oxygen on the outside of the drop[46]. Therefore, a local anode-cathode micro bond is created which is able to trigger the corrosion process. The "E" potential existing between the anode and cathode is a kind of electromotive force that allows the corrosive process to take place: it is called "free corrosion potential".

The anodic reaction and the cathodic reaction are all the same as those observed previously for galvanic contact:

$Fe \longrightarrow Fe^{+2} + 2e^{-}$ (anodic reaction of oxidation)

$\frac{1}{2} O_2 + H_2O + 2e^{-} \longrightarrow 2OH^{-}$ (cathodic reaction of reduction)

overall obtaining:

$$\frac{1}{2} O_2 + H_2O + Fe \longrightarrow Fe(OH)_2$$

with the formation of corrosion products (iron oxides/hydroxides).

If the oxidation reaction of iron occurs in an acid environment (such as when an iron plate is immersed in chloride acid), the cathodic process will be the reduction of the hydrogen ion to hydrogen gas (hydrogen evolution), i.e.:

$Fe \longrightarrow Fe^{+2} + 2e^{-}$ (anodic reaction of oxidation)

$2H^{+} + 2e^{-} \longrightarrow H_2$ (cathodic reaction of reduction)

overall obtaining:

$$2H^{+} + Fe \longrightarrow Fe^{+2} + H_2$$

For corrosion to occur, the two reactions, anodic and cathodic, must happen at the same time: during the oxidation reaction of the iron, a certain number of electrons are generated on the anode which, following the reduction reaction, are consumed by the cathode.

The above reactions are very common in all metal materials subject to corrosion: the presence, for any reason, of an anodic-cathodic micro bond provides the electromotive force required to trigger and supply the degradation process.

However, the phenomenon of differential aeration corrosion is not the only type to give rise anodic-cathodic micro bonds able to trigger degradation: often in the corrosive 'material – environment' combination there are already particular local conditions suitable for generating zones with different electrical potential.

The problem arises for various reasons: heterogeneity of chemical composition of the metal mass, in homogenous phases of the microstructure of the matrix (inclusions, carbides, etc.), Tensile residual stress of high entity traction, local defects of the piece (micro cavities, blowholes, accentuated roughness etc.) All these areas act as the anode of the surrounding metal mass acting as a cathode, causing local micro bonds with preferential corrosion triggers.

Similar situations also arise due to the variability of the electrochemical characteristics of the corrosive

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[46] The anode and the cathode – to clarify further – are areas located in the metal mass in contact with the liquid: where there has been an enrichment of oxygen developed in the cathode area, where there is a lack of oxygen in the anodic area.

environment, such as that which occurs, for example, in solutions with various concentrations of noxious species, in electrolytes with greater or smaller stagnation zones or with non-uniform temperatures.

11.3 Potentiodynamic curves

During a corrosive process there is always a certain number of ions in solution in the electrolyte and a concomitant movement of electrons in the metal, i.e. a circulation of electrical current, as what occurs in a cell.

The mechanism described is concatenated: the higher the quantity of iron ions, which will dissolve in the solution, the greater the number of electrons circulating per surface unit exposed to the corrosive environment. This causes the increase of the surrounding current density[47] "i_c" and the corrosion rate "V_{corr}" of this material will increase in that given environment, i.e.:

corrosion rate $(V_{corr}) \propto i_c = i_{anodic} = i_{cathodic}$[48]

It should be repeated that the corrosive phenomenon is a degradation process that occurs when there is an anodic zone and a cathodic zone[49]: among these two zones a potential difference "E" is established (called free corrosion potential in the case of short circuits between anodes and cathodes) which ensures the circulation of a current density "i" proportional to the corrosion rate of the system.

The correlation between potential "E" and current density "i" of the anode-cathode bond depends on both the electrochemical characteristics of the anodic process (i.e. "how quickly" the metal dissolves) and the electrochemical characteristics of the cathodic process (i.e. "how quickly" the oxygen or the hydrogen evolves).

If the two contributions are separated, i.e. if the correlation "E – i" is studied separately for the anodic reaction and the cathodic reaction, it is possible to estimate what the trend of the surrounding current density "i" will be, in order to change the applied electromotive force "E"[50].

This is exactly what Evans did experimentally and which is still possibly to recreate in the laboratory: to trace the curves that describe the anodic reaction and cathodic reaction with the variation of the tension

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[47] *The parameter that best describes the electrochemical corrosive phenomena is the current density, that is to say the surrounding current per surface unit: this depends on the fact that the corrosion occurs on a given surface with respect to which a given current intensity develops.*

[48] *Simple calculations based on the Faraday alloy allow the numeric correlation of the surrounding current density with the corrosion rate: for every 1 μA/cm^2 there is a degradation penetration equal to 10-12 μm/year. The figure indicated is valid for most of iron alloys, copper alloys, aluminium and nickel.*

[49] *It is worth reiterating that the anodic zone and the cathodic zone can "reside" in two dissimilar materials (case of figure 46) or be present in different areas of the same material (case of figure 47).*

[50] *The potential correlation "E" – current density "i" that is measured experimentally is, mutatis mutandis, similar to what is looked for when you want to establish the electrical resistance of a conductor: the potential "V" continuously changes and the variations of current "I" are measured, obtaining the well noted Ohm relationship V = RI.*

conditions “E” applied, or the reaction existing between the set tension “E” and the surrounding current density “i” both in the anodic area and in the cathodic area.

The curves obtained experimentally are shown in figure 48: they are called potentiodynamic curves, or Evans diagrams, due to the anodic process (anodic characteristics, metal/alloy that is corroded) and the cathodic process (cathodic characteristics, oxygen reduction and hydrogen evolution).

In the very simple case of common carbon steel in an aerated aqueous solution (the cathodic process is oxygen reduction), the two curves are as shown in figure 48a, whereas for a stainless steel, again in the same solution, the situation shown in figure 48b occurs[51].

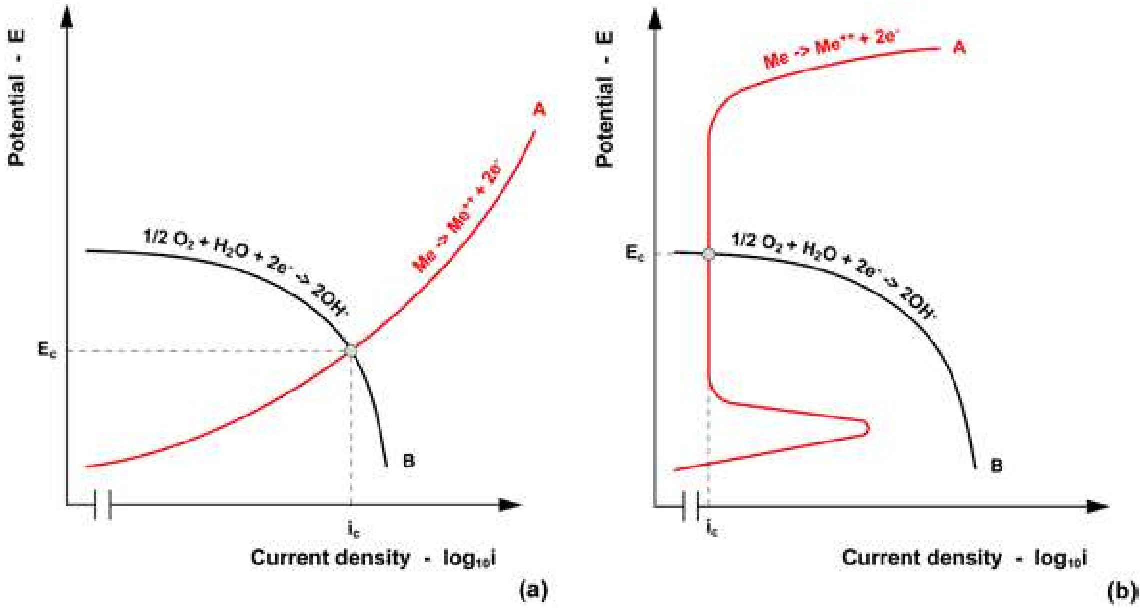

Figure 48 – Indicative potentiodynamic curves (anodic characteristic A: material – cathodic characteristic B: environment) in aqueous solution 0.05 M of H_2SO_4: (a) for a material with active conduct and b) for a material with active-passive conduct.

The intersection point of curves A and B shown in figure 48 represents the condition of equivalence between the surrounding current densities (the rate of the two reactions, anodic and cathodic, is equal): it establishes the functioning point of the material-environment system and allows the determination of the free corrosion potential “E_c” and the surrounding current density “i_c”, as well as estimating the corrosion rate of the material in that particular environment ($V_{corr} \propto i_c$).

In the case of carbon steels, the anodic curve (curve A – figure 48a) increases monotonically: the current increases with the increasing tension applied and with it, the corrosion rate increases. With regards to

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[51] *To be able to observe the typical active passive trend of stainless steel in practice, a small amount of an acid species must be added (in this case ~4.9 g/litre of sulphuric acid to obtain an aqueous solution 0.05 molar = 0.05M of H_2SO_4).*

stainless steels (curve A – figure 48b) typical active-passive behaviour can be seen. It should be remembered that the two cathodic curves indicated by B in figure 48 have the same trend because they represent the same environment in which the two materials are inserted.
The comparison between these two conditions (figure 48a and figure 48b) is significant and accounts for the actual behaviour in operation of the two different materials: because the surrounding current "i_c" of case "a" is much greater than the surrounding current "i_c" of case "b", the corrosion rate of a carbon steel, in that determined environment, will be a lot greater than that of a generic stainless steel[52].

11.3 The wet corrosion of stainless steels

We will now attempt to describe the curve characteristic of stainless steels in more depth (anodic curve), indicating the significant parameters that are better suited to classifying the behaviour of the material: see figure 49.

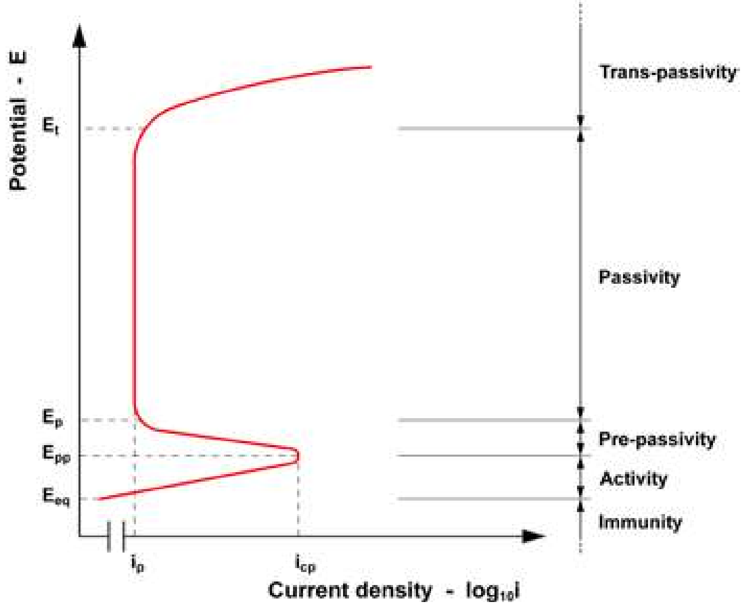

Figure 49 – Schematic of the anodic characteristic of a generic stainless steel.

Below the equilibrium potential "E_{eq}" the stainless steel is immune from any corrosive phenomenon: it is thermodynamically stable and the oxidation reaction cannot take place.

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[52] *It should be noted that the x access shows the current density in a logarithmic scale with the base (not in a linear scale!): this means that a linear variation on the axis, leads to a variation of the size of the surrounding current, or rather the size of the corrosion rate of the material.*

The anodic curve shows an active behaviour (from "E_{eq}", equilibrium potential, up until point "$E_{pp} - i_{cp}$", primary passivation potential and critical current density of passivation): in this area the stainless steel acts like a common carbon steel with gradually increasing corrosion rate values with the increase of the set potential.

The passivation phenomenon occurs starting from point "$E_{pp}- i_{cp}$" with the consequent formation of the protective film of chromium oxide described in chapter 1: the electrochemical characteristic of the stainless steel is radically modified and, with the increase of the applied potential "E", there is a gradual decrease of the current density "i" which is stabilised around the value "i_p" (current density of passivation). In correspondence to "i_p" the corrosion rate is extremely low and can be considered as practically zero[53]: this is the field in which the very thin chromium oxide/hydroxide film is formed and stabilised which protects the stainless steel.

The current density of passivation value "i_p" is constant for a wide potential interval (from "E_p", passivation potential, up to "E_t", transpassivation potential): beyond this value the stainless steel returns to behaving in an active manner due to the dissolution of the chromium oxide film. When the potential "E_t" is exceeded, localised forms of corrosion occur at the points where the passive film has been chemically attacked by the environment.

The high resistance to corrosion of stainless steels is linked to the low i_p values in the passivation field, i.e. in the "E_p-E_t" interval: the formation of the protective film (passivation) notably occurs when the environment has oxidising characteristics, such as for example in air or in aerated aqueous solutions.

However, how does a stainless steel behave in terms of resistance to corrosion when, in practice, it comes into contact with chemical environments having particular characteristics?

To be able to adequately answer this question, it is necessary to assess the interaction between the environment (cathodic curve) and the stainless steel (anodic curve): see figure 50 which shows the effect of four distinct cathodic processes (B1, B2, B3 and B4) alongside the anodic behaviour of a generic stainless steel (A).

The curves indicated by B1, B2, B3 and B4 represent four different cathodic processes (i.e. four different environments) characterised by increasing oxidising power.

Curve B1 is typical of an acid environment in which oxygen (or other oxidising species) is completely absent: the only process that can take place on the cathode is hydrogen evolution. The situation described here would occur for example in the case of a stainless steel immersed in a 50% sulphuric acid solution. In this case the stainless steel "works" at point X_1 and has an active behaviour, i.e. passivation cannot occur: consequently the degradation due to corrosion will be uniform and generalised across the entire surface.

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[53] the current density of passivation "i_p" of the stainless steels is generally very low (10^{-5}-10^{-7} A/cm^2): for this reason it can be reasonably assumed that, once the current density around the passivation value ("i_p") is stabilised, the corrosion rate is practically zero.

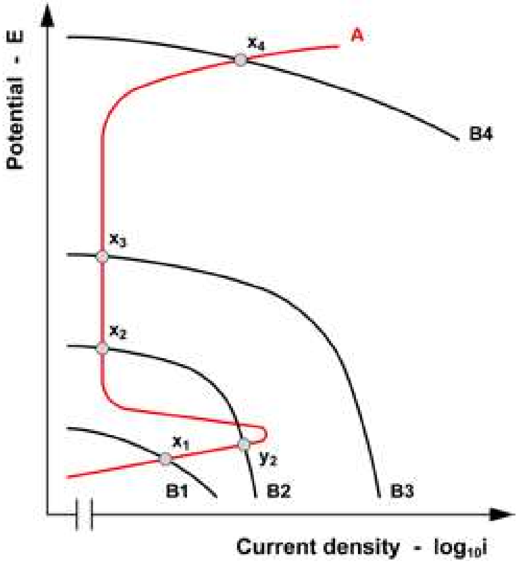

Figure 50 – Cathodic characteristics of four environments with increasing oxidising power (B1, B2, B3 and B4) and relative "functioning points" on the anodic characteristic of a generic stainless steel.

Curves B2 and B3 represent two cathodic processes where there is oxygen reduction; the difference is related to the oxygen concentration in the solution: lower in the case of B2 and greater in the case of B3. This is what would happen in a stagnant (B2 curve) or agitated (B3 curve) aqueous solution.

The two situations described by the cathodic processes B2 and B3 are very different from each other. In the case of the B2 curve, there are two functioning points of the anodic-cathodic system: X_2 and Y_2. If stainless steel is immersed in the aqueous solution and is already in passive conditions[54], it will remain in this condition and preserve its typical resistance to corrosion (functioning point X_2). However, if the passive film becomes damaged for example due to mechanical action, the stainless steel will remain "functioning" in an active way (point Y_2), thus giving rise to localised corrosive phenomena.

If the agitation of the aqueous solution is increased or, in the same way, the concentration of oxygen in the liquid is increased, the cathodic curve will move towards high potentials equal to current density (B3 curve), giving rise to a single functioning point of the anode-cathode system (X_3): in this case the passive film on the stainless steel will be stable and will reform in a compact and adherent manner if mechanically damaged.

Finally, the condition defined by the curve B4: this represents the cathodic behaviour of a strongly oxidising electrolyte, thus it could be an aqueous solution containing chromate. If the stainless steel is placed in this

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[54] *During the production of components in stainless steel, it is common practice to put them in operation only after having performed a pickling treatment and chemical passivation (using nitric acid based solutions): this treatment has the aim of generating a stable and adherent passive film on the surface of the material.*

environment, its passive film will be unstable: in some points there would be the chemical degradation of the protective layer of chromium oxide with consequent localised attacks in the metal mass.

11.4 The resistance to corrosion of stainless steels

The previous paragraphs should have clarified that the resistance to corrosion of any stainless steel is not an absolute characteristic of the material and its chemical composition, but rather depends on the environment in which the material is used[55].

Therefore, with the aim of separately assessing these two aspects (material and environment), we will now examine the changes to the anodic behaviour of the stainless steel with the variation of their chemical composition and the surrounding conditions, or rather the aggressive solutions within which they are put in contact.

First of all, it should be noted that in order to improve the characteristics of resistance to corrosion of a stainless steel (with equal environment) it is important to try to:

- extend the passive field, or widen the interval "E_p-E_t" (in particular, increase the potential value of transpassivation "E_t");
- decrease the value of "i_{cp}", the critical current density of passivation, which represents the level of current density to be exceeded in order to allow passivation of the steel;
- reduce the value of "i_p", the current density of passivation, which indicates the corrosion state of the stainless steel when it is under passive conditions.

In this regard, note figure 51: it clarifies the reason for which stainless steel, in the wide panorama of metal materials (Fe, Ni, Cr, and Mo) is the correct choice to hinder degradation caused by corrosion from very aggressive environments.

If the observation is limited to the iron-chromium-nickel alloys, it can be observed that the passivation phenomenon, in terms of electro chemicals, only becomes apparent when the chromium content increases, similar to that observed in chapter 1 regarding the formation of the protective film (figure 52).

When the chromium content is around 11.7%, the presence of a wide passivation range ("E_p-E_t") is clear, with surrounding current density values of around 10 μA/cm^2 (corrosion penetration: 100-120 μm/year); on increase of the chromium content, the passive film becomes more stable, as can be observed from the decrease of the passivation current density, equal to approx. 0.1 μA/cm^2 (1-1.2 μm/year), and the further enlargement of the interval "E_p-E_t".

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[55] *This statement is completely general and is valid for all metal materials that suffer corrosive phenomona. The resistance to degradation of any material always depends on the surrounding conditions: to understand corrosion fully it is never possible to separate the material from the environment in which the phenomena take place.*

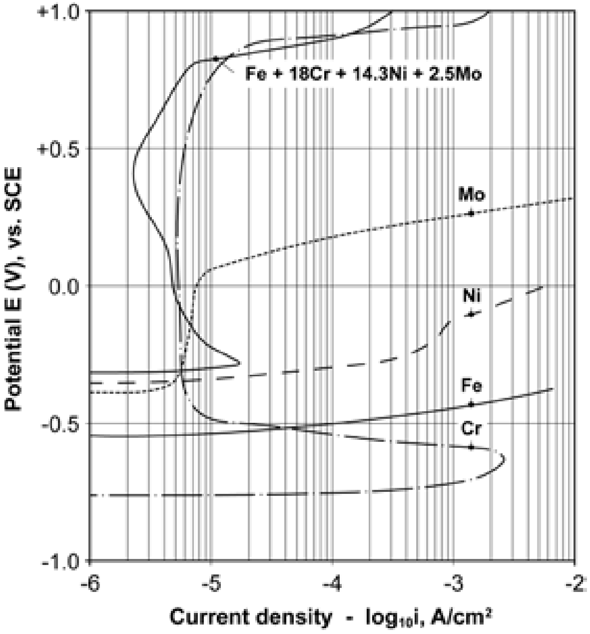

Figure 51 – Potentiodynamic curve for chromium, iron, nickel, molybdenum and stainless steel containing 18% chromium, 14.3% nickel and 2.5% molybdenum, in aqueous solution 0.1M of HCl + 0.4M of NaCl at 25°C [from Olefjord et al. 1985].

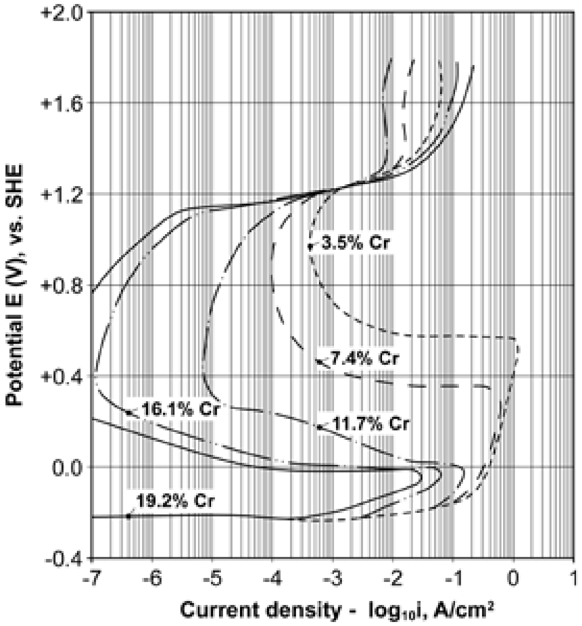

Figure 52 – Effect of chromium on the anodic characteristics (potentiodynamic curve) of iron-chromium alloys containing 8.3-9.6% nickel; 1M aqueous solution of H_2SO_4 at 90°C [from Osozawa and Engell 1966].

Again through the examination of the active-passive curve of stainless steel, it is possible to understand how the various elements of alloy influence the resistance to corrosion of stainless steels (see figure 53).

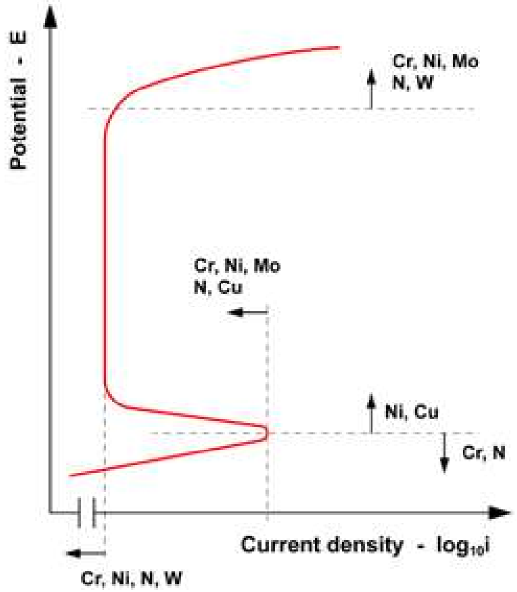

Figure 53 – Schematic trend of the active-passive characteristic of stainless steels according to the addition of various alloy elements [from Sedriks 1986].

The addition of nickel and molybdenum slightly improves the ability of the steel to passivate after the initial active phase (decrease of the current density of passivation "i_{cp}"), while extending the field of potentials in which the material is in passive conditions (increase of transpassivation potential "E_t").
By contrast, the effect of alloy elements on the reduction of the current density of passivation "i_p" is much less evident: when the steel is in fact in these conditions (passive) its corrosion rate, i.e. the surrounding current density, is so low that in practice not very influenced by the chemical composition of the steel (see figure 54).
In a similar way, one can assess the effect of the same environment on the material: in this regard figure 55 should be noted, which shows the anodic behaviours of a type X5CrNi18-10 stainless steel in aqueous solution with varying concentrations of chlorides. Similar effects, with a consequent worsening of the corrosive behaviours of the acid, can be seen by increasing the temperature and/or decreasing the pH of the solution (figure 56).

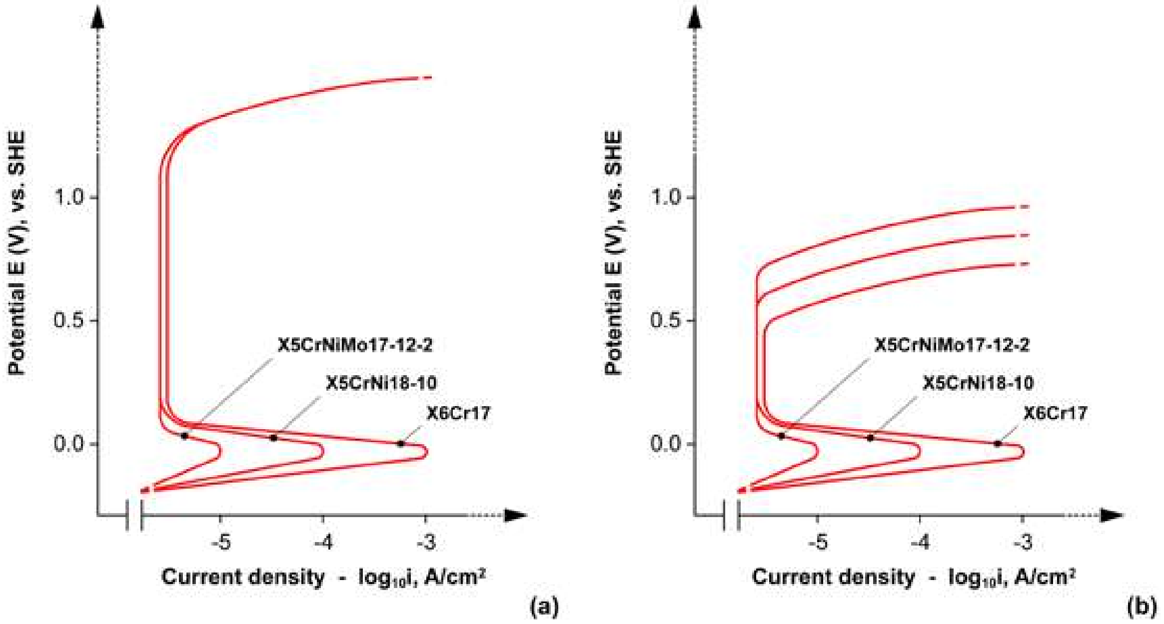

Figure 54 – Guide line potentiodynamic curve for three stainless steels in acid solutions with added chloride: (a) 0.05M solution of sulphuric acid, (b) 0.05M solution of sulphuric acid and 0.1M solution of sodium chloride. [from Talbot and Talbot 1998].

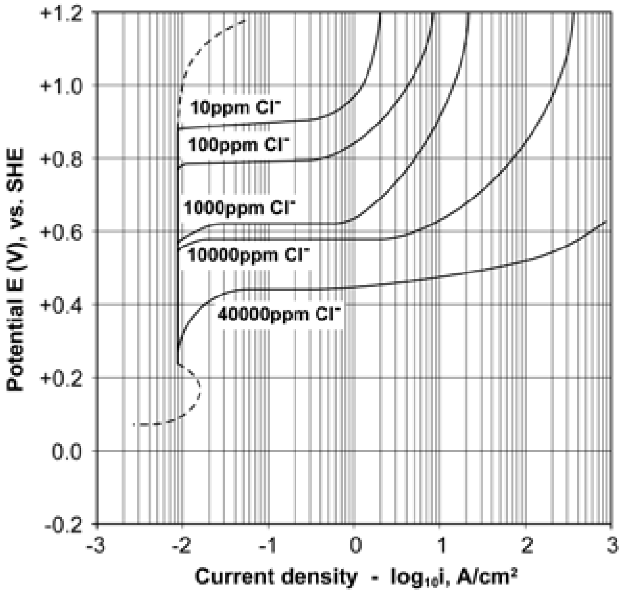

Figure 55 – Potentiodynamic curves for a type X5CrNi18-10 stainless steel in water at 25°C with increasing contents of chloride Cl^-; the dashed curve approximately indicates the position of the peak of anodic current density and the transpassive zone [from Stansbury and Buchanan 2000].

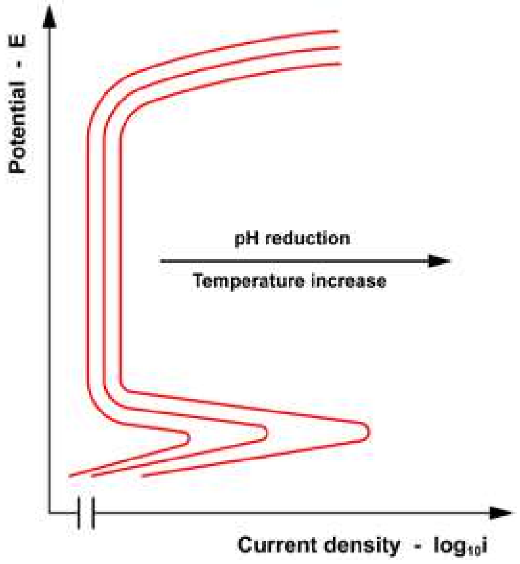

Figure 56 – Schematic trend of the active-passive curve of a generic stainless steel due to the increase of temperature or the acidification of the solution.

12. THE CORROSION MORPHOLOGY OF STAINLESS STEELS

12.1 Introduction[56]

Corrosive phenomena can also be classified based on the morphology with which the degradation occurs in the components, or rather in relation to the aspect of chemical aggression as it appears upon simple visual observation or using magnification microscopy.

An initial distinction can be made between “generalised or uniform corrosion” and “localised corrosion”:

- in the first case the whole surface of the material is subject to corrosive attack (generalised), with penetration of the degradation quite consistent along the whole section of the component (uniform);
- in the second case the aggressive action is only expressed in some areas of the surfaces (localised), with penetrating attacks, craters or cracks.

Many types of corrosion belong to this second morphology category: including those that appear most significant in the context of stainless steels, i.e. galvanic corrosion, pitting corrosion, crevice corrosion, intergranular corrosion and stress corrosion cracking.

12.2 Uniform or generalised corrosion

This form of corrosion affects the whole surface area of the metal material exposed to the aggressive environment, with limited local variations of the degree of penetration of the damage along the thickness of the component. A typical example of generalised and uniform corrosion is represented by stainless steels in contact with acid solutions (aqueous solutions of hydrochloric acid, sulphuric acid, phosphoric acid, oxalic acid, formic acid and citric acid etc.).

From an electrochemical point of view, the generalised corrosion of stainless steels takes place when the system “functions” in the active section of the anodic curve or in the interval between the equilibrium potential “E_q” and the primary passivation potential “E_{pp}” (case B1 of figure 50).

In the cases of generalised corrosion, the corrosion rate “V_{corr}” can be suitably expressed in terms of mass loss (Δm) per surface unit (A) over time (t), or rather:

$$V_{corr} = \Delta m/A \cdot t$$

usually measured in mg per day in dm^2 or 1mdd.

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[56] *This paragraph and the two subsequent paragraphs were partially take from the article Boniardi M., Casaroli A., Tagliabue C., ‘Fenomeni di danneggiamento dei materiali metallici dovuti all’esercizio (Failure Analysis)’ (Damage phenomena of metal materials due to operation(Failure Analysis)), by various authors, Le Prove non Distruttive (Non-destructive tests), Vol. 1, Associazione Italiana di Metallurgia, Milan 2013.*

In industrial applications it is often more interesting to talk about penetration or thinning rate "V_{thin}" of the corrosive phenomenon. To convert corrosion rate to the thinning rate simply add the material density (ρ), according to the formula:

$$V_{ass} = V_{corr}/\rho = \Delta m/\rho \cdot A \cdot t$$

The unit of measurement of thinning is μm/year; for stainless steel and for other metals and common alloys used (steel for general construction use, special steels, copper, brass, zinc etc.) the equivalence between thinning and corrosion rate is around:

1 mdd $\approx$ 5 μm/anno

The intervention methods that allow the preservation of the component from generalised corrosion are multiple. The formula is commonly used to predict the so-called "additional thickness for corrosion", i.e. a thickness "in excess" on the component which, during operation, will be gradually removed due to the corrosive action of the environment.

Usually, isocorrosion diagrams are used to ensure the correct choice of stainless steel. These are graphs that indicate, with the variation of various environments, the condition with constant corrosion rate (0.1 mm/year) for the various stainless steels. Some typical examples are shown in figures 57 and 58.

12.3 Galvanic corrosion

An early form of localised corrosion is galvanic corrosion or corrosion due to galvanic coupling[57]. It occurs when a metal and a metal alloy is connected (i.e. is in electrical contact) with another metal/metal alloy with greater or lower thermodynamic nobility[58]: if there is a significant potential difference, a redox reaction may develop with consequent corrosion phenomena, even in the presence of just a mildly aggressive environment. The mechanism is very similar to that shown in figure 46.

Every metal or metal alloy has its own potential that depends on its nature, its chemical composition and on the environment in which it is placed (temperature, pH, agitation, presence of oxidants or other harmful species, etc.).

If the difference between the various potentials exceeds a certain threshold, a significant passage of electrons is created between the donator (anode – less noble metal) and the receiver (cathode – nobler metal). The intensity of this movement of electrons (actually an electric current) will be greater as the potential difference increases: as a consequence, the corrosion rate will be higher the further distance between the two materials on the nobility scale.

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[57] *This form of corrosion is also called bimetalic corrosion.*

[58] *The thermodynamic nobility scale (or standard potential scale) is the scale of electrode potential measured with regards to the electrode of reference of hydrogen (E_0= 0,00 V) at 298K and 100kPa of pressure, when all the species involved in the electrochemical process have unitary activities.*

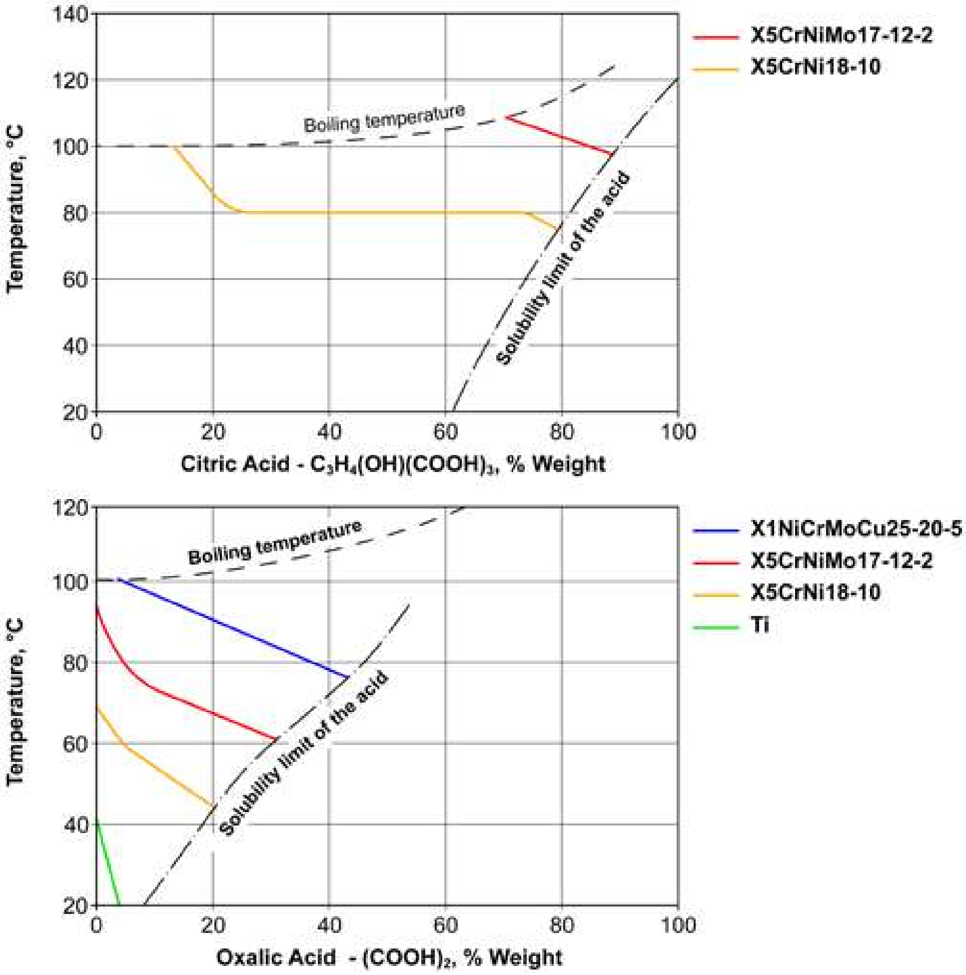

Figure 57 – Isocorrosion curve (0.1 mm/year) for some stainless steels in (a) citric acid and (b) oxalic acid; the dashed curve indicates the boiling temperature [from Outokumpu 2009].

Another relevant aspect that governs the phenomenon of galvanic corrosion is the relationship between the areas of the two materials in contact: the rate of degradation increases with the increase of the ratio between the area of the cathodic zone (nobler) to that of the anodic zone (less noble) exposed to the environment.

In order to assess whether the conditions of galvanic contact between the two metals/metal alloys can cause problems practically, it is better NOT to refer to the standard electrical potential scales: this is because there is a great variability in the behaviour of the same material between one corrosive environment and another (and at times also within the same environment) and also because there are never conditions of equilibrium in the actual environments and electrochemical system. Therefore the saltwater scale of nobility is used (figure 59), which is a scale of the potentials measured under conditions close to actual operation.

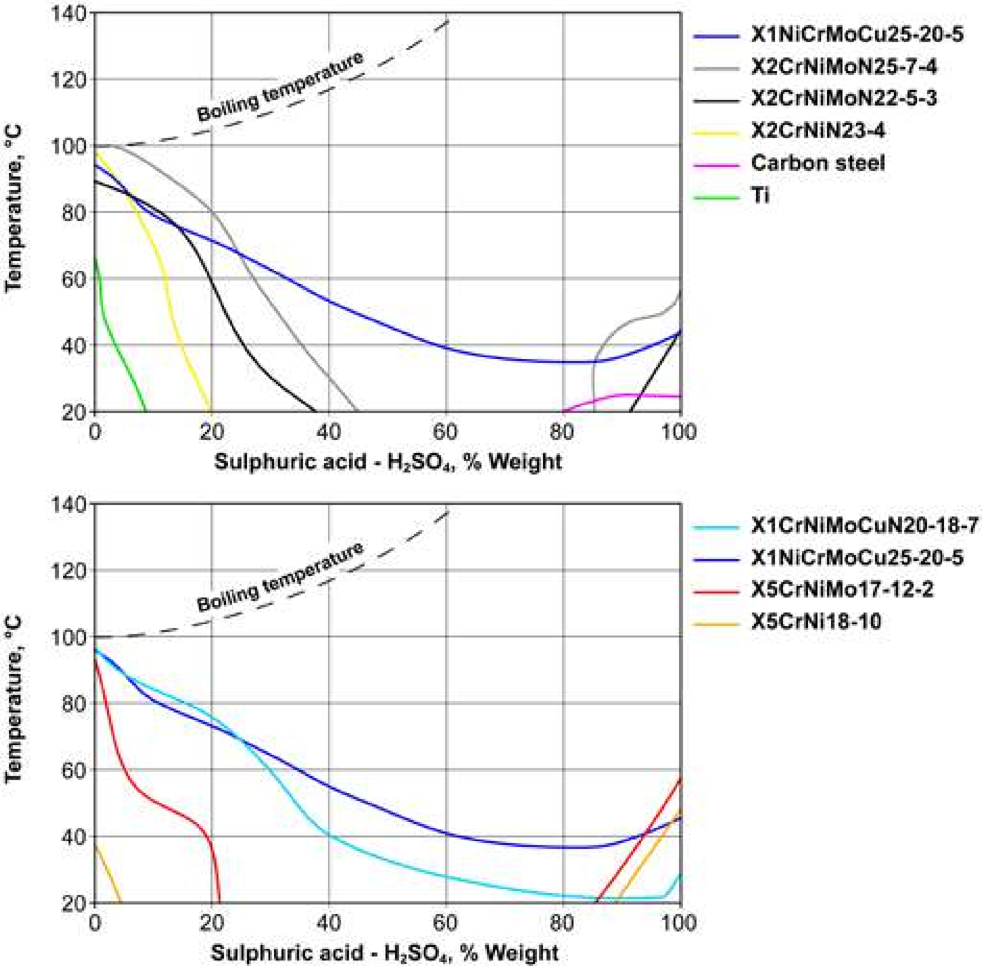

Figure 58 – Isocorrosion curves (0.1 mm/year) for some stainless steels in sulphuric acid; the dashed curve indicates the boiling temperature [from Outokumpu 2009].

A typical example of galvanic corrosion is when it occurs on carbon steel sheet metal (also galvanised) or on aluminium alloy sheet metal in contact with stainless steel fasteners, placed in marine environments, in aerate aqueous solutions or in mildly aggressive environments (see figure 60).
The opposite situation would be much more serious, i.e. that of stainless steel sheets fastened with carbon steel or galvanised steel rivets: in this second case, in addition to the nobility difference between the two materials, the relationship between the areas would be very negative, in favour of stainless steel.

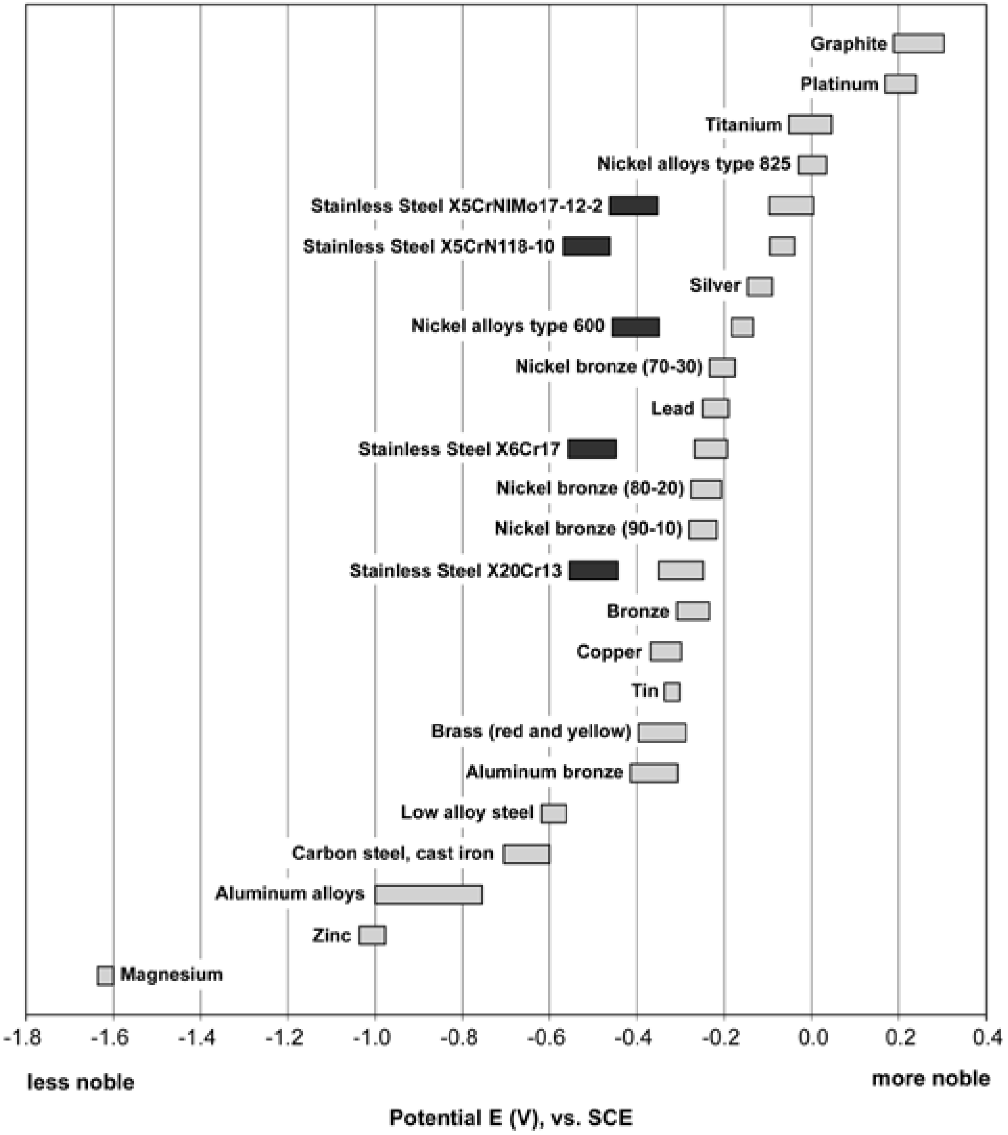

Figure 59 – Saltwater scale of nobility [from ASM-H.13 1992].

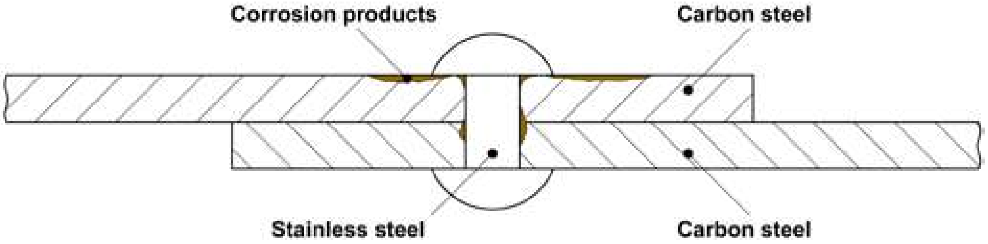

Figure 60 – Galvanic corrosion of a carbon steel plate with stainless steel fasteners.

The most correct solution to eliminate the corrosion phenomenon from galvanic contact is to avoid putting it into "electrical contact" (or direct contract with electronic continuity) with metal materials of different nobility or, if impossible, providing for electrical insulation of the parts (see figure 61).

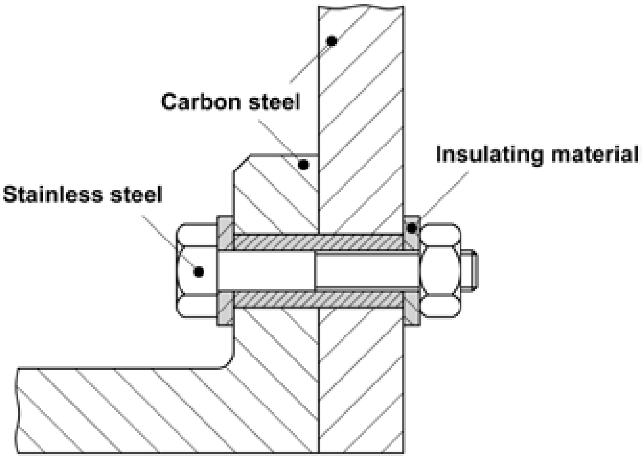

Figure 61 – Electric insulation with a non conductive material between two plates and the relative connection bolt.

A particular type of galvanic corrosion is corrosion by superficial contamination.
The degradation occurs when the surface of the stainless steel is "sullied" by foreign particles, such as dust from ferrous material that is often generated during grinding operations and from common steel.
The particles deposited on the surface can create conditions for localised corrosive attacks, even in not very aggressive environments. Marks appear on the surface (rust-coloured in case of ferrous contamination, whitish in the case of contamination from aluminium or zinc) as a consequence of the rapid oxidation of the contaminant (steel, aluminium or zinc) and not, as wrongly believed, of the stainless steel. In the most extreme situation, the contaminant substance can also cause damage to stainless steel, as it can hinder the passivation phenomenon, as well as constitute a preferential trigger zone for other forms of corrosion.

To work around the problem, greater attention has to be made during all the machining/cutting/handling operations of stainless steel semi-finished or finished products. The working tools and packaging methods (winders, unwinders, cutting systems, shears, brakes, chains, ropes and straps, etc.) must be appropriate for contact with only stainless steel; the use of tools that may have been used in the machining of other materials must be strictly avoided.

If surface contamination is suspected, the foreign particles must be removed through a chemical passivation operation, using nitric acid based dilute solutions.

12.4 Pitting corrosion

Pitting is the phenomenon of localised corrosion of stainless steel: it produces serious penetrating damage and dangerous holes in the components during operation.

Characteristic elements of pitting are the presence on the surface of the work piece of multiple small pits (hence the name of this corrosion); pitting usually leads to even deeper pits, i.e. grooves, ulcers, craters etc. The surface size of the holes is small, between 0.1 and 2 mm, as in the pitting phenomena the extent of the corrosion products is very limited.

The greatest problem related to this form of corrosion is not the loss of mass affected by the degradation phenomenon, but rather the damage caused by penetrating through the resistant section of the component. For example, consider the case of a stainless steel tank affected by the pitting phenomenon: the pitting could lead to the creation of a hole in the recipient, the subsequent spilling of the process fluid and the overall disruption of the system.

Degradation due to pitting has various aspects; figure 62 shows some morphologies typical in sections, as classified by the American standard ASTM G46.

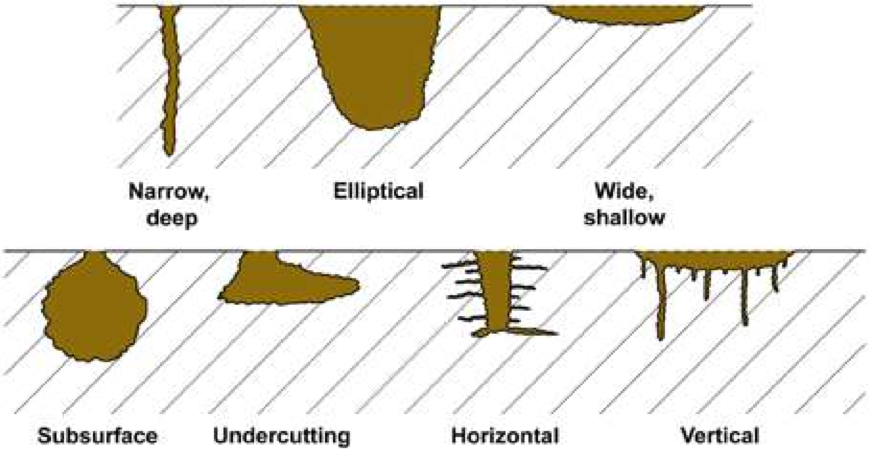

Figure 62 – Typical morphologies of degradation due to pitting [from ASTM G46].

Pitting occurs both on the materials in active behaviour, such as carbon steels, and especially on materials that passivate such as stainless steels[59]. Corrosion is caused by neutral or oxidising environments able to chemically attack the protective film present on the surface of the material.

The typical degradation due to pitting of stainless steels occurs in aqueous solutions containing chlorides, such as in marine environments (wet-dry areas or areas exposed to sea spray).

In addition to the concentration of chlorides[60], the parameters that influence the occurrence of pitting are linked to the increase of temperature, the acidification of the electrolyte and any presence of other aggressive substances in the environment (such as in industrial atmospheres or in the contaminated process fluids).

Corrosion due to pitting is a phenomenon that, once triggered, tends to be self-sustaining: the cavity of the pit gradually recalls chloride ions due to the electrophoresis effect[61] and an increase of the pH occurs due to the acid hydrolysis of the water[62] (figure 63).

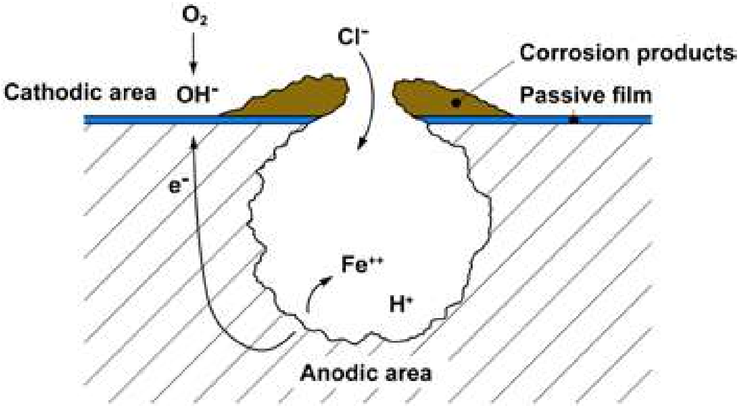

Figure 63 – Schematic of the damage mechanism caused by pitting.

In terms of electrochemistry, pitting occurs when the passivation conditions in the active-passive curve of the stainless steel are exceeded, i.e. when the potential of the cathodic reaction is greater than the transpassivation potential "E_t" of the anodic reaction (case B4 of figure 50). Consequently, the transpassivation potential E_t", also known as pitting potential, is an excellent parameter for classifying, in an equal environment, the

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[59] *Pitting corrosion is also common in other materials that passivate, such as aluminium or its alloys or titanium or its alloys.*

[60] *In the case of stainless steels, pitting occurs not only upon contact with aqueous solutions contaminated by chlorides, but also due to the effect of the presence of other halides, such as fluorides (F^-) and iodides (I^-).*

61 The electrophoresis effect is a phenomenon of the movement of electrically charged particles (ions), immersed in a fluid, as the result of the effect of an electric field induced by the anode-cathode micro bond. The ions move towards the cathode if they have positive charge and towards the anode if they have negative charge. In the case of degradation due to pitting, this attracts Cl^- ions to the anodic zone of the corrosion crater.

[62] *In the presence of metal ions and water, acid hydrolysis can occur with variation of the pH of the solution, according to the reaction:* $Fe^{+2} + 2H_2O \longrightarrow Fe(OH)_2 + 2H^+$.

resistance to corrosion due to pitting of the stainless steels. It also can be used to assess the various effects of the environmental conditions of stainless steels: the higher the pitting potential, the higher the resistance of the material to the phenomenon.

For example figures 64-66 show the potential pitting trend, for two stainless steels commonly used, upon the variation of the temperature, the concentration of chloride and the pH.

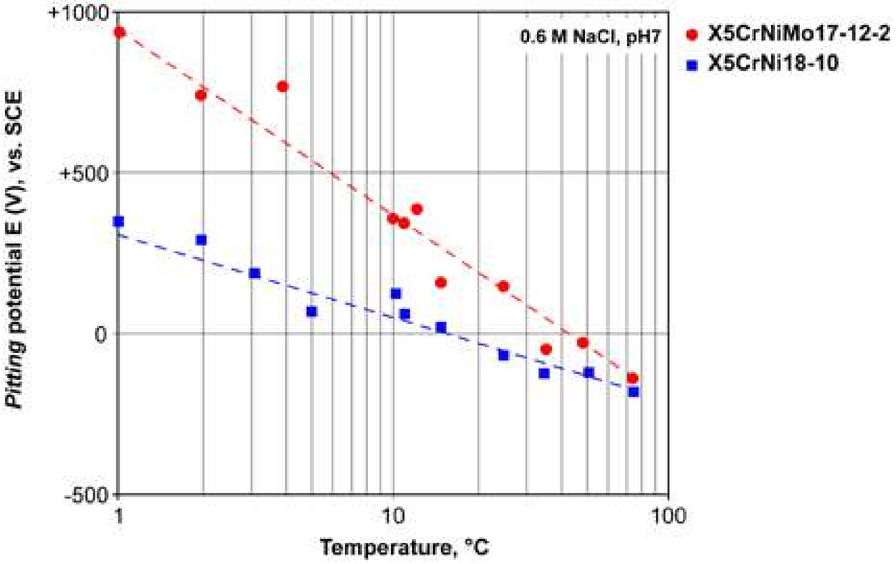

Figure 64 – Pitting potential trend according to the temperature of the solution for the austenitic stainless steels X5CrNi18-10 and X5CrNi17-12-2; aqueous solution 0.6M of NaCl at pH 7 [from Shirer 1994].

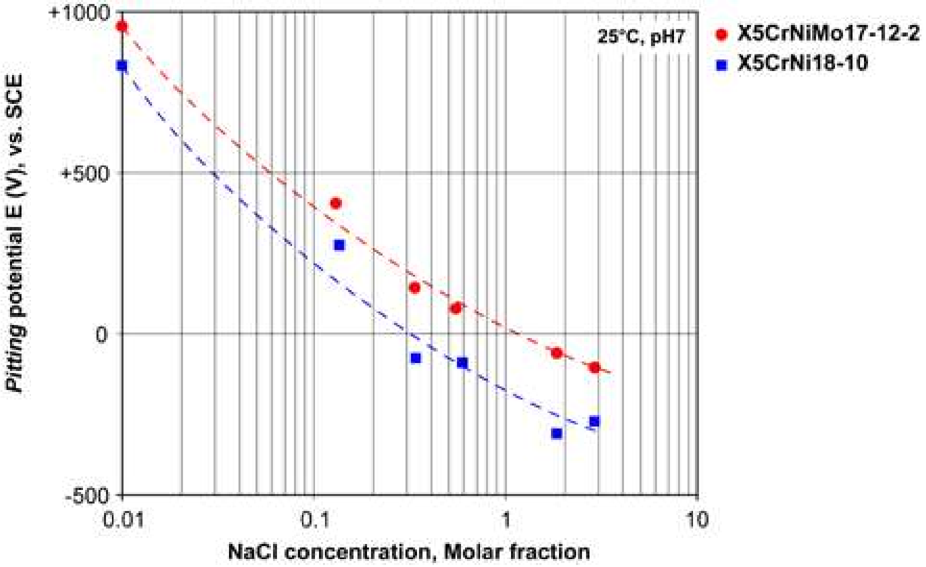

Figure 65 – Pitting potential trend according to chloride solution concentration for austenitic stainless steels X5CrNi18-10 and X5CrNi17-12-2; aqueous solution with pH 7 at 25°C [from Shirer 1994].

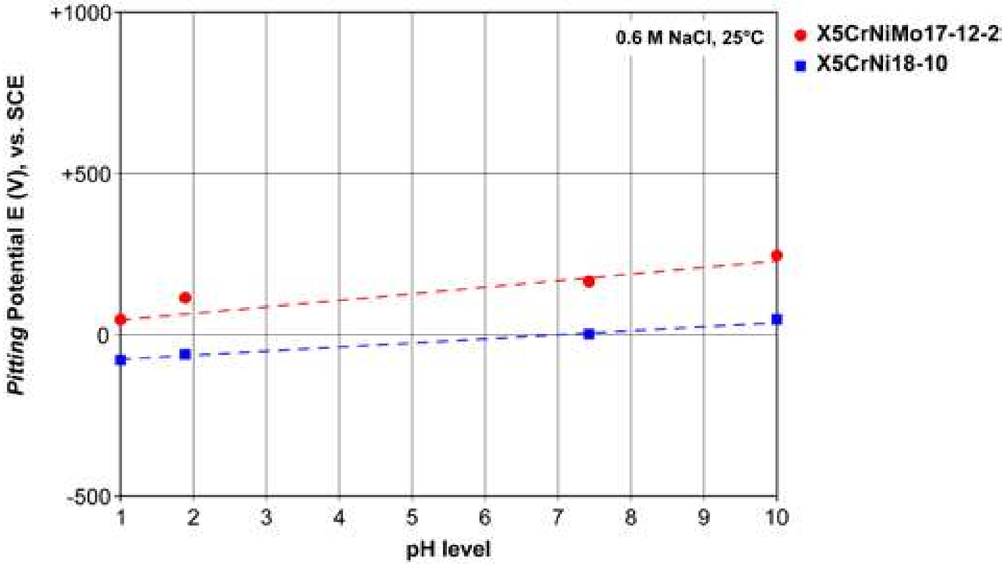

Figure 66 – Pitting potential trend according to the pH of the solution for austenitic stainless steels X5CrNi18-10 and X5CrNi17-12-2; aqueous solution 0.6M of NaCl at 25°C [from Shirer 1994].

In order to determine the pitting resistance without having to resort to experimental tests, it is possible to make assessments based on the chemical composition of these steels: it is well known in fact that elements such as chromium, molybdenum and nitrogen promote the expansion of the passive field (they raise the transpassivation potential "E_t"). To this end, a parameter has been experimentally developed that is well suited to describing the corrosive phenomenon: it is called PREN (Pitting Resistance Equivalent Number) and is directly correlated to the chemical analysis of the material with the formula[63]:

$$\text{PREN} = \%\text{Cr} + 3.3 \cdot \%\text{Mo} + 16 \cdot \%\text{N}$$

This index gives the possibility of classifying the various types of stainless steel with regards to the resistance to corrosion caused by pitting (figure 67): the higher the PREN, the higher the resistance of the steel to pitting.

In addition to the diagram included in figure 67, it also worth observing the graph in figure 68: this demonstrates the great variability existing in the correlation between PREN and the pitting potential, especially for PREN values >30. Therefore, it takes into account that the PREN index, albeit easy to determine, only allows a qualitative classification of the stainless steels; furthermore, it is worth repeating that the PREN can only be used for pitting corrosion.

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[63] *The PREN formula is not unambiguous: various multiplication coefficient are available, in particular for molybdenum and nitrogen. In the case of molybdenum both 3 and 3.3 can be used; in the case of nitrogen a coefficient equal to 13, 16, 27 or 30 can be used. The equation proposed here is the most common.*

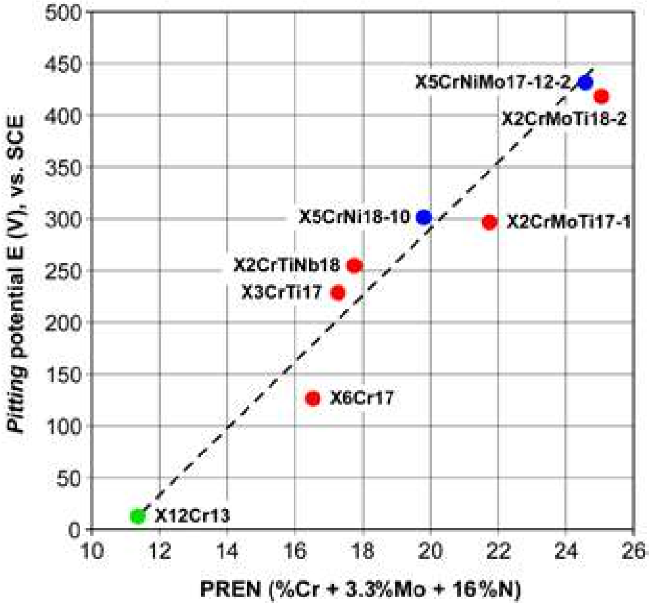

Figure 67 – Potential pitting trend according to the PREN for some stainless steels, aqueous solution 0.5M of NaCl at 50°C with pH 6.6 [from ArcelorMittal 2010].

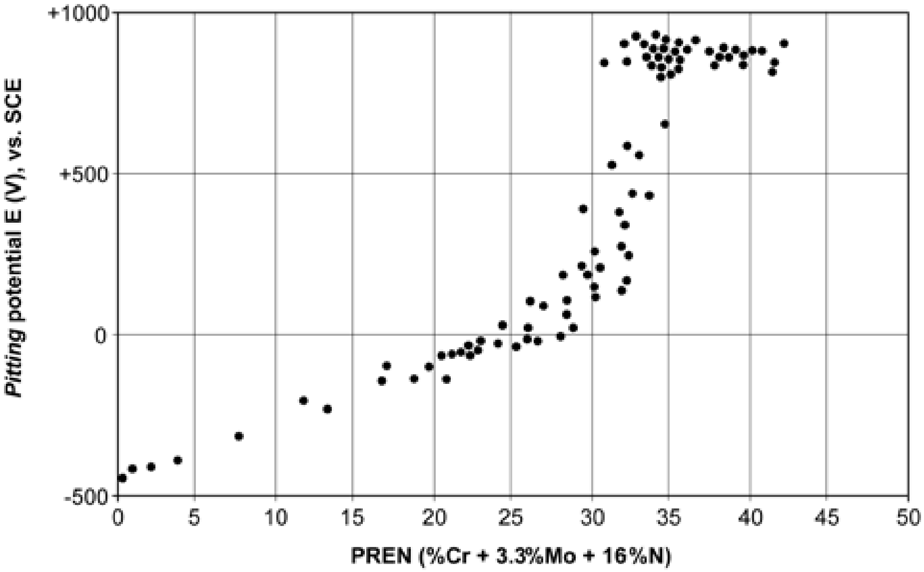

Figure 68 – Pitting potential trend according to the PREN in aqueous solution 0.5M of NaCl at 50°C with pH 6.6; iron based alloys with %Cr=0.021÷28 %Ni=0.22÷20.39 %Mo=0.01÷4.23 %N=0.01÷0.455 %Mn=0.22÷4.53 %Si=0.13÷0.71 [from Shirer 1994].

The tendency of a stainless steel to undergo pitting phenomena can also be evaluated through standard laboratory tests. A typical example is given by the American standard ASTM G48 – 2003 (Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution) which allows the classification of the materials according to the temperature at which pitting corrosion occurs.

The test includes the immersion of the sample in aqueous solution of ferric chloride[64]. By gradually raising the temperature, the threshold at which pitting occurs can be derived experimentally: this threshold, called the Critical Pitting Temperature (CPT), can be used as an index of the resistance to the corrosion of the material (see figure 69).

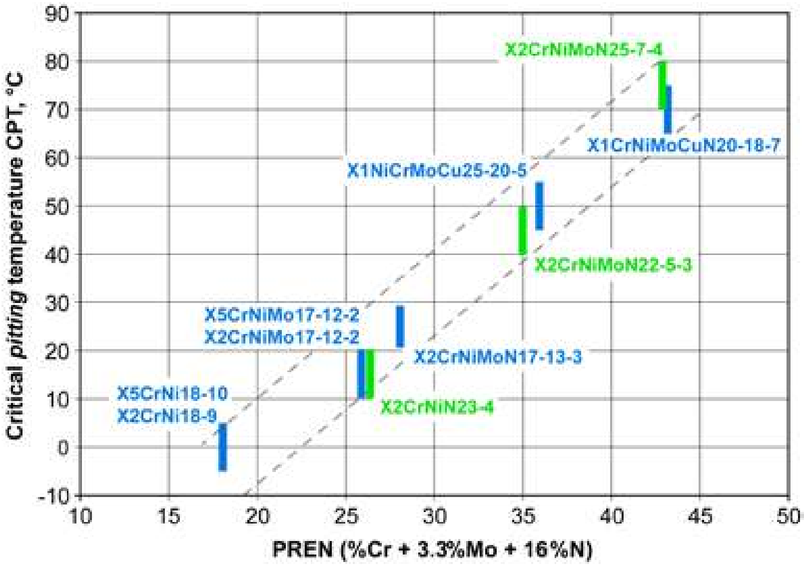

Figure 69 – Critical pitting temperature trend according to ASTM G48 as a function of the PREN for some austenitic and austenitic-ferritic stainless steels.

As is typical for all the morphologies of localised attack, pitting is also a phenomenon that must be prevented rather than hindered: in this regard it is appropriate to choose the material to be used in relation to the environment and its surrounding conditions (temperature, pH, harmful agents, chloride concentration, agitation-stagnation, etc.).

12.5 Crevice corrosion

Crevice corrosion is another form of localised aggression very common in stainless steels: it occurs in the presence of cracks, crevice, incrustations, deposits and geometrical discontinuities in which the electrolyte (generally water) is in stagnation with regards to the surrounding environment.

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[64] *Iron chloride, $FeCl_3$, is the iron salt (III) of hydrochloric acid: it is a compound soluble in water (with solubility equal to 920 g/litre at 20°C) and is very corrosive to common and special steels.*

A typical case of degradation due to crevice corrosion regards the seals of flanged piping or in the contact zones between bolted or riveted plates (figure 70). Similar situations can occur in welded plates for points on cars, in arc welded seals where penetration is incomplete, between the strands of metal cables, underneath lubricating films such as graphite or molybdenum graphite and on surfaces coated with Teflon or polyethylene.

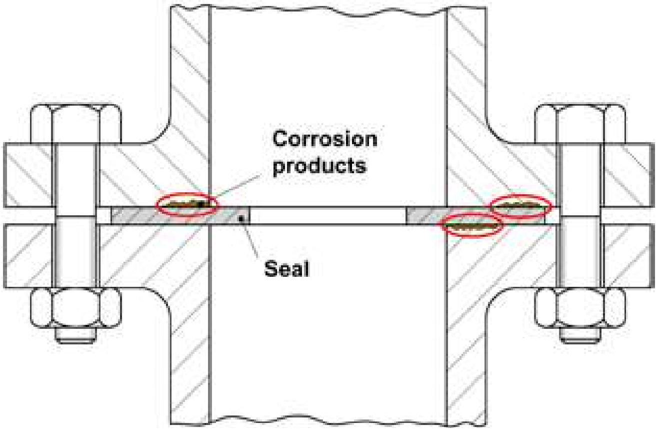

Figure 70 – Schematic of a constructive solution which could cause crevice corrosion.

The presence of the geometric discontinuities create a macro bond due to differential aeration between the interstitial area, i.e. the anodic zone where the diffusion of oxygen is limited, and the surrounding metal mass which represents the cathodic zone in which the oxygen saturation is ensured (figure 71). It should be noted that in the interstices, the same critical factors occur that are in a pit formed by corrosion, i.e. gradual consumption of oxygen, accumulation of positive metal ions, chloride ions attracted due to the electrophoresis effect and acid hydrolysis with pH decrease (compare figure 71 with figure 63).

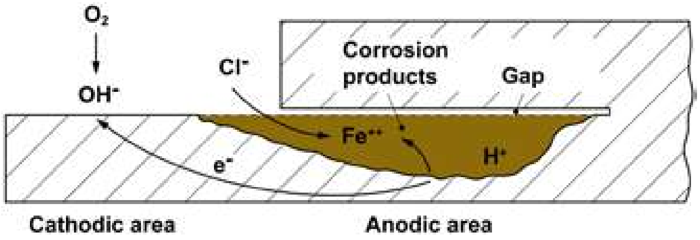

Figure 71 – Schematic of crevice corrosion

The analogy between the two degradation mechanisms leads to a classification identification of the stainless steels in the comparison of pitting and crevice corrosion. The better the behaviour of the material when subject to to pitting corrosion, the better its response against crevice corrosion: therefore the PREN can be a valuable aid to make the correct choice of stainless steel also in the case of crevice corrosion. However, it should be indicated how, if the material used and environmental conditions set are equal, it is much easier to trigger crevice corrosion than pitting corrosion. However, for pitting to occur the cavity must be formed as a result of the chemical aggression of the environment but in the case of crevice corrosion the "cavity" is already physically present in the component due to the geometric discontinuity: and crevice corrosion is much more critical then pitting!

Another important parameter that governs degradation is the dimension of the interstitial area in which the liquid can stagnate: above a certain threshold the electrolyte can flow freely without creating problems, whilst below this threshold stagnation will be promoted and crevice corrosion will be triggered (see figure 72).

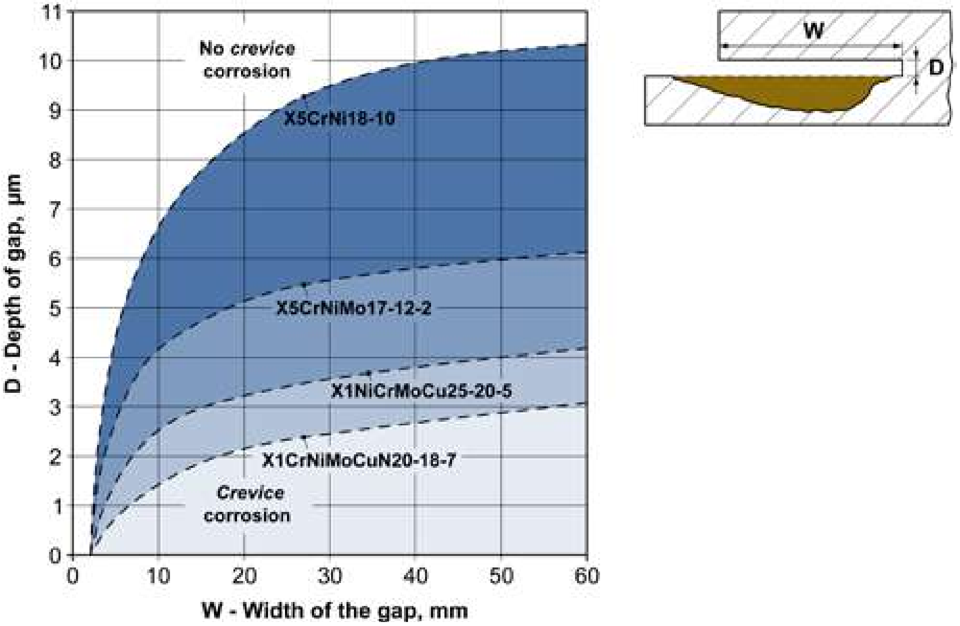

Figure 72 – Geometric characteristics of the interstices that can cause crevice corrosion in relation to the type of stainless steel used [from Sedriks 1996].

As is indicated from the previous observations, focus must be placed on the design of the system, in order to avoid interstices, cracks, incrustations or, in general, the presence of possible points of preferential aggression of the stainless steel.

A particular form of crevice corrosion is corrosion under a deposit. The degradation occurs in the presence of lime scale accumulations and/or deposits (such as in household pipes penetrated by water rich in limestone): in the vicinity of the deposit and below it "clogged cells" are established with the formation of anodic-cathodic macro bonds and degradation phenomena characterised by mechanisms similar to those of the interstitial corrosion (see figure 73).

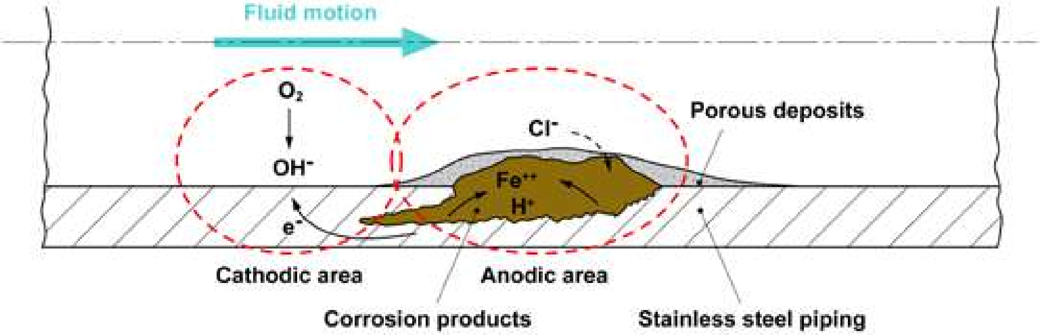

Figure 73 – Schematic of corrosion phenomenon under deposit in a pipe.

12.6 Intergranular corrosion

Intergranular corrosion or intercrystalline corrosion is a form of environmental degradation associated with a chemical composition discontinuity of the material's microstructure: it is a symptom of the formation of a continuous network of carbides or intermetal phases, mainly rich in chromium or chromium/molybdenum, near to the grain boundary of the stainless steel (see figure 10).

It is a mechanism of localised corrosion, also called "sensitisation", that occurs on many families of stainless steels even in mildly aggressive environments; some authors prefer to classify it as selective corrosion because the aggression is preferential and occurs along the boundaries of the crystalline grain.

The cause of the degradation is the local depletion of chromium or chromium/molybdenum in correspondence with the grain boundaries: in the work piece, the corrosion is developed in the form of individual or branched cracks that "follow" the grain boundaries where the precipitation of carbides has occurred.

This issue was discussed at length in chapter 3 (paragraph 3.4) and in the various chapters regarding the individual families of stainless steels: please refer to these chapters for further information. Certain considerations previously mentioned will be repeated below; the list was made starting from the stainless steel families most used industrially.

In the case of austenitic stainless steels, the sensitisation, i.e. the precipitation of the carbides, occurs due to prolonged exposure of the material in the critical interval between 450°C and 900°C. Three factors explain the reason why the depletion of the chromium occurs in this deleterious way at the grain boundary:

- the carbon can "bind" a quantity of chromium, in the form of carbides, equal to about 16 times its own quantity in weight (carbides type $Cr_{23}C_6$);
- the carbon diffuses into the austenite much more quickly than the chromium and then "captures" a very large quantity of chromium; however, the chromium has a much lower diffusivity than carbon and therefore the depletion of chromium only occurs near to the grain boundary;
- the carbides preferentially precipitate at the grain boundary, an area with less atomic density where the nucleation of the precipitates is facilitated.

The austenitic stainless steels with carbon content greater than 0.03% are at risk of intercrystalline corrosion if exposed in the critical temperature interval. This can occur, for example, during the heat treatment of the semi-finished product, due to the effect of inappropriate operating temperatures, or due to welding operations. In the latter case the phenomenon typically occurs in the areas adjacent to the welding bead (heat affected zone), where the time spent in the critical precipitation interval is longer (see Figure 74).

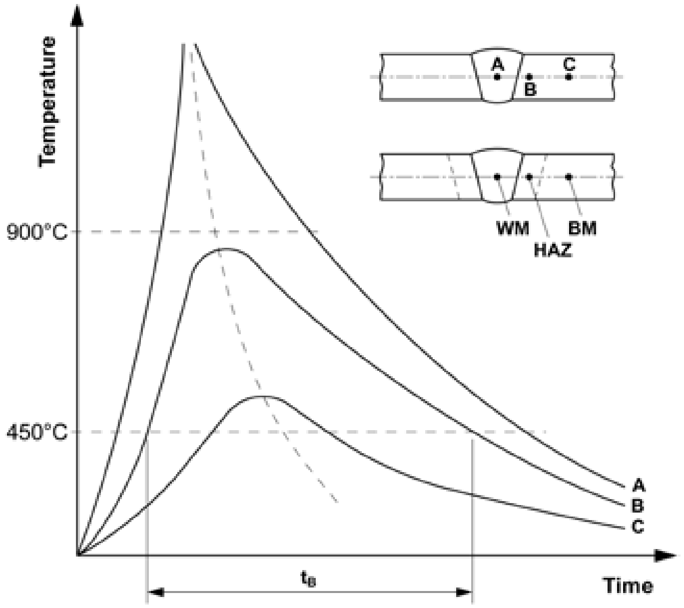

Figure 74 – Temperature trend as a function of time in a welded joint: WM: welded metal (A); HAZ: heat affected zone (B); BM: base metal(C). The zone where intergranular corrosion can occur is zone B because it is more exposed to the critical interval compared to A and C.

In electrochemical terms, the effect of the carbide precipitation occurs as an increase of the surrounding current density equal to the applied potential (Figure 75): consequently, in relation to the environment and the degree of sensitisation of the steel, they may have different criticalities.

To work around this problem, as already mentioned in chapter 8, the carbon content can be reduced to values lower than 0.03% (low carbon austenitic stainless steels) or elements can be added that stabilise the chromium such as titanium or niobium (stabilised austenitic stainless steels). Alternatively, an annealing treatment can be performed at 1050°C, if possible, followed by rapid cooling in water after welding.

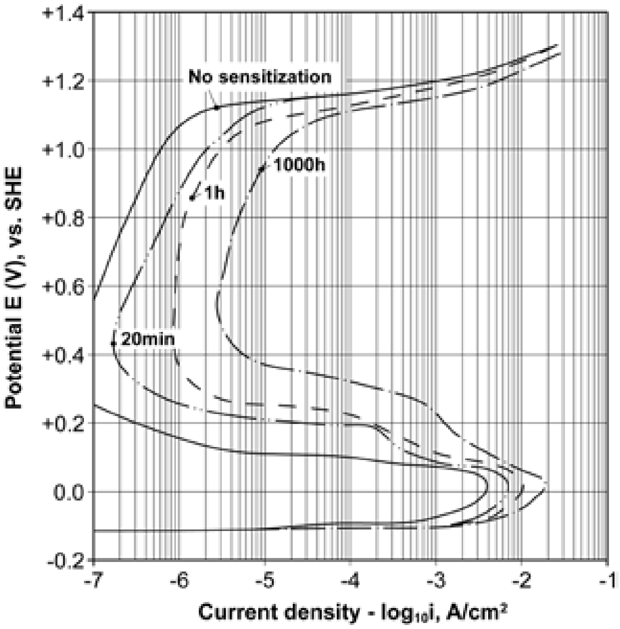

Figure 75 – Trend of the potentiodynamic curves of stainless steel type X5CrNi18-10 in its annealed status and after sensitisation at 650°C for various times; aqueous solution 1M of H_2SO_4 at 90°C [from Osozawa et al. 1966].

In the case of ferritic stainless steels, sensitisation problems can also occur due to the formation of carbides: the critical temperatures are lower than those of austenitic stainless steels and precipitation occurs in very short times (see Figure 76). To alleviate this phenomenon, the semi-finished product must be annealed at temperatures of 800°C during which the chromium notably diffuses towards the depleted zones; alternatively, as in the case of austenitic stainless steels, the material can be stabilised using titanium or niobium during the casting phase. The solution of reducing the carbon content to very low levels is not practicable, as it greatly limits the solubility of the carbon in the body centred cubic matrix of the ferrite.

Finally, duplex stainless steels: these materials have greater resistance to intergranular corrosion compared to both the families of austenitic and ferritic stainless steels.

The lower sensitivity to this problem depends on the fact that, in duplex steels, chromium carbides form at the interface between the austenite grains and the ferrite grains. As the speed of diffusion of chromium in ferrite is 100-150 times greater than what occurs in austenite, the carbides preferentially enrich at the expense of the chromium present in the ferrite: although this causes a depletion of chromium, the γ/α (similar case to what is shown in Figure 10a).

The problem of duplex stainless steels is mainly linked to the formation of the phases rich in chromium or chromium/molybdenum (phases σ, χ and Laves) or to the presence of embrittlement at 475°C, as shown previously in Figure 41.

For this family of stainless steels, stabilisation is not provided for, therefore, in the event of the formation of unwanted phases (such as during welding large sections), performing a solution heat treatment is recommended followed by cooling in water.

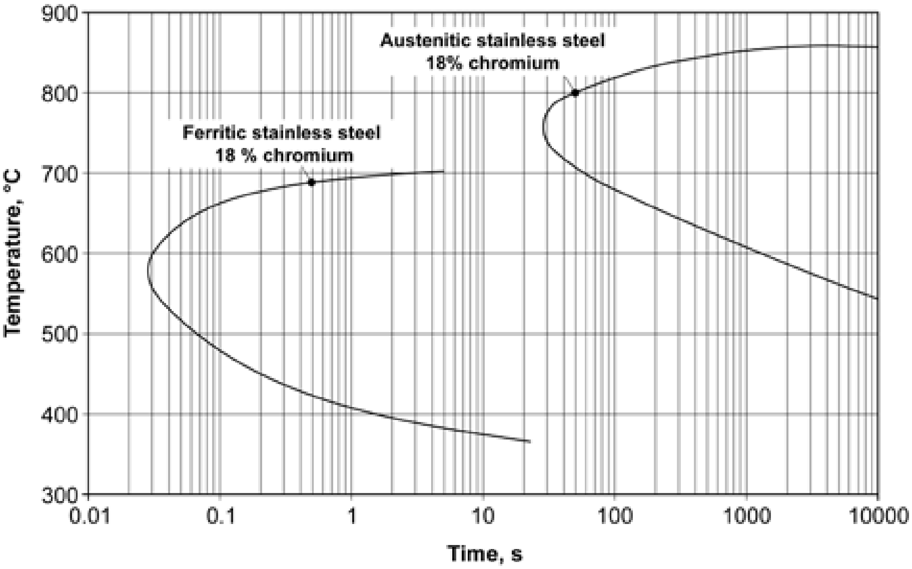

Figure 76 – Schematic trend of the sensitisation curves for ferritic stainless steels and austenitic stainless steels with the same chromium content [from Cowan and Tedmon 1973].

12.7 Stress Corrosion Cracking (SCC)

Stress Corrosion Cracking is another form of localised damage, and is very hazardous because it occurs in environments not particularly aggressive for stainless steel: it generally has very short incubation and propagation times (from 3 to 12 months) and often leads to the malfunction of the component or the plant as the problem is only recognised when the phenomenon is overt[65].

Stress corrosion cracking only occurs if three conditions are simultaneously met:

- a stainless steel with specific chemical composition,
- a specific corrosive environment,
- a mechanical stress traction greater than a specific threshold[66].

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[65] *This problem is common to many families of materials: for example, copper alloys undergo SCC in ammonia rich environments, aluminium alloys in the presence of aqueous solutions with chlorides and high resistant steels in distilled water.*

[66] *The traction forces may derive from the action of external agent force on the component, and the presence of residual stress induced by previous machining of the material (cold moulding, drawing, stamping, folding, welding etc.).*

The combined action of all three conditions is critical: usually mechanical stress and a corrosive environment, if considered individually, do not cause problems of a mechanical nature nor corrosion.

Furthermore, in order for the degradation to develop, the temperature must be greater than ambient temperature: the most common forms of stress corrosion cracking of stainless steels occur in temperatures of 45-50°C.

Stress corrosion causes the formation of simple or branched cracks; propagation of cracks can be both intergranular (i.e. it follows the grain boundary) and transgranular (crosses the grains indistinctly): sometimes the propagation can be mixed.

Usually, products of corrosion are not often observed, so much so that in some cases the cracks are wrongly attributed to problems of an exclusively mechanical nature.

A possible schematic of that described is shown in Figure 77.

In all circumstances of degradation that will be described below, the prevention of stress corrosion cracking is implemented by changing the material in contact with the critical environment. A further solution, only valid in certain conditions, is that of reducing the mechanical stresses applied to the component, both increasing the resistant sections (with a consequent reduction of the nominal forces), and eliminating the auto stresses through suitable heat treatments (stress relieving)[67].

Stress Corrosion Cracking does not occur in all stainless steels in any corrosive environment: in practice there are only two "material – environment" couples that are critical for this form of degradation.

The most common case of SCC is that of austenitic stainless steels in seawater or in chloride solution (even with very low concentrations of Cl^-[68]). Typical components that are susceptible to this form of degradation are seawater heat exchangers.

In environments rich in chlorides, the stress corrosion cracks of austenitic stainless steels are generally transgranular and their trigger is very often associated with the presence of surface pits. The phenomenon is aided by the temperature, the chloride concentration and the dissolved oxygen in the solution increase. The critical stress threshold is between 70-90 MPa, i.e. a third of the yield stress in its solubilised state; beyond this value, the situation worsens and the fracture time gradually reduces with the increase of the load applied.

Stress corrosion cracking of austenitic stainless steels in chloride environments depends on the presence of nickel in the alloy: it is observed how the most critical conditions occur when the nickel content is around 8-10%, i.e. the typical percentages of the most common stainless steels (see figure 78).

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[67] *To further act on the mechanical stress applied to the component, it is also possible to perform mechanical treatments such as shot peening that, by inducing the residual compressive stresses in the material, has a beneficial effect against stress corrosion cracking.*

[68] *Some authors indicate the critical concentration to not exceed to avoid stress corrosion cracking problems in 10ppm of Cl^-.*

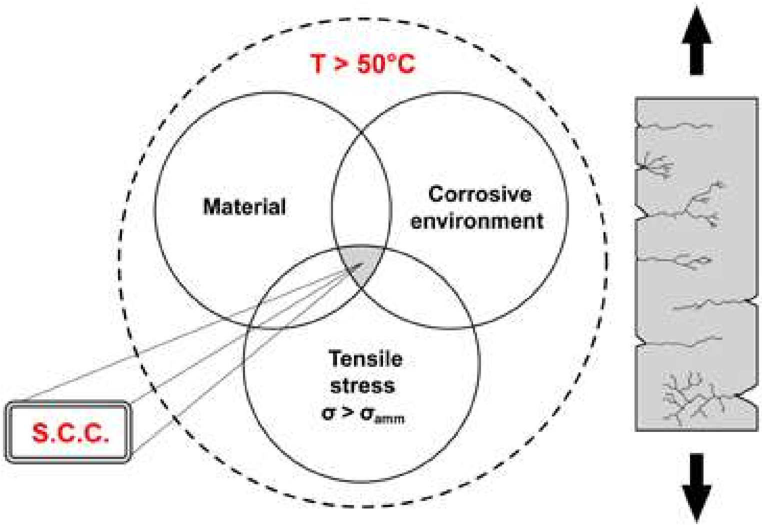

Figure 77 – Schematic of the Stress Corrosion Cracking phenomenon.

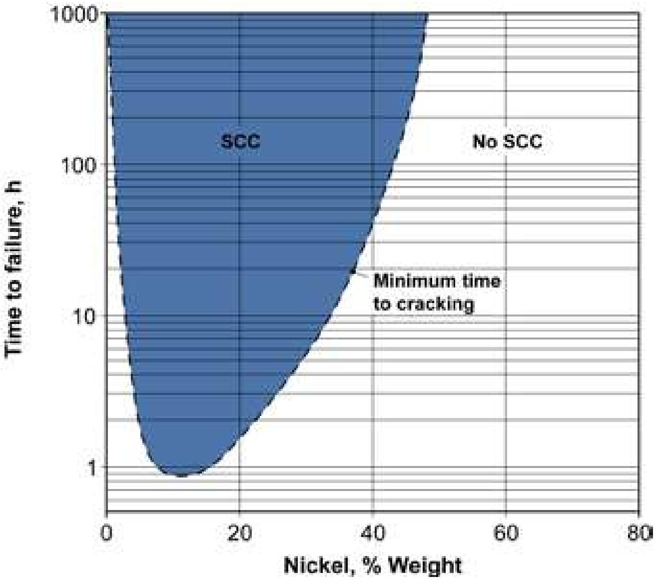

Figure 78 – Stress corrosion cracking of stainless steel wires with 18-20% of chromium, variable nickel content, in aqueous solution with 42% magnesium chloride at 154°C [from Copson 1956].

If the nickel is greater than 40 or completely absent, the steel will be much less sensitive to stress corrosion: this is the reason why nickel based super-alloys or common ferritic stainless steels, in which nickel is absent, are practically insensitive to the problem[69].

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[69] *SCC in chloride environments can also occur on ferritic stainless steels if precipitation of carbides and/or embrittlement has occurred in the material, for example on welded joints.*

Duplex stainless steels are another good alternative in seawater to austenitic stainless steels, due to the high resistance to stress corrosion of the ferritic phase, present in about 50% of their microstructure (figure 79). Finally, a particular case in which SCC occurs is at temperatures much lower than the threshold. The problem, which has flagrantly occurred since the mid-eighties in indoor swimming pools, takes place at around 30°C on tie rods for false ceilings or on support elements: in this environment the high humidity and high chloride concentrations and other harmful species aggravate degradation and encourage the occurrence of the phenomena.

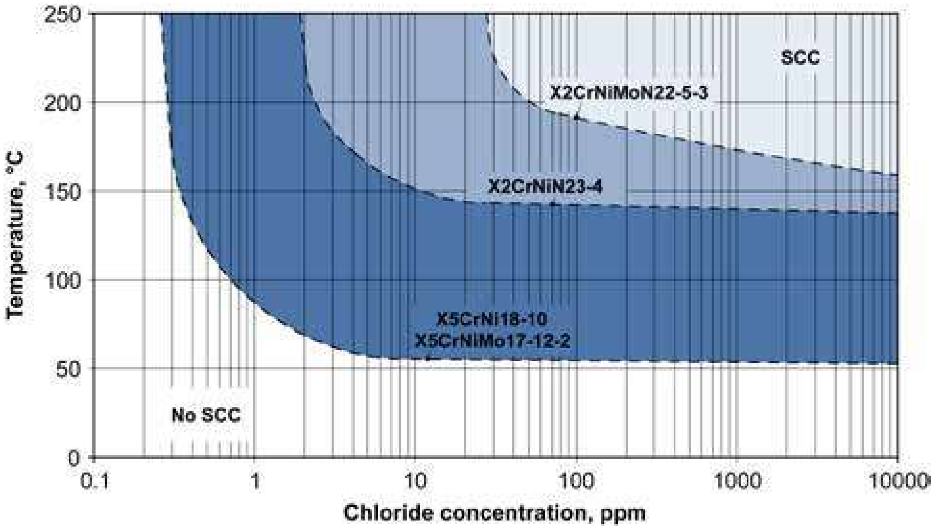

Figure 79 – Effect of the temperature and the concentration of chlorides in solution on the resistance to stress corrosion cracking of some austenitic and austenitic-ferritic stainless steels [from Sedriks 1996].

Caustic solutions (solutions rich in sodium or potassium hydroxide) are also critical for stainless steels: Stress corrosion cracking can occur in these environments, but also pitting or generalised corrosion can also take place.

The phenomenon is typical of austenitic stainless steels and occurs at temperatures between 80°-100°C, both in aerate and deaerate solutions with various concentrations of NaOH (see figure 80). In caustic stress corrosion cracking, the fracture can be transgranular, intergranular or mixed.

The behaviour in operation slightly improves with an increase of the nickel content or using austenitic-ferritic stainless steels, even though, in both cases, it is not possible to guarantee complete immunity from the phenomenon.

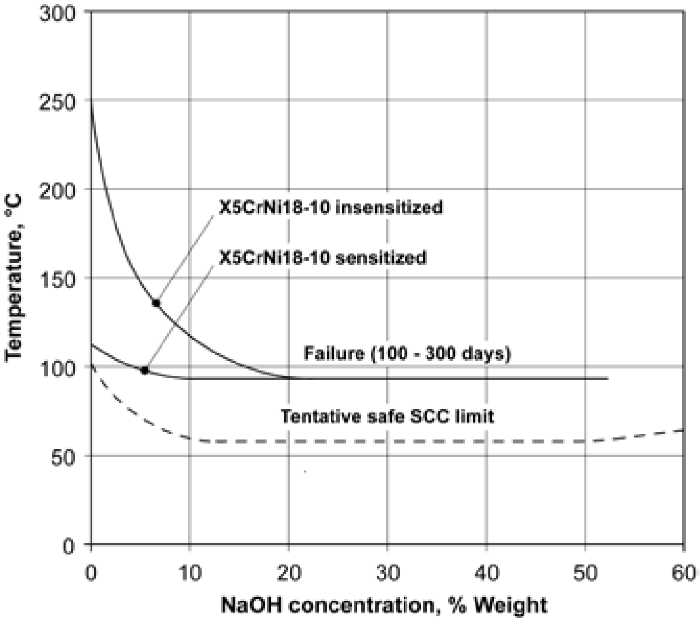

Figure 80 – Effect of the temperature and concentration of sodium hydroxide (NaOH) in solution on the resistance to stress corrosion cracking of austenitic stainless steel X5CrNi18-10 [from Lacombe 1993].

A final combination that can cause stress corrosion cracking is relative to austenitic, duplex or martensitic stainless steels in contact with hydrogen sulphide (H_2S).

This form of corrosion is known as SSCC (Sulphide Stress Corrosion Cracking) but it is, for all effects and purposes, a phenomenon of hydrogen embrittlement[70]: awareness of it is very important in the sector of the extraction and refining of petroleum products and natural gas.

Hydrogen embrittlement is produced due to the reaction between hydrogen sulphide and iron: sulphurs and atomic hydrogen (H^+) form that then easily penetrate the matrix of the steel, inducing intergranular fragility.

The chemical species that encourage the occurrence of SSCC are, in addition to hydrogen sulphide, chloride ions and the presence of H^+ ions in solution (as what occurs in acid environments); the most critical temperatures are located in the interval 60°-100°C.

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[70] *Hydrogen in its ionic state (such as H^+ ions) is a very small atom which, under appropriate conditions of temperature and pressure, diffuses into the crystalline matrix, making the steel particularly fragile.*

In the case of austenitic, martensitic or PH-martensitic stainless steels, the degradation also depends on the mechanical resistance of the material: according to the standard NACE MR0175 / ISO 15156[71], so that the steel is adequate for these uses, it is necessary to prescribe a maximum hardness threshold of 22 HRC. To avoid the problem, it is often preferable to use duplex stainless steels, super-austenitic stainless steels or nickel based alloys.

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[71] *The international standard NACE MR0175/ISO15156 called Petroleum and Natural Gas Industries – Materials for use in* H_2S *containing Environments in Oil and Gas Production.*

13. HIGH TEMPERATURE CORROSION OF STAINLESS STEELS

High temperature corrosion is a phenomenon of degradation that occurs when stainless steels are subject to chemical attack by hot gases, such as in the case of components operating at high temperatures in contact with air, oxygen, carbon dioxide and superheated steam. Forms of degradation with similar morphologies occur in the presence of reducing, fuel, nitrate or sulphurous atmospheres, with salt baths or molten metals (NaCI, KCl, Na_2SO_4, KCN, zinc, aluminium, low-melting metals etc.). Because the temperatures at which all the aforementioned phenomena occur are much higher than ambient temperature ($T>300°C$), the corrosion manifests in the form of dry corrosion or high temperature corrosion.

Typical components that are susceptible to these forms of damage are turbine or compressor blades, combustion chambers, chemical and nuclear reactors, boilers, vehicle exhaust pipes, distillation columns of petroleum products and equipment for industrial furnaces or steel plants.

The degradation that occurs at high temperature derives from the interaction between gas and the metal alloy and can be explained as the sum of an oxidation reaction combined with a reduction reaction, in perfect analogy with what happens for wet corrosion.

For simplicity, we will now consider the high temperature oxidation phenomenon of a stainless steel, i.e. that which occurs when a generic iron-chromium alloy is placed into contact with an oxygen rich environment: for example, a chamber of an industrial furnace of heat treatment operating in air at high temperature.

The chemical species that oxidise are iron and chromium whilst oxygen is the species that reduces. In this specific case the formulae are:

$$2Fe \longrightarrow 2Fe^{+2} + 4e^{-} \qquad 4Cr \longrightarrow 4Cr^{+3} + 12e^{-}$$

$$O_2 + 4e- \longrightarrow 2O^{-2} \qquad 3O_2 + 12e- \longrightarrow 6O^{-2}$$

from which:

$$2Fe + O_2 \longrightarrow 2FeO \qquad 4Cr + 3O_2 \longrightarrow 2Cr_2O_3$$

The reactions indicated represent an oxide-reduction process in which degradation occurs mainly at the interface between metal and oxygen, as the iron oxides and the chromium oxides are permeable to the penetration of oxygen (although in different ways). A possible schematic of the high temperature oxidation phenomenon is described in figure 81.

In order to understand the behaviour of a generic metal material in contact with an oxidising atmosphere, it is necessary to know whether the oxide that will form on the surface of the component will be fragile, porous and not very protective or adherent and compact.

In the first case, the degradation will happen quickly as the metal mass is continually exposed to attack. However, in the second case, a barrier will be created which will impede the oxygen, or other harmful species, from entering into contact with the substrate; consequently the damage of the component in operation will be drastically reduced.

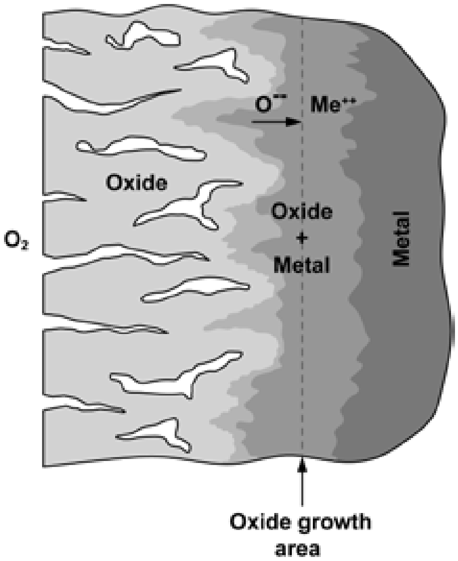

Figure 81 – Schematic of the oxidation phenomenon on the surface of a stainless steel in contact with an oxidising hot gas.

This is precisely what occurs in industrial alloys.

In common steels – i.e. those without alloying elements – only iron oxide will form. Iron oxide (FeO), at temperatures exceeding 570°C, is porous and tends to fragment, breaking away from the surface of the component: in such conditions high temperature oxidation and the degradation phenomenon will continually occur.

In stainless steels, however, the presence of high percentages of chromium ensures the formation of a stable oxide, well adherent to the surface, at least up to 900°C: with the increase of the chromium content in the alloy, the stability of the oxide will also increase along with the resistance to high temperature corrosion of the component.

There are also other chemical elements that could be added to the composition of the stainless steel to improve its behaviour at high temperatures: i.e. silicon, which generates protective and stable oxides up to 1200°C (SiO_2), or aluminium, which forms compact oxides up to 1300°C (Al_2O_3).

Again in relation to stainless steels, it is also worth highlighting what happens when molybdenum and nickel are present.

Molybdenum, like chromium, improves the resistance of stainless steel to high temperature oxidation because it forms a stable and adherent oxide on the surface (MoO_3): however, it should be kept in mind that, at the temperature of 795°C, this oxide becomes liquid and phenomena of catastrophic corrosion will occur.

Instead, nickel is a chemical element always beneficial with regards to high temperature corrosion in that it does not depend on the possibility of forming stable and protective oxides, but rather on the fact that nickel is not very similar to oxygen, i.e. it has a very poor aptitude for the formation of oxides. Furthermore, the presence of nickel encourages the adhesion of the chromium oxides to the surface of the steel.

The fact that the resistance to high temperature corrosion of the stainless steels does not only depend on their chemical composition should be considered. Other factors influence degradation significantly: the temperature of the hot gases, the chemical composition of the atmosphere, the presence of aqueous vapour, as well as the "operating regime" of the same component, i.e. whether it "works" in conditions with stable temperatures (stationary regime) or fluctuating heat (cyclic regime)[72]. An indication of the maximum operating temperatures of common stainless steels, both in stationary and cyclic regime, is reported in table 20.

		Maximum service temperature °C	
EN Designation	Stainless Steels	Intermittent service	Continuous service
X5CrNi18-10 (1.4301)	austenitic	870	925
X6CrNiTi18-10 (1.4541)	austenitic	870	925
X6CrNiNb18-10 (1.4550)	austenitic	870	925
X5CrNiMo17-12-2 (1.4401)	austenitic	870	925
X8CrNi25-21 (1.4845)	austenitic	1035	1150
X12Cr13 (1.4006)	ferritic	815	705
X2CrTi12 (1.4512)	ferritic	815	705
X6Cr17 (1.4016)	ferritic	870	815
X10CrAlSi25 (1.4762)	ferritic	1175	1095
X12Cr13 (1.4006)	martensitic	815	705
X12CrS13 (1.4005)	martensitic	760	675
X30Cr13 (1.4028)	martensitic	735	620
X105CrMo17 (1.4125)	martensitic	815	760

Table 20 – Maximum temperature in cyclic and stationary regime of some of the most common stainless steels [from Schweitzer 2007].

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[72] *Cyclic regimes are more critical than stationary because, due to the repeated heat expansions and contractions of the surface oxide and the metal substrate, fragmentation and detachment from the protective surface layer occur more easily.*

Martensitic stainless steels, ferritic stainless steels and austenitic stainless steels are the three most used to compare degradation in oxidising environments.

In general terms, the rule is that with the increase of chromium content, the resistance to high temperature oxidation increases, at least in a stationary regime: alloys with 13% chromium content are suitable up to 660°-680°C, 17% chromium content up to 800°-820°C and 18-20% up to 960°-980°C. In order to be able to reach the upper use limit of stainless steel in oxidising environments, it is necessary to resort to alloy contents of 25% chromium: in this case the maximum temperatures are between 1050°-1100°C.

However, when the heat regime becomes cyclic, alloying with nickel must be employed. Therefore, at equal temperature of use and chromium alloy content, an austenitic stainless steel will usually have superior behaviour in terms of duration in operation, compared to a martensitic or ferritic stainless steel[73].

Although stainless steels types X6Cr17, X5CrNi18-10 and X5CrNiMo17-12-2 are widely used at high temperatures, it should not be forgotten that there are specific chemical compositions developed for extreme applications. In this regard, some examples are ferritic stainless steel X10CrAlSi25 (similar to AISI 446), with high chromium content with added aluminium and silicon, or austenitic stainless steel X8CrNi25-21, with high chromium and nickel content: in both cases the materials are very resistant up to 1000°-1100°C.

If, at the same time as high temperature corrosion, resistance to creep corrosion is required, ferritic stainless steels are certainly more suitable: beyond 400°C embrittlement occurs of the structure that drastically reduces its mechanical properties at high temperatures.

In these contexts, austenitic stainless steels should be used, which are very resistant to creep corrosion due to the face-centred cubic lattice: they can be used up to temperatures of around 850-870°C. Alternatively, martensitic stainless steels can be used, but only up to a maximum temperature between 500°-550°C.

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[73] *Carefully consult the temperatures indicated in table 20. In the case of ferrtic and martensitic stainless steels, the higher operating temperatures are those in cyclic regime, whilst for austenitic stainless steels the highest are those in stationary regime. This seemingly strange result is linked to greater linear heat expansion of the austenitic structure compared to the ferritic or martensitic structure: a characteristic that induces greater mechanical tension between the substrate and the oxide film, negatively influencing the compactness of the protective barrier.*

BIBLIOGRAPHICAL RECOMMENDATIONS

With regards to stainless steels the bibliography available is extensive; if in addition to books, scientific journals and the conference papers on the subject are considered, the number of contributions – at least just in the English language – becomes endless.

In our opinion, there are three basic reference texts.

Firstly, the now unobtainable Peckner D., Bernstein I. M., Handbook of Stainless Steels, McGraw Hill, New York, USA, 1977. This is a collective works with contributions from various authors. Despite being a little dated, it gives an overall framework of the most important issues relative to stainless steels; it also contains very interesting information which is still very relevant.

The second text we recommend is another collective work: Lacombe P., Baroux B., Beranger G., Stainless Steels, Les Edition de Physique, Les Ulis, France, 1993. Initially published in French, it was then translated into English for greater use by an international audience. Both scientific and the more typically technological and application subjects are addressed in depth.

Last but certainly not least is a reference volume on stainless steel corrosion. It is Sedriks A. J., Corrosion of Stainless Steels, 2nd, John Wiley & Sons, New Jersey, USA, 1996: the text was specifically written to address the issues of stainless and non stainless steel corrosion, as is usual, it is a text about corrosion in which the stainless steels are just one of the many topics described.

In Italian, the choice is much more meagre: there are only two reference texts on stainless steels.

On one hand there is Di Caprio G., Gli Acciai inossidabili (Stainless Steels), 4a ed., Hoepli, Milan, Italy, 2003. The text by Prof. Di Caprio is very good, especially for non-experts: it is a very interesting introduction (the term "introduction" should not be misleading) to stainless steels and their problems; the volume has been translated into various languages. It contains a myriad of information on the application principles of stainless steels that the author has collected starting from the sixties until his death in 2010.

The other Italian book is Nicodemi W., Introduzione agli acciai inossidabili (Introduction to stainless steels), 2a Ed., Associazione Italiana di Metallurgia, Milan, Italy, 2002. First published in the late eighties and nineties of the last century in a single volume; it suffers a little as it has never been re-published in a composite way. It is a very interesting book that also includes some practical cases of failure due to corrosion of stainless steels; it is the metallurgic counterpart to the text by Prof. Di Caprio.

Unfortunately, there is nothing specific in Italian on the subject of corrosion of stainless steels. We refer the reader who wishes to deepen their knowledge to the volume Pedeferri P., Corrosione e protezione dei materiali metallici (Corrosion and protection of metallic materials), Polipress, Milan, Italy 2010 which contains many references to stainless steels.

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APPENDIX 1

MICROSTRUCTURES AND FORMS OF STAINLESS STEEL CORROSION

For the micrographs that follow, hearfelt thanks to the following laboratories:

Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano,
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(Sig. Piero Pellin, Sig. Maurizio Pardi, Ing. Silvia Barella, Ing. Silvia Cincera, Ing. Mattia Bellogini,
Ing. Fabrizio D'Errico, Ing. Andrea Casaroli, Prof. Marco Boniardi)

Hammer Laboratory S.r.l.,
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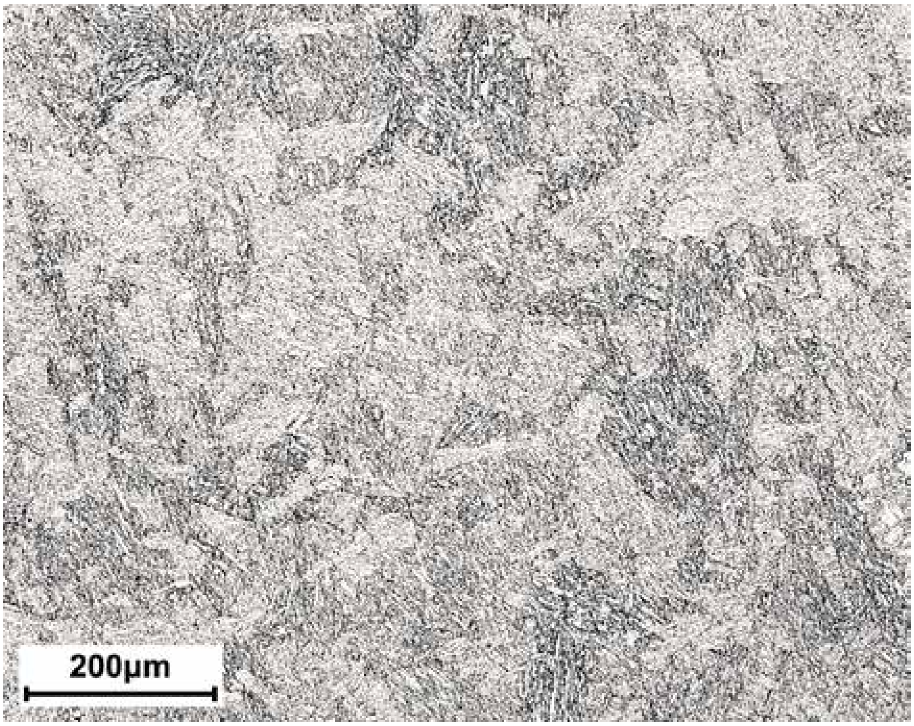
(Sig.ra Patrizia Maio, Ing. Marco Feraboli, Ing. Luca Bonvini)

Omeco Laboratory S.r.l.,
I-20900 Monza (MB), Via Monviso, 56
(Ing. Alessandra Marelli, Ing. Marco Casaril, Ing. HC Clemente Marelli)

Due to constraints of space, it has not been possible to include in this appendix all of the micrographs in our possession. The complete gallery with over fifty images is available free of charge on the following website **www.fa-fe.com** in the micrographs section **http://www.fa-fe.com/files/educational_metallografie.html**



Round bar quenched and tempered at 650°C

Martensitic stainless steel type X20C13 (similar to AISI 420)

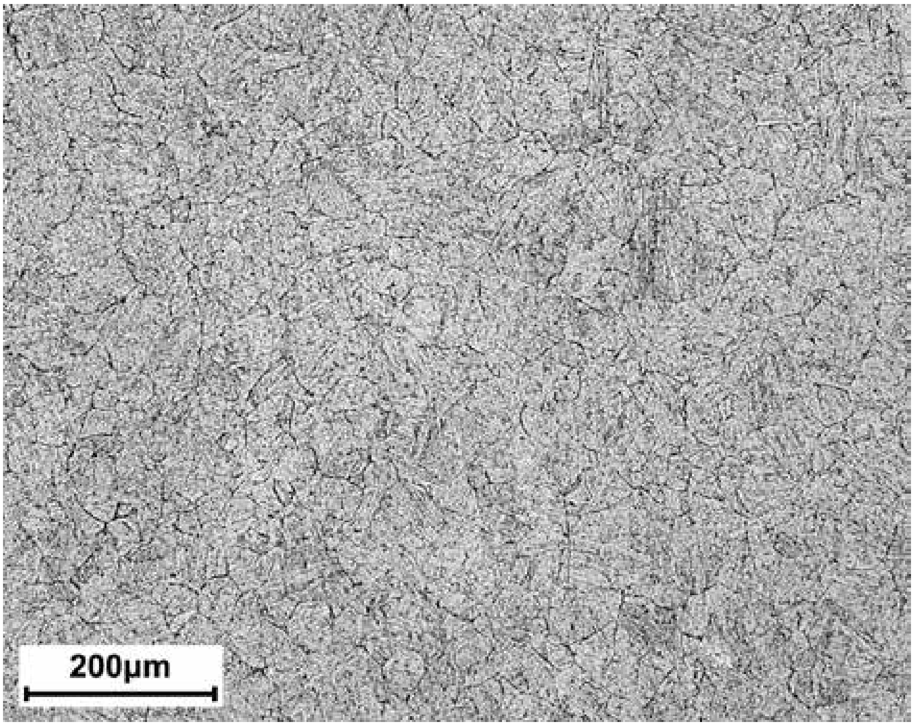
Reactant: Vilella

Homogeneous martensitic structure

Source: Hammer Laboratories S.r.l., Rho (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Semi-finished part, forged, tempered and aged at 620°C

Martensitic PH Stainless Steel type X5CrNiCuNb16-4 (similar to type 17-4PH)

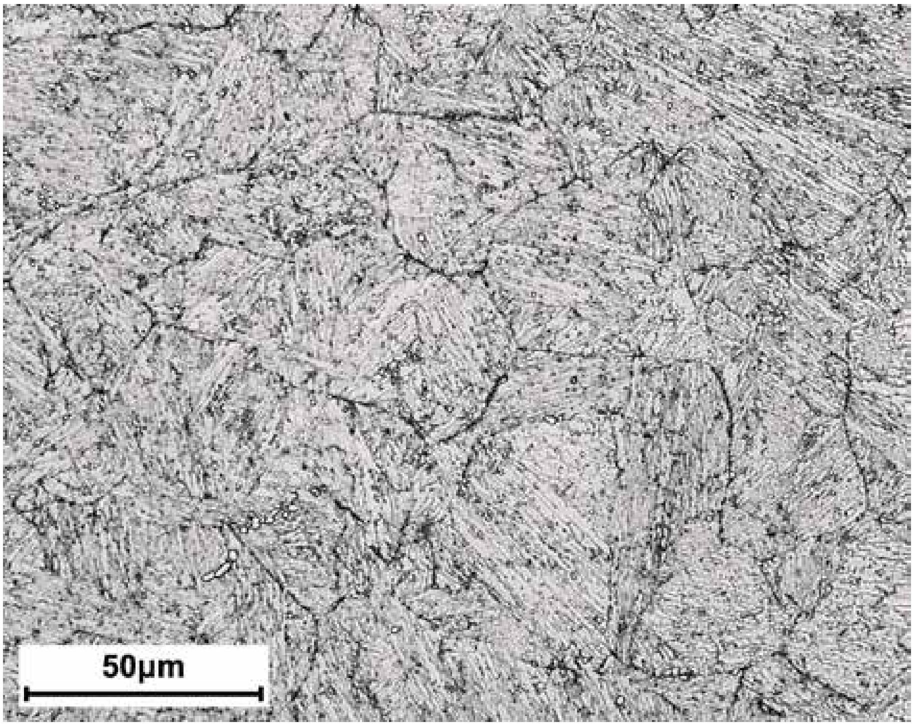
Reactant: Vilella

Homogenous martensitic structure with carbides along the edge of the austenitic grain

Source: Hammer Laboratories S.r.l., Rho (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Details of the previous image with greater enlargements

Martensitic PH Stainless Steel type X5CrNiCuNb16-4 (similar to type 17-4PH)

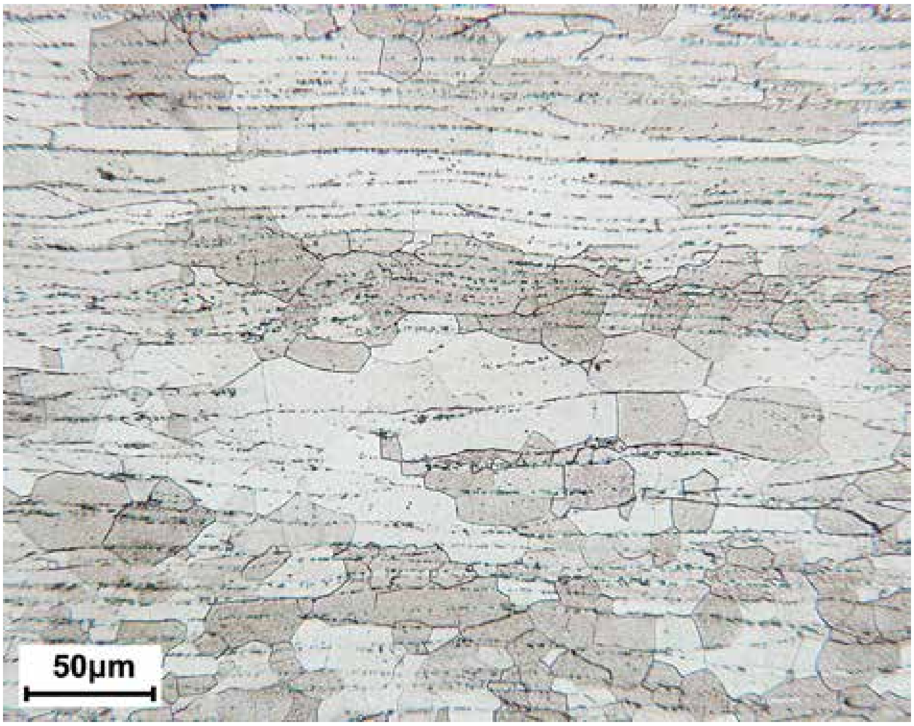
Reactant: Vilella

Homogenous martenistic structure with carbides along the edge of the original austenitic grain

Source: Hammer Laboratories S.r.l., Rho (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Annealed and cold drawn strip

Ferritic stainless steel type X6Cr17 (similar to AISI 430)

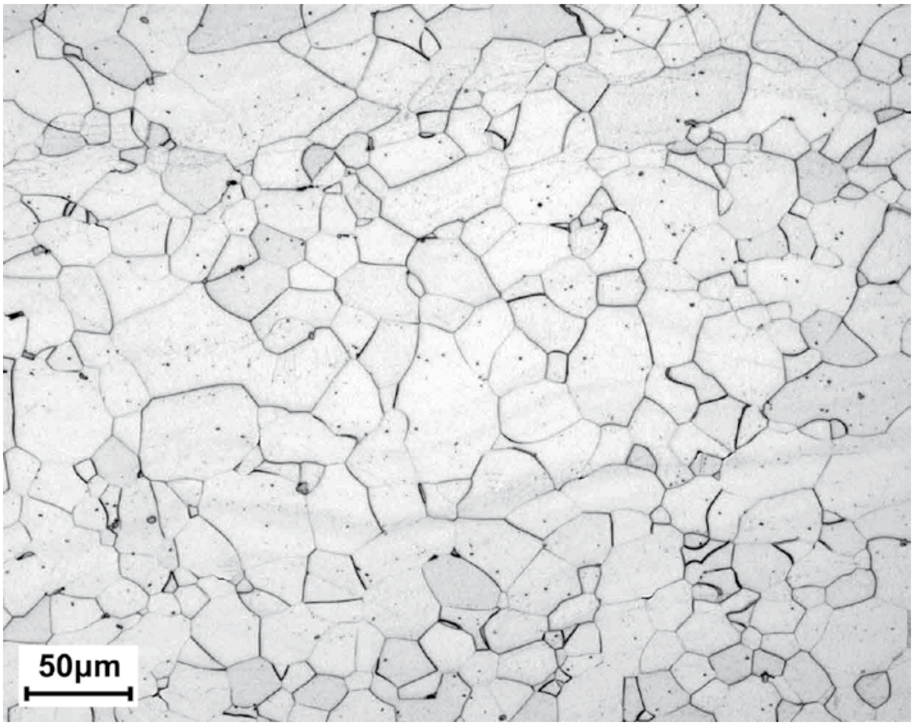
Reactant: Vilella

Homogeneous ferritic types with carbides arranged in the direction of drawing

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Annealed and cold drawn strip

Ferritic stainless steel type X2CrTiNb18 (similar to AISI 441)

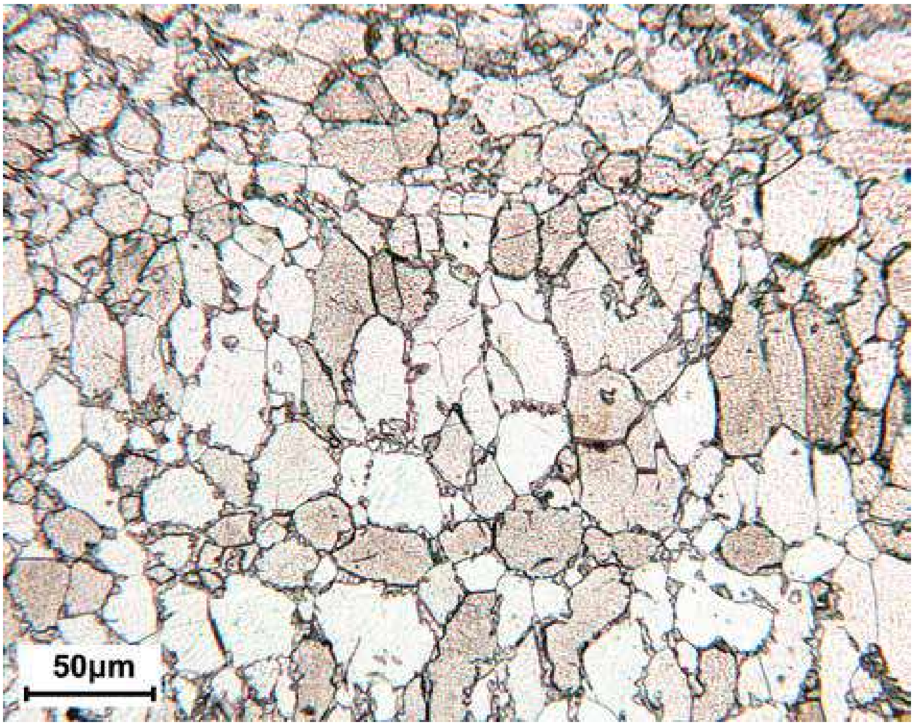
Reactant: Vilella

Homogenous ferritic grains

Source: OMECO Laboratories S.r.l., Monza (MB)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Cold drawn and annealed strip; heat affected zone after resistance welding

Ferritic stainless steel type X6Cr17 (similar to AISI 430)

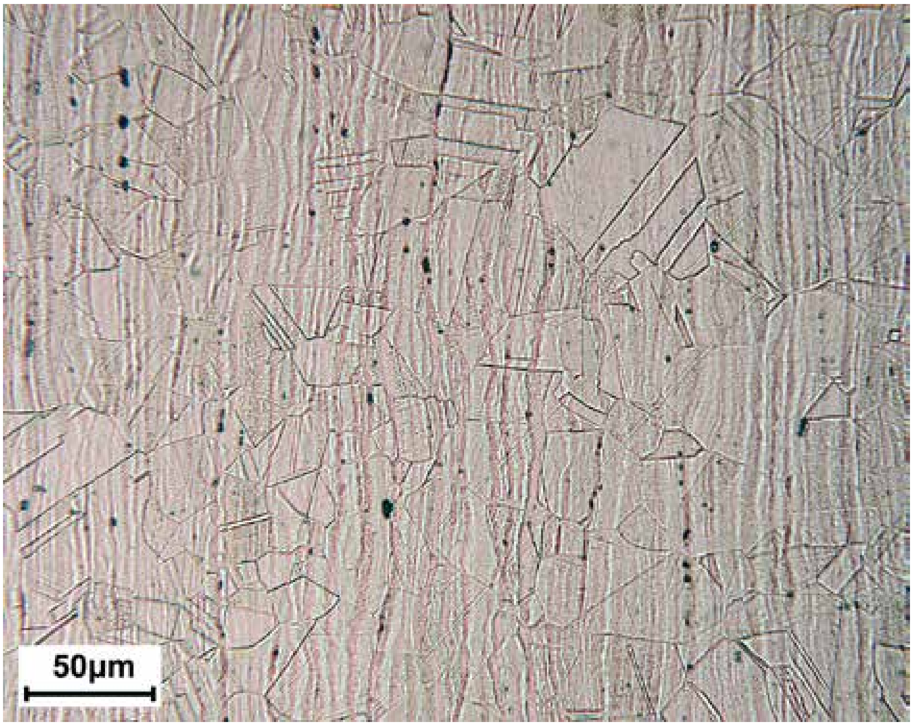
Reactant: Vilella

Homogenous ferritic grains surrounded by martensite blisters

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Round bar solution annealed and drawn in line

Austenitic stainless steel type X5CrNi18-10 (similar to AISI 304)

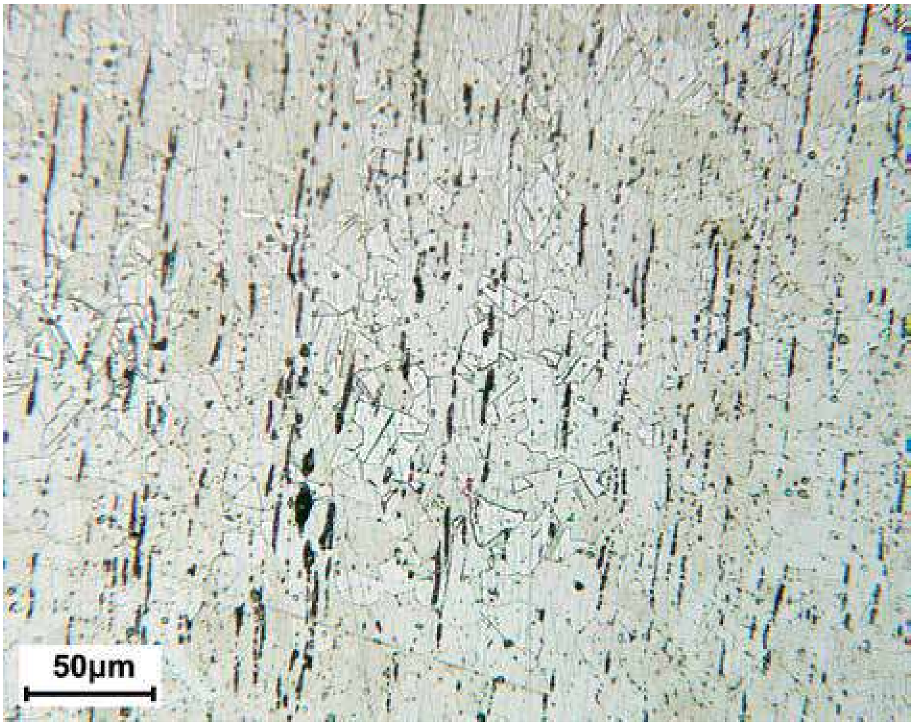
Reactant: Oxalic acid (electrolyte)

Austenitic grains with homogeneous deformation bands arranged in the direction of drawing

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Round bar drawn and solution annealed

Austenitic stainless steel type X8CrNiS18-9 (similar to AISI 303)

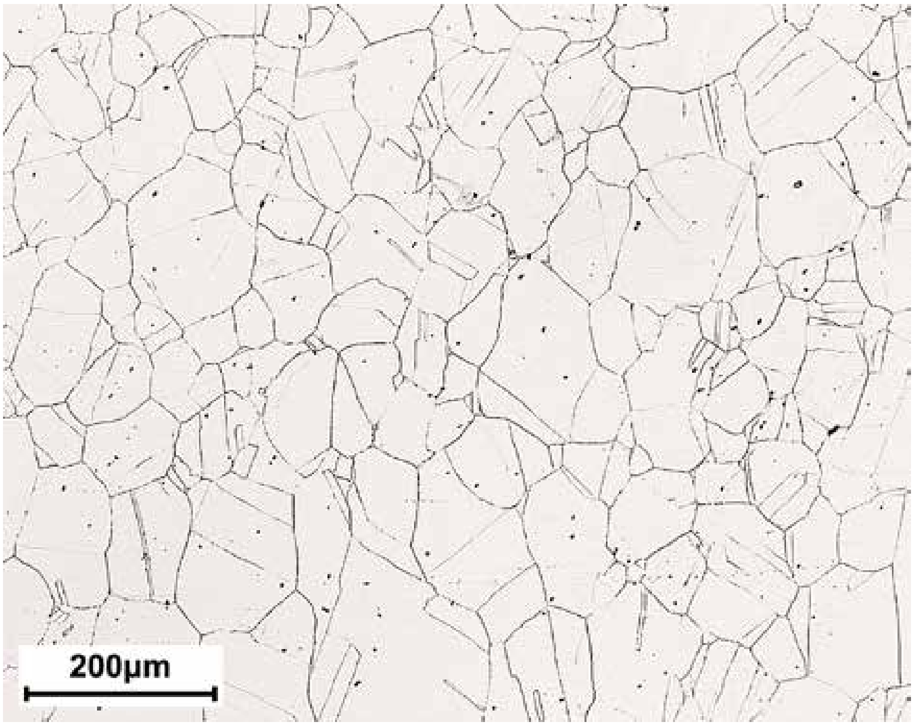
Reactant: Oxalic acid (electrolyte)

Notes: Homogeneous austenitic grains with manganese sulphide in the direction of drawing

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Semi-finished part, forged and solution annealed

Austenitic stainless steel type X2CrNiMoN17-13-3 (similar to AISI 316LN)

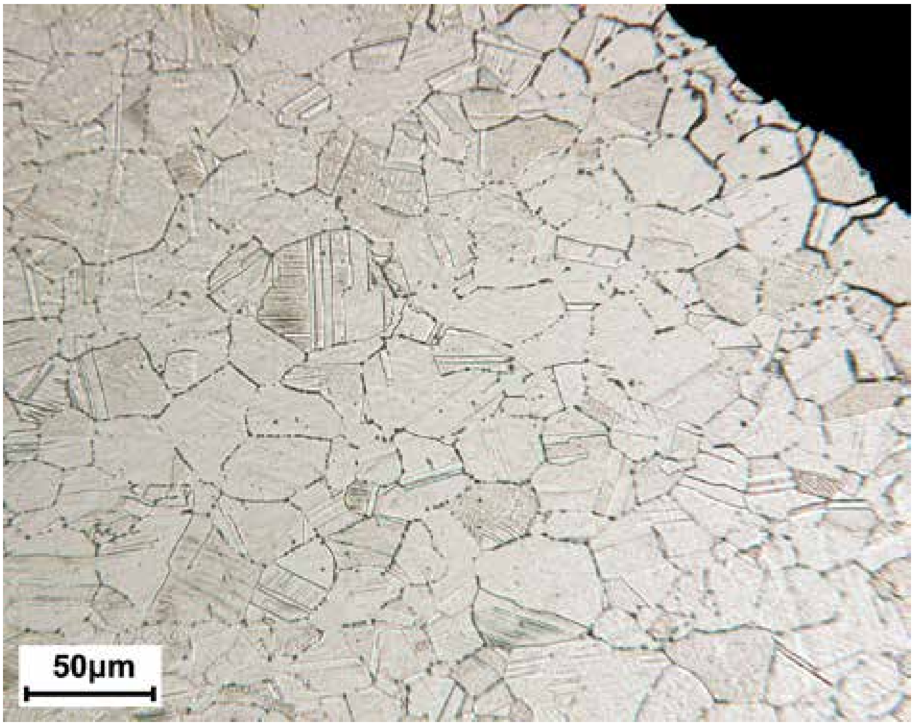
Reactant: Oxalic acid (electrolyte)

Note: Homogeneous austenitic grains

Source: Hammer Laboratories S.r.l., Rho (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Cold drawn solution annealed strip

Austenitic stainless steel type X5CrNiMo17-12-2 (similar to AISI 316)

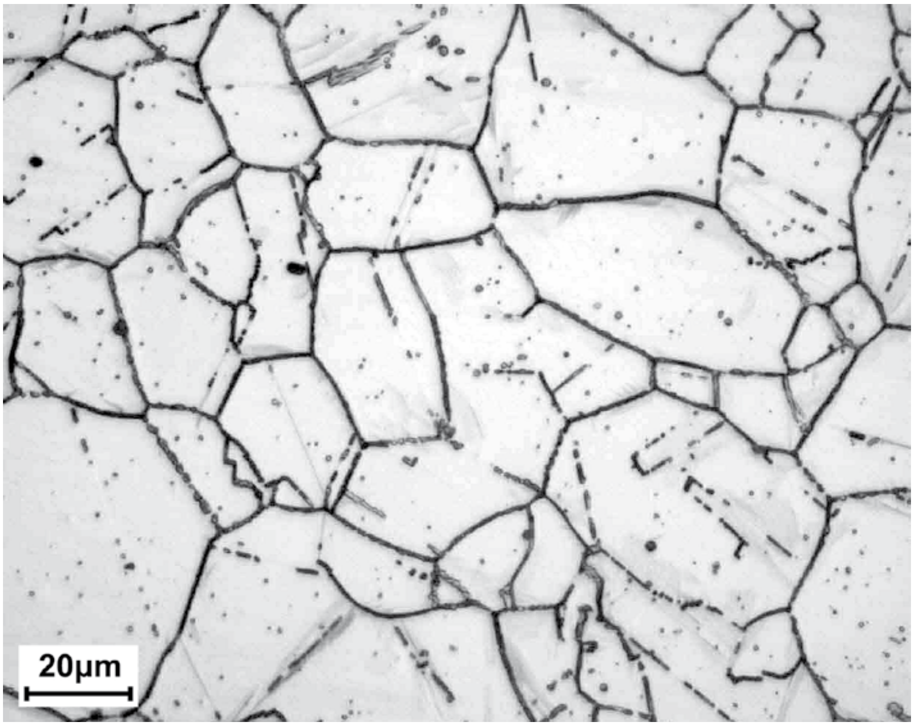
Reactant: Oxalic acid (electrolyte)

Homogeneous austenitic grains with abundant precipitation of carbides at the grain boundary

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Hot rolled sheet, solution annealed and sensitized

Austenitic stainless steel type X2CrNiMo17-12-2 (similar to AISI 316L)

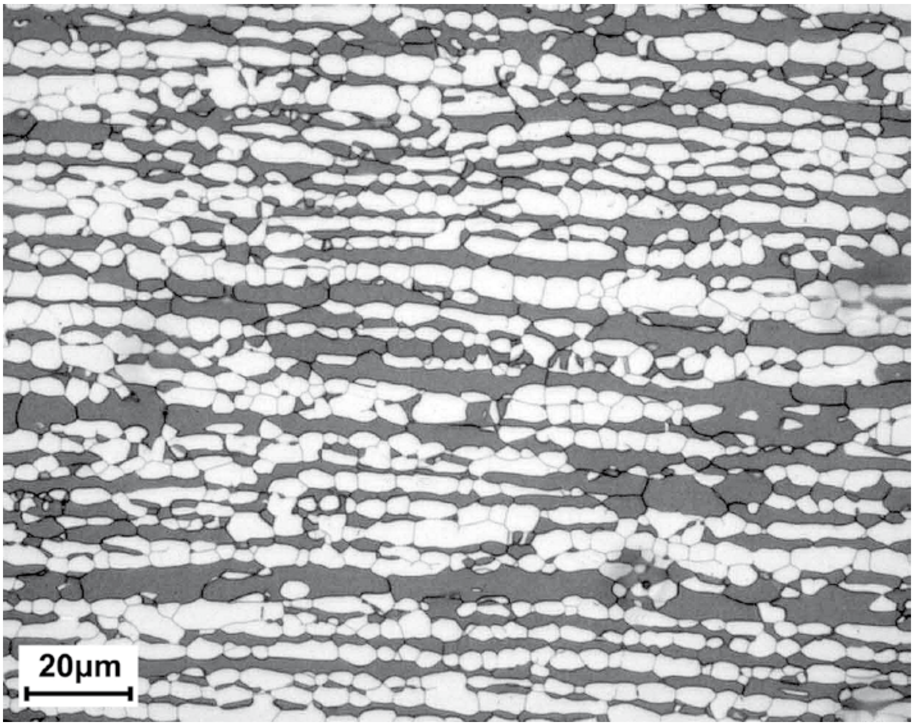
Reactant: Oxalic acid (electrolyte)

Homogeneous austenitic grains with abundant precipitation of carbides at the grain boundary

Source: OMECO S.r.l. Laboratories, Monza (MB)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Hot rolled solution annealed strip

Duplex stainless steel type X2CrNiMoN22-5-3 (similar to 2205)

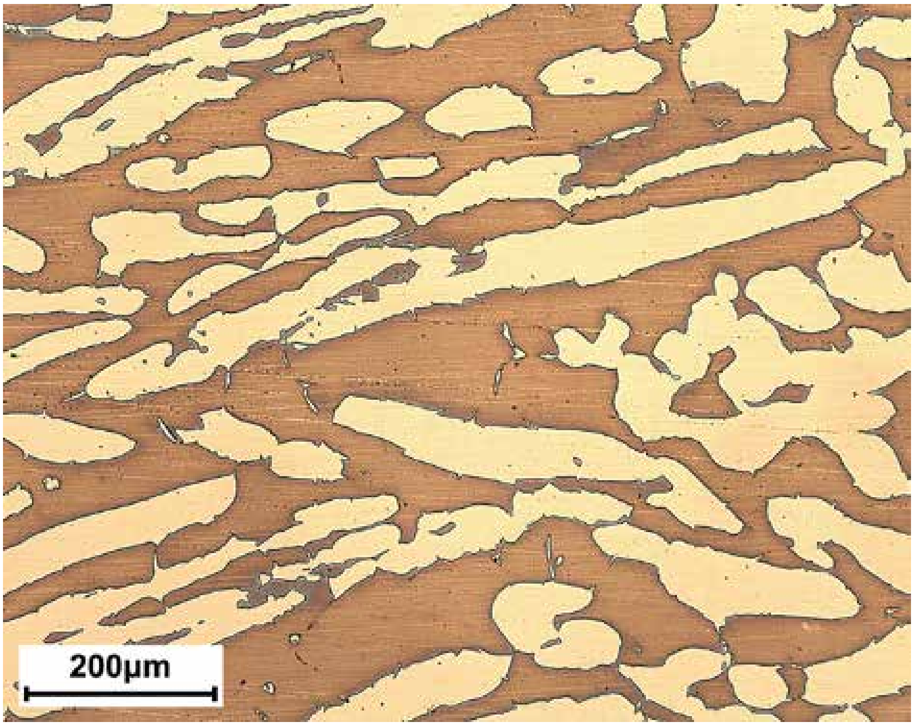
Reactant: Sodium hydroxide solution (electrolyte)

Homogenous austenitic grains and homogeneous ferritic grains extended along the rolling axis

Source: OMECO S.r.l Laboratories, Monza (MB)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Semi-finished part, forged and solution annealed

Duplex stainless steel type X2CrNiMoN22-5-3 (similar to 2205)

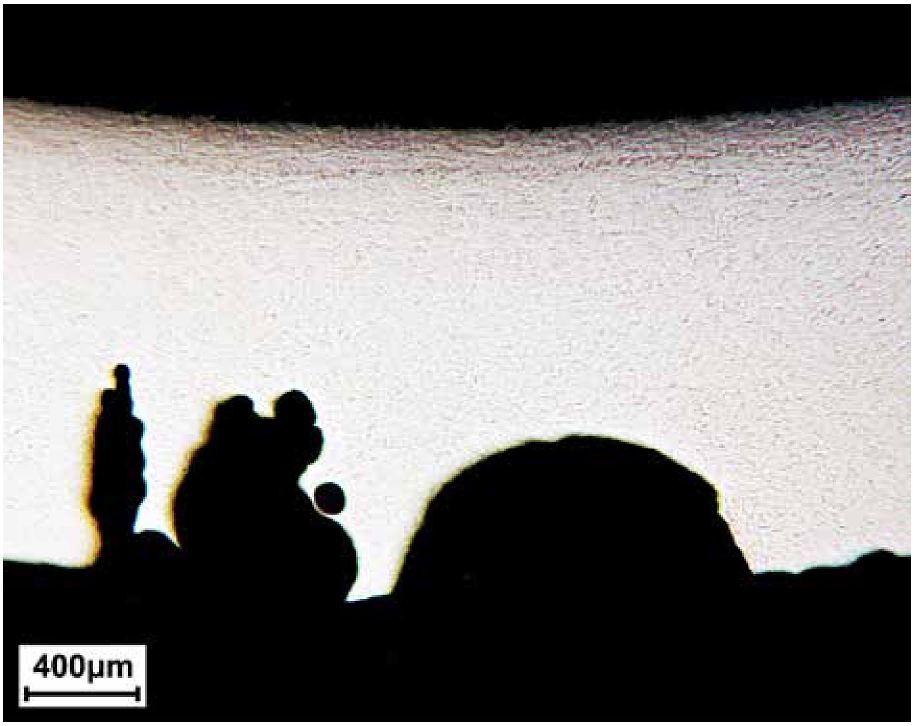
Reactant: Caustic soda (electrolyte)

Note: Clear austenitic grains in a dark ferritic matrix

Source: Hammer S.r.l. Laboratories Rho (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Piping

Austenitic stainless steel type X5CrNi18-10 (similar to AISI 304)

Reactant: Oxalic acid(electrolyte)

Localized corrosion pitting in fresh stagnant water ; temperature ~ 60°C

Multiple pitting with uniform penetration

Homogenous austenitic grains

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**

Piping

Austenitic stainless steel type X5CrNi18-10 (similar to AISI 304)

Reactant: Oxalic acid (electrolyte)

Localized corrosion pitting in fresh stagnant water; temperature ~ 60°C

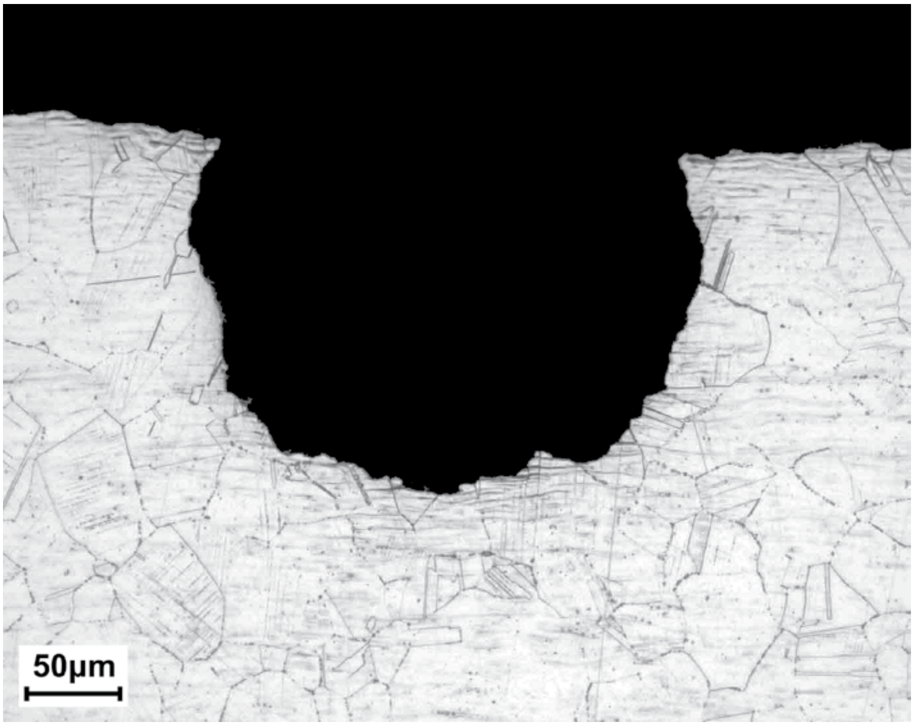
Single pitting with multiple cavities

Homogeneous austenitic grains

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Piping for heat exchanger

Austenitic stainless steel type X5CrNiMo17-12-2 (similar to AISI 316)

Reactant: Oxalic acid (electrolyte)

Localized corrosion pitting in sea water; temperature ~ 50°C

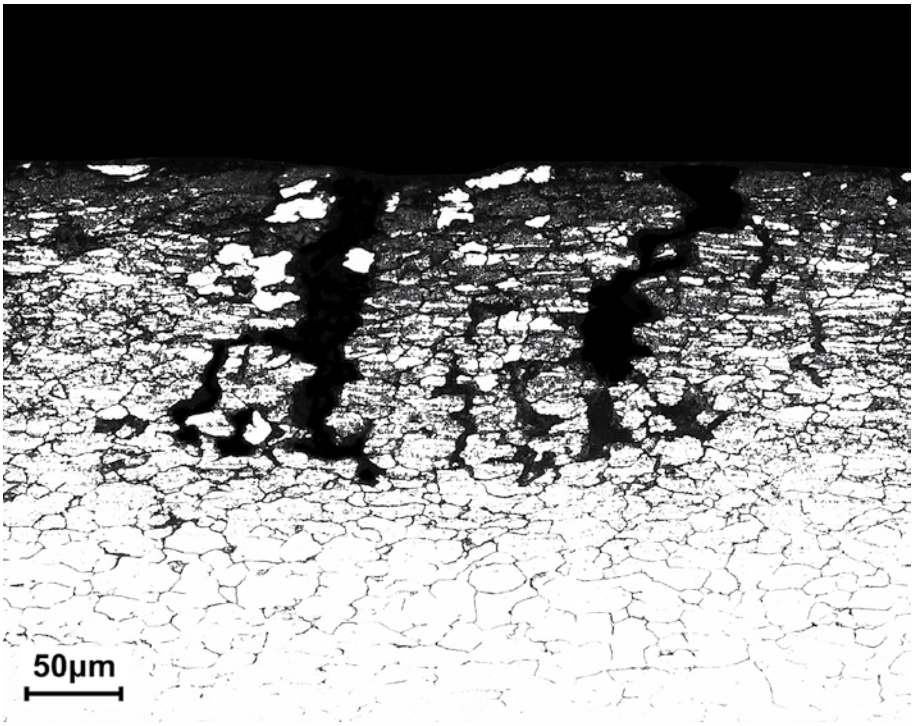
Detail of rounded cavity

Homogeneous austenitic grains

Source: OMECO S.r.l. Laboratories Monza (MB)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Welded join on piping

Austenitic stainless steel type X5CrNi18-10 (similar to AISI 304)

Reactant: Oxalic Acid (electrolyte)

Intergranular corrosion in water solutions pH 5.5; temperature ~ 20°C

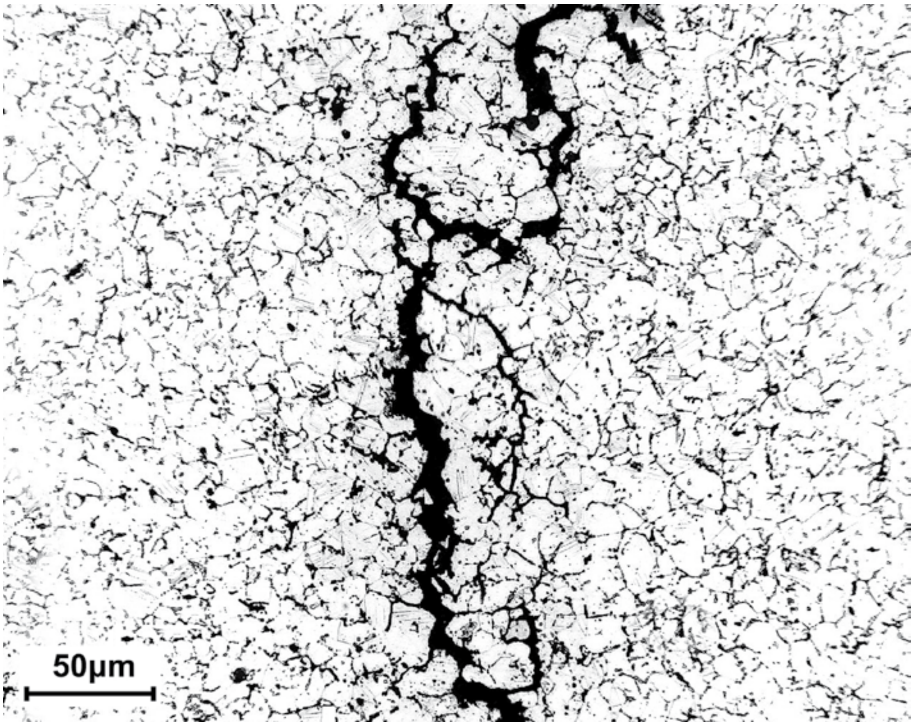
Ramified multiple intergranular cracks

Homogenous austenitic grains with carbides along the grain boundary

Source: OMECO S.r.l. Laboratories, Monza (MB)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Gas check valve

Austenitic stainless steel type X5CrNi18-10 (similar to AISI 304)

Reactant: Oxalic acid (electrolyte)

Intergranular corrosion in humid atmospheres; temperature ~ 20°C

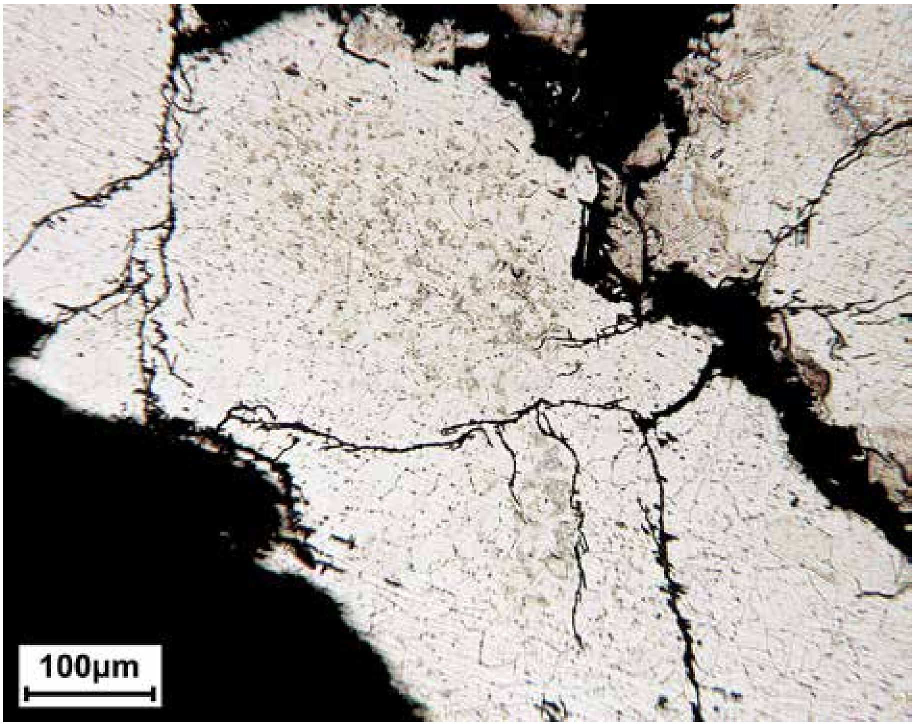
Ramified intergranular cracks

Homogenous austenitic grains with carbides along the grain boundary

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Piping

Austenitic stainless steel type X5CrNi18-10 (similar to AISI 304)

Reactant: Oxalic Acid (electrolyte)

Stress corrosion in water-based solutions containing chloride ; temperature ~ 80°C

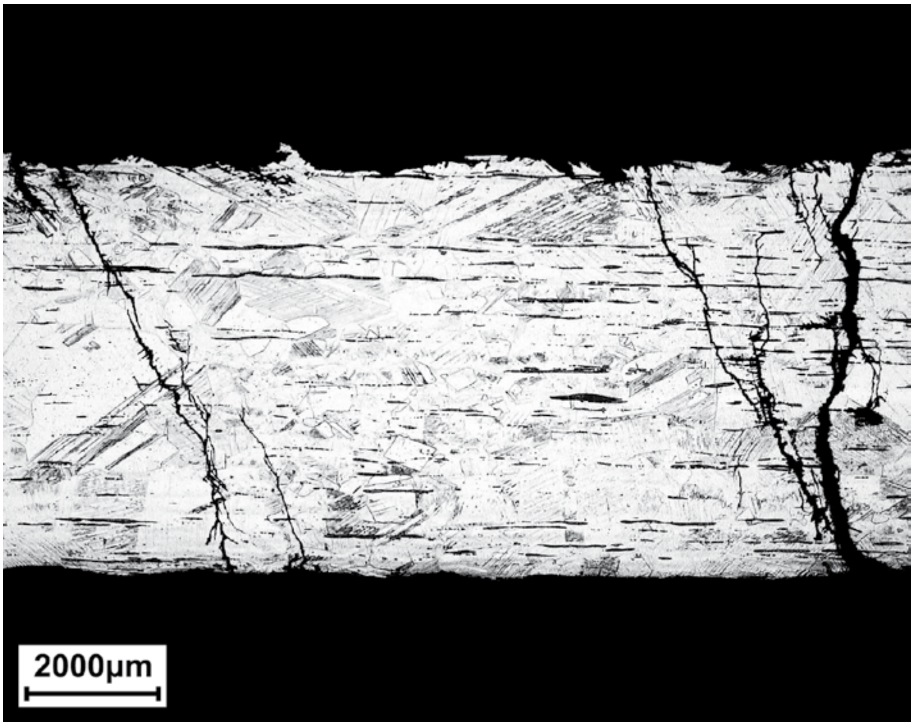
Presence of ramified multiple cross-granular cracks

Homogenous austenitic grains with carbides along the boundary

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Piping

Austenitic stainless steel type X8CrNiS18-9 (similar to AISI 303)

Reactant: Oxalic acid (electrolyte)

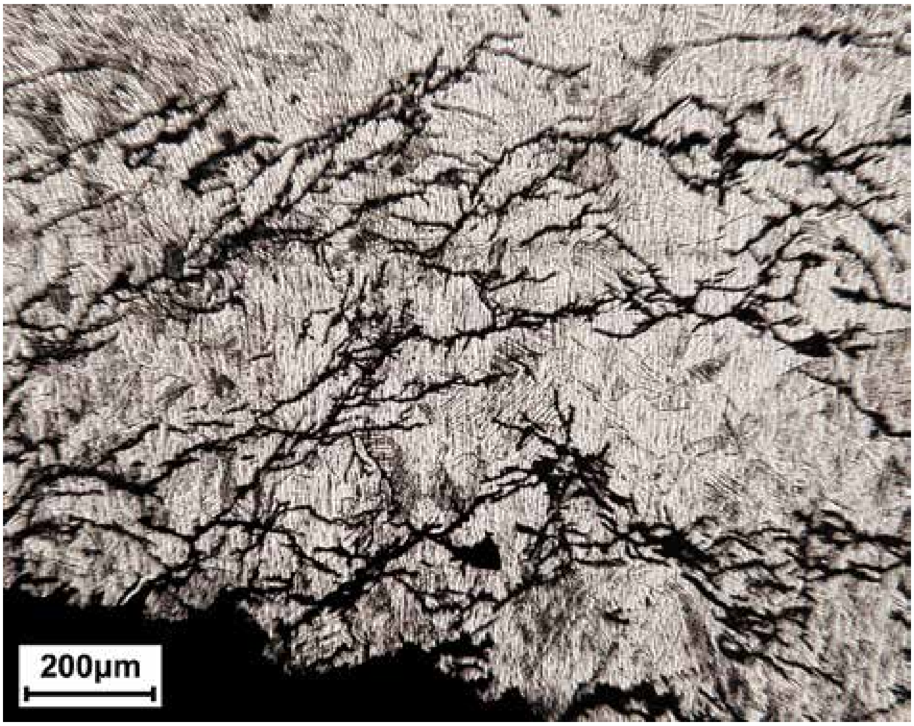
Stressed corrosion in water-based solutions containing chloride; temperature 80°-100°C

Presence of ramified cross-granular cracks; Homogeneous austenitic grains

Source: Omeco S.r.l. Laboratories, Monza (MB)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Fixing screws

Austenitic stainless steel type X5CrNi18-10 (similar to AISI 304)

Reactant: Oxalic acid (electrolyte)

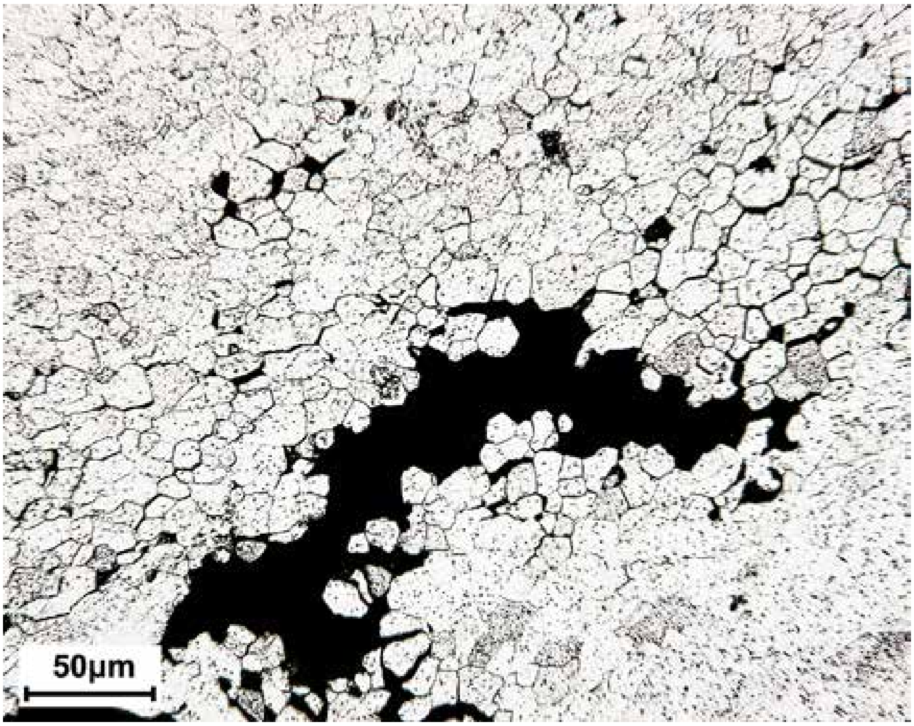
Stressed corrosion in water-based solutions containing chloride; temperature 50°-90°C

Presence of ramified multiple cross-granular cracks; austenitic strain-hardened grains

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**



Basket for washing machine

Ferritic stainless steel type X6Cr17 (similar to AISI 430)

Reactant: Vilella

Stressed corrosion in watery solutions containing chloride; temperature 90°C

Presence of multiple intergranular cracks; homogenous ferritic grains

Source: Metallurgical Laboratory, Department of Mechanical Engineering, Politecnico di Milano (MI)

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**

Santa Caterina del Sasso Hermitage , Leggiuno (VA), repair work

Tie rod in austenitic stainless steel and frame in galvanized carbon steel

Corrosion by galvanic contact in air; temperature range 0°-30°C

Source: photo Marco Boniardi

Further images can be found on **www.fa-fe.com**,

Metallography section **http://www.fa-fe.com/files/educational_metallografie.html**

APPENDIX 2

LUCEFIN S.P.A.

STAINLESS STEEL TECHNICAL DATA SHEETS

Quality	**X12CrS13**	**Martensitic Stainless Steel**	*Technical card* 2014
Number	**1.4005**		***Lucefin Group***

Chemical composition

C%	Si%	Mn%	P%	S%	Cr%	Mo%	
	max	max	max			max	
0,06-0,15	1,00	1,50	0,040	0,15-0,35	12,0-14,0	0,60	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	± 0.02	± 0.15	± 0.03	

Product deviations are allowed

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**	**Full annealing**
1530-1480	1190-925	not suitable	780-750 air	870-840 cooling 15 °C/h to 590, then air
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**	
885-830 controlled cooling to 720, then air	1010-980 oil/polymer air	680- 660 fast cooling in air	250-210 air	

MMA **welding** – AWS electrodes

pre-heating	*after welding*
300	stress-relieving 600

joint with steel

carbon	CrMo alloyed	stainless
E309	E309	E309-E308

cosmetic welding
E410 - E309

Transformation temperature during heating **Ac_1** ~ 820, **Ac_3** ~ 930 and during cooling **Ms** ~ 330, **Mf** ~ 180

Chemical treatment ▪ *Pickling* (10 - 15% HNO_3) + (0.5 – 1.5 HF) cold

Mechanical properties

Heat-treated material 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature					
		R	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** [a]	[a] for information only
from	to	N/mm^2	N/mm^2 min	min	J min	max	
		730 max				220	+A annealed material
	160	650-850	450	12			+QT650 quenched and tempered

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm		Testing at room temperature					
		R	**HB** [a]	**R**	**Rp** 0.2	**A%**	**Kv** +20 °C
from	to	N/mm^2 max	max	N/mm^2	N/mm^2 min	min	J min
	10 [b]	880	280	700-1000	550	8	
10	16	880	280	700-1000	500	8	
16	40	800	250	650-930	450	10	
40	63	760	230	650-880	450	10	
63	160	730	220	650-850	450	12	
		+A annealed material		+QT650 quenched and tempered material			

[a] for information only

[b] In the range of 1 mm $\le d <$ 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged (ASTM A 473-99 steel ASTM 416)

size mm		Testing at room temperature							
		R	**Rp** 0.2	**A%**	**C%**	**Kv** +20 °C	**HB**	**HRC**	
from	to	N/mm^2 min	N/mm^2 min	min	min	J min	max	min	
		485	275	20	45		223		+A annealed material
								35	Quenching at 955 °C in air

Table of tempering values at room temperature on rounds of Ø 10 mm after quenching at 980°C in oil

R	N/mm^2	1490	1450	1420	1410	1430	1450	1420	1150	860	740	690
Rp 0.2	N/mm^2	1210	1170	1150	1150	1160	1180	1140	870	650	550	500
A	%	10.8	10.8	10.9	12.0	12.5	13.0	16.0	16.5	18.0	20.0	21.5
Kv	J	25	30	26	19	18	17	18	20	31	49	90
Tempering	**°C**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

Effect of **cold-working** (hot-rolled +QT+C). Approximate values

R	N/mm^2	720	740	760	770	780	785	800	820	830	835	840
Rp 0.2	N/mm^2	480	625	630	650	660	680	700	730	735	750	760
A	%	19	18	18	16	16	16	15	15	14	14	14
Reduction	**%**	**0**	**7**	**8**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**

X12CrS13 n° **1.4005** martensitic stainless steel

Thermal expansion	$10^{-6} \cdot K^{-1}$	▶	10.5	11.0	11.5	12.0	12.2	12.7
Modulus of elasticity	longitudinal GPa	215	212	205	200	190		
Poisson number	*v*	0.235	0.210					
Electrical resistivity	$\Omega \cdot mm^2/m$	0.60						
Electrical conductivity	$Siemens \cdot m/mm^2$	1.67						
Specific heat	J/(Kg•K)	460						
Density	Kg/dm^3	7.70						
Thermal conductivity	W/(m•K)	30						
Relative magnetic permeability	μr	900 [1]						
°C		**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

[1] max 900 for material in its natural state; max 750 for full annealed material

Corrosion resistance	Atmospheric		Chemical			**x** steam, gasoline, fuel oil, alcohol, ammonia
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	high
Hardening	by quenching
Service temperature in air	continuous service up to 675 °C;intermittent service up to 760 °C

Europe	**USA**	**USA**	**China**	**Russia**	**Japan**	**India**	**Republic of Korea**
EN	UNS	ASTM	GB	GOST	JIS	IS	KS
X12CrS13	S41600	**416**	Y1Cr13		SUS 416		STS 416

Quality	**X12Cr13**	**Martensitic**	*Technical card* 2014
Number	**1.4006**	**Stainless Steel**	***Lucefin Group***

Chemical composition

C%	Si% max	Mn% max	P% max	S% a) max	Cr%	Ni% max	
0,08-0,15	1,00	1,50	0,040	0,015	11,5-13,5	0,75	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.15	± 0.03	

Product deviations are allowed

a) for improving machinability, it is allowed a sulphur content of 0,015 % - 0,030; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**	**Full annealing**
1530-1480	1190-900	not suitable	825-745 air	870-840 cooling 15 °C/h to 590, then air
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**	
885-830 controlled cooling to 705, thenair	1000-950 oil / polymer (HRC 36 ~)	780-650 fast cooling in air	200 air	

MMA **welding –** AWS electrodes

pre-heating	*annealing after w.*	
200	750-700	
joint with steel		
carbon	CrMo alloyed	stainless
E60 xx	E8018-B 2	E309 – E308
cosmetic welding		
E410		

Transformation temperature during heating **Ac$_1$** ~ 810, **Ac$_3$** ~ 885 and during cooling **Ms** ~ 340, **Mf** ~ 190

Chemical treatment ▪ *Pickling* (20 - 50% HNO$_3$) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	 to	Testing at room temperature **R** N/mm^2	 **Rp** 0.2 N/mm^2 min	 **A%** min	 **Kv** +20 °C J min	 **HB** a) max	 a) for information only
		730 max				220	+A annealed material
	160	650-850	450	15	25		+QT650 quenched and tempered

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	 to	Testing at room temperature **R** N/mm^2 max	 **HB** a) max	 **R** N/mm^2	 **Rp** 0.2 N/mm^2 min	 **A%** min	 **Kv** +20 °C J min
	10 b)	880	280	700-1000	550	9	
10	16	880	280	700-1000	500	9	
16	40	800	250	650-930	450	10	25
40	63	760	230	650-880	450	10	25
63	160	730	220	650-850	450	15	25
		+A annealed material		+QT650 quenched and tempered material			

a) for information only

b) in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged EN 10250-4: 2001

size mm from	 to	Testing at room temperature **R** N/mm^2	 **Rp** 0.2 N/mm^2 min	 **A%** min	 **Kv** +20 °C J min	 **HB** max	
		730 max				220	+A annealed
	160	650-850	450	15	25		+QT650 quenched and tempered

Table of tempering values at room temperature on rounds of Ø 10 mm after quenching at 980°C in oil

R	N/mm^2	1490	1450	1420	1410	1430	1450	1420	1150	860	740	690
Rp 0.2	N/mm^2	1210	1170	1150	1150	1160	1180	1140	870	650	550	500
A	%	10.8	10.8	10.9	12.0	12.5	13.0	16.0	16.5	18.0	20.0	21.5
Kv	J	35	40	36	29	28	27	28	30	41	49	100
Tempering	**°C**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

Transition-curve determined with Kv. Material quenched at 970 °C in oli

Average	J	6	16	26	50	80	120	140	150	170	tempering at 790 °C	**690**
Average	J	5	12	18	26	50	84	110	114	140	tempering at 665 °C	**820**
Average	J	4	6	8	14	26	36	76	78	120	tempering at 595 °C	**950**
Tests at	**°C**	-160	-120	-80	-40	0	+40	+80	+100	+200	**tensile strenght**	**N/mm^2**

X12Cr13 **n° 1.4006** martensitic stainless steel

Effect of **cold-working** (hot-rolled +A+C). Approximate values

R	N/mm²	580	650	700	750	790	800	850	920	1050
Rp 0.2	N/mm²	380	500	580	600	690	720	780	810	900
A	%	20	10	8	8	8	8	8	8	7
Reduction **%**		**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**

Minimum values at high temperatures on quenched and tempered material EN 10088-3: 2005

Rp 0.2	N/mm²	420	410	400	385	365	355	305		+QT 650
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**		

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	10.5	11.0	11.5	12.0
Modulus of elasticity	longitudinal GPa	215	212	205	200	190
Poisson number	*v*	0.235	0.210			
Electrical resistivity	Ω • mm²/m	0.60				
Electrical conductivity	Siemens•m/mm²	1.67				
Specific heat	J/(Kg•K)	460				
Density	Kg/dm³	7.70				
Thermal conductivity	W/(m•K)	30				
Relative magnetic permeability	μr	900 1)				
°C		**20**	**100**	**200**	**300**	**400**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

1) max 900 for material in its natural state; max 750 for full annealed material

Corrosion resistance	Atmospheric		Chemical			**x** petroleum, gasoline, alcohol, ammonia, mercury, food
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x			**x**			

Magnetic	yes
Machinability	good on annealed and quenched and tempered
Hardening	by quenching
Service temperature in air	continuous service up to 705 °C; intermittent service up to 815 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X12Cr13	S41000	**410**	1Cr12	12Ch13	SUS 410	X12Cr12	STS 410

Quality	**X6Cr17**	**Ferritic**	*Technical card 2014*
Number	**1.4016**	**Stainless Steel**	***Lucefin Group***

Chemical composition

C%	Si%	Mn%	P%	S% [a]	Cr%	
max	max	max	max	max		
0,08	1,00	1,00	0,040	0,030	16,0-18,0	EN 10088-1: 2005
± 0.01	+ 0.05	+ 0.03	+ 0.005	± 0.005	± 0.2	

Product deviations are allowed

[a] for improving polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**
1510-1425	1120-850	810-700 cooling to 300, then air	850-750 air
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	
not suitable	not suitable	not suitable	

MMA **welding -** AWS electrodes

pre-heating	*annealing after w.*
200	800-750

joint with steel

carbon	CrMo alloyed	stainless
E60 xx	E8018-B 2	E309 – E308

cosmetic welding

E430

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) + (2 - 6% $Na_2Cr_2O_7.2H_2O$) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size		Testing at room temperature					
mm		**R**	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** [a]	[a] for information only
from	to	N/mm^2	N/mm^2 min	min	J min	max	
	100	400-630	240	20		200	+A annealed material

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size		Testing at room temperature					
mm		**R**	**HB**	**R**	**Rp** 0.2	**A%**	**Kv** +20 °C
from	to	N/mm^2 max	max	N/mm^2	N/mm^2 min	min	J min
	10 [b]			500-750	320	8	
10	16			480-750	300	8	
16	40			400-700	240	15	
40	63			400-700	240	15	
63	100			400-630	240	20	
				+A annealed material			

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged EN 10250-4: 2001

size		Testing at room temperature					
mm		**R**	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB**	
from	to	N/mm^2	N/mm^2 min	min	J min	max	
	100	400-630	240			200	+A annealed material

Effect of **cold-working** (hot-rolled +RA+C). Approximate values

R	N/mm^2	550	620	680	700	720	770	790	820	860
Rp 0.2	N/mm^2	320	500	590	620	650	680	700	750	800
A	%	22	11	10	9	9	9	9	9	9
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**75**

Minimum values at high temperatures EN 10088-3: 2005

Rp 0.2	N/mm^2	220	215	210	205	200	195	190	+A annealed
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	

X6Cr17 n° **1.4016** ferritic steel

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	10.0	10.5	10.5	10.5	11.0	12.0
Modulus of elasticity	longitudinal GPa	220	215	210	205	195		
Poisson number	v	0.144	0.138					
Electrical resistivity	$\Omega \bullet mm^2/m$	0.60		0.77		0.93	1.05	1.25
Electrical conductivity	$Siemens \bullet m/mm^2$	1.67						
Specific heat	$J/(Kg \bullet K)$	460		495		570	660	760
Density	Kg/dm^3	7.75						
Thermal conductivity	$W/(m \bullet K)$	25						
Relative magnetic permeability	μr	600-1000 ~						
°C		**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ► indicates between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** phenol, food, detergents, weak organic acids
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**		**x**	**x**		

Magnetic	yes
Machinability	good
Hardening	cold-drawing and other cold plastic deformations
Service temperature in air	up to 800 °C continuous service and up to 875 °C intermittent service

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X6Cr17	S43000	**430**	1Cr17	12Ch17	SUS 430	X07Cr17	STS 430

Quality	**X20Cr13**	**Martensitic**	*Technical card* 2014
Number	**1.4021**	**Stainless Steel**	***Lucefin Group***

Chemical composition

C%	Si% max	Mn% max	P% max	S% a) max	Cr%	
0,16-0,25	1,00	1,50	0,040	0,015	12,0-14,0	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.15	

Product deviations are allowed

a) for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**	**Full annealing**
1510-1460	1200-930	not suitable	825-745 air	900-870 cooling 15 °C/h to 590, then air
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**	
885-830 controlled cooling to 705, then air	1050-950 oil/polymer/air (HRC 46 ~)	700-650 fast cooling in air	250-150 air	

MMA **welding –** AWS electrodes

pre-heating	*annealing after w.*
250-200	750

joint with steel

carbon	CrMo alloyed	stainless
E60 xx	E8018-B 2	E309

cosmetic welding

E420 – E410

Transformation temperature during heating **Ac_1** ~ 790, **Ac_3** ~ 850 and during cooling **Ms** ~ 240, **Mf** ~ 90

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size		Testing at room temperature					
mm		**R**	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** a)	a) for information only
from	to	N/mm^2	N/mm^2 min	min	J min	max	
		760 max				230	+A annealed
	160	700-850	500	13	25		+QT700 quenched and tempered
	160	800-950	600	12	20		+QT800 quenched and tempered

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size		Testing at room temperature					
mm		**R**	**HB** a)	**R**	**Rp** 0.2	**A%**	**Kv** +20 °C
from	to	N/mm^2 max	max	N/mm^2	N/mm^2 min	min	J min
	10 b)	910	290	750-1000	600	8	
10	16	910	290	750-1000	550	8	
16	40	850	260	700-950	500	10	25
40	63	800	230	700-900	500	12	25
63	160	760	220	700-850	500	13	25
		+A annealed material		+QT700 quenched and tempered material			

a) for information only

b) in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged EN 10250-4: 2001

size		Testing at room temperature					
mm		**R**	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB**	
from	to	N/mm^2	N/mm^2 min	min	J min	max	
		760 max				230	+A annealed
	160	700-850	500	13	25		+QT700 quenched and tempered-
	160	800-950	600	12	20		+QT800 quenched and tempered

Table of tempering values at room temperature on rounds of Ø 10 mm after quenching at 970°C in oil

R	N/mm^2	1650	1550	1540	1530	1530	1500	1200	900	790	600
Rp 0.2	N/mm^2	1320	1280	1260	1250	1230	1180	980	680	600	560
A	%	12	11	10.5	10.5	11	12	15	17	18	20
Kv	J	25	22	18	12	10	12	18	32	36	60
Tempering	**°C**	**200**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

Effect of **cold-working** (hot-rolled +A+C). Approximate values

R	N/mm^2	580	650	670	680	685	690	720	745	760
Reduction	**%**	**0**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**

Effect of **cold-working** (hot-rolled +QT+C). Approximate values

R	N/mm^2	760	810	830	840	855	870	880	895
Rp 0.2	N/mm^2	570	740	770	780	795	800	820	830
A	%	18	16	15	15	14	13	12	11
Reduction	**%**	**0**	**8**	**10**	**12**	**14**	**16**	**18**	**20**

Minimum values at high temperatures EN 10088-3: 2005

Rp 0.2	N/mm^2	460	445	430	415	395	365	330	material +QT700
Rp 0.2	N/mm^2	515	495	475	460	440	405	355	material +QT800
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	

Thermal expansion	$10^{-6} \cdot K^{-1}$	▶	10.5	11.0	11.5	12.0
Modulus of elasticity	longitudinal GPa	215	212	205	200	190
Poisson number	*ν*	0.235	0.210			
Electrical resistivity	$\Omega \cdot mm^2/m$	0.60				
Electrical conductivity	Siemens•m/mm^2	1.67				
Specific heat	J/(Kg•K)	460				
Density	Kg/dm^3	7.70				
Thermal conductivity	W/(m•K)	30		31		
Relative magnetic permeability	μr	950 [1]				
°C		**20**	**100**	**200**	**300**	**400**

The symbol ▶ indicates temperatures between 20 °C and 100 °C, 20 °C and 200 °C .....

[1] max 950 for full annealed material

Corrosion resistance	Atmospheric		Chemical			**x** aggressive atmosphere lacking chlorine-derived substances
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	good
Hardening	by quenching
Service temperature in air	continuous service up to 650 °C; intermittent service up to 750 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X20Cr13	S42000	(**420**)	2Cr13	20Ch13	SUS 420J1		STS 420J1

Quality	**X30Cr13**	**Martensitic Stainless Steel**	*Technical card 2014*
Number	**1.4028**		***Lucefin Group***

Chemical composition

C%	**Si%** max	**Mn%** max	**P%** max	**S%** [a)] max	**Cr%**	
0,26-0,35	1,00	1,50	0,040	0,015	12,0-14,0	EN 10088-1: 2005
± 0.02	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.15	

Product deviations are allowed

a) for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**	**Full annealing**
1490-1480	1200-930	not suitable	825-745 air	not suitable
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Tempering +T**	**Stress-relieving +SR**
not suitable	1080-980 oil/air	200-150 fast cooling in air (HRC 50 ~)	675-625 air (HRC 24-31)	300-200 air

MMA **welding** – AWS electrodes

pre-heating	*annealing after w.*
300	750

joint with steel

carbon	CrMo alloyed	stainless
E70 xx	E8018-B 2	E309 – E308

cosmetic welding

E309 – E420

Transformation temperature during heating **Ac_1** ~ 785, **Ac_3** ~ 885 and during cooling **Ms** ~ 280, **Mf** ~ 130

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	**R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** a) max	a) for information only
		800 max				245	+A annealed material
	160	850-1000	650	10	15		+QT850 quenched and tempered

Testing at room temperature

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

Testing at room temperature

size mm from	to	**R** N/mm^2 max	**HB** a) max	**R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min
	10 b)	950	305	900-1050	700	7	
10	16	950	305	900-1150	650	7	
16	40	900	280	850-1100	650	9	15
40	63	840	260	850-1050	650	9	15
63	160	800	245	850-1000	650	10	15
		+A annealed material		+QT850 quenched and tempered			

a) for information only

b) in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged EN 10250-4: 2001

Testing at room temperature

size mm from	to	**R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** max	
		800 max				245	+A annealed material
	160	850-1000	650	10			+QT850 quenched and tempered

Table of tempering values at room temperature on rounds of Ø 10 mm after quenching at 1000°C in oil

R	N/mm^2	1700	1650	1630	1630	1620	1600	1350	1000	850	800
Rp 0.2	N/mm^2	1400	1380	1360	1350	1340	1300	1100	790	650	600
A	%	9	10	10	9	9	10	11	12	15	18
Kv	J	18	20	18	14	12	12	16	22	32	40
Tempering	**°C**	**200**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

Effect of **cold-working** (hot-rolled +A+C). Approximate values

R	N/mm^2	700	780	850	900	950	1000			
Rp 0.2	N/mm^2	500	620	680	720	750	780	800	880	960
A	%	20	13	12	11	11	11	10	10	10
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**

X30Cr13 **n° 1.4028** martensitic stainless steel

Thermal expansion	$10^{-6} \cdot K^{-1}$	►	10.5	11.0	11.5	12.0	12.6
Modulus of elasticity	longitudinal GPa	215	212	205	200	190	
Poisson number	*v*	0.235	0.210				
Electrical resistivity	$\Omega \cdot mm^2/m$	0.65					
Electrical conductivity	$Siemens \cdot m/mm^2$	1.54					
Specific heat	J/(Kg•K)	460					
Density	Kg/dm^3	7.70					
Thermal conductivity	W/(m•K)	30					
Relative magnetic permeability	μr	700-1000 ~					
°C		**20**	**100**	**200**	**300**	**400**	**600**

The symbol ► indicates between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** rust, diluted nitric acid, weak organic acids
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	excellent
Hardening	by quenching
Service temperature in air	continuous service up to 650 °C; intermittent service up to 750 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japane** JIS	**India** IS	**Republic of Korea** KS
X30Cr13	S42020	(**420**)	3Cr13	30Ch13	SUS 420J2	(X30Cr13)	STS 420J2

Quality	**X39Cr13**	**Martensitic Stainless Steel**	*Technical card 2014*
Number	**1.4031**		***Lucefin Group***

Chemical composition

C%	**Si%** max	**Mn%** max	**P%** max	**S%** [a] max	**Cr%**	
0,36-0,42	1,00	1,00	0,040	0,015	12,5-14,5	EN 10088-1: 2005
± 0.02	+ 0.05	+ 0.03	+ 0.005	+ 0.003	± 0.15	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %.

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**
1480-1470	1200-930	not suitable	780 slow cooling to a 630 after air

Quenching +Q	**Tempering +T**	**Stress-relieving +SR**	**Stress-relieving +SR**
pre-heating at 850, then 1025 cooling oil/air	700-650 fast cooling in air	180 air (HRC 52)	550-200 air

MMA **welding –** AWS electrodes

pre-eheating *annealing after w.*

Difficult; address qualified electrodes producers

joint with steel

carbon	CrMo alloyed	stainless
E70 xx	E8015-B 2	E309-E308

cosmetic welding

E420

Transformation temperature during heating **Ac_1** ~ 825, **Ac_3** ~ 930 and during cooling **Ms** ~ 255, **Mf** ~ 105

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** [a] max	[a] for information only
		800 max				245	+A annealed material
	160	800-1000	650	10	12		+QT800 quenched and tempered

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	to	Testing at room temperature **R** N/mm^2 max	**HB** [a] max	**R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min
	10 [b]	950	305	850-1100	700	7	
10	16	950	305	850-1100	700	7	
16	40	900	280	800-1050	650	8	12
40	63	840	260	800-1000	650	8	12
63	160	800	245	800-1000	650	10	12
		+A annealed material		+QT800 quenched and tempered material			

[a] for information only

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** [a] max	
						245	+A annealed material

[a] for information only

Table of tempering values at room temperature on rounds of Ø 10 mm after quenching at 1020 °C in oil

HB	496	482	489	504	512	442	381	336	327	286
HRC	51	50	50.5	51.5	52	47	41	36	35	30
Tempering **°C**	**200**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

X39Cr13 **n° 1.4031** martensitic stainless steel

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	10.5	11.0	11.5	12.0
Modulus of elasticity	longitudinal GPa	215	212	205	200	190
Poisson number	*v*	0,27-0,30 ~				
Electrical resistivity	$\Omega \bullet mm^2/m$	0.55				
Electrical conductivity	$Siemens \bullet m/mm^2$	1.82				
Specific heat	J/(Kg•K)	460				
Density	Kg/dm^3	7.70				
Thermal conductivity	W/(m•K)	30				
Relative magnetic permeability	µr	700-1000 ~				
°C		**20**	**100**	**200**	**300**	**400**

The symbol ► indicates between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** corrosive plastic, dilute nitric acid , weak organic acids
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	mean
Hardening	by quenching
Service temperature in air	continuous service up to 620 °C; intermittent service up to 735 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X39Cr13		(**420**)	4Cr13	(40Ch13)		(X40Cr13)	

Quality	**X46Cr13**	**Martensitic**	*Technical card* 2014
Number	**1.4034**	**Stainless Steel**	**Lucefin Group**

Chemical composition

C%	**Si%** max	**Mn%** max	**P%** max	**S%** a) max	**Cr%**	
0,43-0,50	1,00	1,00	0,040	0,015	12,5-14,5	EN 10088-1: 2005
± 0.02	+ 0.05	+ 0.03	+ 0.005	+ 0.003	± 0.15	

Product deviations are allowed

a) for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**
1480-1470	1180-930	not suitable	850-750 slow cooling to 600, then air
Quenching +Q	**Tempering +T**	**Stress-relieving +SR**	**Stress-relieving +SR** after +C
1050-950 oil / air (HRC 50 ~)	700-650 air	200 fast cooling in air	650-600 furnace cooling

MMA **welding –** AWS electrodes

pre-heating	*annealing after w.*
250-200	750

joint with steel

carbon	CrMo alloyed	stainless
E70 xx	E8016-B 2	E309-E308

cosmetic welding

E420

Transformation temperature during heating **Ac_1** ~ 805, **Ac_3** ~ 870 and during cooling **Ms** ~ 280, **Mf** ~ 130

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature					
		R	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** a)	a) for information only
from	to	N/mm^2	N/mm^2 min	min	J min	max	
		800 max				245	+A annealed material
	160	850-1000	650	10	12		+QT850 quenched and tempered

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm		Testing at room temperature					
		R	**HB** a)	**R**	**Rp** 0.2	**A%**	**Kv** +20 °C
from	to	N/mm^2 max	max	N/mm^2	N/mm^2 min	min	J min
	10 b)	950	305	900-1150	700	7	
10	16	950	305	900-1150	700	7	
16	40	900	280	850-1100	650	8	12
40	63	840	260	850-1000	650	8	12
63	160	800	245	850-1000	650	10	12
		+A annealed material		+QT850 quenched and tempered material			

a) for information only

b) in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged

size mm		Testing at room temperature					
		R	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** a)	
from	to	N/mm^2	N/mm^2 min	min	J min	max	
						245	+A annealed material

a) for information only

Table of tempering values at room temperature on rounds of Ø 10 mm after quenching at 1000°C in oil

R	N/mm^2	1800	1700	1700	1690	1680	1640	1300	1000	840	750
Rp 0.2	N/mm^2	1400	1320	1300	1300	1290	1250	1000	700	600	550
A	%	6	8	8	9	9	10	11	13	16	16
Kv	J	14	20	18	14	12	12	14	20	28	40
Tempering	**°C**	**200**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

Effect of **cold-working** (hot-rolled +A+C). Approximate values

R	N/mm^2	650	750	755	760	770	795	805	835	900	930	960
Reduction	**%**	**0**	**5**	**6**	**8**	**10**	**15**	**18**	**20**	**25**	**30**	**36**

X46Cr13 **n° 1.4034** martensitic stainless steel

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	10.5	11.0	11.5	12.0
Modulus of elasticity	longitudinal GPa	215	212	205	200	190
Poisson number	*v*	0.235				
Electrical resistivity	$\Omega \bullet mm^2/m$	0.55				
Electrical conductivity	$Siemens \bullet m/mm^2$	1.82				
Specific heat	J/(Kg•K)	460				
Density	Kg/dm^3	7.70				
Thermal conductivity	W/(m•K)	30				
Relative magnetic permeability	µr	700 ~				
°C		**20**	**100**	**200**	**300**	**400**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** rust, diluted nitric acid, weak organic acids in the passive state
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	good after annealing
Hardening	by quenching
Service temperature in air	continuous service up to 650 °C; intermittent service up to 750 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X46Cr13		(**420**)		(4Ch13)			

Quality	**1.4034 DE**	**Martensitic Stainless Steel**
Number	(1.4034)	

Chemical composition

C%	**Si%** max	**Mn%** max	**P%** max	**S%**	**Cr%**	
0,43-0,46	1,00	1,00	0,040	0,018-0.026	12,5-14,5	EN 10088-1: 2005
± 0.02	+ 0.05	+ 0.03	+ 0.005	± 0.005	± 0.15	

Product deviations are allowed
Non-metallic inclusions K3 max 50, only for oxides; DIN 50602 standard
Carbide structure max CZ 7.1; SEP 1520 standard

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**
1480-1470	1050-930	not suitable	800-750 750 slow cooling to 600, then air
Globular annealing (Spheroidized) **+AC**	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**
800 cooling furnace to 600, then air (HB max 210)	1030-980 oil / air	650-600 fast cooling in air	200 air (HRC 52)

MMA **welding –** AWS electrodes

pre-heating	*annealing after w.*
250-200	750-700

joint with steel

carbon	CrMo alloyed	stainless
E70 xx	E8016-B 2	E309-E308

cosmetic welding
E420

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot or cold

Mechanical properties (reference values: steel X46Cr13 No. 1.4034)

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** [a] max	[a] for information only
		800 max				245	+A annealed material
	160	850-1000	650	10	12		+QT850 quenching and tempering

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	to	Testing at room temperature **R** N/mm^2 max	**HB** [a] max	**R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min
	10 [b]	950	305	900-1150	700	7	
10	16	950	305	900-1150	700	7	
16	40	900	280	850-1100	650	8	12
40	63	840	260	850-1000	650	8	12
63	160	800	245	850-1000	650	10	12
		+A annealed material		+QT850 quenched and tempered			

[a] for information only
[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** [a] max	
						245	+A annealed material

[a] for information only

Table of tempering values at room temperature on rounds of Ø 10 mm after quenching at 1000°C in oil

R	N/mm^2	1800	1700	1700	1690	1680	1640	1300	1000	840	750
Rp 0.2	N/mm^2	1400	1320	1300	1300	1290	1250	1000	700	600	550
A	%	6	8	8	9	9	10	11	13	16	16
Kv	J	14	20	18	14	12	12	14	20	28	40
Tempering	**°C**	**200**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

Effect of **cold-working** (hot-rolled +A+C). Approximate values

R	N/mm^2	650	750	755	760	770	795	805	835	900	930	960
Reduction	**%**	**0**	**5**	**6**	**8**	**10**	**15**	**18**	**20**	**25**	**30**	**36**

n° 1.4034 DE martensitic stainless steel

Thermal expansion	$10^{-6} \cdot K^{-1}$	►		11.0		11.7	12.3
Modulus of elasticity	longitudinal GPa	206					
Poisson number	*v*	0.235					
Electrical resistivity	$\Omega \cdot mm^2/m$	0.60					
Electrical conductivity	$Siemens \cdot m/mm^2$	1.82					
Specific heat	$J/(Kg \cdot K)$	460					
Density	Kg/dm^3	7.70					
Thermal conductivity	$W/(m \cdot K)$	30					
Relative magnetic permeability	μr	700 ~					
°C		**20**	**100**	**200**	**300**	**400**	**600**

The symbol ► indicates temperatures between 20 °C and 200 °C, 20 °C and 400 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** plastics, weak organic acids, petroleum, gasoline
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	good
Hardening	by quenching
Service temperature in air	continuous service up to 650 °C; intermittent service up to 750 °C

Europe	**USA**	**USA**	**China**	**Russia**	**Japan**	**India**	**Republic of Korea**
EN	UNS	ASTM	GB	GOST	JIS	IS	KS

Quality	**X46CrS13**	**Martensitic Stainless Steel**
Number	**1.4035**	

Chemical composition

C%	**Si%** max	**Mn%** max	**P%** max	**S%**	**Cr%**	
0,43-0,50	1,00	2,00	0,040	0,15-0,35	12,5-14,0	EN 10088-1: 2005
± 0.02	+ 0.05	+ 0.04	+ 0.005	± 0.02	± 0.15	

Product deviations are allowed

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**	MMA **welding –** AWS electrodes *pre-heating* *annealing after w.*
1480-1460	1100-930	not suitable	850-750 slow cooling to 600, then air	not recommended
Quenching +Q		**Tempering +T**	**Stress-relieving +SR**	*joint with steel* carbon CrMo alloyed stainless
1050-950 oil / air		675-625 fast cooling in air	200 air	*cosmetic welding*

Transformation temperature during heating **Ac**$_1$ ~ 805, **Ac**$_3$ ~ 870 and during cooling **Ms** ~ 280, **Mf** ~ 130

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	 to	Testing at room temperature **R** N/mm^2	 **Rp** 0.2 N/mm^2 min	 **A%** min	 **Kv** +20 °C J min	 **HB** a) max	 a) for information only
	63	800 max				245	+A annealed material

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	 to	Testing at room temperature **R** N/mm^2 max	 **HB** a) max	 **R** N/mm^2	 **Rp** 0.2 N/mm^2 min	 **A%** min	 **Kv** +20 °C J min
	10 b)	880	280				
10	16	880	280				
16	40	800	250				
40	63	760	230				
		+A annealed material					

a) for information only

b) in the range 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged

size mm from	 to	Testing at room temperature **R** N/mm^2	 **Rp** 0.2 N/mm^2 min	 **A%** min	 **Kv** +20 °C J min	 **HB** a) max	
						245	+A annealed material

a) for information only

Table of tempering values at room temperature on rounds of Ø 10 mm after quenching at 1000 °C in oil

For information, steel 1.4034 values are quoted

R	N/mm^2	1800	1700	1700	1690	1680	1640	1300	1000	840	750
Rp 0.2	N/mm^2	1400	1320	1300	1300	1290	1250	1000	700	600	550
A	%	6	8	8	9	9	10	11	13	16	16
Kv	J	14	20	18	14	12	12	14	20	28	40
Tempering	**°C**	**200**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

Effect of **cold-working** (hot-rolled +A+C). Approximate values

R	N/mm^2	640	710	740	760	830	840	860	880	895	920
Reduction	**%**	**0**	**8**	**10**	**15**	**18**	**20**	**22**	**24**	**26**	**30**

Thermal expansion	$10^{-6} \cdot K^{-1}$	►	10.5	11.0	11.5	12.0
Modulus of elasticity	longitudinal GPa	215	212	205	200	190
Poisson number	*v*	0.235				
Electrical resistivity	$\Omega \cdot mm^2/m$	0.55				
Electrical conductivity	$Siemens \cdot m/mm^2$	1.82				
Specific heat	$J/(Kg \cdot K)$	460				
Density	Kg/dm^3	7.70				
Thermal conductivity	$W/(m \cdot K)$	30				
Relative magnetic permeability	μr	700-1000 ~				
°C		**20**	**100**	**200**	**300**	**400**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

Corrosion resistance	Atmospheric		Chemical			**x** weak acid, steam, ammonia, petroleum, organic material
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	high
Hardening	by quenching
Service temperature in air	continuous service up to 600 °C; intermittent service up to 700 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X46CrS13							

Quality	**X17CrNi16-2**	**Martensitic**	*Technical card 2014*
Number	**1.4057**	**Stainless Steel**	***Lucefin Group***

Chemical composition

C%	Si% max	Mn% max	P% max	S% [a] max	Cr%	Ni%	
0,12-0,22	1,00	1,50	0,040	0,015	15,0-17,0	1,50-2,50	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.20	± 0.07	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**
1510-1430	1200-930	not suitable	750-680 furnace cooling 10 °C/h to 600, then air
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**
not suitable	1030-980 oil / polymer / air (HRC 45 ~)	670-600 fast cooling in air	250-210 air

MMA **welding** – AWS electrodes

pre-heating	*annealing after w.*
350	750

joint with steel

carbon	CrMo alloyed	stainless
E60–E309	E8016-B 2	E309-E308

cosmetic welding
E309 special

Transformation temperature during heating **Ac1** ~ 725, **Ac3** ~ 815 and during cooling **Ms** ~ 145

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	R N/mm²	Rp 0.2 N/mm² min	A% min	Kv +20 °C J min	HB [a] max	[a] for information only
		950 max				295	+A annealed material
	60	800-950	600	14	25		+QT800 quenched and tempered material (+T 780-800 °C)
60	160	800-950	600	12	20		
	60	900-1050	700	12	20		+QT900 quenched and tempered material (+T 600-670)
60	160	900-1050	700	10	15		

Testing at room temperature

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

Testing at room temperature

size mm from	to	R N/mm² max	HB [a] max	R N/mm²	Rp 0.2 N/mm² min	A% min	Kv +20 °C J min
	10 [b]	1050	330	850-1100	750	7	
10	16	1050	330	850-1100	700	7	
16	40	1000	310	800-1050	650	9	25
40	63	850	295	800-1000	650	12	25
63	160	850	295	800-950	650	12	20
		+A annealed material		+QT800 quenched and tempered material			

[a] for information only

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm have to be agreed at the time of request and order

Forged EN 10250-4: 2001

Testing at room temperature

size mm from	to	R N/mm²	Rp 0.2 N/mm² min	A% min (L)	A% min (T)	Kv +20 °C J min (L)	Kv +20 °C J min (T)	HB max	
	250	1000 max						295	+A annealed
	250	800-950	600	10	8	20	15		+QT800 quenched and tempered
	250	900-1050	700	10	8	15	10		+QT900 quenched and tempered

Table of tempering values at room temperature on hot-rolled rounds of Ø 10 mm after quenching at 1000°C in oil

R	N/mm²	1580	1490	1460	1440	1400	1360	1250	1080	910	800
Rp 0.2	N/mm²	1290	1240	1220	1190	1130	1060	980	860	780	690
A	%	14	15	15	14	14	15	16	17	18	19
Kv	J	20	22	27	18	10	18	27	30	34	38
Tempering	**°C**	**200**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

X17CrNi16-2 n° **1.4057** martensitic stainless steel

Effect of **cold-working** (hot-rolled +QT+C). Approximate values

R	N/mm²	836	900	910	930	945	965	990	1000	1020
Rp 0.2	N/mm²	720	754	792	820	804	880	910	920	950
A	%	23	18	16	14	14	14	14	13	13
Reduction	**%**	**0**	**7**	**8**	**10**	**12**	**14**	**17**	**18**	**20**

Minimum values at high temperatures, quenched and tempered material EN 10088-3: 2005

Rp 0.2	N/mm²	515	495	475	460	440	405	355	+QT800
Rp 0.2	N/mm²	565	525	505	490	470	430	375	+QT900
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	

Thermal expansion	$10^{-6} \bullet K^{-1}$	▶	10.0	10.5	10.5	10.5		
Modulus of elasticity	longitudinal GPa	215	212	205	200	190		
Poisson number	*v*	0.144	0.138					
Electrical resistivity	Ω • mm²/m	0.70						
Electrical conductivity	Siemens•m/mm²	1.43						
Specific heat	J/(Kg•K)	460		500		590	720	860
Density	Kg/dm³	7.70						
Thermal conductivity	W/(m•K)	25						
Relative magnetic permeability	μr	700-1100 ~						
°C		**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C ....

Corrosion resistance	Atmospheric		Chemical			**x** nitric acid, alkaline water and well water
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	x	x	x			

Magnetic	yes
Machinability	good in annealed condition, mean for quenched and tempered material
Hardening	by quenching
Service temperature in air	continuous service up to 750 °C; intermittent service up to 800 °C

Europe	**USA**	**USA**	**China**	**Russia**	**Japan**	**India**	**Republic of Korea**
EN	UNS	ASTM	GB	GOST	JIS	IS	KS
X17CrNi16-2	S43100	**431**	1Cr17Ni2	14Ch17N2	SUS 431	15Cr16Ni2	STS 431

Quality	**X14CrMoS17**	**Martensitic**	*Technical card* 2014
Number	**1.4104**	**Stainless Steel**	***Lucefin Group***

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Mo%**	
	max	max	max				
0,10-0,17	1,00	1,50	0,040	0,15-0,35	15,5-17,5	0,20-0,60	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	± 0.02	± 0.2	± 0.03	

Product deviations are allowed

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**
1510-1430	1100-930	790-710 cooling to 300, then air	850-750 air
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	
not suitable	1060-980 air/oil/ /polymer	650-550 fast cooling in air	

MMA **welding –** AWS electrodes

pre-heating *annealing after w.*

difficult; address qualified electrodes producers

joint with steel

carbon	CrMo alloyed	stainless
E309	E309	E309 – E308

cosmetic welding

E309

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) + (2 - 6% $Na_2Cr_2O_7.2H_2O$) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** [a] max	[a] for information only
		730 max				220	+A annealed material
	60	650-850	500	12			+QT650 quenched and tempered
60	160	650-850	500	10			+QT650 quenched and tempered

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	to	Testing at room temperature **R** N/mm^2 max	**HB** [a] max	**R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min
	10 [b]	880	280	700-980	580	7	
10	16	880	280	700-980	530	7	
16	40	800	250	650-930	500	9	
40	63	760	230	650-880	500	10	
63	100	730	220	650-850	500	10	
		+A annealed material		+QT650 quenched and tempered			

[a] for information only

[b] in the range of $1 \text{ mm} \le d < 5 \text{ mm}$, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged (ASTM A 473-99 steel ASTM 430F)

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**C%** min	**Kv** +20 °C J min	**HB** [a] max	
		485	275	20	45		223	+A annealed material

[a] for information only

Cold-work hardened EN 10088-3: 2005 in conditions 2H (ex. +A+C)

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	
	25	550-750	440	15	+C550 cold-drawn material

Table of tempering values at room temperature on rounds of Ø 20 mm after quenching at 1000°C in oil

R	N/mm^2	880	860	860	900	920	910	880	820	660	600	580
Rp 0.2	N/mm^2	710	690	680	690	700	700	670	610	470	420	380
A	%	12	13	13	13	13	13,5	14	14	15	16	17
Tempering	**°C**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**

X14CrMoS17 **n° 1.4104** martensitic stainless steel

Effect of **cold-working** (hot-rolled +RA+C). Approximate values

R	N/mm^2	550	570	600	620	650	710	755	765	775
Rp 0.2	N/mm^2	320	440	480	490	540	620	635	640	650
A	%	22	18	16	14	13	12	10	10	9
Reduction **%**		**0**	**5**	**8**	**10**	**15**	**20**	**25**	**26**	**29**

Thermal expansion	$10^{-6} \cdot K^{-1}$	▶	10.0	10.5	10.5	10.5
Modulus of elasticity	longitudinal GPa	215	212	205	200	190
Poisson number	*v*	0,27-0,30				
Electrical resistivity	$\Omega \cdot mm^2/m$	0.70				
Electrical conductivity	Siemens•m/mm^2	1.43				
Specific heat	J/(Kg•K)	460				
Density	Kg/dm^3	7.70				
Thermal conductivity	W/(m•K)	25				
Relative magnetic permeability	μr	600-1100				
°C		**20**	**100**	**200**	**300**	**400**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** petroleum, phenol, household cleaners, food
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**		**x**			

Magnetic	yes
Machinability	high
Hardening	by quenching, cold-drawn and and other cold plastic deformations
Service temperature in air	continuous service up to 740 °C; intermittent service up to 820 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X14CrMoS17			Y10Cr17		SUS 430F		STS 430F

Quality	**X6CrMoS17**	**Ferritic**	*Technical card 2014*
Number	**1.4105**	**Stainless Steel**	***Lucefin Group***

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Mo%**	
max	max	max	max				
0,08	1,50	1,50	0,040	0,15-0,35	16,0-18,0	0,20-0,60	EN 10088-1: 2005
± 0.01	± 0.10	± 0.04	+ 0.005	± 0.02	± 0.2	± 0.03	

Product deviations are allowed

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**
1500-1490	1150-815	790-710 cooling to 300, then air	850-750 air
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Annealing** for magnetic properties
not suitable	not suitable	not suitable	825-805 protectet atmosphere cooling 50-100 °C/h to 400, then air

MMA **welding –** AWS electrodes

pre-heating *annealing after w.*

difficult; address qualified electrodes producers

joint with steel

carbon	CrMo alloyed	stainless
E309	E309	E309 – E308

cosmetic welding

E309

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) + (2 - 6% $Na_2Cr_2O_7.2H_2O$) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature					
		R	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** [a]	[a] for information only
from	to	N/mm²	N/mm² min	min	J min	max	
	100	430-630	250	20		200	+A annealed material

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm		Testing at room temperature					
		R	**HB**	**R**	**Rp** 0.2	**A%**	**Kv** +20 °C
from	to	N/mm² max	max	N/mm²	N/mm² min	min	J min
	10 [b]			530-780	330	7	
10	16			500-780	310	7	
16	40			430-730	250	12	
40	63			430-730	250	12	
63	100			430-630	250	20	
				+A materiale ricotto			

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged

size mm		Testing at room temperature					
		R	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min	J min	max	
						200	+A annealed material

[a] for information only

Effect of **cold-working** (hot-rolled +RA+C). Approximate values

R	N/mm²	570	620	690	710	740	780	800	840	880	920
Rp 0.2	N/mm²	280	510	590	620	650	690	730	760	800	850
A	%	20	10	9	9	8	8	8	8	8	8
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**75**	**80**

Minimum values at high temperatures EN 10088-3: 2005

Rp 0.2	N/mm²	230	220	215	210	205	200	195	+A annealed material
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	

X6CrMoS17 **n° 1.4105** ferritic steel

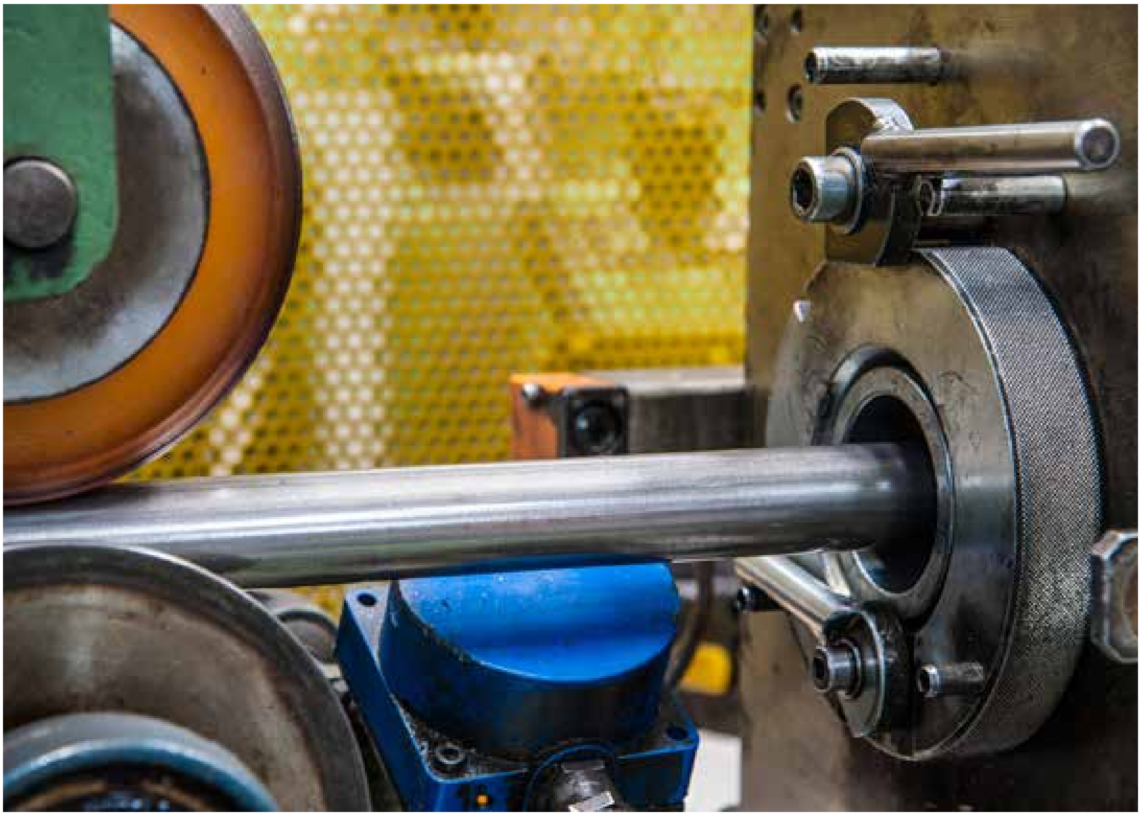
Thermal expansion	$10^{-6} \bullet K^{-1}$	►	10.0	10.5	10.5	10.5	12.0	12.6
Modulus of elasticity	longitudinal GPa	220	215	210	205	195		
Poisson number	*v*	0.27-0,30 ~						
Electrical resistivity	$\Omega \bullet mm^2/m$	0.70						
Electrical conductivity	$Siemens \bullet m/mm^2$	1.43						
Specific heat	J/(Kg•K)	460						
Density	Kg/dm^3	7.75						
Thermal conductivity	W/(m•K)	25						
Relative magnetic permeability	μr	640 ~						
°C		**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

Corrosion resistance	Atmospheric		Chemical			**x** steam, food and dairy food, organic products, nitric acid
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**		**x**			

Magnetic	yes
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 810 °C; intermittent service up to 860 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X6CrMoS17	43020	**430F**					



Quality	**X2CrMoSiS18-2-1**	Free machining **Ferritic Stainless Steel**	*Technical card 2014*
Number	**1.4106 MOD**		***Lucefin Group***

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Mo%**	**N%**	
max			max				max	AFNOR FD A 35-570: 1996
0,03	1,25-1,50	0,30-0,60	0,040	0,25-0,30	17,5-18,5	1,50-2,00	0,04	

Temperature °C

Melting range	**Pre-heating**	**Hot-forming**	**Recrystallization +RA**	MMA **welding –** AWS electrodes *pre-heating* *annealing after w.*
1490-1480	870-815 pause, then ▲	▲ 1150-1050	810-700 cooling to 300, then air	not recommended
Soft annealing +A	**Quenching +Q**	**Tempering +T**	**Annealing** for magnetic properties	*joint with steel* carbon CrMo alloyed stainless
820-750 air	not suitable	not suitable	860-850 protected atmosphere cooling 55 °C/h to 420, then air	*cosmetic welding*

Normally the atmosphere of the furnace for annealing magnetic has a dew point -60 ° C. Curie temperature 660 °C

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot or cold. *Passivation* 20 - 25% HNO_3 hot

Mechanical properties

Hot-rolled (ASTM A 582 582M-05 steel XM-34)

size		Testing at room temperature					
mm		**R**	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** [a]	[a] for information only
from	to	N/mm^2	N/mm^2 min	min	J min	max	
						262	+A annealed material

Thermal expansion	$10^{-6} \bullet K^{-1}$	▶	12.0
Modulus of elasticity [b]	longitudinal GPa	225	
Poisson number	*v*	0,27-0,30~	
Electrical resistivity	$\Omega \bullet mm^2/m$	0.76	
Electrical conductivity	$Siemens \bullet m/mm^2$	1.31	
Specific heat	$J/(Kg \bullet K)$	500 ~	
Density	Kg/dm^3	7.75	
Thermal conductivity	$W/(m \bullet K)$	15	
Relative magnetic permeability	µr	1200 ~	
°C		**20**	**100**

The symbol ▶ indicates temperatures between 20 °C and 100 °C

[b] cold deformations result in a lower modulus of elastucity; it may be increased by stress relief heat treatment

Corrosion resistance	Atmospheric		Chemical			**x** environment with acids and chlorides
Fresh water	*industrial*	*marine*	*mild*	*oxidizing*	*reducing*	
x	**x**					

Magnetic	yes
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 740 °C

Europe	**USA**	**USA**	**China**	**Russia**	**Japan**	**India**	**Republic of Korea**
EN	UNS	ASTM	GB	GOST	JIS	IS	KS

Quality	**X90CrMoV18**	**Martensitic Stainless Steel**	*Technical card 2014*
Number	**1.4112**		***Lucefin Group***

Chemical composition

C%	Si% max	Mn% max	P% max	S% [a] max	Cr%	Mo%	V%	
0,85-0,95	1,00	1,00	0,040	0,015	17,0-19,0	0,90-1,30	0,07-0,12	EN 10088-1: 2005
± 0.03	+ 0.05	+ 0.03	+ 0.005	+ 0.003	± 0.2	± 0.05	± 0.03	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Full annealing**	**Soft annealing +A**
1440-1420	1175-930	910-890 cooling 15 °C/h to 590, then air	840-780 slow cooling
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**
900-840 controlled cooling to 690, then air	1050-1000 oil / polymer (HRC 58)	550-450 air	350-100 air

MMA **welding –** AWS electrodes

pre-heating	*annealing after w.*
200-150	750-700

joint with steel

carbon	CrMo alloyed	stainless
E70 xx	E8018-B 2	E309 – E308

cosmetic welding

E309 special

Transformation temperature during heating **Ac_1** ~ 790, **Ac_3** ~ 870 and during cooling **Ms** ~ 280, **Mf** ~ 130

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot. *Passivation* (20 - 25% HNO_3) + (2.5% $Na_2Cr_2O_7.2H_2O$) hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	R N/mm²	Rp 0.2 N/mm² min	A% min	Kv +20 °C J min	HB [a] max	[a] for information only
	100					265	+A **annealed** material

Bars, typical values according to UNS S44003 steel 440B

size mm from	to	R N/mm² min	Rp 0.2 N/mm² min	A% min	C% min	HB max	R N/mm² min	Rp 0.2 N/mm² min	A% min	C% min	HB max
		738	427	18	35	269	827	655	9	20	285
		+A **hot-rolled** annealed					+A+C **cold-drawn**				

Forged (ASTM A 473-99 steel ASTM 440B)

size mm from	to	R N/mm²	Rp 0.2 N/mm² min	A% min	Kv +20 °C J min	HB [a] max	
						269	+A **annealed** material

[a] Only for guidance

Table of tempering values at room temperature after quenching at 1020 °C in oil

HB	595	560	543	525	525	371	311	279
HRC	57	55	54	53	53	40	33	29
Tempering **°C**	**100**	**200**	**300**	**400**	**500**	**600**	**650**	**700**

X90CrMoV18 **n° 1.4112** martensitic stainless steel

Thermal expansion	$10^{-6} \cdot K^{-1}$	►	10.4	10.8	11.2	11.6	11.9
Modulus of elasticity	longitudinal GPa	215	212	205	200	190	
Poisson number	v	0,27-0,30 ~					
Electrical resistivity	$\Omega \cdot mm^2/m$	0.80					
Electrical conductivity	$Siemens \cdot m/mm^2$	1.25					
Specific heat	$J/(Kg \cdot K)$	430					
Density	Kg/dm^3	7.70					
Thermal conductivity	$W/(m \cdot K)$	15.0					
Relative magnetic permeability	μr	700-1000 ~					
°C		**20**	**100**	**200**	**300**	**400**	**600**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

Corrosion resistance	Atmospheric		Chemical			**x** steam, petroleum, gasoline, alcohol, food, fruit juices
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	difficult
Hardening	by quenching
Service temperature in air	max 300 °C for cold plastic deformations and 760 °C for hot-formed products

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X90CrMoV18	S44003	**440B**	90Cr18MoV		SUS 440B		STS 440B

Quality	**X50CrMoV15**	**Martensitic**	*Technical card 2014*
Number	**1.4116**	**Stainless Steel**	***Lucefin Group***

Chemical composition

C%	**Si%** max	**Mn%** max	**P%** max	**S%** [a] max	**Cr%**	**Mo%**	**V%**	
0,45-0,55	1,00	1,00	0,040	0,015	14,0-15,0	0,50-0,80	0,10-0,20	EN 10088-1: 2005
± 0.02	+ 0.05	+ 0.03	+ 0.005	+ 0.003	± 0.15	± 0.05	± 0.03	

Product deviations are allowed

[a] for improing machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Full annealing**	**Soft annealing +A**
1480-1460	1100-930	930-870 furnace	850-750 slow cooling
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**
910-890 controlled cooling to 750, then air	1030-980 oil / polymer (HRC 55)	500-400 air	250-150 air

MMA **welding –** AWS electrodes

pre-heating	*annealing after w.*	
260	760-740	
joint with steel		
carbon	CrMo alloyed	stainless
E70 xx	E8018-B 2	E309 – E308
cosmetic welding		
E309		

Transformation temperature during heating **Ac**$_1$ ~ 880, **Ac**$_3$ ~ 920 and during cooling **Ms** ~ 280, **Mf** ~ 120

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot. *Passivation* (20 - 25% HNO_3) + (2.5% $Na_2Cr_2O_7.2H_2O$) hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	**R** N/mm^2	**Rp** 0.2 N/mm^2	**A%** min	**Kv** +20 °C J min	**HB** [a] max	[a] for information only
		900 max				280	+A annealed material

Testing at room temperature

Table of tempering values at room temperature after quenching at 990 °C in oil

HB	543	518	512	518	512	525	496	381	301
HRC	54	52,5	52	52.5	52	53	51	41	32
Tempering **°C**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	10.5	11.0	11.0	11.5
Modulus of elasticity	longitudinal GPa	215	212	205	200	190
Poisson number	v	0,27-0,30				
Electrical resistivity	$\Omega \bullet mm^2/m$	0.65				
Electrical conductivity	Siemens•m/mm^2	1.54				
Specific heat	J/(Kg•K)	460				
Density	Kg/dm^3	7.70				
Thermal conductivity	W/(m•K)	30				
Relative magnetic permeability	μ_r	700 ~				
°C		**20**	**100**	**200**	**300**	**400**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** steam, petroleum, gasoline, alcohol, ammonia, organic material
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x			**x**			

Magnetic	yes
Machinability	mean
Hardening	by quenching
Service temperature in air	up to 760 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X50CrMoV15			(7Cr17)	50Ch14MF	(SUS 440A)		

Quality	**X39CrMo17-1**	**Martensitic**
Number	**1.4122**	**Stainless Steel**

Chemical composition

C%	Si% max	Mn% max	P% max	S% [a]	Cr%	Mo%	Ni% max	
0,33-0,45	1,00	1,50	0,040	0,015	15,5-17,5	0,80-1,30	1,00	EN 10088-1: 2005
± 0.02	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.05	± 0.03	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Recrystallization +RA**	**Soft annealing +A**
1480-1465	1100-930	not suitable	850-750 air
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	
not suitable	1060-980 air / oil / polymer (HRC 48)	750-650 air	

MMA **welding –** AWS electrodes

pre-heating *annealing after w.*

Difficult; address qualified electrodes producers

joint with steel

carbon	CrMo alloyed	stainless
E309	E309	E309 – E308

cosmetic welding

E309

Transformation temperature during heating **Ac_1** ~ 810, **Ac_3** ~ 900 and during cooling **Ms** ~ 280, **Mf** ~ 130

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** [a] max	[a] for information only
		900 max				280	+A annealed material
	60	750-950	550	12	20		+QT750 quenched and tempered
60	160	750-950	550	12	14		+QT750 quenched and tempered

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	to	Testing at room temperature **R** N/mm^2 max	**HB** [a] max	**R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min
	10 [b]	1000	340	800-1050	650	8	
10	16	1000	340	800-1050	600	8	
16	40	980	310	800-1000	550	10	20
40	63	930	290	750-950	550	12	20
63	100	900	280	750-950	550	12	14
		+A annealed material		+QT750 quenched and tempered			

[a] for information only

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

Forged

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	**Kv** +20 °C J min	**HB** [a] max	
						280	+A annealed material

[a] for information only

Table of tempering values at room temperature on rounds of Ø 20 mm after quenching at 1050°C in oil

HB	455	432	432	432	442	442	421	400	319
HRC	48	46	46	46	47	47	45	43	34
Tempering **°C**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**

Minimum values at high temperatures on +QT750 material EN 10088-3: 2005

Rp 0.2 N/mm^2	540	535	530	520	510	490	470
Test at **°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**

X39CrMo17-1 **n° 1.4122** martensitic stainless steel

Thermal expansion	$10^{-6} \bullet K^{-1}$	▶	10.4	10.8	11.2	11.6
Modulus of elasticity	longitudinal GPa	215	212	205	200	190
Poisson number	*v*	0,27-0,30 ~				
Electrical resistivity	$\Omega \bullet mm^2/m$	0.80				
Electrical conductivity	$Siemens \bullet m/mm^2$	1.25				
Specific heat	J/(Kg•K)	430				
Density	Kg/dm^3	7.70				
Thermal conductivity	W/(m•K)	15				
Relative magnetic permeability	µr	700-1000 ~				
°C		**20**	**100**	**200**	**300**	**400**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C ....

Corrosion resistance	Atmospheric		Chemical			**x** organic and nitric acids
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	low
Hardening	by quenching
Service temperature in air	good resistance to oxidation and heat up to 500 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X39CrMo17-1				40Ch16M			

Quality	**X105CrMo17**	**Martensitic Stainless Steel**	*Technical card* 2014
Number	**1.4125**		**Lucefin Group**

Chemical composition

C%	**Si%** max	**Mn%** max	**P%** max	**S%** [a] max	**Cr%**	**Mo%**	
0,95-1,20	1,00	1,00	0,040	0,015	16,0-18,0	0,40-0,80	EN 10088-1: 2005
± 0.03	+ 0.05	+ 0.03	+ 0.005	+ 0.003	± 0.2	± 0.05	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Full annealing**	**Soft annealing +A**
1440-1410	1100-930	900-845 furnace cooling to 590 after air	840-780 air (HB max 285)
Isothermal annealing +I	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**
900-840 controlled cooling to 690, then air (HB 243-253)	1050-1000 air / oil / polymer (HRC 60)	425-180 air	300-100 air

MMA **welding –** AWS electrodes

pre-heating *annealing after w.*

Difficult; address qualified electrodes producers

joint with steel

carbon	CrMo alloyed	stainless
E309	E309	E309 – E308

cosmetic welding

E309 special

Transformation temperature during heating **Ac_1** ~ 780, **Ac_3** ~ 835 and during cooling **Ms** ~ 180, **Mf** ~ 30

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) hot. *Passivation* (20 - 25% HNO_3) + (2.5% $Na_2Cr_2O_7.2H_2O$) hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature					
		R	**Rp** 0.2	**A%**	**Kv** +20 °C	**HB** [a]	[a] for information only
from	to	N/mm^2	N/mm^2 min	min	J min	max	
	100					285	+A annealed material

Bars, typical values according to UNS S44004 steel 440C

size mm		Testing at room temperature									
		R	**Rp** 0.2	**A%**	**C%**	**HB**	**R**	**Rp** 0.2	**A%**	**C%**	**HB**
from	to	N/mm^2 min	N/mm^2 min	min	min	max	N/mm^2 min	N/mm^2 min	min	min	max
		758	448	14	25	269	862	689	7	20	285
		+A **hot-rolled** annealed					+A+C **cold-drawn**				

Forged (ASTM A 473-99 steel ASTM 440C)

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**C%**	**Kv** +20 °C	**HB** [a]	
from	to	N/mm^2	N/mm^2 min	min	min	J min	max	
							269	+A annealed material

[a] for information only

Table of tempering values at room temperature on rounds of Ø 16 mm after quenching at 1020 °C in oil

HB	654	634	595	595	595	615	615	432	381
HRC	60	59	57	57	57	58	58	46	41
Tempering **°C**	**100**	**200**	**300**	**350**	**400**	**450**	**500**	**550**	**600**

X105CrMo17 **n° 1.4125** martensitic stainless steel

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	10.4	10.8	11.2	11.6	12.0
Modulus of elasticity	longitudinal GPa	215	212	205	200	190	
Poisson number	*v*	0,283					
Electrical resistivity	$\Omega \bullet mm^2/m$	0.80					
Electrical conductivity	$Siemens \bullet m/mm^2$	1.25					
Specific heat	J/(Kg•K)	430					
Density	Kg/dm^3	7.70					
Thermal conductivity	W/(m•K)	15					
Relative magnetic permeability	μr	700-1000 ~					
°C		**20**	**100**	**200**	**300**	**400**	**500**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

Corrosion resistance	Atmospheric		Chemical			**x** steam, petroleum, ammonia, gasoline, alcohol, foods
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x						

Magnetic	yes
Machinability	difficult
Hardening	by quenching
Service temperature in air	Resistance to oxidation up to 700 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X105CrMo17	S44004	**440C**	108Cr17	95Ch18	SUS 440C	(X108Cr17Mo)	STS 440C

Quality	**X5CrNi18-10**	**Austenitic Stainless Steel**	*Technical card* 2014
Number	**1.4301**		**Lucefin Group**

Chemical composition

C%	Si%	Mn%	P%	S% [a]	Cr%	Ni%	N%	
max	max	max	max	max			max	
0,07	1,00	2,00	0,045	0,015	17,5-19,5	8,0-10,5	0,11	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.1	± 0.01	

Product deviations are allowed

[a] for machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1460-1400	1800-950	1120-1000 water	not necessary	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**	
not recommended	not suitable	not suitable	430-350 air	

MMA **Welding -** electrodes AWS

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E308

cosmetic welding
E308 – E308L

Chemical treatment ▪ *Pickling* (6 - 25% HNO$_3$) + (0.5 - 8% HF) hot ▪ *Passivation* 20 - 50% HNO$_3$ hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size		Testing at room temperature							
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	max	
	160	500-700	190	45		100		215	+AT solubilization
160	250	500-700	190		35		60	215	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	
	10 [b]	600-950	400	25				+AT solubilization
10	16	600-950	400	25				
16	40	600-850	190	30		100		
40	63	580-850	190	30		100		
63	160	500-700	190	45		100		
160	250	500-700	190		35		60	

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

(L) = longitudinal (T) = transversal

Forged +AT solubilization EN 10250-4: 2001

size		Testing at room temperature							
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C	
over	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	J min (T)	
	250	500-700	190		35	100	60		EN 10250-4
	250	500-700	200	45	35	100	60	60	EN 10222-5

Work-hardened by cold-drawing EN 10088-3: 2005 in condition 2H (ex. +AT+C)

size		Testing at room temperature			
mm		**R**	**Rp** 0.2	**A%**	
from	to	N/mm²	N/mm² min	min	
	35	700-850	350	20	+AT+C700 cold-drawn material
	25	800-1000	500	12	+AT+C800 cold-drawn material

Transition curve determined by Kv impacts. Material solubilized at 1050 °C

Average	J	210	210	210	212	218	228	244
Test at	**°C**	**-160**	**-120**	**-80**	**-40**	**0**	**+40**	**+80**

+AT material – approximate values

°C	R	Rp 0.2	A%
	N/mm²	N/mm²	%
+24	520	210	45
-80	860	270	35
-196	1250	350	30
-254	1680	440	30

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	560	715	830	1000	1110	1240	1400	1500	1600
Rp 0.2	N/mm^2	300	490	600	860	1000	1100	1210	1350	1400
A	%	38	20	12	10	10	10	10	8	8
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**75**

Minimum yield stress and tensile strength values at high temperatures on +AT material, EN 10088-3: 2005 / EN 10269: 2001

Rp 0.2	N/mm^2	155	140	127	118	110	104	98	95	92	90
R	N/mm^2	450	420	400	390	380	380	375	360	335	300
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

Thermal expansion	$10^{-6} \bullet K^{-1}$		13.4	13.8	14.8	►	16.0	16.5	17.0	17.5	18.8	20.2
Modulus of elasticity	longitudinal GPa	180				200	194	186	179	172		127
Poisson number	*v*					0.24	0.256					
Electrical resistivity	$\Omega \bullet mm^2/m$	0.55			0.64	0.73		0.86		1.00	1.11	1.21
Electrical conductivity	$Siemens \bullet m/mm^2$					1.37						
Specific heat	$J/(Kg \bullet K)$					500		510		550	585	630
Density	Kg/dm^3					7.93						
Thermal conductivity	$W/(m \bullet K)$					15.0	16.3	17.5	19.9	21.5		25.1
Relative magnetic permeability	μr					1.021						
°C		**-196**	**-184**	**-128**	**-74**	**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ► indicates between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** nitric acid, weak organic acids, rural and urban atmospheres
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**		**x**	**x**		

Magnetic	not
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X5CrNi18-10	S30400	(304)	0Cr18Ni9	07Ch18N10		X04Cr19Ni9	

Quality	**X8CrNiS18-9**	**Austenitic Stainless Steel**
Number	**1.4305**	

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Ni%**	**N%**	**Cu%**	
max	max	max	max				max	max	
0,10	1,00	2,00	0,045	0,15-0,35	17,0-19,0	8,0-10,0	0,11	1,00	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	± 0.02	± 0.2	± 0.1	± 0.01	± 0.07	

Product deviations are allowed

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**
1420-1400	1200-900	1150-1040 water / air	not necessary
Sensitization	**Quenching +Q**	**Tempering +T**	**Soft annealing +A**
sensitization test at 800-450	not suitable	not suitable	not suitable

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not recommended	

joint with steel

carbon	CrMo alloyed	stainless
butter E309 - E312, finish with E308	the same as carbon steels	E308 - E312

cosmetic welding
E308 – E312

Chemical treatment ▪ *Pickling* (20 - 50% HNO_3) + (2 - 6% $Na_2Cr_2O_7.2H_2O$) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	**HB** [a] max	
	160	500-750	190	35				230	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	
	10 [b]	600-950	400	15				+AT solubilization
10	16	600-950	400	15				
16	40	600-850	190	20		100		
40	63	500-850	190	20		100		
63	160	500-750	190	35		100		

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order
(L) = longitudinal (T) = transversal

Forged (ASTM A 473-99 steel ASTM 303)

size mm from	to	Testing at room temperature **R** N/mm^2 min	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**C%** min (L)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	
		515	205	40	50			+AT solubilization

Work-hardned by cold-drawing EN 10088-3: 2005 in condition 2H (ex. +AT+C)

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	
	35	700-850	350	20	+AT+C700 cold-drawn material
	25	800-1000	500	12	+AT+C800 cold-drawn material

Transition curve determined by Kv impacts. Material solubilized at 1050 °C

Average	J	212	222	230	238	244	250	258
Test at	**°C**	**-160**	**-120**	**-80**	**-40**	**0**	**+40**	**+80**

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	610	800	1000	1200	1320	1480	1600	1750
Rp 0.2	N/mm^2	240	550	740	880	1020	1200	1320	1450
A	%	40	20	16	10	8	8	8	6
permeability	μr	1.005	1.06	1.64	3.44				
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

X8CrNiS18-9 **n° 1.4305** austenitic stainless steel

Thermal expansion	$10^{-6} \bullet K^{-1}$	▶	16.0	16.5	17.0	17.5		
Modulus of elasticity	longitudinal GPa	200	194	186	179	172		127
Poisson number	*v*	0.24	0.256					
Electrical resistivity	$\Omega \bullet mm^2/m$	0.73		0.86		0.97		1.15
Electrical conductivity	$Siemens \bullet m/mm^2$	1.37						
Specific heat	$J/(Kg \bullet K)$	500		510		550	585	630
Density	Kg/dm^3	7.84						
Thermal conductivity	$W/(m \bullet K)$	15.3	16.3	17.5	19.9	21.5		25.1
Relative magnetic permeability	μr	1.021						
°C		**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ▶ indicates temperatures between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** food and organic substances, 5% nitric acid
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**			

Magnetic	not
Machinability	high
Hardening	cold-drawn and other cold plastic deformation
Service temperature in air	continuous service up to 870 °C; intermittent service up to 760 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X8CrNiS18-9	S30300	**303**	Y1Cr18Ni9	12Ch18N10E	SUS 303		STS 303

Quality	**X2CrNi19-11**	**Austenitic Stainless Steel**
Number	**1.4306**	

Chemical composition

C% max	**Si%** max	**Mn%** max	**P%** max	**S%** [a] max	**Cr%**	**Ni%**	**N%** max	
0,03	1,00	2,00	0,045	0,030	18,0-20,0	10,0-12,0	0,11	EN 10088-1: 2005
+ 0.005	+ 0.05	± 0.04	+ 0.005	+ 0.005	± 0.2	± 0.15	± 0.01	

Product deviations are allowed

[a] for machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015%

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1450-1400	1200-930	1100-1050 water	885 calm air	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**	
not suitable	not suitable	not suitable	450-230	

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E308

cosmetic welding
E308 L

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot ▪ *Passivation* 20 - 50% HNO_3 hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	Testing at room temperature **R** N/mm²	**Rp** 0.2 N/mm² min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	**HB** [a] max	
	160	460-680	180	45		100		215	+AT solubilization
160	250	460-680	180		35		60	215	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	to	Testing at room temperature **R** N/mm²	**Rp** 0.2 N/mm² min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	
	10 [b]	600-930	400	25				
10	16	600-930	380	25				+AT solubilization
16	40	460-830	180	30		100		
40	63	460-830	180	30		100		
63	160	460-680	180	45		100		
160	250	460-680	180		35		60	

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

(L) = longitudinal (T) = transversal

Forged EN 10250-4: 2001

size mm from	to	Testing at room temperature **R** N/mm²	**Rp** 0.2 N/mm² min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	
	250	460-680	180		35	100	60	+AT solubilization

Work-hardned by cold-drawing EN 10088-3: 2005 in condition 2H (es. +AT+C)

size mm from	to	Testing at room temperature **R** N/mm²	**Rp** 0.2 N/mm² min	**A%** min	
	35	700-850	350	20	+AT+C700 cold-drawn material
	25	800-1000	500	12	+AT+C800 cold-drawn material

Approximate mechanical properties at low temperatures. Material solubilized at 1050 °C

R	N/mm²	1450	1300	1000	600
Rp 0.2	N/mm²	350	320	320	290
A	%	40	45	50	55
Test at	**°C**	**-254**	**-196**	**-100**	**0**

X2CrNi19-11 **n° 1.4306** austenitic stainless steel

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm²	600	780	880	1000	1080	1150	1220	1350
Rp 0.2	N/mm²	300	440	600	720	820	960	1040	1180
A	%	60	40	20	14	12	12	12	12
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

Minimum values at high temperatures on material +AT, EN 10088-3: 2005 solubilized

Rp 0.2	N/mm²	145	130	118	108	100	94	89	85	81	80
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

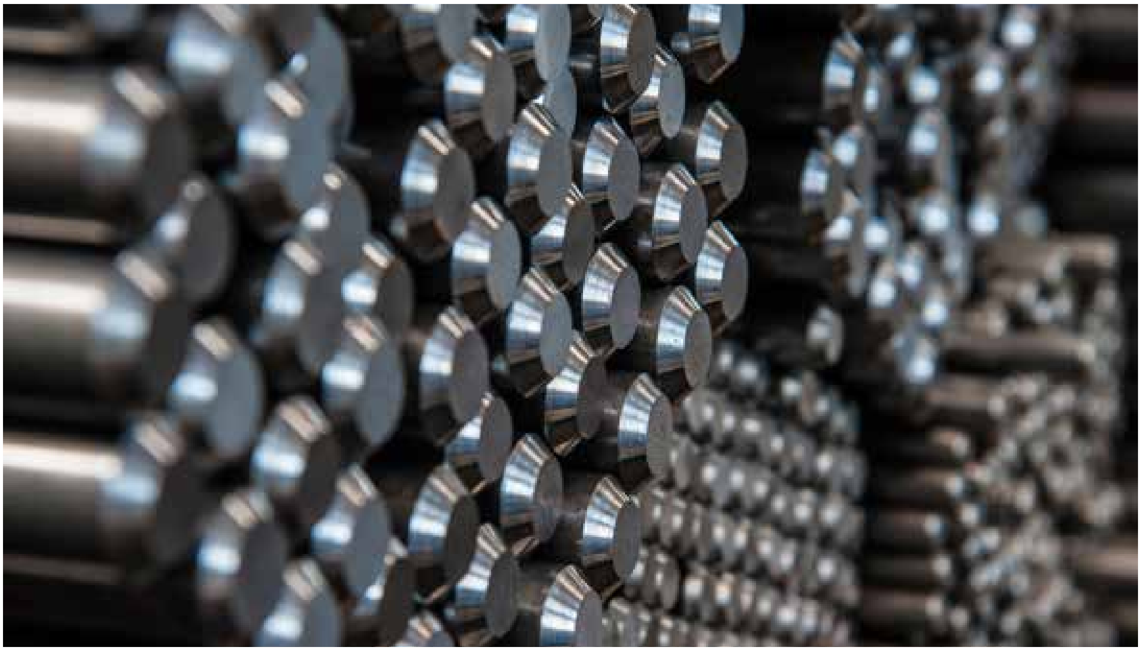
Thermal expansion	$10^{-6} \bullet K^{-1}$		▶	16.0	16.5	17.0	17.5	18.0
Modulus of elasticity	long. GPa		200	194	186	179	172	165
Poisson number	v	0.30	0.30	0.30	0.31	0.31	0.32	0.32
Electrical resistivity	$\Omega \bullet mm^2/m$		0.73					
Electrical conductivity	$Siemens \bullet m/mm^2$		1.37					
Specific heat	$J/(Kg \bullet K)$		500					
Density	Kg/dm^3		7.90					
Thermal conductivity	$W/(m \bullet K)$		15.0					
Relative magnetic permeability	$\mu_{r\ max}$	~ 2	1.02					
°C		**-196**	**20**	**100**	**200**	**300**	**400**	**500**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

Corrosion resistance	Atmospheric		Chemical			**x** intercrystalline corrosion, foods, colouring and organic substances
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	x		x	x	x	

Magnetic	no
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X2CrNi19-11	S30403	(304L)	022Cr19Ni10	(03Ch18N11)		X02CrNi19-10	



Quality	**X2CrNi18-9**	**Austenitic Stainless Steel**
Number	**1.4307**	

Chemical composition

C%	Si%	Mn%	P%	S% [a]	Cr%	Ni%	N%	
max	max	max	max	max			max	
0,03	1,00	2,00	0,045	0,015	17,5-19,5	8,0-10,5	0,11	EN 10088-1: 2005
+ 0.005	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.1	± 0.01	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1460-1400	1200-930	1120-1000 water	not necessary	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**		
sensitization test at 700-450	not suitable	not suitable		

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E308

cosmetic welding
E308 L

Chemical treatment ▪ *Pickling* (10% HNO_3) + (2% HF) at 60° or cold ▪ *Passivation* 20 - 50% HNO_3 cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature							
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a]	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	max	
	160	500-700	175	45		100		215	+AT solubilization
160	250	500-700	175		35		60	215	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	
	10 [b]	600-930	400	25				+AT solubilization
10	16	600-930	380	25				
16	40	500-830	175	30		100		
40	63	500-830	175	30		100		
63	160	500-700	175	45		100		
160	250	500-700	175		35		60	

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

(L) = longitudinal (T) = transversal

Forged +AT solubilization

size mm		Testing at room temperature							
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	J min (T)	
	250	460-680	180		35	100	60		EN 10250-4: 2001
	250	500-700	200	45	35	100	60	60	EN 10222-5: 2001

Work-hardned by cold-drawing EN 10088-3: 2005 condition 2H (es. +AT+C)

size mm		Testing at room temperature			
		R	**Rp** 0.2	**A%**	
from	to	N/mm^2	N/mm^2 min	min	
	35	700-850	350	20	+AT+C700 cold-drawn material
	25	800-1000	500	12	+AT+C800 cold-drawn material

Transition curve determined by Kv impacts. Material solubilized at 1050 °C

Average	J	230	230	232	236	245	268	290
Test at	**°C**	**-160**	**-120**	**-80**	**-40**	**0**	**+40**	**+80**

+AT material - approximate values

°C	R	Rp 0.2	A%
	N/mm^2	N/mm^2	%
+24	550	200	45
-80	830	220	35
-196	1200	300	30

X2CrNi18-9 **n° 1.4307** austenitic stainless steel

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	650	850	1000	1100	1190	1280	1380	1500	1570
Rp 0.2	N/mm^2	300	400	650	790	950	1120	1270	1370	1420
A	%	45	38	32	25	20	18	12	10	8
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**75**

Minimum yield stress and tensile strength values at high temperatures on material +AT, EN 10088-3: 2005 / EN 10269: 2001

Rp 0.2	N/mm^2	145	130	118	108	100	94	89	85	81	80
R	N/mm^2	410	380	360	350	340	340	330			
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	16.0	16.5	17.0	18.0	18.0	
Modulus of elasticity	long. GPa	200	194	186	179	172		127
Poisson number	*v*	0.28						
Electrical resistivity	$\Omega \bullet mm^2/m$	0.72		0.86		1.00	1.11	1.21
Electrical conductivity	Siemens•m/mm^2	1.37						
Specific heat	J/(Kg•K)	500		503		520	541	559
Density	Kg/dm^3	7.90						
Thermal conductivity	W/(m•K)	15.0	16.3	17.2	18.7	20.2		25.8
Relative magnetic permeability	μr_{max}	1.021						
°C		**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** intercrystalline corrosion, rural and urban atmospheres
Fresh water	*industrial*	*marine*	*mild*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**	**x**	

Magnetic	no
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X2CrNi18-9	S30403	(304L)	00Cr19Ni10	03Ch18N11		X02Cr18Ni11	

Quality	**X10CrNi18-8**	**Austenitic Stainless Steel**	*Technical card 2014*
Number	**1.4310**		***Lucefin Group***

Chemical composition

C%	Si% max	Mn% max	P% max	S% max	Cr%	Mo% max	Ni%	N% max	
0,05-0,15	2,00	2,00	0,045	0,015	16,0-19,0	0,80	6,0-9,5	0,11	EN 10088-1: 2005
± 0.01	± 0.10	± 0.10	+ 0.005	+ 0.003	± 0.2	± 0.05	± 0.1	± 0.01	

Product deviations are allowed

Temperatur °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1435-1400	1250-1150	1120-1000 water	not necessary	not suitable

Sensitization	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**
avoid slow heating in the range of 420 and 800	not suitable	not suitable	400-250

MMA **welding -** AWSelectrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E308

cosmetic welding
E308

Chemical treatment ▪ *Pickling* 20 - 50% HNO_3 hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size		Testing at room temperature							
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	max	
	40	500-750	195	40				230	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal

Hot-formed (hot-rolled) ASTM A 276-04

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**C%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm² min	N/mm² min	min (L)	min (L)	J min (L)	J min (T)	
all		515	205	40	50			+AT solubilization

Forged +AT solubilization ASTM A 473-99

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**C%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C
from	to	N/mm² min	N/mm² min	min (L)	min (L)	J min (L)	J min (T)	J min (T)
		517	207	40	50			

Work-hardned EN 10088-3: 2005 in condition 2H (ex. +AT+C)

size		Testing at room temperature			
mm		**R**	**Rp** 0.2	**A%**	
from	to	N/mm²	N/mm² min	min	
	20	800-1000	500	12	+AT+C800 cold-drawn material

Transition curve determined by Kv impacts. Material solubilized at 1050 °C

Average	J	210	220	230	240	245	250	255
Test at	**°C**	**-200**	**-150**	**-100**	**-50**	**0**	**+50**	**+100**

Approximate mechanical properties at low temperatures. Material solubilized at 1050 °C

R	N/mm²	660	1100	1570	1900
Rp 0.2	N/mm²	145	350	550	860
A	%	50	40	30	20
Test at	**°C**	**+24**	**-74**	**-196**	**-253**

After cold forming, a stress relieving treatment at 280-420 °C, can increase the value of tensile strength of about 250 N/mm². This heat treatment also increases the fatigue limit

X10CrNi18-8 **n° 1.4310** austenitic stainless steel

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	620	820	1000	1200	1320	1440	1620	1780
Rp 0.2	N/mm^2	300	580	730	880	1020	1180	1300	1460
A	%	46	22	14	10	9	9	9	9
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

Minimum yield stress values at high temperatures on hot-rolled material +AT EN 10088-3: 2005

Rp 0.2	N/mm^2	210	200	190	185	180
Test at	**°C**	**100**	**150**	**200**	**250**	**300**

Thermal expansion	$10^{-6} \cdot K^{-1}$		►	16.0	17.0	17.0	18.0	18.0	
Mod. of elasticity [b]	long. GPa	186	200	194	186	179	172	165	
Poisson number	v		0.28						
Electrical resistivity	$\Omega \cdot mm^2/m$		0.72	0.78	0.86		1.00		1.11
Electrical conductivity	Siemens•m/mm^2		1.39	1.28	1.16		1.00		0.90
Specific heat	J/(Kg•K)		500						
Density	Kg/dm^3		8.027						
Thermal conductivity	W/(m•K)		15.0	16.3				21.5	
Relative magnetic permeability	$\mu_{r\ max}$		1.02 [a]						
°C		**-196**	**20**	**100**	**200**	**300**	**400**	**500**	**600**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C ….. [a] solubilized material

[b] cold deformations result in a lower modulus; it may be increased by stress-relief heat treatment

Corrosion resistance	Atmospheric		Chemical			**x** foods, organic acids, urban atmosphere, petroleum
Fresh water	*industrial*	*marine*	*mild*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	no
Machinability	difficult
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	max 400 °C for cold plastic deformations and 780 °C for hot-formed products

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X10CrNi18-8	S30100	**301**	1Cr17Ni7	07Ch16N6	SUS 302	X07Cr18Ni9	STS 302

Quality	**X2CrNiN18-10**	**Austenitic** **Stainless Steel**	*Technical card rev. 2014* ***Lucefin Group***
Number	**1.4311**		

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%** [a)]	**Cr%**	**Ni%**	**N%**	
max	max	max	max	max				
0,03	1,00	2,00	0,045	0,015	17,5-19,5	8,5-11,5	0,12-0,22	EN 10088-1: 2005
+ 0.005	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.1	± 0.02	

Product deviations are allowed

[a)] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Soft** annealing +A
1460-1400	1200-950	1120-1000 water	not suitable
Stress relieving +SR	**Quenching +Q**	**Tempering +T**	**Stabilizzazione**
450-230 furnace	not suitable	not suitable	not necessary

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloy.	stainless
E309-E308	E309-E308	E308

cosmetic welding
E308 L

Chemical treatment ▪ *Pickling* (15 - 25% HNO_3) + (1 - 8% HF) hot or cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature							
		R	**$Rp_{0.2}$**	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a)]	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	max	
	160	550-760	270	40		100		230	+AT
160	250	550-760	270		30		60	230	solubilization

[a)] for information only (L) = longitudinal (T) = transversal

Flat products EN 10028-7: 2007 +AT solubilized material

thickness mm		Testing at room temperature						
		R	**$Rp_{0.2}$**	**A_{80}** (tr)	**A_5** (tr)	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C
from	to	N/mm^2	N/mm^2 min	% min t < 3	% min t > 3	J min (l)	J min (tr)	J min (tr)
	8	550-750	290	40	40			
	13,5	550-750	270	40	40	100	60	60
	75	550-750	270	40	40	100	60	60

C = cold rolled strip; H = hot rolled strip; P = hot rolled plate
(tr) = transversal; (l) = longitudinal

Forged +AT solubilized material

size mm		Testing at room temperature							
		R	**$Rp_{0.2}$**	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	J min (T)	
	250	550-760	270		30	100	60		EN 10250-4
	250	550-750	270	45	35	100	60	60	EN 10222-5

Hot rolled ASTM A 479 +AT condition

size mm		Testing at room temperature			
		R	**$Rp_{0.2}$**	**A%**	**C%**
from	to	N/mm^2 min	N/mm^2 min	min	min
	all	515	205	30	40

Transition curve determined by Kv impacts. Material solubilized at 1050 °C

Average	J	62	85	180	200	232	236	245	270	290
Test at	°C	**-253**	**-196**	**-160**	**-120**	**-80**	**-40**	**0**	**+40**	**+80**

EN 10028-7: 2007 +AT condition

°C	R	$Rp_{0.2}$	A
	N/mm²	N/mm²	%
+ 20	550	270	40
-80	850	350	40
-150	1050	450	35
-196	1250	550	35

X2CrNiN18-10 n° **1.4311** austenitic

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm²	620	800	950	1080	1180	1280	1390	1520	1580
Rp 0.2	N/mm²	250	440	630	810	970	1120	1230	1380	1480
A	%	46	38	30	24	18	16	14	9	6
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**

Mnimum yield stress and tensile strength values at high temperatures on material +AT,EN 10088-3: 2005 / EN 10222-5: 2001

Rp 0.2	N/mm²	205	175	157	145	136	130	125	121	119	118
R	N/mm²	490	460	430	420	410	410				
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

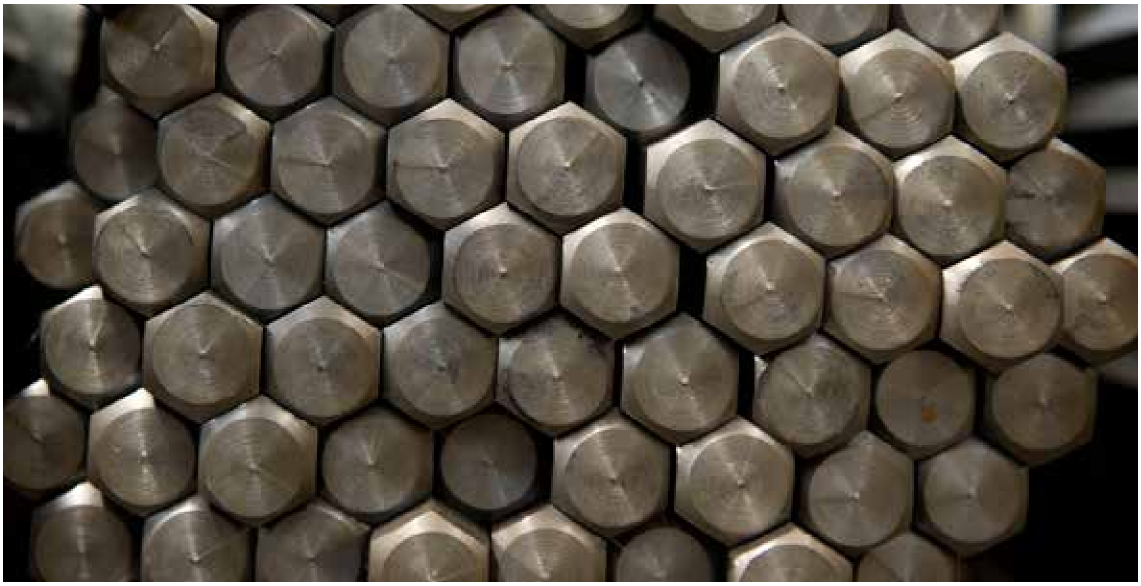
Thermal expansion	$10^{-6} \cdot K^{-1}$	▶	16.0	16.5	17.0	17.5	18.0	
Modulus of elasticity	longitudinal GPa	200	194	186	179	172	165	
Modulus of elasticity	tangential GPa	77	75	71	68	65	62	
Poisson number	*v*	0.30						
Electrical resistivity	$\Omega \cdot mm^2/m$	0.73	0.78	0.86	0.91	1.00	1.02	1.11
Electrical conduc.	Siemens•m/mm²	1.37						
Specific heat	J/(Kg•K)	500	500	520	530	540	540	
Density	Kg/dm³	7.90						
Thermal conductivity	W/(m•K)	15.0	16.0	17.5	19.0	20.5	22.0	
Relative magnetic permeability	μr_{max}	1.02						
°C		**20**	**100**	**200**	**300**	**400**	**500**	**600**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

Corrosion resistance	Atmospheric		Chemical			**x** intergranular,
Fresh water	*industrial*	*marine*	*mild*	*oxidizing*	*reducing*	petrochemical, foods,
x	**x**	**x**	**x**	**x**		textile, dyeing

Magnetic	no
Machinability	good
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X2CrNiN18-10	S30453	304LN	00Cr18Ni10N		SUS 304LN		STS 304LN



Quality	**X2CrNiN23-4**	**Austenitic-Ferritic Stainless Steel** (Duplex)	*Technical card 2014*
Number	**1.4362**		***Lucefin Group***

Chemical composition

C% max	**Si%** max	**Mn%** max	**P%** max	**S%** max	**Cr%**	**Ni%**	**N%**	**Cu%**	**Mo%**	
0,03	1,00	2,00	0,035	0,015	22,0-24,0	3,5-5,5	0,05-0,20	0,10-0,60	0,10-0,60	EN 10088-1: 2005
+ 0.005	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.25	± 0.07	± 0.02	± 0.07	± 0.03	

Product deviations are allowed

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1480-1460	1150-1000	1100-1020 water	not required	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR** short stay	**Recrystallization +RA**
not suitable	not suitable	not suitable	600-550 air	1050-950 quick cooling

MMA **welding –** AWS electrodes

preheating	*post welding*	
not necessary	solubilization	
oint with steel		
carbon	CrMo alloyed	stainless
E2209	E309L	E309LMo

cosmetic welding
AWS A 5.9

Chemical treatment ▪ *Pickling* (52% HNO_3) + (65% HF) hot ▪ *Passivation* 20 - 45% HNO_3 cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size		Testing at room temperature							
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** -40 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min [b] (L)	max	
	160	600-830	400	25		100	40	260	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal [b] EN 10272 : 2003

Forged +AT solubilization EN 10250-4: 2001

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	J min (T)
	160	600-830	400	25	20	100	60	

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm²	740	780	830	880	910	950
Rp 0.2	N/mm²	520	690	720	800	840	870
A	%	40	38	34	28	25	16
Reduction	**%**	**0**	**5**	**10**	**15**	**20**	**30**

Minimum yield stress and tensile strength values at high temperatures on material +AT EN 10028-7: 2007

Rp 0.2	N/mm²	374 [a]	330	300	280	265
R	N/mm²	577 [a]	540	520	500	490
Test at	**°C**	**50**	**100**	**150**	**200**	**250**

[a] determined by linear interpolatio

X2CrNiN23-4 **nr° 1.4362** austenitic-ferritic stainless steel (Duplex)

Thermal expansion	$10^{-6} \bullet K^{-1}$	▶	13.0	13.5	14.0
Modulus of elasticity	longitudinal GPa	200	194	186	180
Poisson number	*v*	0.33			
Electrical resistivity	$\Omega \bullet mm^2/m$	0.80			
Electrical conductivity	$Siemens \bullet m/mm^2$	1.25			
Specific heat	J/(Kg•K)	482			
Density	Kg/dm^3	7.75			
Thermal conductivity	W/(m•K)	15.0			
Relative magnetic permeability	μ_r	magnetizable			
°C		**20**	**100**	**200**	**300**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** intercrystalline, stress corrosion, pitting
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	yes
Machinability	difficult
Hardening	cold-drawn and other cold plastic deformations
Service temperature	do not protractedly expose to temperatures over 300 ° C; results in a reducing in impact strength

Europe	**USA**	**USA**	**China**	**Russia**	**Japan**	**India**	**R. Corea**
EN	UNS	ASTM	GB	GOST	JIS	IS	KS

Quality	**X5CrNiMo17-12-2**	**Austenitic Stainless Steel**	*Technical card* 2014
Number	**1.4401**		**Lucefin Group**

Chemical composition

C%	Si%	Mn%	P%	S% [a]	Cr%	Ni%	N%	Mo%	
max	max	max	max	max			max		
0,07	1,00	2,00	0,045	0,015	16,5-18,5	10,0-13,0	0,11	2,0-2,5	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.15	± 0.01	± 0.1	

Product deviation are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1400-1380	1200-900	1100-1050 water	unnecessary	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**	**Stress relieving +SR**	
sensitization test at 800-450	not suitable	not suitable	400 furnace	

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E308

cosmetic welding

E 316 or E 16-8-2

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot ▪ *Passivation* 20 - 50% HNO_3 hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size		Testing at room temperature							
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a]	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	max	
	160	500-700	200	40		100		215	+AT
160	250	500-700	200		30		60	215	solubilization

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	
	10 [b]	600-950	400	25				
10	16	580-950	380	25				+AT
16	40	500-850	200	30		100		solubilization
40	63	500-850	200	30		100		
63	160	500-700	200	40		100		
160	250	500-700	200		30		60	

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

(L) = longitudinal (T) = transversal

Forged +AT solubilization

size		Testing at room temperature							
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	J min (T)	
	250	500-700	200		30	100	60		EN 10250-4
	250	510-710	205	45	35	100	60	60	EN 10222-5

Work-hardned by cold-drawing EN 10088-3: 2005 in condition 2H (es. +AT+C)

size		Testing at room temperature			
mm		**R**	**Rp** 0.2	**A%**	
from	to	N/mm^2	N/mm^2 min	min	
	35	700-850	350	20	+AT+C700 cold-drawn material
	25	800-1000	500	12	+AT+C800 cold-drawn material

Transition curve determined by Kv impacts. Material solubilized at 1050 °C

Average	J	198	206	218	225	238	245	250
Test at	**°C**	**-160**	**-120**	**-80**	**-40**	**0**	**+40**	**+80**

Approximate mechanical properties at low temperatures. Material solubilized at 1080 °C

R	N/mm^2	580	820	1270	1440
Rp 0.2	N/mm^2	245	330	520	580
A	%	55	50	45	40
Test at	**°C**	**+24**	**-74**	**-196**	**-254**

X5CrNiMo17-12-2 **n° 1.4401** austenitic stainless steel

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	550	660	800	1000	1110	1220	1320	1430
Rp 0.2	N/mm^2	260	510	640	790	840	920	1020	1120
A	%	50	22	14	13	10	8	8	8
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

Minimum yield stress and tensile strength values at high temperatures on material +AT, EN 10088-3: 2005/EN 10269: 2001

Rp 0.2	N/mm^2	175	158	145	135	127	120	115	112	110	108
R	N/mm^2	460	440	420	415	410	410	410	405	390	375
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

Thermal expansion	$10^{-6} \bullet K^{-1}$	12.8	13.3	14.1	▶	16.0	16.5	17.0	17.5	18.8	20.2
Modulus of elasticity	longitudinal GPa				200	194	186	179	172		127
Poisson number	*v*				0.256	0.280					
Electrical resistivity	$\Omega \bullet mm^2/m$	0.58		0.66	0.75		0.86		0.97	1.07	1.15
Electrical conductivity	$Siemens \bullet m/mm^2$				1.33						
Specific heat	J/(Kg•K)				500		510		550	585	630
Density	Kg/dm^3				7.98						
Thermal conductivity	W/(m•K)				15.0		17.5	19.9			25.1
Relative magnetic permeability	μ_r				1.02						
°C		**-184**	**-128**	**-74**	**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ▶ indicates between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** halides, sulfuric acid, phosphoric, organic and formic acids
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**	**x**	

Magnetic	no
Machinability	low
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe	**USA**	**USA**	**China**	**Russia**	**Japan**	**India**	**Rep. of Korea**
EN	UNS	ASTM	GB	GOST	JIS	IS	KS
X5CrNiMo17-12-2	S31600	**316**	0Cr17Ni12Mo2	08Ch17N13M2	SUS 316	X04Cr17Ni12Mo2	STS 316

Quality	**X2CrNiMo17-12-2**	**Austenitic Stainless Steel**	*Technical card 2014*
Number	**1.4404**		***Lucefin Group***

Chemical composition

C% max	**Si%** max	**Mn%** max	**P%** max	**S%** [a] max	**Cr%**	**Ni%**	**N%** max	**Mo%**	
0,03	1,00	2,00	0,045	0,015	16,5-18,5	10,0-13,0	0,11	2,0-2,5	EN 10088-1: 2005
± 0.005	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.15	± 0.01	± 0.1	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1400-1380	1200-925	1110-1040 water	885 calm air	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**		
sensitization test at 700-450	not suitable	not suitable		

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E308

cosmetic welding
E 316L

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot ▪ *Passivation* 20 - 50% HNO_3 hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	**HB** [a] max	
	160	500-700	200	40		100		215	+AT solubilization
160	250	500-700	200		30		60	215	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	
	10 [b]	600-930	400	25				+AT solubilization
10	16	580-930	380	25				
16	40	500-830	200	30		100		
40	63	500-830	200	30		100		
63	160	500-700	200	40		100		
160	250	500-700	200		30		60	

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order
(L) = longitudinal (T) = transversal

Forged +AT solubilization

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	**Kv** -196 °C J min (T)	
	250	500-700	200		30	100	60		EN 10250-4
	250	490-690	190	45	35	100	60	60	EN 10222-5

Work-hardened by cold-drawing EN 10088-3: 2005 in condition 2H (es. +AT+C)

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	
	35	700-850	350	20	+AT+C700 cold-drawn material
	25	800-1000	500	12	+AT+C800 cold-drawn material

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	500	650	790	850	940	1030	1100	1200
Rp 0.2	N/mm^2	200	520	700	760	830	920	1000	1080
A	%	55	30	14	12	10	9	8	8
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

+AT material – Approximate values

°C	R N/mm^2	Rp 0.2 N/mm^2	A %
+24	520	220	45
-80	840	275	40
-196	1200	350	35

X2CrNiMo17-12-2 **n° 1.4404** austenitic stainless steel

Minimum yield stress and tensile strength values at high temperatures on material +AT, EN 10088-3: 2005/EN 10269: 2001

Rp 0.2	N/mm²	165	150	137	127	119	113	108	103	100	99
R	N/mm²	430	410	390	385	380	380	380	375	360	335
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

Thermal expansion	$10^{-6} \bullet K^{-1}$	▶	16.0	16.5	17.0	17.5		
Modulus of elasticity	longitudinal GPa	200	194	186	179	172		127
Poisson number	v	0.256	0.280					
Electrical resistivity	$\Omega \bullet mm^2/m$	0.75						
Electrical conductivity	$Siemens \bullet m/mm^2$	1.33						
Specific heat	J/(Kg•K)	500						
Density	Kg/dm^3	8.00						
Thermal conductivity	W/(m•K)	15.0						
Relative magnetic permeability	μr	1.02						
Temperature	**°C**	**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** intercrystalline c. pitting from chlorides, salts, organic acids
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**	**x**	

Magnetic	no
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**R. Corea** KS
X2CrNiMo17-12-2	S31603	**316L**	022Cr17Ni12Mo2	03Ch17N13M2	SUS 316L	X02Cr17Ni12Mo2	STS 316L

Quality	**X2CrNiMo18-14-3**	**Austenitic Stainless Steel**	*Technical card 2014*
Number	**1.4435**		***Lucefin Group***

Chemical composition

C%	Si%	Mn%	P%	S% [a]	Cr%	Ni%	N%	Mo%	
max	max	max	max	max			max		
0,03	1,00	2,00	0,045	0,015	17,0-19,0	12,5-15,0	0,11	2,5-3,0	EN 10088-1: 2005
± 0.005	+ 0.05	± 0.04	+ 0.005	± 0.005	± 0.2	± 0.15	± 0.01	± 0.1	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1450-1400	1150-980	1180-1120 water	not required	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**		
not required	not suitable	not suitable		

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E308

cosmetic welding

E 316L

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot ▪ *Passivation* 20 - 50% HNO_3 hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size		Testing at room temperature							
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a]	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	max	
	160	500-700	200	40		100		215	+AT solubilization
160	250	500-700	200		30		60	215	+AT solubilization
		660	*320*	*55*		*210*		*200*	*Typical values*

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	
	10 [b]	600-950	400	25				+AT solubilization
10	16	600-950	400	25				
16	40	500-850	235	30		100		
40	63	500-850	235	30		100		
63	160	500-700	235	40		100		
160	250	500-700	235		30		60	

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

(L) = longitudinal (T) = transversal

Forged EN 10250-4: 2001

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm^2	N/mm^2 min	min (L)	min ((T)	J min (L)	J min (T)	
	250	500-700	200		30	100	60	+AT solubilization

Transition curve determined by Kv impacts. Material solubilized at 1050 °C

Average	J	190	210	215	220	230	240	250
Test at	**°C**	**-160**	**-120**	**-80**	**-40**	**0**	**+40**	**+80**

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	640	780	900	1050	1180	1280	1350	1400
Rp 0.2	N/mm^2	320	640	800	910	1000	1080	1120	1190
A	%	50	30	18	12	8	8	8	7
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

Minimum values at high temperatures on material +AT

Rp 0.2	N/mm²	165	150	137	127	119	113	108	103	100	98
R	N/mm²	420	400	380	375	370	370				
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	16.0	16.5	17.0	17.5	18.0	
Modulus of elasticity	GPa	200	194	186	179	172	165	
Poisson number	*v*	0.28						
Electrical resistivity	Ω • mm²/m	0.75						
Electrical conductivity	Siemens•m/mm²	1.33						
Specific heat	J/(Kg•K)	500						
Density	Kg/dm³	8.00						
Thermal conductivity	W/(m•K)	15.0						
Relative magnetic permeability	μr	1.1 ~						
°C		**20**	**100**	**200**	**300**	**400**	**500**	

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

Corrosion resistance	Atmospheric		Chemical			**x** intergranular, food, acids (organic, sulfuric and phosphoric acids), oil
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	no
Machinability	mean
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**R. Corea** KS
X2CrNiMo18-14-2	(S31603)	(**316L**)	00Cr18Ni15Mo3	03Ch17N14M3	(SUS 316L)	(X02Cr17Ni12Mo2)	(STS 316L)

Quality	**X2CrNiMoN22-5-3**	**Austenitic-Ferritic**
Number	**1.4462** [a]	**Stainless Steel** (Duplex)

Chemical composition

C%	Si%	Mn%	P%	S%	Cr%	Ni%	N%	Mo%	
max	max	max	max	max					
0,03	1,00	2,00	0,035	0,015	21,0-23,0	4,5-6,5	0,10-0,22	2,5-3,5	EN 10088-1: 2005
± 0.005	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.25	± 0.10	± 0.02	± 0.10	

Product deviations are allowed

[a] subject to agreement, this steel grade can be delivered with a Pitting Resistance Equivalent n° (PRE = Cr +3,3Mo + 16N) higher than 34

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1440-1390	1150-950	1100-1020 water	not suitable	not suitable
Embrittlement	**Carbides precipitation**	**Sigma phase formation**	**Stress-relieving +SR** short stay	**Recrystallization +RA**
475	800-450	950-700	600-550 air	1100-1020 quick cooling

MMA **welding –** AWS electrodes

pre-heating	*post welding*
100	solubilization

joint with steel

carbon	CrMo alloyed	stainless
E309L-16	E309MoL-15	E317L

cosmetic welding
E 2209-17

Chemical treatment ▪ *Pickling* (52% HNO_3) + (65% HF) hot ▪ *Passivation* 20 - 45% HNO_3 cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature							
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** -40 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min [b] (L)	J min (L)	max	
	160	650-880	450	25		40	40	270	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal [b] EN 10272 : 2003

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	
	10 [b]	850-1150	650	12				+AT solubilization
10	16	850-1100	650	12				
16	40	650-1000	450	15		100		
40	63	650-1000	450	15		100		
63	160	650-880	450	25		100		

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order
(L) = longitudinal (T) = transversal

Forged +AT solubilization EN 10250-4: 2001

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C
from	to	N/mm²	N/mm² min	min (L)	min ((T)	J min (L)	J min (T)	J min (T)
	350	650-880	450	25	20	100	60	

Cold-hardened EN 10263-5: 2003

size mm		Testing at room temperature					
		R	**Z%**		**R**	**Z%**	
from	to	N/mm²	min		N/mm²	min	
5	10	1020 max		+AT+C	900 max	55	+AT+C+AT
10	25	1000 max		+AT+C	880 max	55	+AT+C+AT

Effect of **coldworking** (hot-rolled +AT+C). Approximate values

R	N/mm²	750	850	1000	1120	1210	1300	1340	1370	1370
Rp 0.2	N/mm²	560	800	960	1080	1160	1270	1280	1330	1350
A	%	34	23	13	8	6	5	4,5	3	2
Riduzione	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**

After cold deformation with a reduction higher than 10%, it i recommended solution annealing

X2CrNiMoN22-5-3 **n° 1.4462** austenitic-ferritic stainless steel (Duplex)

Minimum yield stress and tensile strength values at high temperatures on material +AT EN 10028-7: 2007

Rp 0.2	N/mm^2	422 [a)]	360	335	315	300
R	N/mm^2	621 [a)]	590	570	550	540
Test at	**°C**	**50**	**100**	**150**	**200**	**250**

[a)] determined by linear interpolation

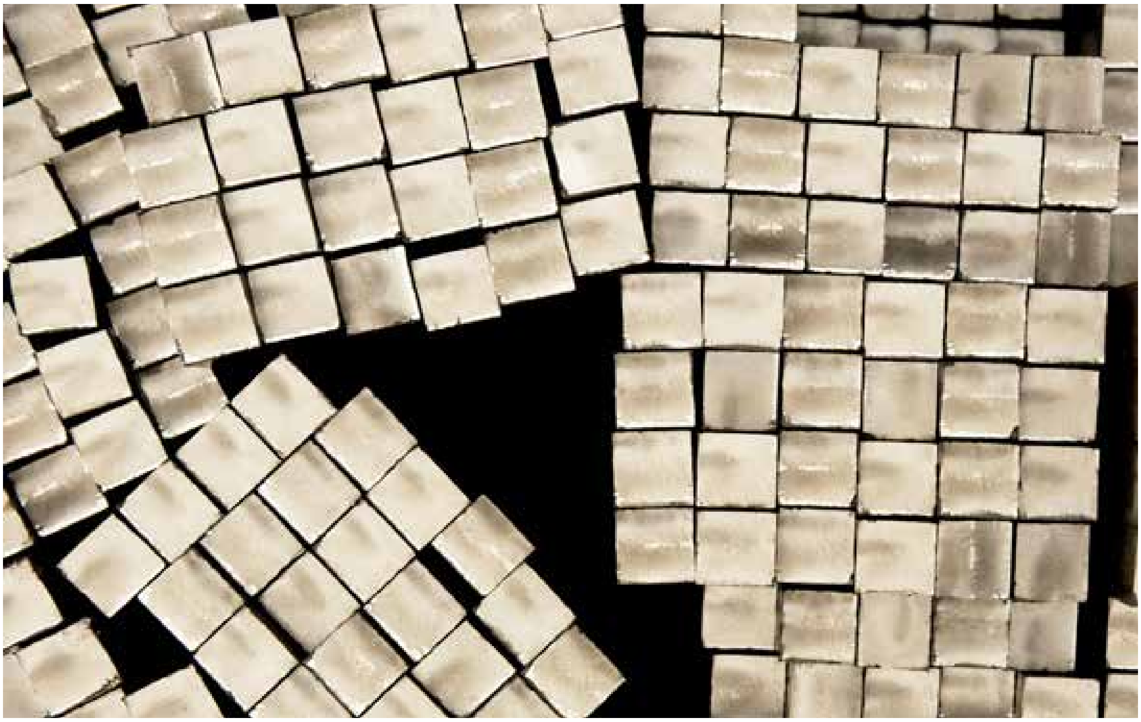
Thermal expansion	$10^{-6} \bullet K^{-1}$	►	13.0	13.5	14.0
Modulus of elasticity	longitudinal GPa	200	194	186	180
Poisson number	*v*	0.25			
Electrical resistivity	$\Omega \bullet mm^2/m$	0.80	0.85	0.90	1.00
Electrical conductivity	Siemens•m/mm^2	1.25			
Specific heat	J/(Kg•K)	500	530	560	590
Density	Kg/dm^3	7.8			
Thermal conductivity	W/(m•K)	15.0	16.0	17.0	18.0
Relative magnetic permeability	μr	magnetizable			
°C		**20**	**100**	**200**	**300**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** intercrystalline, pitting, crevice, stress corrosion cracking
Brackish water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	yes
Machinability	difficult
Hardening	cold-drawn and other cold plastic deformations
Service temperature	in pressure vessels, up to -200 °C; do not use over +340 °C. Ossidazione in aria 1000 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**R. Corea** KS
X2CrNiMoN22-5-3	S31803	Type 2205	022Cr22Ni5Mo3N	02Ch22N5AM2	(SUS 329J3L)		(STS 329J3L)



Quality	**X2CrNiMoCuWN25-7-4**	**Austenitic-Ferritic** **Stainless Steel** (Superduplex)	*Technical card* 2014 ***Lucefin Group***
Number	**1.4501**		

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Ni%**	**N%**	**Mo%**	**Cu%**	**W%**	
max	max	max	max	max							EN 10088-1: 2005
0,03	1,00	1,00	0,035	0,015	24,0-26,0	6,0-8,0	0,20-0,30	3,0-4,0	0,5-1,0	0,5-1,0	
± 0.005	+ 0.05	+ 0.03	+ 0.005	+ 0.003	± 0.25	± 0.10	± 0.02	± 0.10	± 0.07	± 0.05	

Product deviations are allowed.
PRE (Cr+3,3Mo+16N) > 40 (Pitting Resistance Equivalent)

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1480-1440	1250-1100	1120-1050 water	not suitable	not suitable
Embrittlement	**Carbides precipitation**	**Sigma phase formation**	**Stress-relieving +SR**	**Recrystallizat. +RA**
-50 +300	950-600	1000-600	not suitable	not suitable

MMA **welding –** AWS electrodes

pre-heating	*post welding*

not recommended

oint with steel

carbon	CrMo alloyed	stainless

cosmetic welding

Chemical treatment ▪ *Pickling* (52% HNO_3) + (65% HF) hot ▪ *Passivation* 20 - 45% HNO_3 cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature								
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -40 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	J min [b] (L)	max	
	160	730-930	530	25		100		40	290	+AT
	75 [c]	730-930	530	25	25	100	60			solubilizat.

[a] for information only. [b] EN 10272 : 2003. [c] EN 10088-2 : 2005. (L) = longitudinal (T) = trasversal

Cold-work

1.4501 steel can be adequately cold formed by various processes (cold-dreawn, cold-reduced, deep-drawn). It is recommended that any cold work in excess of 10% - 20% is removed by solution annealing and water quenching. It should be noted that cold working above these limits can result in hardness levels above those specified in standards such as ISO 15156 / NACE MR0175.

Forged +AT solubilization EN 10250-4: 2001

size mm		Testing at room temperature					
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C
from	to	N/mm²	N/mm² min	min (L)	min ((T)	J min (L)	J min (T)
	160	730-930	530	25	20	100	60

Typical values at high temperature, hot-formed flats +AT (Rolled Alloys US data sheet)

Test temperature		thickness up to 30 mm.		thickness 31 to 70 mm	
		R	**Rp** 0.2	**R**	**Rp** 0.2
°C	°F	N/mm²	N/mm²	N/mm²	N/mm²
20	68	780	580	750	550
50	122	725	500	700	470
100	212	700	470	670	430
150	302	680	450	620	400
200	392	670	430	610	380
250	482	650	400	600	370
300	572	635	385	590	360

X2CrNiMoCuWN25-7-4 **n° 1.4501** Superduplex

Minimum yield stress and tensile strength values at high temperatures on material +AT EN 10028-7: 2007

Rp 0.2	N/mm²	500 [a]	450	420	400	380
R	N/mm²	711 [a]	680	660	640	630
Prova a	**°C**	**50**	**100**	**150**	**200**	**250**

[a] determined by linear interpolation

Thermal expansion	$10^{-6} \bullet K^{-1}$		►	13.0	13.5	14.0
Modulus of elasticity	longitudinal	GPa	200	194	186	180
Poisson number	*v*		0.32			
Electrical resistivity	$\Omega \bullet mm^2/m$		0.80	0.89	0.95	1.01
Electrical conductiv.	Siemens•m/mm²		1.25			
Specific heat	J/(Kg•K)		500		523	547
Density	Kg/dm³		7.8			
Thermal conductivity		W/(m•K)	15.0		16.3	18.2
Relative magnetic permeability		μr	29			
°C			**20**	**100**	**200**	**300**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** erosion, pitting, crevice,
Brackish water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	organic and inorganic a.
x	**x**	**x**	**x**			stress corrosion cracking

Magnetic	yes
Machinability	a higher wear rate of the tools than that of austenitic steels
Hardening	cold-drawn and other cold plastic deformations
Service temperature	not recommended for uses to temperatures greater than +300 °C and lower -50 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**R. Corea** KS
X2CrNiMoCuWN25-7-4	S32760	Type F 55	022Cr25Ni7Mo3WCuN		SM25Cr		

Quality	**X6CrNiTi18-10**	**Austenitic Stainless Steel**
Number	**1.4541**	

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%** [a]	**Cr%**	**Ni%**	**Ti%**	
max	max	max	max	max			max	
0,08	1,00	2,00	0,045	0,015	17,0-19,0	9,0-12,0	> 5 x C < 0,70	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.1	± 0.05	

Product deviations are allowed

[a] for improving machinability, it is suggested a controlled sulphur content of 0,015 % - 0,030 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1430-1400	1200-1000	1120-1010 water	900-840 calm air	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**		
not suitable	not suitable	not suitable		

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E308-E347

cosmetic welding
E347

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot or cold. *Passivation* 20 - 45% HNO_3 cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature							
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	max	
	160	500-700	190	40		100		215	+AT
160	250	500-700	190		30		60	215	solubilization

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	
	10 [b]	600-950	400	25				
10	16	580-950	380	25				+AT solubilization
16	40	500-850	190	30		100		
40	63	500-850	190	30		100		
63	160	500-700	190	40		100		

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order
(L) = longitudinal (T) = transversal

Forged +AT solubilization

size mm		Testing at room temperature							
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	J min (T)	
	450	500-700	190		30	100	60		EN 10250-4
	450	510-710	200	40	30	100	60	60	EN 10222-5

Work-hardned by cold-drawing EN 10088-3: 2005 in condition 2H (es. +AT+C)

size mm		Testing at room temperature			
		R	**Rp** 0.2	**A%**	
from	to	N/mm²	N/mm² min	min	
	35	700-850	350	20	+AT+C700 cold-drawn material
	25	800-1000	500	12	+AT+C800 cold-drawn material

Transition curve determined by Kv impacts. Material solubilized at 1050 °C

Average	J	230	240	240	250	250	260	260
Test at	**°C**	**-160**	**-120**	**-80**	**-40**	**0**	**+40**	**+80**

+AT material – Approximate values

°C	R	Rp 0.2	A
	N/mm²	N/mm²	%
+24	500	200	401
-80	855	300	35
-196	1440	380	30
-254	1645	630	20

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	600	710	850	1000	1120	1240	1360	1500	1600
Rp 0.2	N/mm^2	280	600	760	880	990	1100	1200	1330	1390
A	%	38	20	9	8	8	8	8	8	8
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**75**

Minimum values at high temperatures on material +AT, EN 10088-3: 2005

Rp 0.2	N/mm^2	175	165	155	145	136	130	125	121	119	118
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

Thermal expansion	$10^{-6} \bullet K^{-1}$	▶	16.0	16.5	17.0	17.5	18.0
Modulus of elasticity	longitudinal GPa	200	194	186	179	172	165
Poisson number	*v*	0.30	0.30	0.31		0.32	
Electrical resistivity	$\Omega \bullet mm^2/m$	0.73					
Electrical conductivity	$Siemens \bullet m/mm^2$	1.37					
Specific heat	J/(Kg•K)	500					
Density	Kg/dm^3	7,90					
Thermal conductivity	W/(m•K)	15.0					
Relative magnetic permeability	µr	1.02					
°C		**20**	**100**	**200**	**300**	**400**	**500**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** intergranular corrosion, industrial furnace
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	no
Machinability	low on cold-work hardened material
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 750 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**R. Corea** KS
X6CrNiTi18-10	S32100	**321**	0Cr18Ni11Ti	06Ch18N10T	SUS 321	X04Cr18Ni10Ti	STS 321

Quality	**X5CrNiCuNb16-4**	**Precipitation hardening Stainless Steel**
Number	**1.4542** (17-4 PH)	

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%** a)	**Cr%**	**Ni%**	**Cu%**	**Nb%**	
max	max	max	max	max					
0,07	0,70	1,50	0,040	0,015	15,0-17,0	3,0-5,0	3,0-5,0	5 x C < 0,70	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.07	± 0.10	± 0.05	

Product deviations are allowed

[a] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C. Recommended atmospheres protected with argon or helium, avoiding the nitrogen.

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Precipitation hardening +P**	
1440-1400	1175-1095	1060-1030 oil, air (HB max 360)	+P800 760 air + 620 air	
Stress-relieving +SR	**Mill annealing**		+P930 620 air	+P960 590 air
660-600 furnace	1050-1020 air, oil under Mf (HB max 229)		+P1070 550 air	+P1300 480 oil

MMA **welding –** AWS electrodes

pre-heating	*annealing after w.*
100-200	aging

oint with steel

carbon	CrMoalloyed	stainless
E308L	ER630	E630-16

cosmetic welding
E630-16

Transformation temperature during heating $\mathbf{Ac_1}$ ~627, $\mathbf{Ac_3}$ ~ 704 and during cooling **Ms** ~ 130, **Mf** ~ 30

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot or cold. *Passivation* 20 - 25%HNO_3 hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature							
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** a)	heat treatment
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	max	condition
	100	1200 max						360	+AT
	100	800-950	520	18		75			+P800
	100	930-1100	720	16		40			+P930
	100	960-1160	790	12					+P960
	100	1070-1270	1000	10					+P1070

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	heat treatment
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	condition
	10 b)	900-1100	600	10				+P800
10	16	900-1100	600	10				
16	40	800-1050	520	12		75		
40	63	800-1000	520	18		75		
63	160	800-950	520	18		75		
	100	930-1100	720	12		40		+P930
	100	960-1160	790	10				+P960
	100	1070-1270	1000	10				+P1070

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order (L) = longitudinal (T) = transversal

Forged EN 10250-4: 2001 solubilized and precipitation hardening material

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	heat treatment
from	to	N/mm^2 min	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	condition
	250	930	720	15	12	40	30	+P930
	250	1070	1000	12	10	20	15	+P1070
	250	1300	1150	8	6			+P1300

Precipitation hardening temperature °C / Hardness. Material solubilized at 1040 °C . Approximate values

HRC	34	34	38	43	47	42	36	33
HV 10	336	336	372	423	458	412	354	327
N/mm^2	1050	1050	1180	1390	1700	1340	1110	1030
°C	**100**	**200**	**300**	**400**	**450**	**500**	**600**	**650**

Effect of **cold-working** (hot-rolled, solution annealing and cold-drawn). Approximate values

R	N/mm^2	880	960	1000	1020	1060	1100	1120	1160	1200	1260
Rp 0.2	N/mm^2	700	820	860	900	980	1000	1000	1020	1050	1080
A	%	20	12	11	10	8	8	8	8	8	8
Reduction	**%**	**0**	**10**	**15**	**20**	**30**	**40**	**50**	**60**	**70**	**75**

Minimum yield stress and tensile strength values at high temperatures.
Solubilized and precipitation hardening material EN 10088-3: 2005

							heat treatment condition
Rp 0.2	N/mm^2	500	490	480	470	460	+P800
Rp 0.2	N/mm^2	680	660	640	620	600	+P930
Rp 0.2	N/mm^2	730	710	690	670	650	+P960
Rp 0.2	N/mm^2	880	830	800	770	750	+P1070
Prova a	**°C**	**100**	**150**	**200**	**250**	**300**	

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	10.8	11.0	11.3	11.6	12.0
Modulus of elasticity	longitudinal GPa	200	193	186	180	175	170
Poisson number	v	0.291					
Electrical resistivity	$\Omega \bullet mm^2/m$	0.71					
Electrical conductivity	$Siemens \bullet m/mm^2$	1.41					
Specific heat	J/(Kg•K)	500					
Density	Kg/dm^3	7,80					
Thermal conductivity	W/(m•K)	14.0	16	18.5	20.0	22.0	23.0
Relative magnetic permeability	μr	max 135					
°C		**20**	**100**	**200**	**300**	**400**	**500**

The symbol ► indicates between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** petrolchemical, stress corr. cracking, food processing
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	yes
Machinability	related to ist hardness
Hardening	precipitation hardening
Service temperature in air	do not use at temperatures higher than those of artificial aging (max 540 °C)

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**R. Corea** KS
X5CrNiCuNb16-4	S17400	Type 630	05Cr17Ni4Cu4Nb		SUS 630		STS 630

Quality	**X3CrNiCu18-9-4**	**Austenitic Stainless Steel**
Number	**1.4567**	

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%** [a]	**Cr%**	**Ni%**	**N%**	**Cu%** [b]	
max	max	max	max	max			max		
0,04	1,00	2,00	0,045	0,015	17,0-19,0	8,5-10,5	0,11	3,0-4,0	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	+ 0.003	± 0.2	± 0.1	± 0.01	± 0.1	

Product deviations are allowed

[a] for improving machinability, it is suggested a controlled sulphur content of 0,015 % - 0,030 %

[b] for steel intended to cold-work hardening and extrusion, it is allowed a Cu content of max 1,0 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1450-1400	1200-900	1100-1000 water	not necessary	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**		
sensitization test at 700-450	not suitable	not suitable		

MMA **welding –** AWS electrodes

pre-heating	*post welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E 316L	E 316L	E 316L

cosmetic welding
E 316L

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot or cold. *Passivation* 20 - 45% HNO_3 cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm		Testing at room temperature							
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a]	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	max	
	160	450-650	175	45				215	+AT solubilization

[a] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	J min (T)	
	10 [b]	600-850	400	25				+AT solubilization
10	16	600-850	340	25				
16	40	450-800	175	30		100		
40	63	450-800	175	30		100		
63	160	450-650	175	40		100		

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order

(L) = longitudinal (T) = transversal

Forged

size mm		Testing at room temperature						
		R	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**HB** [a]	
from	to	N/mm^2	N/mm^2 min	min (L)	min (T)	J min (L)	max	
							215	+AT solubilization

[a] for information only

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	560	720	820	940	1010	1120	1180	1300	1380
Rp 0.2	N/mm^2	300	560	710	820	900	990	1070	1200	1270
A	%	60	30	18	12	10	8	8	8	8
Reduction	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**75**

Thermal expansion	$10^{-6} \bullet K^{-1}$	►	16.7	17.2	17.7	18.1		
Modulus of elasticity	longitudinal GPa	200	194	186	179	172		127
Poisson number	*v*	0.28						
Electrical resistivity	$\Omega \bullet mm^2/m$	0.73						
Electrical conductivity	$Siemens \bullet m/mm^2$	1.33						
Specific heat	J/(Kg•K)	500						
Density	Kg/dm^3	8.027						
Thermal conductivity	W/(m•K)	15.0	16.6					
Relative magnetic permeability	μr_{max}	1.02						
°C		**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C ……….

Corrosion resistance	Atmospheric		Chemical			**x** intercrystalline c. pitting, urban water, stress corrosion
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	no
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X3CrNiCu18-9-4	S30430		06Cr18Ni9Cu3		SUS XM7		STS XM7

Quality	**X6CrNiCuS18-9-2**	**Austenitic Stainless Steel**
Number	**1.4570**	

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Ni%**	**N%**	**Cu%** [b]	**Mo%**	
max	max	max	max				max		max	
0,08	1,00	2,00	0,045	0,15-0,35	17,0-19,0	8,0-10,0	0,11	1,40-1,80	0,60	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	± 0.02	± 0.2	± 0.1	± 0.01	± 0.1	± 0.03	

Product deviations are allowed

[b] for steels intended to cold-work hardening and extrusion, it is allowed a Cu content of max 1,0 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**	MMA **welding –** AWS electrodes *pre-heating* *post welding*
1460-1450	1150-900	1100-1050 water	not necessary	not suitable	not welded
Sensitization	**Quenching +Q**	**Tempering +T**			*joint with steel* carbon CrMo alloyed stainless
sensitization test at 800-450	not suitable	not suitable			*cosmetic welding*

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot or cold. *Passivation* 20 - 45% HNO_3 cold

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size		Testing at room temperature							
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	max	
	160	500-710	185	35				215	+AT solubilization

[a] for information only. (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	J min (T)	
	10 [b]	600-950	400	15				+AT solubilization
10	16	600-950	400	15				
16	40	500-910	185	20				
40	63	500-910	185	20				
63	160	500-710	185	35				

[b] in the range of 1 mm ≤ d < 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order.

(L) = longitudinal (T) = transversal

Forged

size		Testing at room temperature						
mm		**R**	**Rp** 0.2	**A%**	**A%**	**Kv** +20 °C	**HB** [a]	
from	to	N/mm²	N/mm² min	min (L)	min (T)	J min (L)	max	
							215	+AT solubilization

[a] for information only

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm²	600	680	800	960	1100	1180	1220
A	%	50	30	20	10	8	8	8
Reduction	%	**0**	**10**	**20**	**30**	**40**	**50**	**60**

X6CrNiCuS18-9-2 **n° 1.4570** austenitic stainless steel

Thermal expansion	$10^{-6} \bullet K^{-1}$	►		18.0		18.5	19.2	
Modulus of elasticity	longitudinal GPa	200	194	186	179	172		127
Poisson number	*v*	0,28 ~						
Electrical resistivity	$\Omega \bullet mm^2/m$	0.73						
Electrical conductivity	$Siemens \bullet m/mm^2$	1.37						
Specific heat	J/(Kg•K)	500						
Density	Kg/dm^3	7.90						
Thermal conductivity	W/(m•K)	14.6						
Relative magnetic permeability	μr	1.005 ~						
°C		**20**	**100**	**200**	**300**	**400**	**600**	**800**

The symbol ► indicates temperature between 20 °C and 200 °C, 20 °C and 400 °C ……….

Corrosion resistance	Atmospheric		Chemical			**x** chemical and organic products
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**		**x**			

Magnetic	no
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 820 °C; intermittent service and up to 750 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
X6CrNiCuS18-9-2	S30331						

Quality	**X6CrNiMoTi17-12-2**	**Austenitic Stainless Steel**
Number	**1.4571**	

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%** [a)]	**Cr%**	**Ni%**	**Mo%**	**Ti%**	
max	max	max	max	max				max	
0,08	1,00	2,00	0,045	0,015	16,5-18,5	10,5-13,5	2,0-2,5	0,70	EN 10088-1: 2005
± 0.01	+ 0.05	± 0.04	+ 0.005	± 0.005	± 0.2	± 0.15	± 0.1	± 0.05	

Product deviations are allowed

[a)] for improving machinability, it is allowed a controlled sulphur content of 0,015 % - 0,030 %; for polishability, it is suggested a controlled sulphur content of max 0,015 %

Temperature °C

Melting range	**Hot-forming**	**Solution annealing** (Solubilization) **+AT**	**Stabilizing**	**Soft annealing +A**
1470-1450	1180-950	1120-1020 water	900-845 calm air	not suitable
Sensitization	**Quenching +Q**	**Tempering +T**	**Stress-relieving +SR**	
not suitable	not suitable	not suitable	420-240 air	

MMA **welding –** AWS electrodes

pre-heating	*after welding*
not necessary	slow cooling

joint with steel

carbon	CrMo alloyed	stainless
E309-E308	E309-E308	E316L

cosmetic welding
E 318

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot or cold. *Passivation* 20 - 25% HNO_3 hot

Mechanical properties

Heat-treated material EN 10088-3: 2005 in conditions 1C, 1E, 1D, 1X, 1G, 2D

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	**HB** [a)] max	
	160	500-700	200	40		100		215	+AT solubilization
160	250	500-700	200		30		60	215	

[a)] for information only (L) = longitudinal (T) = transversal

Bright bars of heat-treated material EN 10088-3: 2005 in conditions 2H, 2B, 2G, 2P

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	
	10 [b)]	600-950	400	25				+AT solubilization
10	16	580-950	380	25				
16	40	500-850	200	30		100		
40	63	500-850	200	30		100		
63	160	500-700	200	40		100		

[b)] in the range of 1 mm $\le d <$ 5 mm, values are valid only for rounds – the mechanical properties of non round bars of < 5 mm of thickness have to be agreed at the time of request and order
(L) = longitudinal (T) = transversal

Forged +AT solubilization

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min (T)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	**Kv** -196 °C J min (T)	
	450	500-700	200	30	100	60		EN 10250-4: 2001
	450	510-710	210	35	100	60	60	EN 10222-5: 2001

(L) = longitudinal (T) = transversal

Work-hardned by cold-drawing EN 10088-3: 2005 in condition 2H (es. +AT+C)

size mm from	to	Testing at room temperature **R** N/mm^2	**Rp** 0.2 N/mm^2 min	**A%** min	
	35	700-850	350	20	+AT+C700 cold-drawn material
	25	800-1000	500	12	+AT+C800 cold-drawn material

Minimum values at high temperatures on material +AT, EN 10088-3: 2005

Rp 0.2	N/mm^2	185	175	165	155	145	140	135	131	129	127
Test at	**°C**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm^2	600	730	880	1040	1140	1280	1360	1600
Rp $_{0.2}$	N/mm^2	230	590	780	920	1100	1220	1230	1420
Reduction **%**		**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

Typical values at high temperature properties. For information only

R	N/mm^2	518	455	443	433	423	375	261	155	78
Rp $_{0.2}$	N/mm^2	208	179	159	146	145	146	146	112	55
Test temperature **°C**		**93**	**204**	**316**	**427**	**538**	**649**	**760**	**871**	**982**

Thermal expansion	$10^{-6} \cdot K^{-1}$	▶	16.5	17.5	18.0	18.5	19.0
Modulus of elasticity	longitudinal GPa	200	194	186	179	172	165
Poisson number	v	0,30					
Electrical resistivity	$\Omega \cdot mm^2/m$	0.75	0.79	0.87	0.94	0.98	0.102
Electrical conductivity	Siemens•m/mm^2	1.33					
Specific heat	J/(Kg•K)	500	500	520	530	540	540
Density	Kg/dm^3	8.0					
Thermal conductivity	W/(m•K)	15	16	17.5	19	20.5	22
Relative magnetic permeability	μ_r	1.02					
°C		**20**	**100**	**200**	**300**	**400**	**500**

The symbol ▶ indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** salts, organic acids, food
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**			

Magnetic	no
Machinability	the presence of carbides and nitrides of titanium suggests to use carbide cutting inserts
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 800 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Korea** KS
X6CrNiMoTi17-12-2	S31635	Type 316Ti	06Cr17Ni12Mo2Ti	08Ch17N13M2T	SUS 316Ti	X04Cr17Ni12Mo2Ti	STS 316Ti

Quality	**X15CrNiSi25-21**	**Austenitic**	*Technical card 2014*
Number	**1.4841**	**Stainless Steel** (refractory steel)	***Lucefin Group***

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Mo%**	**Ni%**	**N%**	
max		max	max	max				max	
0,20	1,50-2,50	2,00	0,045	0,015	24,0-26,0		19,0-22,0	0,11	EN 10088-1: 2005
± 0.01	± 0.10	± 0.10	+ 0.005	+ 0.003	± 0.25		± 0.15	± 0.01	

Product deviations are allowed

Temperature °C

Melting range	**Hot-forming**	**Solution annealing +AT**	**Soft annealing +A**	**Stabilizing**
1430-1400	1190-1000	1150-1050 water	not suitable	not necessary
Sensitization	**Quenching +Q**	**Tempering +T**	**Stress relieving +SR**	
avoid slow heating in the range of 600 and 900	not suitable	not suitable	650 air	

MMA **welding –** AWS electrodes

pre-heating	*post weldin*
not necessary	solution annealing

joint with steel

carbon	CrMo	stainless
E309-E308	E309-E308	E310

cosmetic welding

E312

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot or cold. *Passivation* 20 - 25%HNO_3 hot

Mechanical properties

Products obtained with plastic deformation EN 10095: 2001

bar size mm		Testing at room temperature **R** 1)	**Rp** 0.2	A% min for products			**HB** 1)	
				long 1)	flat			
from	to	N/mm^2 min	N/mm^2 min	(l)	da 0,5 a < 3 (l) (tr)	≥ 3 (l) (tr)	max	
	160	550-750	230	30	28	30	223	+AT solution annealing

1) The max HB values may be raised by 100 units or the max tensile strength value may be raised by 200 N/mm^2 and the min elongation value be lowered to 20% for section and bars of ≤ 35 mm thickness having a final cold deformation.
(l) = longitudinal (tr) = transversal

Hot-finished (Hot-rolled) ASTM A 276-04

size mm		Testing at room temperature **R**	**Rp** 0.2	**A%**	**C%**	**Kv** +20 °C	**Kv** +20 °C	
from	to	N/mm^2 min	N/mm^2 min	min (L)	min (L)	J min (L)	J min (T)	
all		515	205	40	50			+AT solution annealing

Forged +AT solubilized material ASTM A 473-99

ssize mm		Testing at room temperature **R**	**Rp** 0.2	**A%**	**C%**	**Kv** +20 °C	**Kv** +20 °C	**Kv** -196 °C
from	to	N/mm^2 min	N/mm^2 min	min (L)	min (L)	J min (L)	J min (T)	J min (T)
		515	205	40	50			

Hard-drawn ASTM A 276-04 (+AT+C)

size mm		Testing at room temperature **R**	**Rp** 0.2	**A%**	**C%**
from	to	N/mm^2 min	N/mm^2 min	min	min
	12.7	620	310	30	40
12.7		515	205	30	40

Creep properties EN 10095 : 2001. Estimated average value of the strength for 1% ($Rp_{1,0}$) elongation and estimated average value of the strength for rupture (*Rm*) at elevated temperature for 1 000 h, 10 000 h and 100 000 h.

Test temperature **°C**	Strength elongation **Rp** 1.0 N/mm^2 1000 hours	10.000 hours	100.000 hours	Strength rupture **R** N/mm^2 1000 hours	10.000 hours	100.000 hours
600	105	95		170	130	80
700	50	35		90	40	18
800	23	10		45	20	7
900	10	4		20	10	3
1000	3			5		

X15CrNiSi25-21 n° **1.4841** austenitic

Transition-curve determined with Kv. Solubilized material at 1050 °C

Average	**J**	60	70	85	100	120	150	170
Test at	**°C**	**-160**	**-120**	**-80**	**-40**	**0**	**40**	**80**

Approximate values at high temperatures. Material +AT solubilized at 1050 °C

R	N/mm^2	630	610	580	560	520	460	400	300
Rp 0.2	N/mm^2	290	240	200	190	180	170	150	140
A	%	46	42	40	40	38	34	25	22
C	%	72	70	68	62	58	40	28	38
Test at	**°C**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**

Thermal expansion	$10^{-6} \cdot K^{-1}$	►		15.5		17.0		17.5	18.0	19.0
Modulus of elasticity	longitudinal GPa	200		184		167		150	135	
Modulus of elasticity	tangential GPa	86								
Poisson number	*v*	0.30 ~								
Electrical resistivity	Ω • mm^2/m	0.90								
Electrical conductiv.	Siemens•m/mm^2	1.11								
Specific heat	J/(Kg•K)	500								
Density	Kg/dm^3	7.90								
Thermal conductivity	W/(m•K)	15								
Relative magnetic permeability	μr_{max}	1.02								
°C		**20**	**100**	**200**	**300**	**400**	**500**	**600**	**800**	**1000**

The symbol ► indicates temperature between 20 °C and 200 °C, 20 °C and 400 °C .....

Corrosion resistance	Atmospheric		Chemical			**x** radiant tubes, boiler, heat treating boxes
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	no
Machinability	mean
Hardening	by cold-drawn and and other cold plastic deformations
Service temperature	max 1125 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**R. of Korea** KS
X15CrNiSi25-21	S31400	**314**	1Cr25Ni20Si2	20Ch25N20S2	SUH 310 ~	X20Cr25Ni20	STS 310 TB ~

Quality	**X8CrNi25-21**	**Austenitic**	*Technical card* 2014
Number	**1.4845**	**Stainless Steel** (refractory steel)	*Lucefin Group*

Chemical composition

C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	N%	
max	max	max	max	max				max	
0,10	1,50	2,00	0,045	0,015	24,0-26,0		19,0-22,0	0,11	EN 10088-1: 2005
± 0.01	± 0.10	± 0.10	+ 0.005	+ 0.003	± 0.25		± 0.15	± 0.01	

Product deviations are allowed

Temperature °C

Melting range	**Hot-forming**	**Solution annealing +AT**	**Soft annealing +A**	**Stabilizing**
1450-1400	1175-990 water	1150-1040 water	not suitable	not necessary
Sensitization	**Quenching +Q**	**Tempering +T**	**Stress relieving +SR**	
avoid slow heating in the range of 600 and 900	not suitable	not suitable	after hard-drawn 1080-1050 water 400-200 air	

MMA **welding –** AWS electrodes

pre-heating	*post weldin*
not necessary	solution annealing

joint with steel

carbon	CrMo alloyed	stainless
ENiCrFe-3	ENiCrFe-3	E310Nb

cosmetic welding

E310

Chemical treatment ▪ *Pickling* (10% HNO_3) + (0.5 – 1.5% HF) hot or cold. *Passivation* 20 - 45% HNO_3 cold

Mechanical properties

Products obtained with plastic deformation EN 10095: 2001

flat size mm		Testing at room temperature						
from	to	**R** N/mm^2 min	**Rp** 0.2 N/mm^2 min	**A%** min	**C%** min	**Kv** +20 °C J min	**HB** max	
	75	500-700	210	35			192	+AT solution annealing
	35	500-900	210	20			292	+AT+C

Hot-finished (Hot-rolled) ASTM A 276-04

size mm		Testing at room temperature						
from	to	**R** N/mm^2 min	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**C%** min (L)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	
all		515	205	40	50			+AT solubilized material

Forged +AT solubilized material ASTM A 473-99

size mm		Testing at room temperature						
from	to	**R** N/mm^2 min	**Rp** 0.2 N/mm^2 min	**A%** min (L)	**C%** min (L)	**Kv** +20 °C J min (L)	**Kv** +20 °C J min (T)	**Kv** -196 °C J min (T)
		515	205	40	50			

Hard-drawn ASTM A 276-04 (+AT+C)

size mm		Testing at room temperature			
from	to	**R** N/mm^2 min	**Rp** 0.2 N/mm^2 min	**A%** min	**C%** min
	12.7	620	310	30	40
12.7		515	205	30	40

Creep properties EN 10095 : 2001. Estimated average value of the strength for 1% (*Rp*$_{1,0}$) elongation and estimated average value of the strength for rupture (*R*m) at elevated temperature for 1 000 h, 10 000 h and 100 000 h.

Test temperature °C	Strength elongation **Rp** $_{1.0}$ N/mm^2 1000 hours	10.000 h.	100.000 h.	Strength rupture **R** N/mm^2 1000 h.	10.000 h.	100.000 h.
600	100	90		170	130	80
700	45	30		80	40	18
800	18	10		35	18	7
900	10	4		15	8.5	3

Transition-curve determined with Kv. Solubilized material at 1050 °C

Average **J**	50	62	84	106	130	150	170
Test at **°C**	**-160**	**-120**	**-80**	**-40**	**0**	**40**	**80**

X8CrNi25-21 n° **1.4845** austenitic

Effect of **cold-working** (hot-rolled +AT+C). Approximate values

R	N/mm²	600	760	880	990	1080	1150	1220	1260
Rp 0.2	N/mm²	310	460	690	880	990	1040	1080	1100
A	%	42	30	18	8	6	6	5	5
Reduct.	**%**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

Relative magnetic permeability **μr** as a function of magnetic field intensity and reduction. Approximate values

Reduction %	**0**	**14,7**	**26,8**	**64,2**
Magnetic field intensity 4000 A/m	1.0018	1.0016	1.0018	1.0019
Magnetic field intensity 16000 A/m	1.0035	1.0041	1.0043	1.0041

Mechanical properties on various temperatures. Material +AT solubilized at 1050 °C. Approximate values

R	N/mm²	1223	1085	658	620	600	580	550	520	440	380	240
Rp 0.2	N/mm²	796	585	310	280	230	200	190	180	170	160	150
A	%	52	54	60	44	42	40	40	40	38	28	20
C	%	50	54	65	70	68	66	62	58	40	28	38
Test at	**°C**	**-254**	**-195**	**24**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**

Thermal expansion	$10^{-6} \bullet K^{-1}$	▶		15.5		17.0		17.5	18.5	19.0
Modulus of elasticity	longitudinal GPa	200	190	185	180	170	158	150	130	120
Modulus of elasticity	tangential GPa	86								
Poisson number	*v*	0.29 ~								
Electrical resistivity	Ω • mm²/m	0.85								
Electrical conductiv.	Siemens•m/mm²	1.18								
Specific heat	J/(Kg•K)	500								
Density	Kg/dm³	7.90								
Thermal conductivity	W/(m•K)	15					19			
Relative magnetic permeability	μr max	1.008								
°C		**20**	**100**	**200**	**300**	**400**	**500**	**600**	**800**	**1000**

The symbol ▶ indicates temperature between 20 °C and 200 °C, 20 °C and 400 °C .....

Corrosion resistance	Atmospheric		Chemical			**x**oil pumping station, hig-heat salt bath, hot gases> 550 °C
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	no
Machinability	high
Hardening	by cold-drawn and and other cold plastic deformations
Service temperature in air	continuous service up to 1050 °C; intermittent service up to 1000 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**R. of Korea** KS
X8CrNi25-21	S31008	**310S**	0Cr25Ni20	10Ch23N18	SUH 310	10Cr25Ni18 ~	STS 310S

Quality	**430FMo**	**Ferritic Stainless Steel**
Number	(1.4105)	

Chemical composition

C% max	**Si%**	**Mn%**	**P%** max	**S%**	**Cr%**	**Mo%**	**Ni%** max
0,08	0,30-0,80	0,40-1,25	0,040	0,20-0,30	16,0-18,0	0,80-1,10	1,00
± 0.01	+ 0.05	+ 0.03	+ 0.005	± 0.02	± 0.2	± 0.05	± 0.03

Product deviations are allowed

Temperature °C

Melting range	**Pre-heating**	**Hot-forming**	**Soft annealing** **+A**
1500-1480	870-820 pause	1140-900	800-780 air (HB max 190)
Natural state **+U**	**Recrystallization** **+RA**	**Quenching** **+Q**	**Annealing** for magnetic properties a)
(HB min 195)	820-760 slow cooling (HB max 195)	930 calm or forced air	845-800 cooling 50 °C/h to 430, then air

MMA **welding –** AWS electrodes

pre-heating	*post welding*
difficult; address qualified electrodes producers	

joint with steel

carbon	CrMo alloyed	stainless
E430	E430	E309

cosmetic welding
E309

Curie temperature 671 °C

Chemical treatment ▪ *Pickling* (6 - 25% HNO_3) + (0.5 - 8% HF) hot or cold. *Passivation* 20 - 25% HNO_3 hot

Mechanical properties

Hot-formed

size mm from	to	Testing at room temperature **R** N/mm² min	**Rp** 0.2 N/mm² min	**A%** min	**Kv** +20 °C J min	**HB** a) max	a) for information only
	100	430	245	16		200	+RA recrystallization annealing

Cold-drawing

size mm from	to	Testing at room temperature **R** N/mm² min	**Rp** 0.2 N/mm² min	**A%** min	**Kv** +20 °C J min	**HB** max	
	10	520	320	7			
10	16	480	300	7			+RA+C recrystallization annealing and cold-drawing
16	40	420	240	12			
40	63	420	240	12			

Thermal expansion	$10^{-6} \cdot K^{-1}$	▶	10.6	11.4	12.0
Modulus of elasticity	longitudinal GPa	206			
Poisson number	*ν*	0.29 ~			
Electrical resistivity	Ω • mm²/m	0.70			
Electrical conductivity	Siemens•m/mm²	1.42			
Specific heat	J/(Kg•K)	460			
Density	Kg/dm³	7.61			
Thermal conductivity	W/(m•K)	25			
Relative magnetic permeability	μr	600-800 ~			
°C		**20**	**200**	**400**	**600**

The symbol ▶ indicates temperature between 20 °C and 200 °C, 20 °C and 400 °C …..

Corrosion resistance Fresh water	Atmospheric *industrial*	*marine*	Chemical *medium*	*oxidizing*	*reducing*	**x** food, nitric acid, dairy products
x	**x**		**x**			

Magnetic	yes
Machinability	high
Hardening	cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 780 °C; intermittent service up to 830 °C

Europe EN	**USA** UNS	**USA** ASTM	**China** GB	**Russia** GOST	**Japan** JIS	**India** IS	**Republic of Korea** KS
(X6CrMoS17)							

Quality	**X2CrMoTi18-2**	**Ferritic**
Number	**1.4521**	**Stainless Steel**

Chemical composition

C%	**Si%**	**Mn%**	**P%**	**S%**	**Cr%**	**Ti%** [a]	**N%**	**Mo%**	
max	max	max	max	max		max	max		
0,025	1,00	1,00	0,040	0,015	17,0-20,0	0,80	0,030	1,80-2,50	EN 10088-1: 2005
+ 0.005	+ 0.05	+ 0.03	+ 0.005	+ 0.003	± 0.2	± 0.05	± 0.01	± 0.1	

Product deviations are allowed [a] Ti: (4 x(C + N) + 0.15)

Temperature °C

Melting range	**Hot-forming**	**Solution annealing +AT**	**Stabilizing**	**Curie temperature**
1510-1480	1100-950	not suitable	not necessary	650
Sensitization	**Quenching +Q**	**Tempering +T**	**Soft annealing +A** (controlled atmosphere)	
avoid slow heating in the range of 900 and 600	not suitable	not suitable	880-820 air, awater	

MMA **welding –** AWS electrodes

pre-heating	*post weldin*	
not necessary	not necessary	
joint with steel		
carbon	CrMo	stainless
E309-E308	E309-E308	E308L

cosmetic welding
1.4430

Chemical treatment ▪ *Pickling* (20 - 40% HNO_3) + (2 - 6% $Na_2Cr_2O_7 . 4\% 2H_2O$) hot ▪ *Passivation* 20 - 25% HNO_3 hot

Mechanical properties

EN 10088-2: 2005 in annealing condition +A

size mm		Testing at room temperature						
		R	**Rp** 0.2	**Rp** 0.2	**A%** t < 3	**A%** t < 3	***HB***	product
from	to	N/mm^2	N/mm^2 min (L)	N/mm^2 min (T)	min (L)	min (T)	*for inf. only*	form
	8	420-640	300	320	20	20	*125-198*	C
	13,5	400-600	280	300	20	20	*119-178*	H
	12	420-620	280	300	20	20	*125-190*	P

(L) = longitudinal (T) = transversal C = cold rolled strip; H = hot rolled strip; P = hot rolled plate

ASTM A240/A240M-11b plate, sheet and strip in annealed condition +A

size mm		**R**	**Rp** 0.2	**A%**	**HB**
from	to	N/mm^2 min	N/mm^2 min	min	max
5		415	275	20	217

Effect of **cold-working** (hot-rolled +A+C). Approximate values

R	N/mm^2	480	660	740	780	800	810	850	900
Reduction	%	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**

Minimum values for the 0,2 % proof strength at elevated temperatures, annealed material +A EN 10088-2: 2005 / EN 10028-7: 2008

Rp 0.2	N/mm^2	294	250	240	230	220	210	205	200
Test at	**°C**	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**

Thermal expansion	10^{-6} • K^{-1}	►	10.4	10.8	11.2	11.6	11.9	12.0
Modulus of elasticity	longitudinal GPa	220	215	210	205	195		158
Modulus of elasticity	tangential GPa	65						
Poisson number	*v*	0.28 ~						
Electrical resistivity	Ω • mm^2/m	0.80						
Electrical conductiv.	Siemens•m/mm^2	1.25						
Specific heat	J/(Kg•K)	430						
Density	Kg/dm^3	7.70						
Thermal conductivity	W/(m•K)	23.0	26.8	29.0		34.0		35.0
Relative magnetic permeability	μr at 0.8 kA/m DC / AC	800						
°C		**20**	**100**	**200**	**300**	**400**	**500**	**600**

The symbol ► indicates temperature between 20 °C and 100 °C, 20 °C and 200 °C …..

Corrosion resistance	Atmospheric		Chemical			**x** pitting, crevice, intercrystalline, stress corrosion, food
Fresh water	*industrial*	*marine*	*medium*	*oxidizing*	*reducing*	
x	**x**	**x**	**x**	**x**		

Magnetic	yes
Machinability	good
Hardening	moderate by cold-drawn and other cold plastic deformations
Service temperature in air	continuous service up to 850 °C; intermittent service up to 950 °C

Europe	**USA**	**USA**	**China**	**Russia**	**Japan**	**India**	**Republic of Korea**
EN	UNS	ASTM	GB	GOST	JIS	IS	KS
X2CrMoTi18-2	S44400	**444**	019Cr19Mo2NbTi		SUS 444		STS 444

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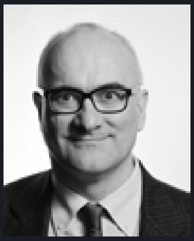
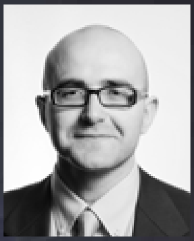


Marco V. Boniardi (Milan, 1964)

Full Professor of Metallurgy in the Mechanical Engineering Department of the Polytechnic University of Milan. For more than twenty years Prof. Boniardi has conducted research and technological transfer activities in the sector of Materials Science & Engineering. His main areas of interest are stainless steels, common and special steels, heat treatments, fatigue, fracture mechanics, corrosion, the manufacturing processes and the transformation of steels.

Prof. Boniardi is author of over 100 scientific publications, and collaborates with national companies and international corporations in the field of forensic engineering, and analysis of failures and operational inefficiencies; he was also involved in the extensive media coverage of the train accident in Viareggio on 29th June 2009 and the sinking of the Costa Concordia cruise ship on 13th January 2012. He is the Executive Director of the course Failure Analysis & Forensic Engineering held as part of the permanent training courses at the Polytechnic of Milan.

Along with Andrea Casaroli he is the founder of the **www.fa-fe.com** website.



Andrea Casaroli (Castel S. Giovanni - PC, 1984)

Andrea Casaroli conducts his research in the field of Metallurgy with the Mechanical Engineering Department at the Polytechnic University of Milan, working in particular with stainless steels, coatings and the mechanical behaviour of materials. He is also involved in Failure Analysis and industrial accidents, where he has developed a specialist skills in fires and fire resistance. He is author of 15 scientific publications, collaborating with national and international corporations in seeking solutions to problems of mechanical failure, corrosion, fatigue, component and industrial site malfunctions.

Along with Marco Boniardi he is the founder of the **www.fa-fe.com** website.

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