

THE FERRITIC STAINLESS STEEL FAMILY: THE APPROPRIATE ANSWER TO NICKEL VOLATILITY ?

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Abstract

Due to recent nickel price volatility, ferritic stainless steels – having no or very low nickel content – can be very interesting to stainless steels users. Although ferrite is the most common structure in steel, it represents only about 26% of the total stainless steel production nowadays. The paper presents the ferritic stainless steel family: mechanical properties of the grade including drawability as well as corrosion resistance properties. Experimental data of the newly developed 20% Cr ferritic grade are discussed and compared to the properties of existing 200 and 300 series grades. High temperature properties of ferritic stainless steels designed for exhaust systems are also presented.

Introduction

Stainless steels are ‘stainless’ because their chromium content – minimum 10.5% – gives them remarkable resistance to wet corrosion and high temperature oxidation. Ferritic grades, containing only chromium and possibly other elements (Mo, Ti, Nb, etc.), are well known as cost savings materials since most of them have no expensive nickel additions. Furthermore, the chromium content can be optimized taking into account a very wide range of applications: from 10.5 to 29%. Chromium content of austenitic grades is generally kept in the 17-18% range because of austenitic phase stability considerations (lower or increased Cr content in 300-series austenitic grades requires further increase of expensive Ni to stabilize the austenitic phase).

Standard ferritic grades such as 409, 410 and 430 are readily available all over the world. Very successfully used in important applications, such as washing-machine drums and exhaust systems, they actually have much broader application potential, in numerous fields.

More recently developed ferritic grades, such as 439 and 441 meet an even wider range of requirements. They can be formed into more complex shapes and joined using most conventional joining methods, including welding. In material selection decisions, these grades are often weighed against 304 austenitic grades.

The addition of molybdenum enhances the resistance of ferritic stainless steels to localised corrosion (434, 436). Grade 444 is even considered at least equal to austenitic grade 316 in most of the cases when considering corrosion resistance properties.

Superferritic grades have also been developed since many years. Their very high chromium content (25-29%) with additional Ni and Mo alloying make them well-known highly corrosion resistant products albeit restricted to marginal applications. This is due to their high sensitivity to embrittling phase transitions.

Recently, newly developed ferritic grades with the aim to replace 304 austenitic grades have been introduced into the market. Their chromium content lies in the 20-22% range and they are free of expensive nickel or molybdenum additions. The grades are stabilized by minor additions of Ti/Nb/Cu.

The recent volatility of Ni has brought the 400 series under the spotlights. A key note lecture devoted to new developments, properties and applications of ferritic grades seemed to be more than welcome in the scientific program of the Stainless Steel Science and Market 2008, Helsinki international conference.

Stainless Families and Alloying Costs

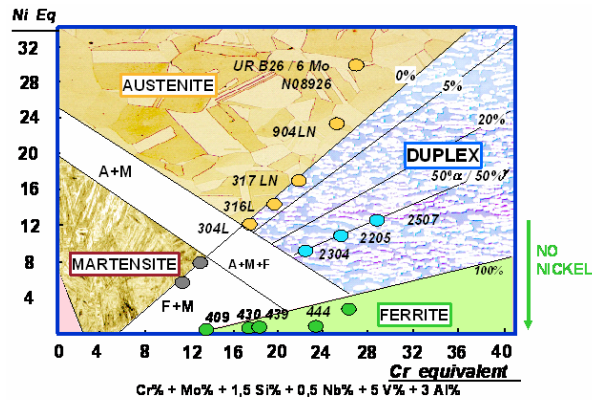


Figure 1. Schaeffler diagram

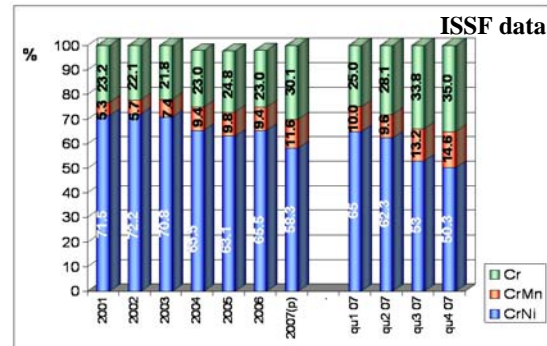


Figure 2. Market share of various stainless steel families

Although the Schaeffler diagram (Figure 1) is mainly used for welded structures, it is very useful to illustrate the different areas of stability of stainless steel microstructures. The classical austenitic grades – the so called 300 series – contain generally 8-10% Ni while the more (Cr and Mo) alloyed grades require even more Ni to stabilise the austenitic phase. The most popular stainless steel – 304 – is one of the lowest alloyed grades of the austenitic area (not including nitrogen alloyed grades). 316 grade having 2% Mo content is considered as the standard alloyed austenitic stainless steel for corrosion resistance properties. Until 2003, austenitic grades 304 and 316 represented together about 70% of the total stainless steel production. (Figure 2).

With the extreme volatility of alloying element costs, new grades have recently been introduced in the market. (Figures 3 to 6) These grades are also austenitic grades, but with partial replacement of Ni by combined Mn and N additions. Their share in stainless steel production has recently increased to more than 10%. The Asian market is particularly involved in this booming development.

A paper about the recent developments of the 200 series in general and the introduction of a particular 200 series grade (with VDEh designation 1.4618) is presented at this conference too. The grade is designed to feature nearly equivalent properties to the 304 grade.(1)

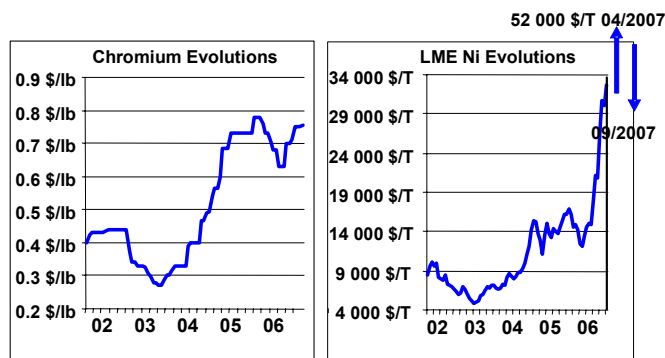
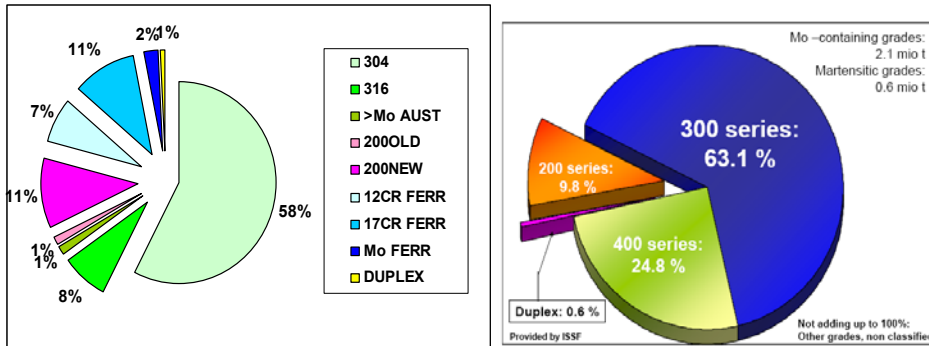


Figure 3. Cr and Ni price evolution in latest years



Figures 4 and 5. Stainless worldwide crude production in 2004 by grades.

Another family is also growing, particularly for the most severe corrosion resistance applications: the duplex grades. Despite their very attractive features – combining high mechanical properties with corrosion resistance – they still account for less than 1% of the total stainless steel production. More recently, the development of the lean duplex grades and duplex cold rolled products were introduced. This may have a significant effect on duplex growth in the near future. Ferritic stainless appears to be the most effective answer to nickel volatility. Their market share has grown in the recent past and they represent already about 30% of total stainless steel production. They represent a significant cost saving advantage. Moreover, many grades have been developed in order to optimize corrosion resistance or mechanical properties. Because of welding aspects and toughness properties, they are mainly restricted to thinner gauges even if they often show cost saving potential (Figure 6). They cover a very wide area of applications.

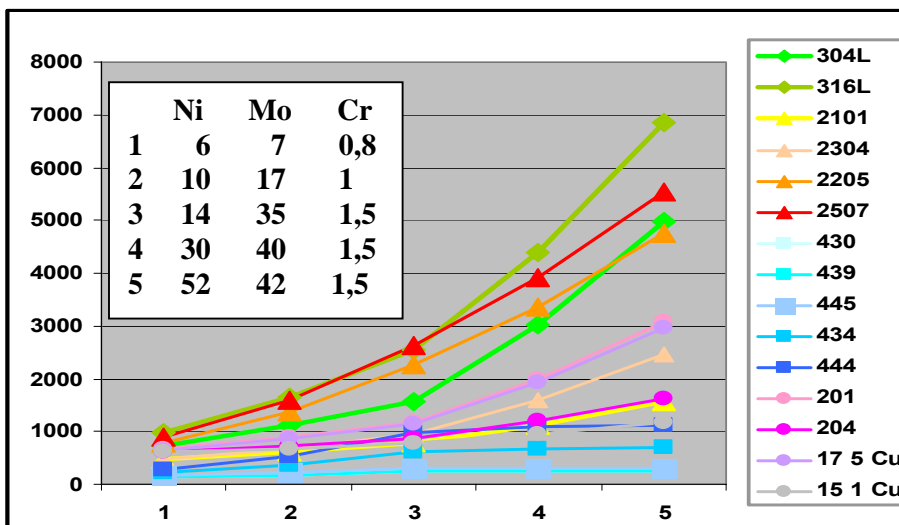


Figure 6. Raw material cost models (real figures observed from 2004 to 2007).

The ferritic grades

Ferritic grades may be classified into five groups – three families of standard grades and two of “special” grades. By far the greatest current use of ferritics, both in terms of tonnage and number of applications, is centered around the standard grades (Figure 7). Table 1 presents the chemical composition of the most relevant ferritic stainless steels.

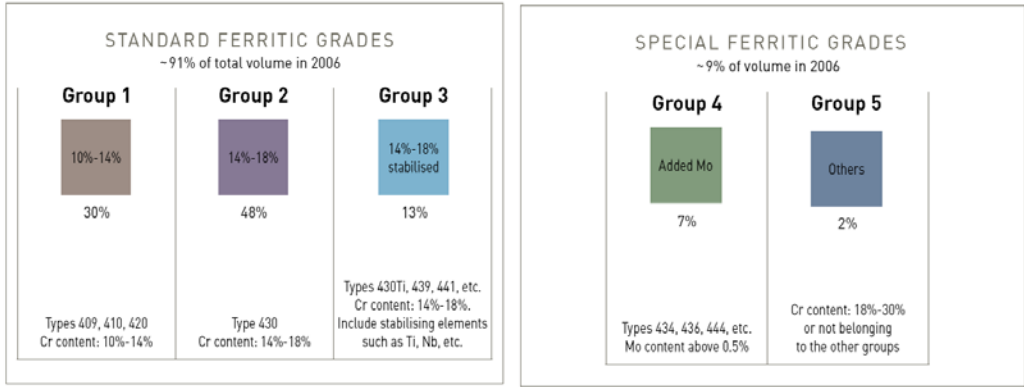
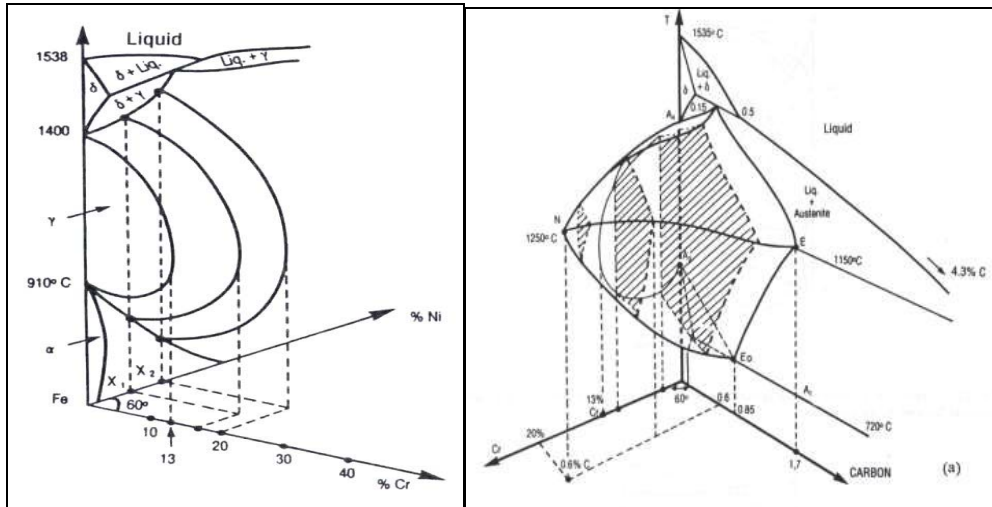


Figure 7. Ferritic stainless steels families

Group 1: 10-14% Cr (type 409/410L) has the lowest chromium content of all stainless steels. Figures 8 and 9 present the effects of Cr, Ni and C/N alloying on phase stability. Clearly the stable austenite domain (“gamma loop”) which is observed around 1000-1200°C is extended by nickel or carbon (or nitrogen) additions while chromium additions stabilize the ferritic phase. As a result, stainless steel with a minimum of 13% Cr, no Ni and extra low interstitial elements (C/N) may present a fully ferritic structure at all temperatures.



Figures 8 and 9. Fe-Ni-Cr and Fe-Cr-C phase diagrams.

When reducing Cr and/or increasing C+N, the grade, when heated, undergoes a ferrite/austenite transformation. Grain refining treatments can be performed and the grades having a stable austenitic loop may undergo martensitic transformation when quenched to room temperature. Several investigators have studied the influence of alloying elements on the M_s temperature (4,5,6). In the case of 12% Cr steels, table 1 gives the change in M_s per weight percent of element added, the value for the base alloy being 300°C. Table 1 also presents the effect of alloying elements on the Ac_1 temperature (temperature at which the austenite starts to form on heating). C and N appear to have no significant effect on Ac_1 temperature in 12% Cr grades.

Table 1. Effects of alloying elements on the Ac_1 and M_s temperatures of 13% Cr ferritic steels.

Element	C	Mn	Mo	Cr	Ni	W	Si
Change in M_s (°C) per % addition	-475	-33	-21	-17	-17	-11	-11
	Ni	Co	Si	C	Al	Mo	V
Change in Ac_1 (°C) per % addition	-30	-25	-5	0	30	35	50

The mechanical properties of 12-13% Cr alloys are closely related to the carbon and nitrogen contents. This is particularly the case for quenched products from the gamma loop. Figure 10 shows hardness values obtained on austenitized 13% Cr samples, oil quenched at 0°C and stress relieved at 200°C.

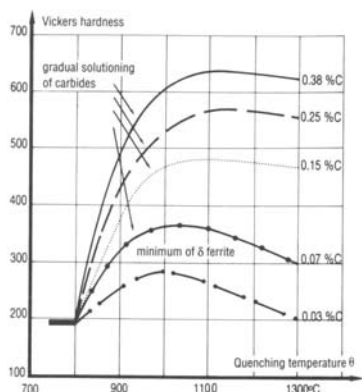


Figure 10. Effects of carbon content on mechanical properties of 13% Cr stainless after water quenching and 200°C stress relieving heat treatment.

Hardness clearly increases with carbon content. Hardness is even higher than that of C-Mn steels with the same amount of carbon due to simultaneous Cr solid-solution hardening effects and lower M_s temperature which reduce the self-tempering effects. Higher quenching temperatures make it possible to further increase the hardness by enhancing the dissolution of carbides which further contributes to increase the carbon content in solid solution. At higher quenching temperatures, beyond 1150°C, the hardness can fall due the formation of delta ferrite and for the highest carbon content grade, the presence of retained austenite.

Obviously, ferritic 12-14% Cr grades with sufficient ductility can only be produced by an optimum heat treatment and a stringent control of chemistry including interstitial elements (carbon/nitrogen) or in the fully annealed condition.

This group can be ideal for non- or lightly corrosive environments or applications where slight localised rust is acceptable. Type 409 was originally designed for automotive exhaust system silencers (exterior parts in non-severe corrosive environments). Type 410L is often used for containers, buses and coaches and, recently, LCD monitors frames.

Group 2: 14-18 Cr % (type 430) is the most widely used family of ferritic alloys. Most of the industrial grades have between 16 and 18% Cr. AISI 430 is the most widely used ferritic stainless steel. Its typical composition, by weight, is 16-18% Cr, <0.08% C. In order to increase the ductility, the actual carbon content, particularly in the case of thin sheet, is often much lower, typically in the range 0.02 to 0.05%. Nitrogen is generally of the order of 0.030%, but can be significantly reduced. Figure 11 illustrates the influence of combined carbon and nitrogen contents on the iron-chromium equilibrium diagram. It can be seen that for common (C+N) values, (typically 0.08%), the high temperature structure consists of two phases (austenite + ferrite), the maximum level of austenite being obtained at about 1100°C.

Consequently, after fast cooling to room temperature from the high temperature mixed austenite/ferrite region, the microstructure of the alloy will transform into a mixed ferrite/martensite microstructure. It is necessary to temper anneal the martensite to restore the ductility. Tempering can be carried out at a temperature below A_{c1} . Final heat treatment is closely linked to the chemistry of the grade. The final microstructure generally presents a mixed ferrite/carbides microstructure. The highest density of carbides being related to carbon content and the former austenitic grains enriched in carbon when heat treated occurs in the duplex ferrite/austenite region. The carbon enrichment of the austenite versus ferrite results from higher carbon solubility in austenite versus ferrite.

16-18% Cr ferritic grades are known to present potentially brittle microstructures when welded. This is explained by the combined negative effects of grain coarsening at very high temperature in the HAZ close to the fusion line, possible martensitic transformation in the austenitized areas and/or intergranular carbide precipitations (Figure 11).

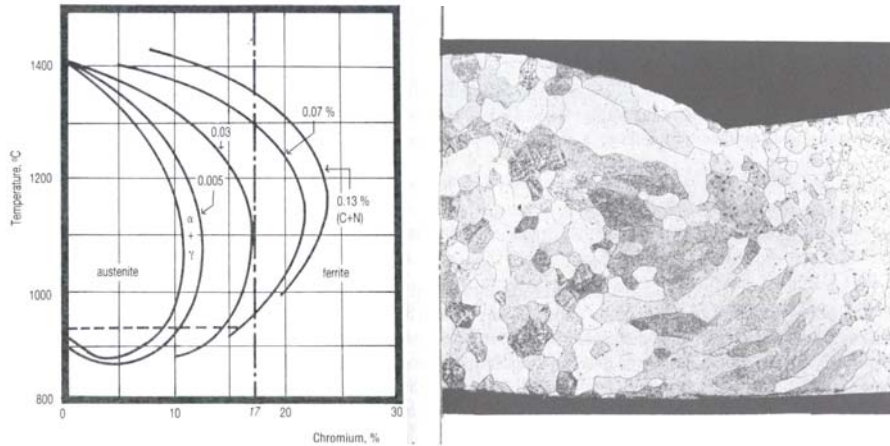


Figure 11. Fe-Cr-C phase diagram and Fe-17Cr ferritic welded structure.

Having a higher chromium content, Group 2 grades show higher resistance to corrosion and behave more like austenitic grade 304. In situations, where corrosion resistance is less of a concern, these grades are suitable to replace type 304 and are usually sufficiently alloyed for indoor applications. Type 430 is often substituted for type 304 in household utensils, dishwashers, pots, pans and decorative panels.

Group 3: 14-18% Cr + stabilization elements (Ti, Nb, Zr...) includes types 430Ti, 439, 441, etc. During solidification and cooling, Ti, Nb, Zr additions in steels tie up carbon and/or nitrogen in the form of highly stable compounds. Carbides and nitrides are precipitated leaving the ferritic structure with much lower carbon / nitrogen contents in solid-solution. As a result, the 16-18% Cr stabilized grade often has a fully ferritic microstructure at all temperatures. The amount and nature of stabilization elements can be optimized taking into account the requested in-service properties. Specific improvements in functional properties such as drawability, pitting corrosion resistance, high temperature strength, creep resistance, may be achieved by adding the appropriate alloying elements and selection of one or more stabilization elements. Typically, stability of the carbides increases from NbC, TiC to ZrC, the latter being extremely stable at high temperature. Mixed TiC/NbC are preferred for pitting corrosion resistance, the NbC compound is the carbide of choice in order to obtain creep resistance properties... The minimum amount of Ti or Nb is generally included in a range of 6 to 8 times (x) the C+N content. Of course the C+N content is optimized for specific applications. For room temperature applications, carbon content is typically kept at the lowest possible level (taking into account economical considerations) so that the amount of expensive Ti, Nb can be reduced and a fully stabilized microstructure still be maintained.

Ti and Nb are the most popular stabilization elements. They have strong affinities with other residual elements such as oxygen and sulphur and act as intrinsic ferrite forming elements of the steel microstructure. As a major consequence of this, the steel is fully ferritic at all temperatures and Cr-carbide precipitations are inhibited, particularly in the HAZ (prevention of intergranular corrosion along depleted Cr areas). Furthermore, the nature of inclusions (oxides, nitrides, sulphides) and precipitations (carbides, carbonitrides, phosphides, intermetallic phases...) is different from that of the basic non-stabilized 17% Cr steel (Figure 12).

Precipitate size	17 Cr - Ti	17 Cr - Zr	17 Cr - Nb
> 2 μm	TiN TiC	ZrN ZrC	Nb(C,N)
from 1000 to 5000 Å	TiC (Fe,Ti) ₃ P	X	Nb(C,N) (Fe,Cr) ₂ Nb
≤ 500 Å	X	Zr ₂ P	X

Figure 12. Type of precipitations observed in a 17 Cr ferritic stabilized grade.

Compared with Group 2, these grades show better weldability and formability than 430 grade. Their behaviour is, in most cases, equivalent to that of 304 austenitic grades.

Typical applications include sinks, heat exchanger tubes (the sugar industry, energy, etc.), exhaust systems (longer life than with type 409) and the welded parts of washing machines. Group 3 grades can even replace type 304 in applications where this grade is overspecified. The best in-service wet corrosion resistance properties are observed for the highest Cr content (17-18% Cr) and a mixed Nb / Ti stabilization effect.

Group 4: 10-18% Cr and Mo content higher than 0.5% includes types 434, 436, 444, etc.

These grades are molybdenum alloyed, for extra corrosion resistance. Cr content is mainly in the 17-18% range. Due to the increase of ferrite forming elements (Mo), these grades present a fully ferritic microstructure and most of them are fully stabilized by Ti and/or Nb additions. The grades are also more sensitive to intermetallic phase precipitations (χ , σ) when heated to high temperatures. Brittle behaviour may occur if improperly heat treated or after long term use at high temperatures. Nevertheless, since Cr content is kept at a relatively low level, those grades show satisfactory structural stability and welding properties.

Typical applications include hot water tanks, solar water heaters, visible parts of exhaust systems, electric kettle and microwave oven elements, automotive trim and outdoor panels, etc. Type 444's corrosion-resistance can be similar to that of type 316.

Group 5: Cr content higher than 18% and not belonging to other groups, includes types 446, 445, 447 etc.

Those grades traditionally have molybdenum additions, for extra wet corrosion resistance. Having most often 25-29% Cr and 3% Mo, these grades are superior to type 316 with respect to this property. They are very sensitive to embrittlement due to intermetallic phase precipitations and are very difficult to weld. Their uses are restricted to thin gauges (mainly below 2 mm). Extra low carbon + nitrogen are required to ensure sufficient structure stability. Ni additions are considered (2-4%) to increase toughness properties. Nickel has controversial effects since Ni simultaneously reduces the brittle/ductile transition temperature and enhances phase precipitation kinetics which decrease the ductility. The high Cr and Mo containing grades are called superferritics. The new generation of superferritics is designed to have an extra low interstitial content thanks to specific melting procedures. The grades are designed to replace titanium in the most severe corrosion resistance applications (including nuclear power station condensers and seawater exchanger tubes, geothermal, desalination...). Only marginal worldwide production numbers are reported.

More recently, a new family of ferritic grades has been developed. They are designed to replace 304 grade and generally contain about 20% Cr. Since they are Mo-free, they can be considered as the best alternative to Ni and Mo price volatility. For corrosion resistance properties and weldability the grades are fully stabilized by mixed Ti/Nb/Cu additions. The grades present attractive properties for an extremely wide range of applications.

Group 5 also contains a family of grades developed for exhaust applications, including grades containing exotic additions such as high Al (2-5%) and Ce, Y,... but also a 19Cr-2Mo-Nb grade designed for high temperature applications. Due to its high resistance to scaling, this grade is particularly well designed for exhaust manifold applications.

Physical and mechanical properties

Physical properties of ferritic stainless steels

The most obvious difference between ferritic stainless and austenitic properties is their ferromagnetic behavior at room temperature and up to a critical temperature known as the Curie point, temperature typically in the range of 650-750°C at which the magnetic order disappears. Magnetism has nothing to do with corrosion resistance which is closely linked to chemical composition (Cr, Mo ...). Moreover, corrosion resistance is almost independent from the microstructure (not considering the specific case of stress corrosion cracking where ferritic structure is an advantage or crevice corrosion propagation rate where nickel plays a beneficial role). The popular link between magnetism and poor corrosion resistance results from an inappropriate comparison i.e. comparing a ferritic grade with lower Cr content (13-16%) with the austenitic 304 grade (18%).

In fact, the magnetism of ferritic grades is one of the material's major assets in some applications. This includes advantages ranging from the ability to stick memos on the refrigerator door to storing knives and other metallic implements. Indeed, it is also an essential property for ferritic stainless uses in applications dealing with induction heating such as the familiar pans and other cookware for "induction" cooking. In those applications, magnetic materials are requested to generate heat from magnetic energy.

Ferritics' lower thermal expansion coefficient combined with their improved thermal conductivity often provides a key advantage to ferritics over austenitics when considering applications involving heat transfer. Typical physical properties of ferritic stainless compared to austenitics are presented in Table 2

Table 2. Physical properties of ferritic stainless steels

PHYSICAL PROPERTIES							
Type of stainless steel	Density g/cm ³	Electric resistance Ω mm ² /m	Specific heat 0 - 100°C J/kg • °C	Thermal conductivity 100°C W/m • °C	Thermal expansion coefficient		Young's modulus x10 ³ N/mm ²
					0-200°C 10 ⁻⁶ /°C	0-600°C 10 ⁻⁶ /°C	
409/410 10%-14% Cr	7.7	0.58	460	28	11	12	220
430 14%-17% Cr	7.7	0.60	460	26	10.5	11.5	220
Stabilised 430Ti, 439, 441	7.7	0.60	460	26	10.5	11.5	220
Mo > 0,5% 434, 436, 444	7.7	0.60	460	26	10.5	11.5	220
Others 17%-30% Cr	7.7	0.62	460	25	10.0	11.0	220
304	7.9	0.72	500	15	16	18	200
Carbon steel	7.7	0.22	460	50	12	14	215

The modulus of elasticity of ferritic grades (at 20°C) is superior to that of 304 austenitic.
 IS units: g/cm³ = kg/dm³ - J/kg • °C = J/kg • °K - W/m • C = W/m • K - 10⁻⁶/°C = 10⁻⁶/°K - N/mm² = MPa.

Mechanical Properties

Table 3. Typical mechanical properties of ferritic stainless grades

MECHANICAL PROPERTIES (COLD ROLLED)												
ASTM A 240				JIS G 4305				EN 10088-2				
	R _m min	R _{p02} min	A ₅ min		R _m min	R _{p02} min	A ₅ min			R _m	R _{p02} min	A ₈₀ min
409	380	170	20	--	--	--	--	X2CrTi12	1.4512	380-560	220	25
410S	415	205	22	SUS 410	440	205	20	X2CrNi12	1.4003	450-650	320	20
430	450	205	22	SUS 430	420	205	22	X6Cr17	1.4016	450-600	280	18
434	450	240	22	SUS 434	450	205	22	X6CrMo17-1	1.4113	450-630	280	18
436	450	240	22	SUS 436	410	245	20	X6CrMoNb17-1	1.4526	480-560	300	25
439	415	205	22	--	--	--	--	X2CrTi17	1.4520	380-530	200	24
439	415	205	22	--	--	--	--	X2CrTi17	1.4510	420-600	240	23
441	415	205	22	--	--	--	--	X2CrMoNb18	1.4509	430-630	250	18
S44400 (444)	415	275	20	SUS 444	410	245	20	X2CrMoTi18-2	1.4521	420-640	320	20
304	515	205	40	SUS 304	520	205	40	X5CrNi1-80	1.4301	540-750	230	45

Mechanical properties of ferritic grades are presented in Table 3. Ferritics have generally lower elongation and strain hardening properties than austenitics.

As for plain carbon steels, ferritic stainless steels in the annealed state present a yield point followed by a stress drop on the stress/strain curves. This behavior is caused by the breakaway of pinned dislocations and enables a “true yield stress” to be defined. It is accompanied by the formation of localized deformation bands named “Piobert-Lüders” bands. As a result, after plastic deformation on annealed samples, surface defects may be observed. In the case of deep drawing, they are called “stretcher strains” or “worms”. It can be avoided partially by stabilisation or by a skin pass operation which introduce “fresh” dislocations in the structure.

Ferritic stainless exhibit a non-uniform texture which leads to heterogeneous mechanical behaviour. Phenomena such as “earing” as well as “roping” (sometimes called “ridging”) are observed. Roping (Figure 13) generally occurs during deep drawing and involves the formation of small undulations elongated in the tensile direction. Those defects must be eliminated during finishing. The stabilized ferritics steels are less sensitive to roping than basic AISI 430 grade. In practice, optimization of process parameters makes it possible to significantly attenuate this phenomenon. Deep drawing performance is determined by the limit drawing ratio (LDR),



Figure 13. Deep drawn cup of AISI 430 grade showing “roping” phenomenon.

which is well correlated with the mean strain ratio. Ferritics have higher LDR values than austenitics, which makes them particularly suitable for deep drawing applications. The main stress ratio may be optimized in ferritic stainless by process cycle parameters including slab microstructure control and cold rolling parameters preceding the final heat treatment. In industrial practice, for a single cycle cold rolling process, values of 1.8-1.9 LDR are obtained for a conventional 430 grade.

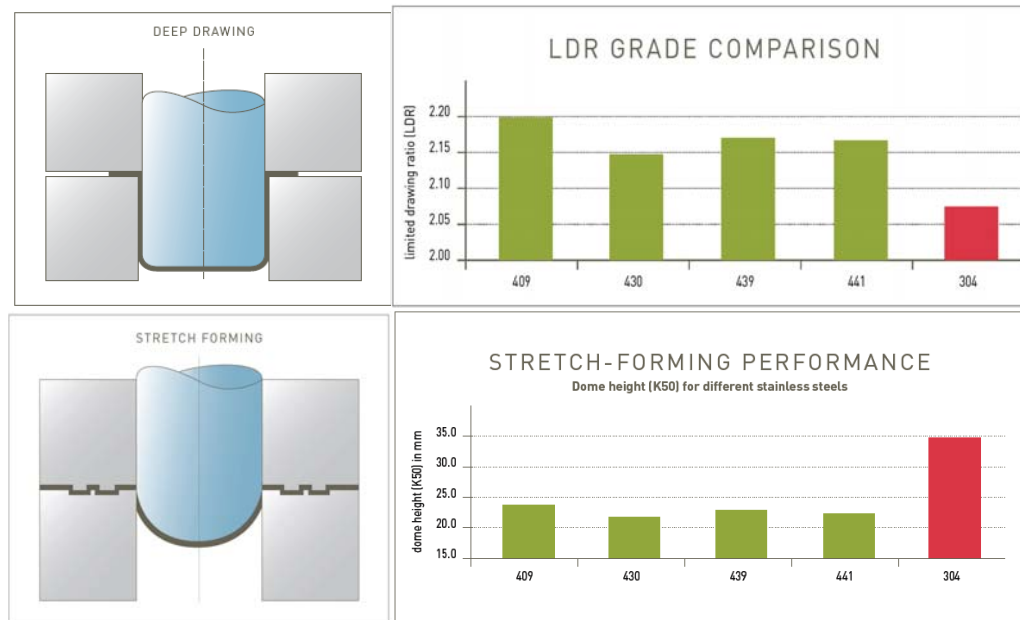


Figure 14. LDR and dome height values of several ferritic and 304 austenitic grades.

The LDR may reach values higher than 2.1 for optimized process including a two step cold rolling process (Figure 14).

Stabilization (by Ti, Nb addition...) of ferritic stainless steel induces a significant modification in the crystalline texture leading to a sharp improvement of the strain ratio. Improved LDR values are observed.

The performance regarding pure deep drawing aside, ferritic grades are inferior to austenitics in pure stretch forming. “Dome height” refers to the maximum degree of deformation – of a blank undergoing stretching – before “necking”. Dome height (K50, in mm) values of ferritic and 304 austenitic grades are presented (Figure 14).

In practice, industrial forming operations involve a combination of both drawing and stretch-forming deformation, in a series of “passes”. Forming limit curves are a useful guide to assess maximum deformation before failure, in both deep drawing and stretching processes. These curves define local deformations during and after forming in terms of two principal “true strains”: longitudinal (“major strain”) and transverse (“minor strain”). The curves plot the effects of the various combinations of these two strains, up to the point of fracture. Typical results obtained for ferritics and 304 grade are presented (Figure 15). Ferritics clearly have less combined forming properties than austenitics. For the most severe forming conditions, the switch from austenitics to ferritics may need some design optimisation with shape modifications of the most critical areas.

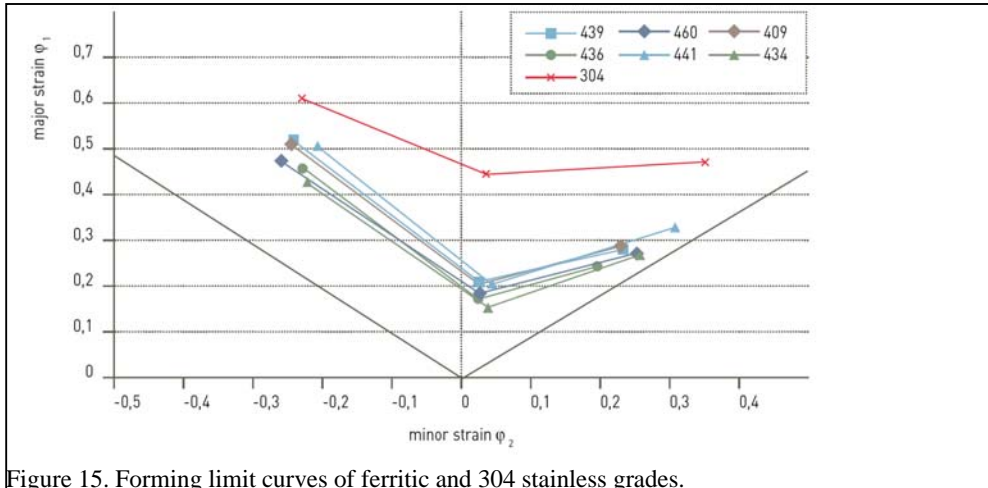


Figure 15. Forming limit curves of ferritic and 304 stainless grades.

Wet Corrosion Resistance Properties

Localised corrosion resistance

Pitting and crevice corrosion resistance are one of the major issues regarding material selection in aqueous solutions. Pitting corrosion resistance is one of the key properties for material selection in neutral, oxidizing conditions typically observed in halogen (Cl, F...) containing solutions. Seawater and brine solutions even with few additions of salt (cooking) are the most common in service conditions related to pitting corrosion.

Pitting corrosion resistance is clearly linked to the PREN value ($\% Cr + 3.3\% Mo + 16\% N$). In the case of ferritics nitrogen additions are kept to minimum values in order to avoid nitride precipitations. Only Cr and Mo play a positive role. Typical data are presented in Figure 16 (pH 6.6, 0.02 M NaCl, 23°C). Of course, an increase of temperature or salinity will reduce the pitting corrosion resistance. No effect of structure – ferritic or austenitic – on the pitting corrosion resistance properties can be observed. Chemical composition and cleanliness are the most important parameters when considering pitting corrosion resistance. Sulfur content, particularly, must be kept at a very low level to obtain sufficient pitting corrosion resistance properties.

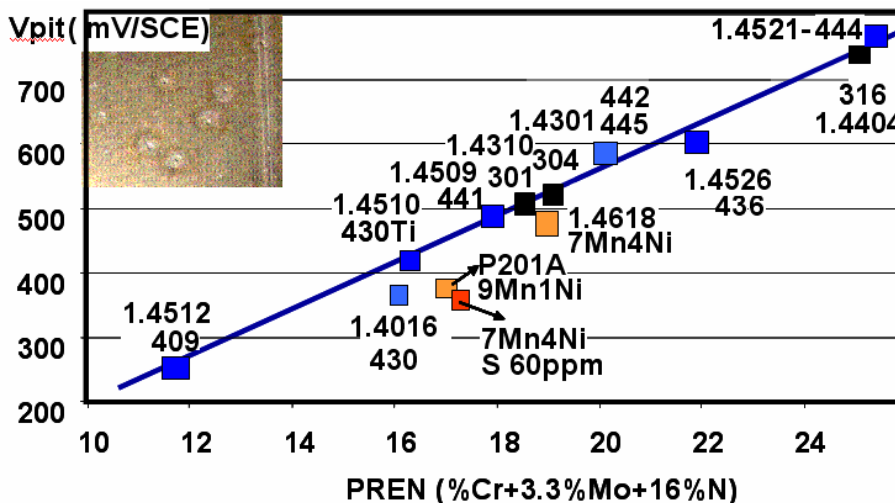


Figure 16. Pitting corrosion resistance properties (critical pitting potential) of several stainless steels. Pitting potentials are plotted versus PREN value. (solution: 0.02 M NaCl, 23°C pH=6.6).

Crevice corrosion is specific to confined zones, such as under a joint or under deposits. The acidity may increase locally triggering the destruction of the passive film. Test results performed in a 2M NaCl solution at room temperature with different pH show that depassivation of the stainless grades is directly related to their composition i.e. Cr and Mo content. No clear effect of structure – ferrite or austenite – is reported.

Electrochemical examination shows that when the pH drops to levels lower than the depassivation pH, current density increases. Clearly ferritic stainless presents higher current density than austenitics. This confirms the in-service properties: where initiated, crevice corrosion propagates very quickly in ferritic structures. Repassivation mechanisms almost never occur in ferritic grades in such acidic conditions. Clearly, standard ferritic grades are not to be used in acidic solutions and crevice-like configurations have to be avoided. Optimum design of equipment is of utmost importance.

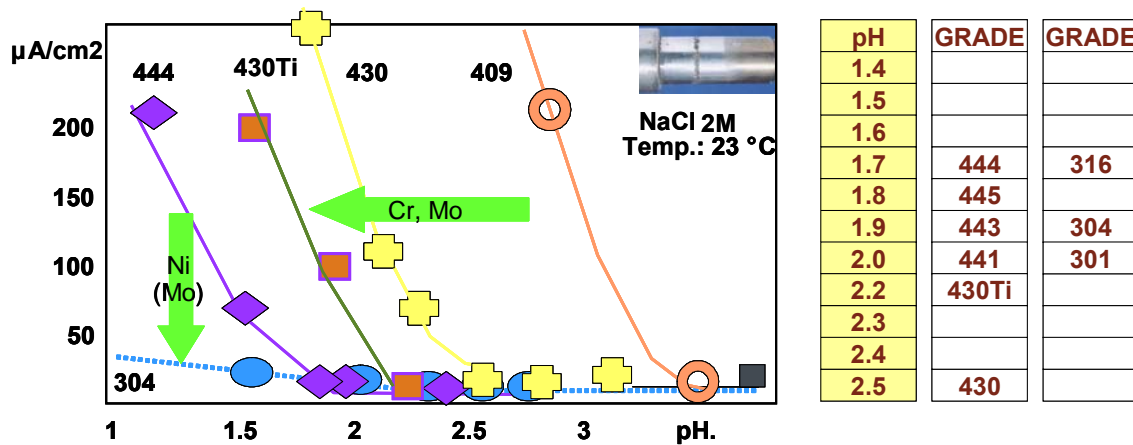


Figure 17. Crevice corrosion resistance data. Tests performed in a 2M NaCl solution at room temperature.

Intergranular corrosion resistance

The most sensitive structure to intergranular corrosion is the HAZ of welded structures. Carbides generally precipitate at grain boundaries and consequently in the case of chromium carbides, chromium depletion areas may form. This is a well known mechanism in austenitic steels. For ferritics, diffusion mechanisms are enhanced and as solubility limits of interstitial elements are very low compared to austenitics, carbides and nitrides will precipitate when the structure is cooled down. In case of non-stabilized grades, chromium diffuses quickly to re-enrich the depleted zones. This is the case in most annealed industrial products. Nevertheless in many cases the as-welded structure – particularly the HAZ – of non stabilized steels remains sensitive to intergranular corrosion. For ferritic welded structures, Ti or Nb stabilized grades are strongly recommended (Figure 18).

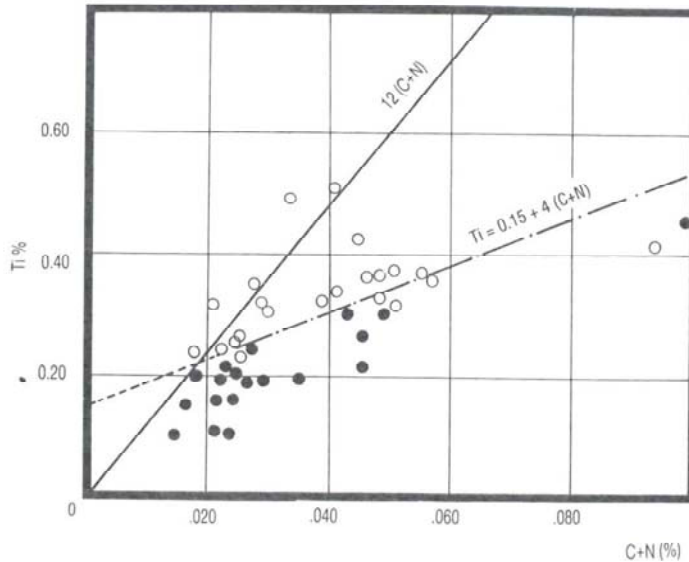


Figure 18. Intergranular corrosion resistance of 17CrTi steels, determined by the sulfuric acid/copper sulfate test on TIG weld seams in 1mm thick sheets

Stress corrosion cracking resistance

In comparison to austenitics, the ferritic stainless steels are generally considered to resist better to stress corrosion cracking in chloride containing environments. However, their resistance is not limitless. Their cracking potential is generally higher than the free corrosion potential. This is related to their deformation mode and relatively poor capacity to repassivate. The risk of cracking mainly appears in concentrated acidic environments. In neutral media, the ferritic steels can generally be used.

Development of high temperature ferritic stainless steel grades

Despite their lower mechanical properties at high temperature compared to those of austenitic grades, ferritic grades exhibit a better resistance to the cyclic oxidation and thermal fatigue and present lower coefficients of thermal expansion [3,4]. Niobium addition improves high temperature mechanical properties significantly, an addition of half a percent or more of molybdenum allows to reach a good resistance in severe internal or external corrosion conditions. Consequently, ferritic grades are well adapted to exhaust system applications (Figure 19).

The increase of the exhaust gas temperature beyond 800°C made the use of titanium stabilized 12% Cr grades (AISI 409, EN 1.4512) impossible and led to the use of high temperature resistant ferritic grades containing 17% Cr and stabilized by both Ti and Nb (AISI 441 EN 1.4509). In such a grade, an excess of niobium improves the mechanical properties at high temperatures, in particular its creep resistance and its thermal fatigue resistance.

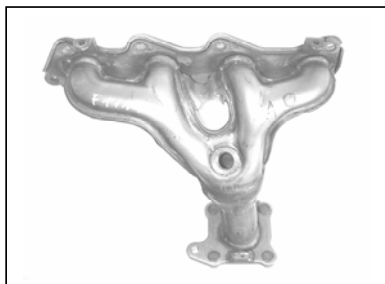


Figure 19. Example of a ferritic stainless steel exhaust Manifold, made of deep drawn clam-shells (Benteler).

A maximal service temperature of 950°C can be reached. On the other hand, the ferritic grades are known to have a lower forming capacity, often illustrated by their moderate elongation (maximal

elongation generally around 35%). The hardening coefficient (n) and the anisotropy r-value are in fact more valuable parameters to characterize the formability. Ferritic grades generally exhibit higher r-mean values. The latter parameter is exactly the one that well controls the deep-drawing of clam-shell made of ferritics.

New ferritic grades for exhaust manifolds

Requirements related to severe forming operations, especially for hydroforming and tube bending, originally lead to the development of a new 14% Cr (1.4595) metallurgy which combined an improved formability compared to the EN 1.4509 (AISI 441), while still keeping its high temperature resistance. This grade can be used in replacement of austenitic grades in many situations, see reference [3]. On the other hand, the Euro V norm will very soon require higher durability (160.000 km) and ability to be used up to 1000°C. ASME has developed a new 19% Cr grade (modified 1.4521) to meet this new demand. The HT mechanical properties are significantly improved as shown by Figure 20.

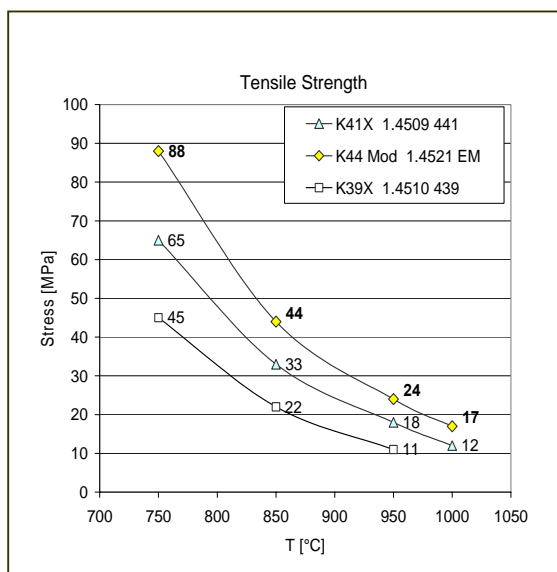


Figure 20. HT tensile strength and Creep sag resistance of the new K44X compared to 1.4509 and 1.4510 ferritic grades

Conclusion

Properties of ferritic stainless steels have been presented. They present a very wide range of chemical analysis – from 11 to 29% Cr. with possible complementary additions of Mo, Al, Ti, Nb...

The grades are the appropriate answer to versatility of alloying element costs. Most of the grades have no expensive nickel additions. They are to be considered for an extremely wide number of applications. Specification must be carefully prepared.

Chromium content can be reduced down to 11-13%. The grades are well designed to replace mild steel with improved corrosion resistance properties.

Several 16-18%Cr ferritic grades are produced. Their corrosion resistance are mainly linked to the chemistry while their mechanical properties (drawability) may be enhanced by appropriate thermomechanical process. Stabilization elements like Nb, Ti must be considered for the most severe conditions and welded structures. The best performing grades are to be considered to replace austenitic 304 grades.

Appliances and decorative pannels often use non stabilized grades. Ti, Nb stabilized grades are typically considered for exhaust applications, welded structures (tubes), collectivities and country side roofings.

For the most severe conditions 20% Cr ferritics have to be considered to replace 304 grades. New grades have been recently designed. They offer new opportunities to replace austenitics in wet corrosion applications and high temperature applications.

Mo containing ferritics are to be considered for the most severe conditions. 444 grade has corrosion resistance properties close to 316 austenitic grades.

The super-ferritics grades having 25% Cr minimum have only marginal applications and are very difficult for manufacturing and transformation.

Ferritic grades are a whole family presenting in most of the applications an alternative solution to 301, 304 and 316 austenitic grades. Their weaknesses are brittleness for the thicker gauges and reduced formability when compared to austenitics. In most of the cases complementary work on modeling, design of the finishing products provides further possibilities to switch from austenitics to ferritics.

Ferritics will continue to grow since they have a unique combination of properties and cost advantages. Learning curve will provide confidence in their uses.

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GROUP 1																
AISI,ASTM	Chemical component (maximum weight %)														Standard	Ref.
	C	Si	Mn	P	S	Cr	Mo	Ti	Nb	Cu	Al	N	Ni			
403(M)	0,15 0,12-0,17	0,50 1,00	1,00 1,00	0,04 0,04	0,03 0,015	11,5-13,0 12,0-14,0									JIS EN	SUS403 1.4024
405,00	0,08 0,08 0,08 0,08	1,00 1,00 1,00 1,00	1,00 1,00 1,00 1,00	0,04 0,04 0,04 0,04	0,03 0,015 0,015 0,03	11,5-14,5 12,0-14,0 12,0-14,0 11,5-14,5					0,1-0,3 0,1-0,3 0,1-0,3		0,60		UNS EN EN JIS	S40500 1.4000 1.4002 SUS405
409 L	0,03 0,03 0,03 0,03 0,03 0,03 0,03 0,03 0,08 0,03	1,00 1,00 1,00 1,00 1,00 1,00 1,00 1,00 0,70 1,00	1,00 1,00 1,00 1,00 1,00 1,00 1,00 1,00 1,50 1,00	0,04 0,04 0,04 0,04 0,04 0,04 0,04 0,04 0,04 0,04	0,02 0,02 0,02 0,02 0,02 0,015 0,015 0,015 0,015 0,03	10,5-11,7 10,5-11,7 10,5-11,7 10,5-11,7 10,5-11,7 10,5-12,5 10,5-12,5 10,5-12,5 10,5-12,5 10,5-11,75		6x(C+N)-0,5 8x(C+N)-0,5 [0,08+8x(C+N)]-0,75 0,05-0,2 0,18-0,4 6x(C+N)-0,75 6x(C+N)-0,65 0,05-0,35 6x C-0,75	0,17 0,10			0,03 0,03 0,03 0,03 0,03 0,03	0,50 0,50 0,50 0,50 0,5-1,0 0,3-1,0 0,50 0,5-1,5 0,60		UNS UNS UNS UNS UNS EN EN JIS	S40910 S40920 S40930 S40945 S40975 S40977 1.4512 1.4516 SUH409L
10%-14%C 410(M)	0,08-0,15 0,08-0,15 0,15	1,00 1,00 1,00	1,00 1,50 1,00	0,04 0,04 0,04	0,03 0,015 0,03	11,5-13,5 11,5-13,5 11,5-13,5									UNS EN JIS	S41000 1.4006 SUS410
410 L	0,03 0,03 0,04 0,03	1,00 1,00 1,00 1,00	1,50 1,00 1,00 1,00	0,04 0,04 0,045 0,04	0,03 0,03 0,03 0,03	10,5-12,5 12,0-13,0 10,5-12,5 11,0-13,5			9(C+N)-0,6			0,03 0,03 0,10	1,50 0,50 0,6-1,10		UNS UNS UNS JIS	S41003 S41045 S41050 SUS410L
	0,03	1,00	1,50	0,04	0,015	10,5-12,5								0,3-1,0	EN	1.4003
410S(M)	0,08 0,08	1,00 1,00	1,00 1,00	0,04 0,04	0,03 0,03	11,5-13,5 11,5-13,5								0,60 0,60	UNS JIS	S41008 SUS4105
420J1(M)	0,16-0,25 0,16-0,25	1,00 1,00	1,00 1,50	0,04 0,04	0,03 0,015	12,0-14,0 12,0-14,0									JIS EN	SUS420J1 1.4021
420J2(M)	0,26-0,40 0,26-0,35 0,36-0,42 0,43-0,5	1,00 1,00 1,00 1,00	1,00 1,50 1,00 1,00	0,04 0,04 0,04 0,04	0,03 0,015 0,015 0,015	12,0-14,0 12,0-14,0 12,5-14,5 12,5-14,5									JIS EN EN EN	SUS420J2 1.4028 1.4031 1.4034
GROUP 2																
AISI,ASTM	Chemical component (maximum weight %)														Standard	Ref.
	C	Si	Mn	P	S	Cr	Mo	Ti	Nb	Cu	Al	N	Ni			
420	0,08 0,08	1,00 1,00	1,00 1,00	0,045 0,04	0,03 0,015	13,5-15,5 13,5-15,5	0,2-1,2 0,2-1,2	0,3-0,5 0,3-0,5						1,0-2,5 1,0-2,5	UNS EN	S42035 1.4589
429	0,12 0,12	1,00 1,00	1,00 1,00	0,04 0,04	0,03 0,030	14,0-16,0 14,0-16,0									UNS JIS	S42900 SUS429
429J1(M)	0,25-0,40	1,00	1,00	0,04	0,03	15,0-17,0									JIS	SUS429J1
14%-18%C 430	0,12 0,08 0,12	1,00 1,00 0,75	1,00 1,00 1,00	0,04 0,04 0,04	0,03 0,015 0,03	16,0-18,0 16,0-18,0 16,0-18,0								0,75	UNS EN JIS	S43000 1.4016 SUS430
1,4017	0,08	1,00	1,00	0,04	0,015	16,0-18,0								1,2-1,6	EN	1.4017
440(M)	0,6-0,75	1,00	1,00	0,04	0,030	16,0-18,0									JIS	SUS440A

GROUP 3																
AISI,ASTM	Chemical component (maximum weight %)														Standard	Ref.
	C	Si	Mn	P	S	Cr	Mo	Ti	Nb	Cu	Al	N	Ni	Other		
430J1L	0,025	1,00	1,00	0,04	0,03	16,0-20,0			8x(C+N)-0,8	0,3-0,8		0,025			JIS	SUS430J1L
430LX	0,03	0,75	1,00	0,04	0,03	16,0-19,0		0,1-1,0					0,60		JIS	SUS430LX
439	0,03 0,05	1,00 1,00	1,00 1,00	0,04 0,04	0,03 0,015	17,0-19,0 16,0-18,0		[0,2+4x(C+N)]-1,10 [0,15+4(C+N)]-0,8			0,15	0,03	0,50		UNS EN	S43035 1.4510
14%-18%Cr stabilised	0,03	1,00	1,00	0,04	0,03	17,0-19,0		[0,2+4x(C+N)]-0,75			0,15	0,03	0,50		UNS	S43932
	0,03	1,00	1,00	0,04	0,015	17,5-18,5		0,1-0,6	[0,3+(3xC)]						UNS	S43940
	0,025	1,00	1,00	0,04	0,015	16,0-17,5			0,35-0,55						EN	1.4590
	0,025	0,50	0,50	0,04	0,015	16,0-18,0		0,3-0,6							EN	1.4520
430TI	0,05	1,00	1,00	0,40	0,015	16,0-18,0		0,60							EN	1.4511
441	0,03 0,03	1,00 1,00	1,00 1,00	0,04 0,04	0,03 0,015	17,5-18,5 17,5-18,5		0,1-0,6 0,1-0,6	9xC+0,3-1 3xC+0,3-1				1,00		UNS EN	S.44100 1.4509
GROUP 4																
AISI,ASTM	Chemical component (maximum weight %)														Standard	Ref.
	C	Si	Mn	P	S	Cr	Mo	Ti	Nb	Cu	Al	N	Ni	Other		
415	0,05	0,60	0,5-1,0	0,03	0,03	11,5-14,0	0,5-1,0								UNS	S41500
434	0,12	1,00	1,00	0,04	0,03	16,0-18,0	0,75-1,25								UNS	S43400
	0,08	0,75	0,80	0,04	0,015	16,0-18,0	0,9-1,4					0,04			EN	1.4113
	0,08	1,00	1,00	0,04	0,015	16,0-18,0	0,8-1,4		[7x(C+N)+0,1]-1,0					EN	1.4526	
	0,12	1,00	1,00	0,04	0,03	16,0-18,0	0,75-1,25								JIS	SUS 434
436	0,12	1,00	1,00	0,04	0,03	16,0-18,0	0,75-1,25		8x(C+N)-0,8			0,025			UNS	S43600
	0,025	1,00	1,00	0,04	0,015	16,0-18,0	0,9-1,4		0,3-0,6					EN	1.4513	
	0,025	1,00	1,00	0,04	0,03	16,0-19,0	0,75-1,25		8x(C+N)-0,8			0,025			JIS	SUS 436 L
1,4419(M)	0,36-0,42	1,00	1,00	0,04	0,015	13,0-14,5	0,6-1,0								EN	1,4419
1,4110(M)	0,48-0,60	1,00	1,00	0,04	0,015	13,5-15,0	0,5-0,8						V≤0,15		EN	1,4110
1,4116(M)	0,45-0,55	1,00	1,00	0,04	0,015	14,0-15,0	0,5-0,8						0,1≤V≤0,2		EN	1,4116
1,4122(M)	0,33-0,45	1,00	1,50	0,04	0,015	15,5-17,5	0,8-1,3						≤1,0		EN	1,4122
1,4313(M)	≤0,05	0,70	1,50	0,04	0,015	12,0-14,0	0,3-0,7					≥0,02	3,5-4,5		EN	1,4313
1,4418(M)	≤0,06	0,70	1,50	0,04	0,015	15,0-17,0	0,8-1,5					≥0,02	4,0-6,0		EN	1,4418
436J1L	0,025	1,00	1,00	0,04	0,03	17,0-20,0	0,4-0,8		8x(C+N)-0,8			0,025			JIS	SUS 436 J1L
444	0,025	1,00	0,7-1,5	0,04	0,03	17,5-19,5	1,75-2,5		0,2+4(C+N)-0,8				1,00		UNS	S44400
	0,025	1,00	1,00	0,04	0,015	17,0-20,0	1,8-2,5		4x(C+N)+0,15-0,8			0,03		EN	1.4521	
	0,025	1,00	1,00	0,04	0,03	17,0-20,0	1,75-2,5		8x(C+N)-0,8			0,025		JIS	SUS 444	
AISI,ASTM	Chemical component (maximum weight %)														Standard	Ref.
	C	Si	Mn	P	S	Cr	Mo	Ti	Nb	Cu	Al	N	Ni	Other		
445	0,02	1,0	1,0	0,04	0,012	19,0-21,0			10x(C+N)-0,8	0,3-0,6		0,03	0,6		UNS	S44500
445J1	0,025	1,0	1,0	0,04	0,03	21,0-24,0			0,7-1,5			0,025			JIS	SUS445J1
445J2	0,025	1,0	1,0	0,04	0,03	21,0-24,0	1,5-2,5					0,025			JIS	SUS 445J2
Others	0,06	0,75	0,75	0,04	0,02	25,0-27,0	0,75-1,5	0,2-1,0		0,05-0,02	0,20	0,04	0,5		UNS	S44626
	0,01	0,4	0,4	0,02	0,02	25,0-27,5	0,75-1,5			0,20	0,015	0,035	3,5-4,5		UNS	S44627
	0,025	0,75	1,0	0,04	0,03	24,5-26,0	3,5-4,5	[0,2+4(C+N)]-0,80			0,035	0,04	1,0-3,5		UNS	S44635
	0,03	1,0	1,0	0,04	0,03	25,0-28,0	3,0-4,0	6x(C+N)-1,0			0,015	0,04	0,5		UNS	S44660
	0,01	0,4	0,4	0,03	0,02	25,0-27,5	0,75-1,5				0,015	0,5		JIS	SUS XM27	
447	0,01	0,2	0,3	0,025	0,02	28,0-30,0	3,5-4,2				0,15	0,02	0,15	(C+N) 0,025	UNS	S44700
	0,03	1,0	1,0	0,04	0,03	28,0-30,0	3,6-4,2		6x(C+N)-1,0			0,045	1,0		UNS	S44735
	0,025	1,0	1,0	0,03	0,01	28,0-30,0	3,5-4,5	4x(C+N)+0,15]-0,8				0,045			EN	1.4592
	0,01	0,4	0,4	0,03	0,02	28,5-32,0	1,5-2,5					0,015			JIS	SUS 447J1
448	0,01	0,2	0,3	0,025	0,02	28,0-30,0	3,5-4,2				0,15	0,02	2-2,5	(C+N) 0,025	UNS	S44800

