Damstahl Academy

Ferritic Stainless Steel

Metallurgy and corrosion – properties and possibilities

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A few years ago, the nickel-free, ferritic, stainless steel was regarded as a bit of a joke. A poor corrosion resistance combined with poor weldability and poor mechanical properties was not enough to compensate for the low price, and ferritic, stainless steels were only considered useful for making very simple, not-critical parts, such as cheap tea spoons.

However, the unpredictable fluctuations of the nickel price during the last few years have changed this pattern markedly. From 2006 to the middle of 2007, the nickel price increased from 15,000 to 55,000 $/ton, and shortly thereafter, it dropped steeply to 30-35,000, and in the time of writing (July 08), the price has landed on 20-21,000 $/ton. Due to its high price, nickel is the price determining element in normal, austenitic stainless steel, and most of the alloy surcharge for an EN 1.4301 steel (= AISI 304) is nickel. For higher alloyed steel types, this pattern is even more evident.

In short, nickel is a pricey and economically unstable element, and a lot could be gained if nickel was bypassed as alloying element. What if one could maintain the corrosion resistance without the nickel?

Fortunately, that scenario is not entirely science-fiction. In most cases, the corrosion resistance depends on molybdenum (Mo) or chromium (Cr), while the main purpose of nickel (Ni) in stainless steel is to stabilize the ductile austenitic phase. Ni owes its presence to mechanical reasons rather than the corrosion resistance, and by cutting down the Ni content, one gets a stainless steel possessing great corrosion resistance at a much lower cost. In short, that is the “secret” of the ferritic stainless steels”: High Cr, perhaps Mo and little or none Ni.

The table below shows the alloy composition of the most common ferritic steel types compared to the common austenitic ones. Please note that the Ni content of the five ferrites is close to zero, while the austenites contain at least 8 % Ni.

EN 1.-	Structure	% C	% Cr	% Ni	% Mo	Andet	AISI (UNS)	SS
4003	Ferritic	≤ 0,08	10,5-12,5	0,30-1,00	-	N ≤ 0,030	410S	-
4016	Ferritic	≤ 0,03	16,0-18,0	-	-	-	430	2320
4509	Ferritic	≤ 0,030	17,5-18,5	-	-	Ti 0,10-0,60; Nb 3xC+0,30-1,00	(UNS 43932)	-
4512	Ferritic	≤ 0,03	10,5-12,5	-	-	Ti 6x(C+N)–0,65	409	-
4521	Ferritic	≤ 0,025	17,0-20,0	-	1,80-2,50	N ≤ 0,030; Ti 4(C+N)+0,15– 0,80	444	2326
4301	Austenitic	≤ 0,07	17,5-19,5	8,00-10,5	-	N ≤ 0,11	304	2333
4306	Austenitic	≤ 0,030	18,0-20,0	10,0-12,0	-	N ≤ 0,11	304L	2352
4307	Austenitic	≤ 0,030	17,5-19,5	8,00-10,5	-	N ≤ 0,11	304L	-
4401	Austenitic	≤ 0,07	16,5-18,5	10,0-13,0	2,00-2,50	N ≤ 0,11	316	2347
4404	Austenitic	≤ 0,030	16,5-18,5	10,0-13,0	2,00-2,50	N ≤ 0,11	316L	2348

Because of the attractive ratio in between corrosion resistance and price, the consumption of ferritic, stainless steels has almost exploded. In 2006, 27 % of the world-wide consumption of stainless steel was ferritic alloys, but in 2010, it is estimated that the percentage may reach as high as 47. In particular the car factories are major consumers of ferritic stainless steel, and as Scandinavia possesses a comparatively small car industry, the 2006 and 2010 numbers for Scandinavia are “only” 15 and 25 %, respectively. This increase is due to household appliances, catering and so.

Pitting Corrosion

In most media, local corrosion resistance is dependent upon the contents of Cr and Mo, and while the ferrites of the past usually contained around 12 % Cr and no Mo at all, the ferrites of today are much higher alloyed and the corrosion resistance correspondingly higher. With respect to pitting corrosion, one of the most destructive types of corrosion for stainless steel, the corrosion resistance, is determined by the Pitting Resistance Equivalent, the PREN:

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

Please note that nitrogen part is being relevant for high-alloyed austenites and duplex steels, and sulphur, phosphorous and others may affect PREN in a negative way.

Empirically, two stainless steel grades with equal PREN numbers posses the same resistance towards initiation of pitting corrosion, and, using the table above, 4301 (AISI 304) has a PREN of 17.5. The ferritic 4509 has exactly the same PREN, which means that the two types 4301 and 4509 can be expected to perform equally well towards pitting corrosion. Similarly, the austenitic 4404 (316L) has a PREN of 23.1 while the ferritic counterpart, 4521, has a PREN of 22.9, making the two types almost identical with respect to pitting corrosion resistance.

Based on their performance against pitting corrosion, 4509 can replace 4301 in many applications, and, similarly, 4521 can replace the “acid resistant” 4401/04 – in both cases at a much lower price, as the pricey Ni does not play any role in the PREN equation.

The above considerations apply for the initiation of pitting corrosion. Should the corrosion, against all precautions, start, Ni is a beneficial element, and corrosion tends to propagate faster in a Ni-free, ferritic steel than an austenitic steel type. However, this is just an additional argument for choosing stainless steel with care. Quite simply, one has to choose a stainless steel where the corrosion will never initiate. Just choose a steel with a sufficiently high PREN.

Stress Corrosion Cracking and General Corrosion

Stress Corrosion Cracking (SCC) is a type of corrosion giving rise to cracks due to a combination of mechanical stress and exposure to certain corrosive media, and it is normally regarded as the most destructive type of corrosion. SCC specifically attacks the austenitic steel types, and in particular the 4301 and 4401/04 groups are vulnerable, particularly in chloride containing media.

As a guideline, SCC is a risk for 4301 at temperatures above only 50-60 ºC while the “acid resistant” 4401 class lasts until 100-110 ºC. This actually makes the austenitic stainless steel inadequate for a number of technical appliances ranging from reactors and distillation columns to heat exchangers, evaporators and drying equipment.

In such conditions, the ferritic stainless steels posses a tremendous advantage, as chloride induced SCC specifically attacks the austenites – not the ferrites. Consequently, the ferritic types can be used in a lot of applications where the austenitic 4301 and 4401 groups will suffer from SCC.

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General corrosion is a type of corrosion, which takes place in either very strong acids or very strong alkalines. In these media, the austenites are normally slightly more resistant than the ferritic alternatives, so for handling extreme pH media it is safer to stick to the traditional steel types.

It should be mentioned that the different types of passive, stainless steel normally can be connected with no risk of galvanic corrosion provided that both types are sufficiently corrosion resistant. Normally, there is no corrosion problems connected with putting i.e. 4301 and 4509 together in the same media.

Mechanical Properties

Mechanically, the differences in between the austenitic and ferritic types are more evident. Measured by HRC, Rp 0.2 or Rm, most ferrites equal the austenitic steel types. However, ferritics possess higher yield strength (Rp0.2) and lower tensile strength (Rm). In general, their mechanical properties are comparable to high strength carbon steels.

A major difference in between the ferrites and the austenites is the elongation, i.e. the possible deformation until breakage. For the austenitic 4301 or 4401 groups, the minimum elongation is around 45 % meaning that these steel types may be stretched and deformed very much, before they break.

In contrast, the ferritic types posses a minimum elongation of 18-20 % which means that they are much less useful in the case of mechanical deformation, such as pure stretch forming. On the contrary, ferritics are more suitable for deep drawing, such as complex exhaust systems. With regards to cold forming, the ferrites are comparable with carbon steels, and less powerful machines are needed in comparison with austenitics. Notably, alloys like 4016 are widely used in i.e. England and Italy for catering purposes. However, do not expect to be able to make a very complicated double kitchen sink from a ferritic stainless steel. In such a case, the traditional 4301 is better.

Another notable difference is the mechanical properties at extreme temperatures, i.e. notch toughness (AV) and creep strength, respectively, although Nb stabilized ferritics deform less than austenitics in response to long term stresses. Unlike the austenites, the ferrites may become brittle at very low temperatures, and they do not maintain their excellent tensile stress at very high temperatures (typically 7-800 ºC and above). In addition, long-term exposure to temperatures in between 400 and 550 °C may give rise to”475°-brittleness”, an “illness” which may also attack the duplex stainless steels in the same temperature range.

In short, the ferritic steels are less useful in extreme temperatures than the austenites; however, ferritics are more suited for cyclic high temperature applications while austenitics are preferably used in isothermal applications. In any case, each and every situation should be evaluated separately.

Despite a shorter elongation (compared to the austenites), the ferrites can be used for deep-drawing. This Syrian made Turkish coffee pot has been made of 4016 (AISI 430), a widely used alloy within the catering business.

Magnetism, Thermal Elongation and Wear

Magnetically, the ferritic stainless steels resemble mild steel. All ferritic stainless steels are strongly magnetic while the nickel containing austenites are either non-magnetic or, in the case of cold working, slightly magnetic.

Also with respect to thermal properties, the ferritic stainless steels are closer to the carbon steels than the austenites. The thermal elongation of the ferrites is about 30-35 % lower than that of the austenitic types thereby reducing the risk of deformation during welding or subsequent operation. This is particular important if the equipment is to be made from both stainless steel and mild steel, as the thermal tension in between the mild steel, and the austenitic steel is larger than in between the mild steel and the ferrites.

With regard to wear, stainless steel against stainless steel has a nasty habit of adhesive wear. This risk may be reduced by choosing two different types of stainless steel (i.e. with two different grain structures). A ferrite against an austenite is a better wear combination than austenite against austenite, although still inferior to well-known combinations as, say, bronze against stainless steel.

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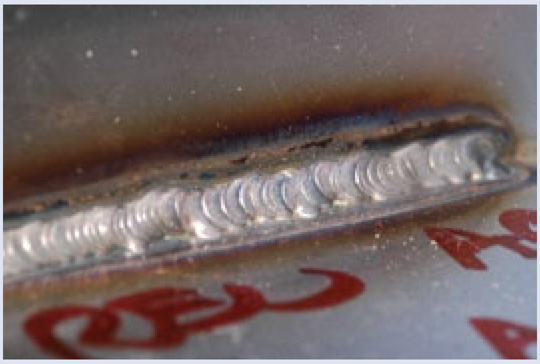
Welding of Ferritic Stainless Steel

In contrast to previous teachings, it is perfectly possible to weld ferritic stainless steel, although they are less foolproof than the austenites. The lack of Ni increases the risk of grain growth and the forma-tion of unwanted phases as a result of the heating. Such effects may cause brittleness and reduced corrosion resistance, and therefore, one has to be more careful when welding the ferrites as compared with the au-stenites, in particular with regard to the heat input. The thicker the steel, the more important it is to keep the heat input low in order to avoid unwanted side effects.



Welded sample of ”acid resistant” ferritic 4521.
Thickness: 2 mm; method: TIG; filler metal: AISI 316LSi;
current: 90 A; and purge gas: pure Ar.

This said, the present-day ferritic steels are much easier to weld than the past generations of steel. This is due to the fact that the higher alloyed ferrites are “stabilized” by adding titanium (Ti) and/or niobium (Nb), both of which stabilize against grain growth during welding. It is essential to employ stabilizers in sufficient quantities, e.g. Ti and/or Nb, both strong carbide formers and blocking grain growth. Thereby, chromium carbides are unable to form during the thermal cycles of welding.

Unstabilized ferritic grades, such as 4016, can therefore be susceptible to intergranular corrosion in the HAZ, due to chromium carbide formation. For this reason, the non-stabilized types, such as 4003 and 4016, are not recommended for welding without a subsequent heat treatment.

4509. 4521 and 4526 and the low-alloyed 4512 (10.5-12.5 Cr, 0 Mo) can be welded (TIG or MIG) by using filler metal type 4430 (20 Cr, 2.5-3.0 Mo) or similar types. In the case of 4512 and 4509, the lower alloyed ”308L” (18-21 Cr, 10-12 Ni, 0 Mo) may be used, although the 4430 provides a better corrosion resistance.

Up to 1-1½ mm thickness, welding can be done with no filler metal at all. No particular problems should occur when welding ferrites (4509. 4521) and austenites (4301. 4401 groups) together. Recommended filler metal is 309L (22-24 Cr, 12-15 Ni, 0 Mo).

An important difference in between the ferrites and the austenites is the use of purge gas. For TIG, wel-ding of ferritic stainless steel, argon (Ar) or argon-helium (< 20 % He) is recommended, while formier gas ($N_2 + H_2$) should not be used due to the risk of grain growth and brittleness. For MIG welding, Ar + 2 % CO_2 is recommended; higher content of CO_2 may give rise to carbide formation (sensitization).

Chemical Surface Treatment

High-alloyed types, such as 4509, 4521 and 4526 can be pickled, passivated and even electro polished, although it is recommended to be more careful than with the austenitic types. This is particularly important with regard to the pickling, as the ferritic steels are generally etched more quickly than the austenites. Only relatively mild nitric acid / hydrofluoric acid pickles should be used, and consequently, welding should be carried out with a minimum of heat tinting.

Passivation may be carried out with a pure nitric acid. The lowest alloyed ferrites, such as 4003 and 4512, can neither be pickled nor electro polished, and passivation should only be done with a dichromate inhibited nitric acid.

Food Appliances and Nickel Problems

Without any problems, ferritic stainless steel may be used in most applications where the austenitic steels are, at present, the state of the art. This includes the food industry, and the ferritic 4016 is widely used for catering purposes in England and Italy, and the higher alloyed 4509. 4521 and 4526 may easily be used in the same business.

A particular advantage with the ferritic steel types is the absence of nickel and with a Ni content of zero, the risk of Ni leaking into the media is equally zero. In contrast, the 4301 and 4404 contain 8 and 10 % Ni, respectively, which (mostly by corrosion) may be leaked into the media. At present, there are no rules and regulations with regard to the use of nickel free steel types in the food industry. However, should this ever be the case, it does not hurt to be ahead of time.

Supply, Dimensions and Prices

The most important ferritic stainless steels are the 4509, the “acid resistant” 4521 and the very popular 4016. They are all available as sheets (various surfaces) and pipes; however, in all cases, the thickness hardly ever exceeds 3 mm, apart from hot-rolled sheets. In any case, the supply time for any ferritic stainless steel may be longer than for the similar austenites, and despite the increasing production and demand it will take a few years until the supply of the ferrites exceeds that of the austenites.

The prices depend upon the steel type, the dimensions, and, of course, the fluctuations in the alloy surcharge. In particular, this is dependent upon the nickel content, for which reason the economical advantage of using the ferrites more or less follows the development in the nickel prices. The higher the nickel price, the larger the economical advantage by switching to ferrites, and depending on the cost evolution of the raw material, especially Ni, 4509 as thin sheets or coil (July 08) is about 25 % cheaper than a similar, austenitic 4301, and the 4016 is even less expensive. As sheet, the acid resistant ferrite 4521 is slightly more expensive than the 4301 which in turn makes it significantly cheaper than the austenitic 4404.

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Advantages, Disadvantages and Possible Applications

The ferrites are less ductile than the austenites (making cold forming a bit more complicated), and the welding process is somewhat more sensitive than that of the traditional austenites. In addition, the reduced supply is bound to have a negative effect, but the ferrites are nevertheless extremely useful. With regard to manufacturing and corrosion, a list of possible pros and cons are, among others, given below:

Fordele	Ulemper
Comparable local corrosion resistance (PREN4509 = PREN4301)	Due to risk of crevice corrosion, more attention for design is needed
Excellent resistance towards SSC; much better than the austenites	Welding parameters are more critical
Good corrosion resistance towards general and intergranular corrosion	Low notch toughness for thicknesses above 3 mm
Pickling, passivation and electro polishing possible	Lower elongation = less suitable for pure stretch-forming
No risk of Ni leakage to food	Reduced toughness at very low (cryogenic) temperatures
Low thermal expansion	Brittleness at long-term exposure to tempera-tures around 475 °C
High thermal conductivity	Magnetic (sometimes a disadvantage)
Less prone to spring-back during cold-forming	Lower availability, in particular thick dimensions; better planning required
Magnetic (sometimes an advantage)	
Lower price!	

Consequently, the “prime targets” of ferritic stainless are:

- Simple equipment with easy bending, stretching and welding
- Thin goods, mainly sheets and coils
- Simple manufacturing
- Large steel costs (= great savings)

A major consumer of stainless ferrites is the car industry of Europe and USA and also within building and construction, industry, mailboxes, signboards, household appliances, white goods and catering there is an expanding market for the corrosion resistant and inexpensive stainless ferrites. The higher alloyed ferrites are bound to replace some of the applications within the 4301 and 4401 groups, and the cheap, low-alloyed 4512 may even replace galvanized steel.

In particular, the weldable alloys, 4509 and 4521 are expected to posses a great future as they - with respect to pitting corrosion - are quite close to the 4301 and 4401 groups, respectively. In these applications, where pitting corrosion is the limitation, it is frequently possible to switch from austenite to ferrite with no loss of corrosion resistance.

Above water (in cold conditions), superficial pitting corrosion is the major problem, and in such cases, 4301 can frequently be replaced by the ferritic 4509 – and the 4401/4 by the 4521. Such replacements are not uncommon in the catering and kitchen industry; however, there is still plenty of room for such substitutions. The 4509 is perfect indoor, and the 4521 is bound to be an inexpensive standard steel for outdoor purposes, where the 4404 is too expensive, and where the 4301 is not good enough – despite the fact that lots of contractors use it almost anywhere.

When SCC is the problem, the advantage of using ferrites is magnified. At temperatures above 60 ºC (for the 4301; about 100 ºC for the 4404 class), extreme care should be taken when using the austenites, and for exhaust pipes, baking ovens or heat exchangers, the ferrites are a much safer choice. By switching from austenites to ferritic stainless steel, one gets a more corrosion resistant material at a lower price. Not a bad combination!