Langley Alloys

FERRALIUM® 255 SD50

The Original Super Duplex Stainless Steel with 85ksi Proof Stress

Super-Duplex
Duplex
Stainless
Copper Alloys
Nickel Alloys

Contents

Aims of the brochure

- To illustrate that copper is a key factor in the corrosion performance of superduplex stainless steels
- To demonstrate that in critical or large sectional parts FERRALIUM 255-SD50 is the superduplex of choice
- To show that, with respect to strength ability and reliability, FERRALIUM 255-SD50 has set new heights for a superduplex alloy
- To bench mark FERRALIUM 255-SD50 with other key alloys within its class.
- To provide information to designers on the properties and corrosion resistance of FERRALIUM 255-SD50 and the current products form and size availability.
- To demonstrate the weakness of PREN as a measure of corrosion performance.

“...higher copper containing superduplex is far less likely to suffer from corrosion...”

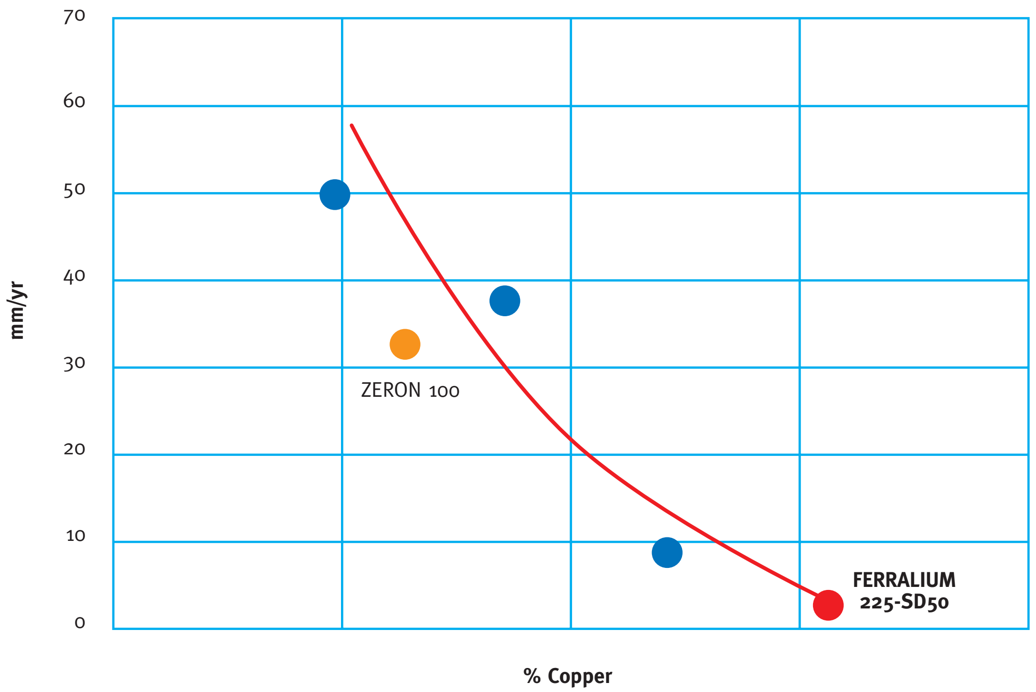
Pitting inhibition - the benefits of Copper

For over 6000 years copper has been recognised as a material with significant corrosion resistance. FERRALIUM 255-SD50 has been designed to harness together this particularly advantageous aspect of copper with the passivating elements chromium and molybdenum in order to produce a superduplex stainless steel with proven enhanced corrosion resistance in chemical and seawater environments.

The beneficial effect of copper in suppressing the corrosion of FERRALIUM exposed to chemical environments and seawater has been proved by work carried out over a number of years at Oxford University, copies of the original Research Papers being available on request. The stability of the passive film on stainless steels, and hence its ability to withstand attack by potentially aggressive chemical species, is the key to corrosion–free handling of seawater and chemical process fluids. FERRALIUM, as a superduplex which has successfully been used in industrial applications for over thirty years, has consistently demonstrated its capability to resist corrosion in chemical and offshore environments. Detailed electrochemical measurements on FERRALIUM 255-SD50, coupled with electron microscopy, has determined that copper actively inhibits pitting corrosion. The mechanism whereby this is achieved involves copper dissolution from the alloy and its re-deposition on active corrosion sites, thus acting to stifle incipient pit growth.

The effect of Copper in acid environments

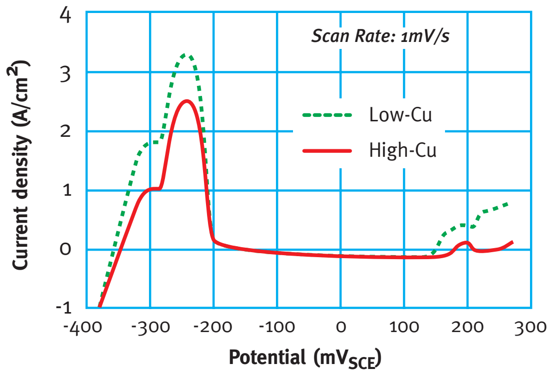
Graph showing the beneficial effect of copper on the corrosion rate of superduplex stainless steels in 70% sulphuric acid at 60°C.



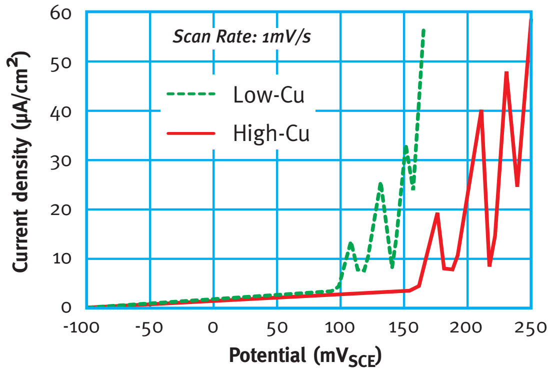
The addition of copper to superduplex stainless steel has an exceptionally advantageous effect on corrosion resistance in sulphuric acid environments. The graph above shows the corrosion rate in 70% sulphuric acid at 60°C taken from tests on range of superduplex stainless steel samples with varying copper levels from 0.5% to 2%. Particular data points from two of the leading alloys of this type, ZERON 100 (0.7%Cu) and FERRALIUM 255-SD50 (1.7%Cu) have been added and these emphasise the favourable effect of copper.

Pitting prevention in Chloride environments

The beneficial influence of copper on the pitting resistance of superduplex stainless steels in chloride environments is shown in the accompanying polarisation curves. These graphs show a comparison of a superduplex stainless steel with a low (0.6%Cu) copper content with that of a superduplex with the same alloy make-up except for a higher (1.6%Cu) copper content. In both hydrochloric acid and sodium chloride environments, the current density trace for the 1.6%Cu alloy displays a lower passive current than that of the 0.6% copper alloy and a pitting potential which is 50-100mV more positive. In practice this means that the higher copper containing superduplex is far less likely to suffer from corrosion in chloride environments.



Electrochemical Polarisation Curves in 1M HCl at 65°C of superduplexes of similar composition containing 0.6% Cu (low-Cu) and 1.6% Cu (high Cu)



Electrochemical Polarisation Curves in 3.5% NaCl at 65°C of superduplexes of similar composition containing levels of copper at 0.6% (low copper) and 1.6% (high copper)

Effect of Copper in environments with Hydrogen Sulphide

Corroborativae evidence of the beneficial effect of copper has been obtained for dual phase steels and ferritic steels exposed to seawater containing dissolved hydrogen sulphide. In these cases, there is evidence that copper heightens the passivating properties of molybdenum in the steel and reacts with absorbed sulphides on the surface, forming insoluble copper sulphide which stifles the debilitating action of hydrogen sulphide.

Effect of H_2S Contamination on Corrosion of Copper-containing and Copper-free Duplex Steels and 13% Cr Steels *Relative loss of Material in Media Containing H_2S (pH 5.5, 50°C, velocity = 50m/s)*		
Alloy Type	**Without Copper**	**With Copper**
Austenitic-Ferritic Steels	6000-7000	30-400
13% Cr Steels	30000-50000	600-700

In conclusion

The presence of copper in superduplex stainless steels has been shown to impart corrosion resistance improvements, as the copper is chemically able to stifle incipient pit growth. FERRALIUM 255-SD50, which contains between 1.5% and 2.0% copper, has been demonstrated to have superior corrosion resistance to superduplexes with lower copper levels in acid environments, seawater and seawater containing H_2S.

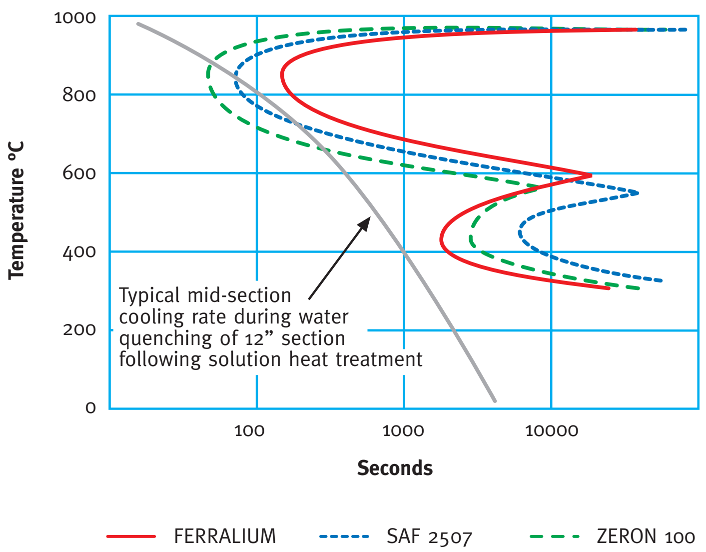
The fact that copper has been shown to benefit corrosion resistance of superduplex emphasises the shortcomings of the use of the pitting resistance equivalent number (PREN) which does not include copper or other influential elements in its derivation. The PREN is calculated solely from the chromium, molybdenum and nitrogen content of stainless steels, and it has been widely used to give a guide to their corrosion resistance. However, the use of this empirically derived number for purposes of specification should be treated with caution as the PREN is no guarantee of corrosion performance. In order to have absolute confidence in any material to be used in service, corrosion testing to determine the critical pitting temperature (CPT) of each batch of material should be undertaken. PREN and CPT will be discussed further on page 13.

“...PREN is no guarantee of corrosion performance...”

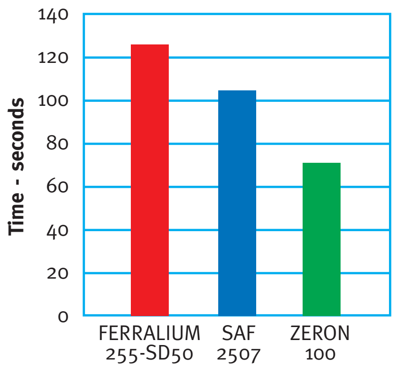
Sigma - a phase to avoid

All high alloy stainless steels are prone to the formation of detrimental intermetallic phases, the most notable of which is the chromium-molybdenum rich phase, sigma, which forms in the temperature range 565°C to 980°C. Of all the possible phases which can form, sigma is by far the worst in terms of its effect on alloy properties, as massive pit formation can occur in chloride environments. The sigma forms in the ferrite phase and strongly encourages pitting in the chromium-molybdenum-depleted ferrite-sigma boundary, with fine distributions of sigma being more pernicious than larger particles. Superduplex stainless steels which contain sigma are thus rendered highly susceptible to intergranular, pitting and crevice corrosion and they also exhibit low fracture toughness, particularly at sub-zero temperatures. Therefore, it is important to know the particular characteristics of the various superduplex stainless steels in terms of the speed of formation of sigma phase and whether appropriate testing of the products can be carried out to determine whether the superduplex is free from sigma.

Transformation Time/Temperature for the three main superduplex stainless steels



Time required to produce a detectable level of sigma phase at a temperature of 850°C (1562°F)



FERRALIUM 255-SD50 - your best solution

“...making FERRALIUM 255-SD50 the preferred alloy for large section forgings...”

Transformation Time/Temperature diagrams for the three main superduplex stainless steels are shown above, together with a line showing the typical cooling characteristics of the central region of a 12" thick superduplex section during water quenching after solution treatment . The upper ‘nose’ of the TTT diagram represents the formation of sigma phase and it can be seen that this intersects the cooling line in the case of UNS S32760 and UNS S32750 but is clear of the cooling curve for FERRALIUM 255-SD50. This means that, due to the relatively slow transfer of heat in superduplex stainless steels, it is very difficult to avoid the formation of sigma phases in UNS S32760 and UNS S32750, making FERRALIUM 255-SD50 the preferred alloy for large section forgings. It has been widely reported that the particular presence of tungsten in duplex stainless steels acts to enhance the formation of sigma and this would appear to be indicated by the enhanced sigma formation characteristics depicted for UNS S32760. The chart above depicts the time required to produce a detectable level of sigma phase at a temperature of 850°C (1562°F), and this clearly demonstrates an advantage of FERRALIUM 255-SD50 over S32760 and S32750. The time taken for sigma phase to develop in FERRALIUM 255-SD50 is significantly slower than both the other superduplexes.

Inhibition of the formation of sigma phase makes FERRALIUM 255-SD50 the most risk-free of the superduplexes for large forgings. Obtaining an adequately fast quench for thick sections is rarely physically feasible, due to the constraints of transfer from heat treatment furnace to quench tank and the relatively slow heat transfer characteristics of the material. As FERRALIUM is the superduplex most able to avoid sigma phase formation during the quenching operation, it has become generally known as 'the most forgiving superduplex'.

FERRALIUM 255-SD50 - guaranteed quality

Having determined that it is difficult to avoid sigma phase formation during the production of superduplex stainless steels, it is imperative that engineers have confidence that sufficient testing is carried out on superduplex components to ensure that sigma phase and other deleterious phases are absent. It is important to realise that the standard ASTM UNS superduplex stainless steel specifications do not stipulate adequate tests of this nature. This is demonstrated on the table below, which lists the international standards applicable to the UNS S32550, UNS 32750 and UNS S32760 superduplex grades together with their mandatory testing requirements. From this table, it is clear that only proprietary FERRALIUM 255-SD50 offers a significantly wide range of tests carried out on a mandatory basis on each batch of product. These tests are designed in the following ways to give assurance to designers, fabricators and engineers that the FERRALIUM 255-SD50 is metallurgically sound and has a consistent set of properties.

- **Impact energy test** at -46°C used to give assurance that the material toughness is appropriate for offshore use. This property would be significantly debilitated, particularly at sub-zero temperatures, by the presence of sigma and other deleterious phases.
- **Ferrite count** used to give assurance that the ferrite level lies between 35% and 55%, the heat treatment was carried out at the correct temperature and the material will behave entirely as a dual phase stainless steel
- **Micrographic examination** at x500 magnification used to give assurance that no sigma or other deleterious macro phases are present in the microstructure
- **ASTM G48A corrosion test** at 50°C used to give certainty that the CPT has a minimum value of 50°C. This demonstrates that the corrosion resistance is good due to the absence of sigma phase and other deleterious phases. Also, this gives assurance that the ferrite/austenite phase balance is correct and that the general impurity content is low.
- **Eddy Current Test** used on bar product to give assurance that crack and surface defects are not present
- **Ultrasonic Test** used to give assurance that internal cracks or voids are not present

FERRALIUM Grade	Specifications	Mechanical Properties	Hardness	Impact (RT)	Impact (-46°C)	Ferrite Count	Micro	Corrosion Test	Corrosion Test G48A 50°C Max Wt Loss 0.8g/m²	Corrosion Test G48A 50°C Max Wt Loss 4.0g/m²	Eddy Current Test	Ultrasonic Test	DP Test
Solution Annealed	**FERRALIUM to MSA-MDS 255-SD50**	●	●	●	●	●	●	●	●		□	●*	○
	FERRALIUM to MSA-MDS 255-SD40	●	●	●	●	●	●	●		●	□	●*	○
	FERRALIUM to MSA-MDS 255-3SF (Forgings)	●	●	●	○	○	○	○		○		●	●
	NORSOK MDS D51 to D55 and D57	●	●	●	●	●	●	●		●			
	ASTM A479 Bar	●	●										
	ASTM A240 Sheet and Plate	●	●										
	ASTM A473 Forgings	●	●										
	ASTM A182 Forged Flanges/Fittings Grade F61	●											
	ASTM A276 Condition A	●	●										
	ASTM A790/A789 Seamless and Welded Pipe	●	●										
	ASTM A815 Pipe Fittings	●	●										
	ASME Approval as Table UHA 23 and Code Case 1883	●	●										
Cold Worked	**FERRALIUM to MSA-MDS FG-46 Bar**	●	●	●	●	●	●	○				●	○
	ASTM A276 Condition S	●	●										
Age Hardened	**FERRALIUM to MSA-MDS-51VA-Bar/Forgings**	●	●	●		●	●	●			●	●	
	Stamicarbon 21022	●	●			●	●	●			●	●	
	Stamicarbon 18005 MS47	●	●			●	●	○			○		
	Stamicarbon 53961 MS47	●	●			●	●	○			●		
Castings	**FERRALIUM to MSA-MDS-41VS-Castings**	●	●	●									
	ASTM A890 Grade 1C, UNS J93373, ACI CD3MCuN	●											

○ *Testing is carried out according to specific contract details*

* *FERRALIUM SD50 and SD40 is ultrasonic tested according to specific contract details*

□ *Eddy Current testing is carried out on smaller diameter bars only*

In Conclusion

Due to the complex nature of superduplex stainless steels, the ease with which sigma and other deleterious phases can be formed during manufacture and the physical impossibility of sufficiently fast quenching, it is apparent that the production of large section FERRALIUM 255-SD50 is much more risk-free than other superduplexes. Thus, FERRALIUM 255-SD50 particularly lends itself to large forgings, where the formation of sigma is much less likely than it is for other superduplexes.

FERRALIUM 255-SD50 - a chemistry of precision

In order to ensure complete reliability, FERRALIUM 255-SD50 has been developed with a notably precise chemistry range and minimised impurity levels. The benefits which these characteristics impart to the alloy can be listed as:

- Overall consistency of properties
- Enhanced mechanical properties
- Increased corrosion resistance

The chemical compositions of three current FERRALIUM 255-SD50 product groups is shown below, illustrating the restricted composition range compared to that of international standards representing generic grades of similar types of duplex stainless steel. The restricted composition of FERRALIUM 255-SD50 enables complete control of product consistency and also gives the alloy reliability for application in seawater and chemical processing plant. This is due to the fact that tight control of chemistry has a direct correlation to consistent performance in service.

Specification	Cr	Ni	Mo	Cu	N	W	Si_{max}	Mn	P_{max}	S_{max}	C_{max}	Fe
FERRALIUM 255-SD50	**24.50-26.50**	**5.50-6.50**	**3.10-3.80**	**1.50-2.00**	**0.20-0.25**	- -	**0.70**	**0.80-1.20**	**0.025**	**0.005**	**0.025**	**Rem**
FERRALIUM 255-SD40	**24.0-27.0**	**4.5-6.5**	**2.9-3.9**	**1.50-2.50**	**0.10-0.25**	-	**1.00**	**1.50**	**0.040**	**0.030**	**0.04**	**Rem**
FERRALIUM 255-3SF	**24.0-27.0**	**4.5-6.5**	**2.9-3.9**	**1.50-2.50**	**0.10-0.25**	-	**1.00**	**1.50**	**0.040**	**0.030**	**0.04**	**Rem**
FERRALIUM Cast	**24.0-26.0**	**5.50-7.50**	**2.7-3.9**	**1.00-2.00**	**0.14-0.25**	- -	**0.75**	**2.00 max**	**0.035**	**0.010**	**0.03**	**Rem**
UNS S32550	24.0-27.0	4.5-6.5	2.9-3.9	1.50-2.50	0.10-0.25	-	1.00	1.50	0.040	0.030	0.04	Rem
UNS S32750	24.0-26.0	6.0-8.0	3.0-5.0	0.50 max	0.24-0.32	-	0.80	1.20	0.035	0.020	0.030	Rem
UNS S32760	24.0-26.0	6.0-8.0	3.0-4.0	0.50-1.00	0.20-0.30	0.50-1.00	1.00	1.00	0.030	0.010	0.030	Rem

NB. All standard grades of FERRALIUM meet a minimum of PREN 40

Superduplex Stainless Steels - chemical comparisons

A comparison of the chemical composition ranges of the three major superduplex stainless steel grades is given in the table shown above. A significant difference exhibited by the chemistry of both FERRALIUM 255-SD50 and UNS S32550 is the presence of 2% copper as one of their alloying additions. This element has been purposely included to impart particular corrosion resistance to the alloy in chemical plant and seawater applications. The other two superduplexes contain less copper than FERRALIUM 255-SD50 and UNS S32550. As a consequence, they do not exhibit the same degree of resistance to corrosion in common chemical environments. Also, FERRALIUM 255-SD50 contains a lower quantity of those elements which can cause the generation of deleterious phases in manufactured products. Such elements are tungsten, which favours the formation of sigma phase, and nitrogen, which encourages the presence of nitride phases. Thus, FERRALIUM 255-SD50 is generally known as the most forgiving of the superduplexes in terms of the ease of manufacturing intermetallic-free hot worked products.

"...control of chemistry has a direct correlation to consistent performance in service..."

The melting and processing of FERRALIUM 255-SD50 are carried out under exacting controlled conditions to detailed manufacturing procedures. Electric arc melting and argon-oxygen decarbonisation/ desulphurisation are carried out during the melting process and the degassing procedure is carefully controlled, these steps being taken in order to minimise the level of impurities present. Also, at all stages of the production process, hot working temperatures are restricted to as narrow a range as possible to ensure that intermetallic phase generation is minimised. The final stage heat treatment is followed by a rapid transfer to quench tank and fast water quench, both of which processes are carefully monitored to maintain the correct austenite/ferrite phase balance and the absence of deleterious phases in the microstructure. A mandatory microstructural examination is made of all FERRALIUM 255-SD50 production batches to verify the clarity of the metallic structure.

FERRALIUM - mechanical properties

As a continuation of FERRALIUM's premier role at the forefront of superduplex technology, FERRALIUM 255-SD50 now sets a new bench mark for superduplex as the first to state 600N/mm² as the minimum 0.2% Proof Stress, as shown in the table below. This advantage given by FERRALIUM allows equipment designers the ability to reduce section thickness and therefore weight and cost if FERRALIUM 255-SD50 is used as the superduplex of choice.

Minimum mechanical properties

Grade	0.2% Proof Stress (N/mm²)	[ksi]	Ultimate Tensile Strength (N/mm²)	[ksi]	Elongation (%)	Hardness (HBN)	Impact (J) [20°C]	(J) [-46°C]
FERRALIUM 255-SD50 Bars up to 4"Ø	**600**	**[87]**	**790**	**[114.6]**	**25**	**270max**	**80**	**45**
FERRALIUM 255-SD50 Bars above 4"Ø	**586**	**[85]**	**790**	**[114.6]**	**25**	**270max**	**80**	**45**
FERRALIUM 255-SD50 Plate	**570**	**[82]**	**790**	**[114.6]**	**25**	**270max**	**80**	**45**
FERRALIUM 255-SD40	**550**	**[79.8]**	**760**	**[110.3]**	**25**	**270max**	**80**	**45**
FERRALIUM 255-3SF	**550***	**[79.8]**	**750***	**[108.8]**	**25***	**270max**	**80**	
FERRALIUM 255-FG46	**720**	**[103.5]**	**860**	**[124.8]**	**16**	**220-335**		**40**
FERRALIUM 255-3AF	**570**	**[82.6]**	**860**	**[120.4]**	**23**	**250-330**	**70**	
FERRALIUM 255-3SC	**450**	**[65.3]**	**700**	**[101.5]**	**25**	**270max**	**80**	
UNS 32550, UNS 32750, UNS 32760	550	[79.8]	750	[108.8]	25	270max		

**Minimum mechanical properties can be matched to specific contract details if required*

In torsion FERRALIUM 255-SD50 shows typical values for 0.2% proof stress of 450N/mm² and 850N/mm² for ultimate tensile strength with an angle of twist of 1020°. It should be emphasised that FERRALIUM 255-SD50 in all aspects satisfies the requirements of the previous FERRALIUM alloy grades FERRALIUM 255, FERRALIUM 255-3SF and FERRALIUM SD40.

FERRALIUM - galvanic compatibility

FERRALIUM 255-SD50 is galvanically compatible with a number of metals and alloys. It is relatively 'noble' in a galvanic table, comparing with titanium, and has a rest potential of +0.04 volts (SCE) in 3% NaCl. Care is required when used in combination with some less noble materials where insulation between the two materials may be needed. The relative area of noble to less noble alloy is important in addition to the potential difference.

FERRALIUM is used successfully in combination with the high strength cupronickels HIDURON and MARINEL in subsea control equipment and in the control gear for submarine bow planes. It is generally found to be galvanically compatible with copper alloys containing aluminium as an alumina based protective layer is formed which acts to provide a degree of electrical insulation.

In Conclusion

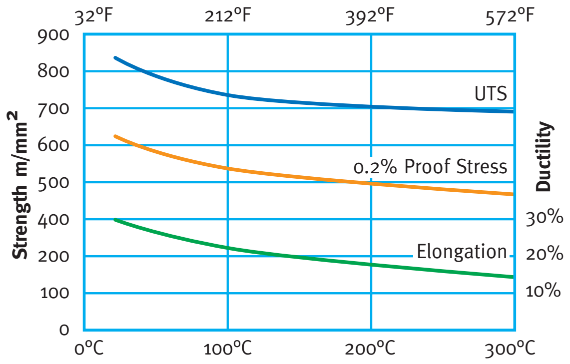
The chemistry of FERRALIUM is be very carefully selected and tightly controlled to ensure that phase balance is correct and impurities are kept as low as is physically possible. As well as chemistry, the production technology for the melting and processing of FERRALIUM has been maintained at the forefront of materials manufacturing science, resulting in the latest grade of FERRALIUM, FERRALIUM 255-SD50, being the first superduplex to guarantee a minimum 0.2% Proof Stress of 600N/mm².

Also, as it is imperative that engineers have confidence that sufficient testing is carried out on superduplex components to ensure that harmful phases are absent, both FERRALIUM 255-SD50 and FERRALIUM 255-SD40 must undergo a high degree of mandatory testing. These tests are designed to guarantee that the trade-marked product possesses high integrity, a correct phase balance and the absence of sigma and other deleterious phases.

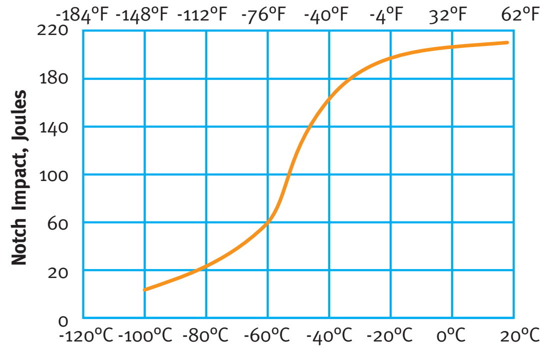
"...FERRALIUM 255-SD50 first to set 600N/mm² bench mark for superduplex..."

Typical mechanical properties - non-ambient temperatures

Typical mechanical properties and impact properties achieved over a range of temperatures are shown in the graphs below. It can be seen that FERRALIUM 255-SD50 maintains a high level of notch ductility at subzero temperatures. In common with all duplex and superduplex stainless steels, the recommended maximum continuous operating temperature for FERRALIUM 255-SD50 is 275°C [527°F]. The alloy can be used for occasional short periods at slightly elevated temperatures but care should be exercised.



Graph showing the typical mechanical properties of FERRALIUM 255-SD50 at elevated temperatures



Graph showing the typical impact properties of FERRALIUM 255-SD50 at ambient and subzero temperatures

“FERRALIUM 255-SD50 maintains a high level of notch ductility at subzero temperatures”

FERRALIUM - allowable design stresses

Allowable design stresses (ASME VIII) for a number of materials are shown below in tabular form. Due to the higher minimum properties offered for FERRALIUM 255-SD50 compared to the other commercial superduplex stainless steels, there is an opportunity to reduce component dimensions and therefore weight by preferentially using FERRALIUM. The ASME figure shown here for S32550, pertains to a minimum 0.2% Proof Stress figure of 550N/mm². Thus, it is expected that the higher minimum 0.2% Proof Stress figure of 600N/mm² for FERRALIUM 255-S50 would produce the allowable design stress of 197N/mm². This would allow more scope for designers to reduce weight and cost, not only by thickness but also by size. In the case of tube product, with the added consideration of the high erosion resistance of FERRALIUM, there could be a reduction in the weight of any contained liquid. FERRALIUM 255-SD50 sheet, plate, bar, pipe and tubing are covered by **ASME code case No.1883**.

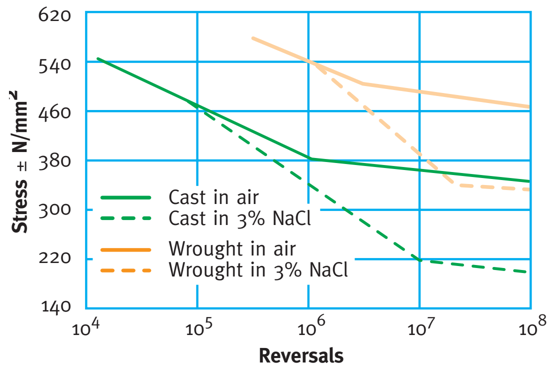
Alloy	**Allowable Design Stress, [ASME VIII] (N/mm²)**
FERRALIUM 255-SD50	**197***
UNS S32550, UNS S32760, UNS S32750 Superduplexes	190
UNS S31260 Duplex (25%Cr , low copper with tungsten)	187
HASTELLOY® alloy C-276	172
UNS S31803 Duplex (22% Cr)	162
INCOLOY® alloy 825	146
UNS S31254 6% Mo Austenitic	155
CARPENTER 20 Cb-3®	137
UNS S31600 Austenitic	108
Cu/Ni (90/10)	70

**Figure based on increased mechanical properties, pending ratification by ASME*

FERRALIUM - fatigue characteristics

FERRALIUM possesses excellent resistance to fatigue and corrosion fatigue, as shown in the accompanying graphs. The results for FERRALIUM 255-SD50 make the alloy particularly suitable for rotating items such as shafts in seawater and chemical environments.

“FERRALIUM... shows excellent resistance to both abrasion and corrosion”

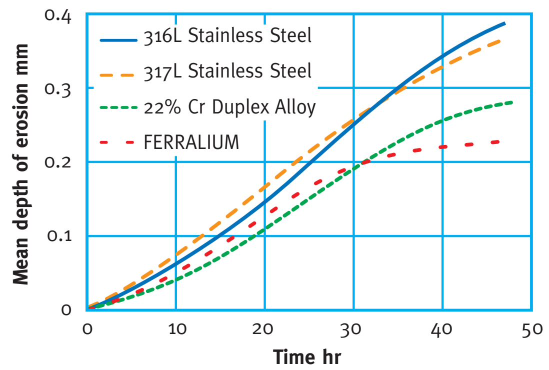


Graph showing the fatigue and corrosion fatigue properties of FERRALIUM 255-SD50 as wrought and cast product forms

FERRALIUM - erosion and abrasion properties

The resistance of FERRALIUM 255-SD50 to erosion, abrasion and cavitation-erosion is extremely good and is superior to standard and high alloy austenitic alloys and other duplex stainless steels. Many long established applications utilise this property to advantage in agitators, pumps and valves. For instance, hot acid gypsum slurries are handled very successfully by FERRALIUM pumps, with casings and high speed impellers produced in the alloy.

FERRALIUM propellers on fast patrol boats have shown good resistance to cavitation-erosion.



Graph showing comparative cavitation erosion properties of FERRALIUM 255-SD50 as determined using the ASTM G32 vibratory cavitation erosion test method

FERRALIUM - typical physical properties

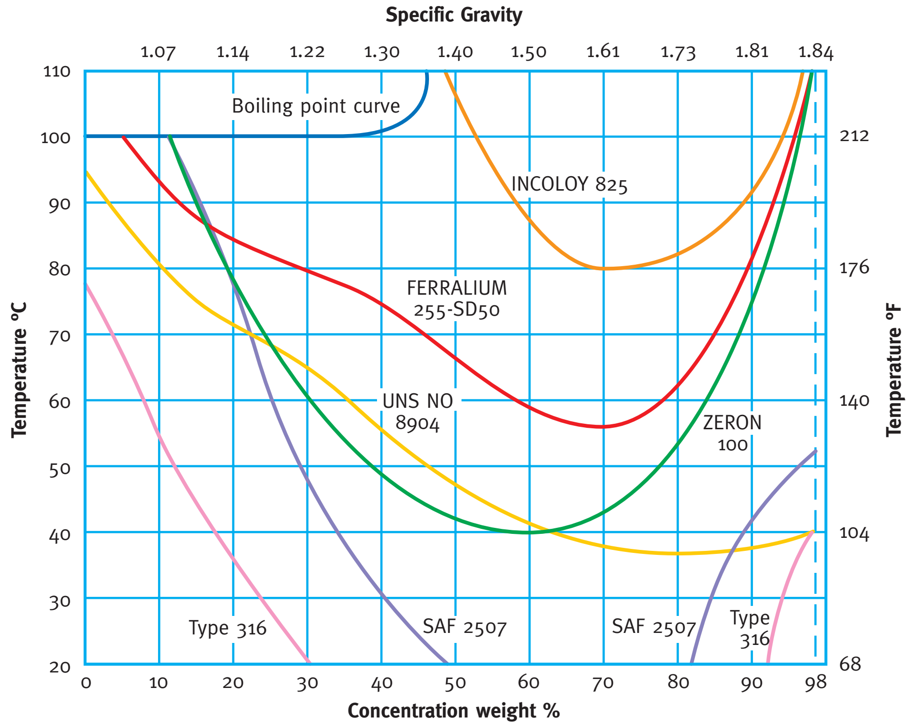
Density at 20°C g/cc	**7.81**	
Mean Coefficient of Thermal Expansion °K^{-1}	20 - 100°C 20 - 200°C 20 - 300°C	11.1 x 10^{-6} 11.5 x 10^{-6} 12.0 x 10^{-6}
Thermal Conductivity, W/M°K	20°C 100°C 200°C	14.2 16.3 18.4
Specific Electrical Resistance, Microhm-m	20°C 100°C 200°C	0.80 0.88 0.93
Specific Heat, J/Kg.°K	20°C 100°C 200°C	475 500 532
Magnetic Permeability	33	
Young's Modulus, MPa	199 x 10^3	
Compression Modulus, MPa	150 x 10^3	
Torsional Modulus, MPa	75 x 10^3	
Fracture Toughness, K_Q, MPa .m$^{1/2}$	98	
Poisson's Ratio	0.32	

FERRALIUM in chemical environments

Sulphuric Acid

As explained previously, the presence of copper in FERRALIUM 255-SD50 is particularly beneficial regarding corrosion behaviour in sulphuric acid. In this medium, FERRALIUM 255-SD50 exhibits higher corrosion resistance than the two other main superduplex stainless steels, S32750 and S32760. The isocorrosion curve (at 0.1mm/y) for sulphuric acid is shown, and the gradation of behaviour between FERRALIUM 255-SD50, Zeron 100 and SAF 2507 is noted, these alloys nominally containing 1.7% copper, 0.75% copper and less than 0.5% copper respectively.

"FERRALIUM 255-SD50 clearly demonstrates its superiority, with a 40 times greater life expectancy than its nearest rivals"



Comparative Isocorrosion Curves shown at a Corrosion Rate of 0.1mm/y in Sulphuric Acid

From the isocorrosion curves shown above, it can be seen that the nickel alloy INCOLOY 825 has the highest corrosion resistance of the materials displayed. All the alloys have the same shape of curve, with the lowest corrosion resistance generally being in the range 50% to 80%. Of the three superduplex stainless steels shown, FERRALIUM 255-SD50 (1.50%-2.00% Cu) shows the highest resistance to corrosion. ZERON 100 (0.50%-1.00% Cu) and SAF 2507 (maximum 0.5% Cu) exhibit progressively lower corrosion resistances, giving a clear relationship of corrosion resistance to copper content for the three superduplexes. A pictorial comparison of the corrosion properties of the FERRALIUM 255-SD50 and ZERON 100 superduplexes together with 316 stainless steel is shown in the photographs displayed. These show the surfaces of coupons of rolled sheet following exposure for 48 hours in 70% sulphuric acid at 37°C. The relative corrosion rates determined for the alloys after exposure, as measured by weight loss, are given below the photographs and these demonstrate that FERRALIUM would have comparative life of sixty times that of 316 and forty times that of ZERON 100 in this environment. Thus, FERRALIUM 255-SD50 clearly demonstrates its superiority, with a forty times greater life expectancy than its nearest rivals.

Corrosion test results after immersion in 70% wt Sulphuric Acid at 37°C for 48 hours. Corrosion rates based on weight loss are given below.

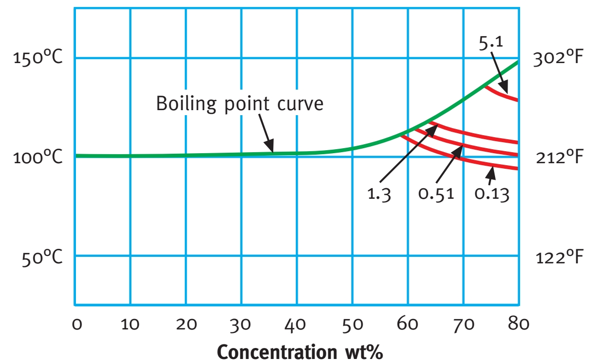
FERRALIUM 255-SD50
0.05mm per year

ZERON 100
2.00mm per year

316
3.00mm per year

Phosphoric Acid

Although 316 stainless steels are generally resistant to pure phosphoric acid in all concentrations at temperatures up to around 80°C, FERRALIUM 255-SD50 alloy shows marked superiority and is generally suitable for handling the boiling acid up to 60% concentration. For higher concentrations of phosphoric acid, there would be an operating temperature limit of 110°C. The iso-corrosion curve for FERRALIUM 255-SD50 is given below.



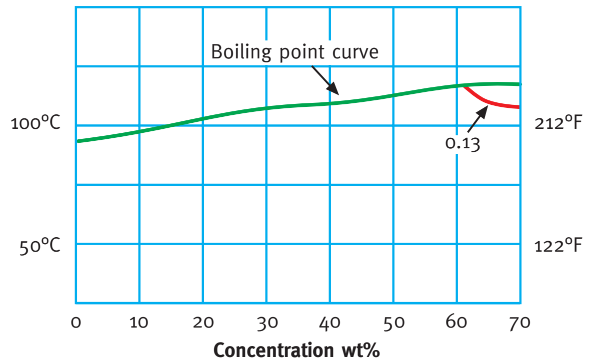
Isocorrosion Curves for FERRALIUM 255-SD50 in Phosphoric Acid shown at Corrosion Rates of 0.13mm/y, 0.51 mm/y, 1.3 mm/y and 5.1mm/y.

FERRALIUM 255-SD50 shows outstanding resistance to commercial phosphoric acid containing impurities such as fluorides, chlorides and sulphuric acid (see corrosion resistance guide). This, combined with its excellent resistance to abrasion and erosion from the high gypsum solids content, renders FERRALIUM 255-SD50 of special interest for pumps, valves, agitators and other critical components in the production of fertilizer grade acid by the 'wet' process. The alloy continues to perform well in this processing environment and under other extremely demanding service conditions around the world. FERRALIUM 255-SD50 has often replaced the more costly nickel base alloys and provided economic service when considering life/cost assessment.

"FERRALIUM replaces your more costly nickel based alloys"

Nitric Acid

The iso-corrosion curve for FERRALIUM 255-SD50 in nitric acid is shown below, demonstrating that the material is resistant to corrosion in this environment over a wide range of concentrations. Thus, FERRALIUM 255-SD50 is commonly used for handling nitric acid and the alloy successfully resists a wide range of acid mixtures such as sulphuric/nitric, phosphoric/nitric and nitric/adipic.



Isocorrosion Curve for FERRALIUM 255-SD50 in Nitric Acid shown at a Corrosion Rate of 0.13mm/y.

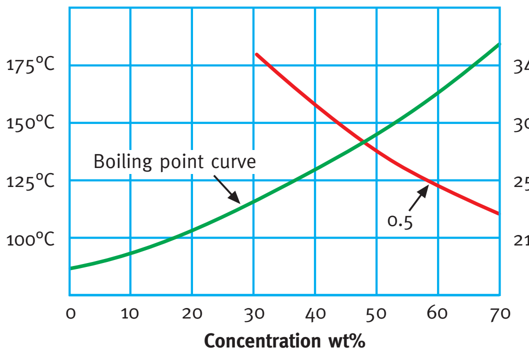
Chemical Plant Life/Cost Assessment

Chemical plant life/cost assessment can be carried out on a basis which recognises that nickel alloys are more long-lasting in sulphuric acid but with the consideration that this gain is made at an added cost which represents a 2-3 times increase in material costs. Thus, the increased expense of using INCOLOY 825 is only justified if it represents a doubling in the life of the plant.

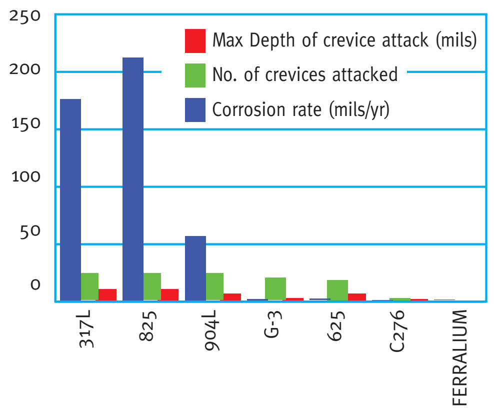
Other common chemical environments

FERRALIUM 255-SD50 is highly resistant to acetic, formic and other organic acids. It is particularly suitable for the higher concentrations and temperatures where pitting is a common cause of failure with most conventional austenitic stainless steels in the presence of halides and other impurities.

An isocorrosion curve (0.5mm/year) for FERRALIUM 255-SD50 in high temperature solutions of sodium hydroxide is shown, as these environments are particularly encountered in the Bayer process for bauxite purification.



Isocorrosion Curve for FERRALIUM 255-SD50 in Sodium Hydroxide shown at a Corrosion Rate of 0.5mm/y



A chart showing the comparative corrosion behaviour of a number of alloys in a simulated FGD process environment of 45, 000 ppm Cl- [0.003% $FeCl_3$, 0.11% KCl, 0.5% $MgCl_2$, 1.1% $CaCl_2$, 0.02% CaF_2, 5.56% NaCl, 200 g/l $CaSO_4.2H_2O$] at 66°C, pH ~2.5 with SO_2/O_2 (1:1) bubbled through the solution.

“faster processing makes FERRALIUM the cost effective alloy for the pulp and paper industry”

Flue Gas desulphurisation plant environments

Flue gas desulphurisation (FGD) for pollution control is now undertaken on a number of coal burning power plants and the correct choice of materials to resist corrosion and erosion in plant to reduce sulphur dioxide emissions is vital to ensure reliable operation. The excellent resistance of FERRALIUM 255-SD50 to corrosion and erosion in the hot acid gypsum slurries which develop in 'wet' process phosphoric acid production originally indicated the suitability of the alloy for equipment such as pumps, valves, agitators, mixers and seals in FGD plant. This has been borne out in the process experience obtained for FERRALIUM used in FGD applications in the USA and UK.

Comparative tests have been carried out on a number of alloys in a variety of simulated FGD environments. Crevice corrosion test results in a simulated SO_2 scrubber environment are summarised in the bar chart shown and demonstrate that FERRALIUM ranked highest out of seven alloys tested as it exhibited no crevice attack. FERRALIUM 255-SD50 is also up to three times less expensive than HASTELLOY C-276 and INCOLOY 625.

Pulp and Paper Plant

FERRALIUM has been successfully used to replace shorter-lived stainless steels in chlorine dioxide environments involved in the bleaching process in paper pulp production. Rotors, shafts and filter plate components have been found to be very cost effective and its high strength has enabled faster processing speeds to be employed.

FERRALIUM 255-SD50 - pitting resistance evaluation

Assessment of resistance to pitting is often made by use of a pitting resistance equivalent number (PREN) which is a function of the chromium, molybdenum and nitrogen content of the alloy. Calculation is made on the basis of the following, using weight %:

PREN = % Cr + 3.3x% Mo + 16x% N

However, it must be appreciated that the PREN is not an absolute measure of pitting resistance as it can only give an indication of the potential corrosion properties of superduplex stainless steel. The PREN does not take into account the metallurgical state of the material after manufacture and the possible presence of deleterious phases which would promote corrosion. Also, it is also somewhat incongruous to use a single PREN for superduplex, as this material consists of two phases with different chemical compositions.

A more realistic evaluation of corrosion resistance can be made using the Critical Pitting Temperature (CPT), defined as the maximum temperature attainable without detectable weight loss or evidence of pitting corrosion when a stainless steel is exposed to 6% ferric chloride solution. CPT is determined through the use of the standard corrosion test ASTM G48 Method A. As this test is designed to be carried out on a sample taken from the final product, it gives a definitive assessment of the material's ability to resist pitting.

The table shows typical CPT values and demonstrates the superior corrosion characteristics for FERRALIUM 255-SD50. The mandatory determination of CPT for each batch of FERRALIUM 255-SD50 to ensure that it exceeds a temperature of 50°C gives confidence that the FERRALIUM manufacturing procedures are thoroughly under control.

Stainless Steel	CPT
FERRALIUM SD-50	50°C
UNS S31803	20°C
CN-7M modified (4.5 Mo)	20°C
316 stainless steel	0°C

FERRALIUM - Intercrystalline corrosion & stress

Corrosion properties

High chromium stainless steels do not normally suffer from intercrystalline corrosion. In austenitic steels, intergranular corrosion attack can occur as a result of chromium denudation along a continuous grain boundary network, due to the precipitation of carbides. The low impurity content and dual phase structure of FERRALIUM, with its network of austenite within a ferrite matrix, allows a proportion of chromium to be present in the austenite. This is able to act to prevent severe chromium denudation at the grain boundaries and thus mitigates against intergranular corrosion.

“FERRALIUM is suitable for sour service applications.”

U-bend test results (30-day exposure) comparing 316 stainless steel with FERRALIUM 255-SD50 are given in the accompanying table

Media	Exposure time (days)	Temperature (°C)	316 Stainless Steel	FERRALIUM 255-SD50
ASTM Synthetic Seawater	30	80	Pitting	No pitting or cracking
0.8%NaCl + 0.5% Oxalic acid	30	141	No cracking	No cracking
0.8%NaCl + 0.5% Acetic acid	30	141	Cracking	No cracking
0.8%NaCl + 0.5% Citric acid	30	141	Cracking	No cracking
0.1%NaCl + 0.05% $FeCl_3$	30	100	Cracking	No cracking
25% NaCl	21	200	-	No cracking
30% NaCl	100	Boiling	-	No cracking

U-Bend stress corrosion cracking tests have also been carried out on FERRALIUM 255-SD50 in a sulphide-containing acidic environment. This consisted of a solution of 70,000 ppm NaCl with 35% CO_2 at 760 psi and 70 ppm sulphide. No cracking was observed to occur.

FERRALIUM has been tested by static loading in NACE TM -01-77 acidic sulphide solution at 20°C and 80°C and has been found to be not susceptible to sulphide stress corrosion cracking at 90%-100% of the 0.2% proof stress. FERRALIUM alloy in its standard solution treated and stress relieved condition meets the requirements of NACE MR-01-75 in that it has a hardness which is less than 28 HRC. Thus FERRALIUM is suitable for sour service applications.

FERRALIUM 255-SD50 - Fabrication

Welding

All product forms of FERRALIUM 255-SD50 can be easily welded, and this includes welding FERRALIUM to other stainless steels. Welding can be carried out by all the usual methods although oxy-acetylene welding and electron beam welding have been found to be not suitable. As a result of FERRALIUM 255-SD50's welding versatility, the designer is provided with full scope to incorporate both castings and wrought forms into a single assembly. It should be emphasised that only genuine FERRALIUM 255 electrodes and filler wire should be used, so as to ensure sound welds and a satisfactory weldment in respect of mechanical strength, ductility and corrosion resistance.

FERRALIUM 255-SD50 alloy is normally supplied in the solution treated and stress relieved condition, which is ideal for welding. Welds in light sections and minor repair welds do not generally require post-weld heat treatment but heavy section welds should be given a solution heat treatment after welding to ensure maximum corrosion resistance and ductility.

A detailed welding information document is available upon request - please discuss any specific welding details required with our Technical Department. FERRALIUM 255-SD50 alloy can be welded to carbon steel, austenitic stainless steels and other metal based alloys using suitable welding consumables.

Heat Treatment

The solution heat treatment process for FERRALIUM 255-SD50 is carried out at 1070°C (+/-10°C) and this must be followed by a rapid quench, preferably in water. Lack of temperature variation during heat treatment is essential and adequate time must be allowed so as to ensure that the section is fully soaked throughout at temperature. Quenching must be carried out immediately on removal from the furnace, with the minimum of cooling in air during transfer to the quench tank.

A stress relief heat treatment, when required, should be carried out by heating to 350°C and holding for 2 hours at temperature followed by air cool. Heating should be carried out in an air circulating furnace to ensure uniformity of temperature. Depending upon the nature of the component, the extent of machining and the tolerances required, this treatment may be carried out at one or more stages of the machining cycle.

Machining and Cutting

FERRALIUM 255-SD50 alloy can be readily machined and it has been found that its machinability is superior to other superduplex stainless steels, for instance, ZERON 100 (UNS S32760). Although FERRALIUM 255-SD50 is considerably harder than the austenitic stainless steels, the same techniques can generally be used, and carbide tipped tools are recommended. A detailed machining information document is available upon request.

In common with many stainless steels and high strength materials, heavy machining on FERRALIUM 255-SD50 can set up superficial internal stress and can sometimes result in slight movement during subsequent operations. This may be accentuated by surface work hardening if blunt tools are used. Whilst this movement is not significant in most cases, components requiring specially close tolerances which have been subject to heaving machining should be given a stress relief heat treatment at 350°C.

Forming

Hot forming can be carried out between 1150°C and 1000°C. At temperatures below 1000°C (primarily in the range 800°C to 950°C) embrittlement takes place due to intermetallic phase precipitation, thus a solution heat treatment at 1070°C followed by rapid water quenching must be carried out after hot forming.

For cold forming, when the deformation required is above 10%, a solution heat treatment at 1070°C followed by water quenching should be carried out after the forming process. For deformations higher than 20%, intermediate solution heat treatment stages at 1070°C (with water quenching) need to be carried out after the accomplishment of 20% deformation, 40% deformation and 60% deformation, as appropriate.

After any hot forging operation, such as the production of hot-headed fasteners, it must be emphasised that a solution heat treatment at 1070°C followed by a rapid water quench must be carried out after the hot forming process. Insufficiently rapid quenching from the hot heading temperature will cause the formation of deleterious phases which will markedly reduce the corrosion resistance.

The figures quoted in this publication do not constitute a specification for any specific contract. It should be noted that continuing research and development may lead to the modification of certain values.

FERRALIUM 255-SD50 - Applications

Chemical Industry

Equipment	Processes
Mixers • Pumps Reactor Vessals Centrifuges Valves Pipework Ducting • Filters Folding Tanks Evaporators Heat Exchangers Scrubbers	Sulphuric acid • Phosphoric acid Titanium Dioxide • Ammonia Sodium Hydroxide • Urea Metal Solvent Extraction Nitric Acid • Nylon Acrylic • Polypropylene PVC • Petroleum Resins Paper Pulp • FGD Plant Copper Smelting Sugar Production

Marine/Oil & Gas

Equipment	Applications
Pumps Pump shafts Valve Bodies Actuators Valve Spindles Pipework Subsea Couplings Bolting and Fasteners Cables Seals	Seawater injection Seawater lifting Riser Protection Systems Christmas Trees Buoyancy Modules Tension Leg Monitoring Riser Clamp Bolting • Bow Planes Anchor Blocks & Cables Heat Exchangers • Guide Rails Propellor Shafts

Civil Engineering

Applications	Principal Examples
Support Structure • Fasteners Dynamic Roof Systems Glass Facia Support Systems Roof Support Systems	US Statue of Liberty Hong Kong Airport Main Building Queen Sofia Museum, Madrid Leisure Centres/Swimming Pool

FERRALIUM Project Portfolio Selection

Offshore Oil & Gas

BP Amoco	Sullum Voe, Dalmeny, West Sole, Wytch Farm, N W Hutton, Forties, Sohio Alaska, Miller, Montrose, Foinaven
Chevron	Ninian N, S & C
Conoco	Hutton TLP, Heidrun, Victor, Viking, Valiant
Kerr Mcgee	Murchison
British Gas	Rough
Phillips	Hewitt, Maureen, Ekofisk
Marathon	Celtic Sea
Texaco	Tartan
Shell	Brent A, C & D, Dunlin A, Fulmar, Kingfisher
Total	Frigg
Mobil	Beryl A & B, Statfjord A & B
Aramco	Saudi Arabia
Adco	Abu Dhabi
Maracaibo	Venezula
PDO	Sultanate of Oman
Sonatrach	Algeria
Statoil	Vselefrikk
Hamilton	Ravenspurn North

Marine

US Navy	Seawolf, Los Angeles Class Submarines, Aircraft Carrier launch systems
Royal Navy	Vanguard & Trafalgar Class Submarines, Christchurch Bay Tower Project, Propellers for fast patrol boats

Chemical Plant

Titanium Dioxide Plant
Alcohol Distillation
Hypochlorite scrubbers
Carbamate Plant
Copper Smelting Fans
Centrifuge Equipment

Flue Gas Desulphurisation

Gibson Power Station, Indiana, USA
Big Rivers, Seebree, Kentucky, USA
Drax Power Station, UK

Pulp & Paper

North American and Scandanavian paper companies

Nuclear

USA and UK Nuclear processing plants

Availability

Hot Worked Products	Products Size Range Availability			LA Stock Availability	
Standard Bar Products	**Unit**	**Min**	**Max**	**Min**	**Max**
• Bar Standard grade	Diameter	10 mm (.39”)	450 mm (17.5”)	12 mm (1/2”)	355 mm (14”)
• Bar FG-46 grade	Diameter	10 mm (.39”)	50 mm (2”)	12 mm (1/2”)	50 mm (2”)
• Bar Aged grade	Diameter	10 mm (.39”)	450 mm (17.5”)	25 mm (1”)	300 mm (12”)
• Ground Reforging Bar	Diameter	150 mm (6”)	450 mm (17.5”)	150 mm (6”)	450 mm (17.5”)
Special Long Products	**Products Size Range Availability**				
	Min Dia	**Min Section**	**Max Dia**	**Max Section**	**Max Length**
• Extruded Section			300 mm (12”)	20mm (3/4”)	
• Hot extruded tube	75 mm (3”)		215 mm (8.5”)		
• Flat Bar		10 mm (.39”)		300 mm (12”)	
• Square Section		10 mm (.39”)		450 mm (17.5”)	
• Bored Bar	20 mm (3/4”)				4,000 mm (157”)

Plate & Sheet Products	Products Size Range Availability			LA Stock Availability		
	Min Thickness	**Max Thickness**	**Max Length**	**Min Thickness**	**Max Thickness**	**Max Length**
• Hot Rolled Plate	2 mm (.078”)	100 mm (4”)	9,000 mm (354”)	2 mm (.078”)	90 mm (3.5”)	6,000 mm (236”)
• Cold Rolled Sheet	0.5 mm (.024”)	3 mm (.118”)	3,000 mm (118”)	0.5 mm (.024”)	3 mm (.118”)	2,000 mm (79”)

Forging capabilities	Products Size Range Availability			
	Max. Diameter	**Max. Section**	**Max. Height**	**Max. Length**
• Hollow Forgings	1,525 mm (60”)			1,525 mm (60”)
• Blocks		450 mm (17.5”)	450 mm (17.5”)	
• Disks	2,286 mm (90”)	450 mm (17.5”)		
• Shafts	450 mm (17.5”)			13,000 mm (512”)
• Rolled Ring	4,800 mm (190”)	450 mm (wall) (17.5”)	1,250 mm (Face) (50”)	

Pipe and Fittings	Products Size Range Availability			LA Stock Availability
	Min Size	**Max Size.**	**Schedule Availability**	
• Hot Extruded Pipe	3 inch NB	8 inch NB	Sch. 40 – XXS	
• Cold Reduced Tube	3/8 inch NB	4 1/2 inch NB	Sch. 5 – 80	1” – 6” Sch 10 – 80
• Welded tube	6 inch Ø	36 inch Ø		
• Pipe Fittings			A Full Range of fittings available to Order	

Welding Consumables	Products Size Range Availability		LA Stock Availability
• MIG	0.8mm (.032”)	1.6mm (.064”)	1.00mm, 1.2mm
• TIG	1.2mm (.048”)	3.2mm (.128”)	1.6mm,2.4mm,3.2mm
• Submerged Arc	1.6mm (.064”)	3.2mm (.128”)	3.2mm
• Coated Electrodes	2.4mm (.094”)	4.0mm (.160”)	2.4mm,3.2mm,4.00mm

FERRALIUM Publication List

Copies of publications are available on request from Meighs Ltd, Langley Alloys Division

1. **“The Effect of Copper on Active Dissolution and Pitting Corrosion of 25% Cr Duplex Stainless Steels”**, L F Garfias-Mesias, J M Sykes and C D S Tuck. Corrosion., Vol. 54, No. 1, 1998, p. 40.
2. **“FERRALIUM alloy - 30 Years Service in the Engineering and Construction Industries”**, C Tuck, Stainless Steel Focus, Iss No. 186, 1997, p.15
3. **“The effect of Phase Compositions on the Pitting Corrosion of 25% Cr Duplex Stainless Steels”**, L F Garfias-Mesias, J M Sykes, and C D S Tuck. J Corr Sci., Vol. 38, No. 8, 1996, p. 1319.
4. **“Welding of FERRALIUM alloy SD40 superduplex stainless steel”**, R D Doggett, Anti-Corrosion Methods and Materials, No. 4, 1996, p.4
5. **“The influence of Copper on the pitting corrosion of Duplex Stainless Steel UNS S32550”**, L F Garfias-Mesias, J M Sykes, and C D S Tuck. Proceedings of the NACE Conference CORROSION/96, Denver, 1996, (Published by NACE, Houston), Paper No. 96417.
6. **“The influence of specific alloying elements in the control of pitting mechanisms of 25%Cr Duplex Steels”**, C D S Tuck, J M Sykes and L F Garfias-Mesias. Proceedings of the 4th International Conference on Duplex Stainless Steels, Glasgow, 1994, (Published by The Welding Institute), Paper No.15.
7. **“Duplex Stainless Steels for Offshore Use”**, K Bendall, Steel Times, August 1992
8. **“Alloy 255 for FGD Application”**, K Bendall, Stainless Steel Europe, c, p.21
9. **“Pulp and Paper Industry Applications for a 25%Cr Duplex Stainless Steel”**, K Bendall, Stainless Steel Europe, 1991, p.22
10. **“The Materials Choice for FGD Equipment”**, K Bendall, Process Industry Journal, 1989, p.19
11. **“The influence of Structure and Composition on Alloys selected for Chemical Plant”**, P Guha. Proceedings of the Conference UK CORROSION/88, Brighton, 1988, (Published by Institute of Corrosion, UK)
12. **“Corrosion Behaviour of cast Duplex Stainless Steels in Sulphuric Acid containing Chloride”**, J P Simpson. Proceedings of the 2nd International Conference on Duplex Stainless Steels, The Hague, 1986, p. 121
13. **“A Duplex Stainless Steel for Chloride Environments”**, N Sridhar, L H Flasche and J Kolts. J. Metals, March 1985, pp 31-35
14. **“Improvements in Corrosion Resistance, Mechanical Properties and Weldability of Duplex Austenitic/Ferritic Steels”**, C A Clark and P Guha, Werkstoffe und Korrosion., Vol. 34, pp 27-31 (1983)
15. **“Effect of Welding Parameters on Localised Corrosion of a Duplex Stainless Steel - FERRALIUM alloy 255”**, N Sridhar, L H Flasche and J Kolts. Paper No. 244 Corrosion /83, NACE 1983
16. **“Laboratory and Field Corrosion Test Results related to Pulp and Paper Industry Applications”**, P E Manning, W F Tuff, R D Zordan and P D Schuur. Paper No. 201 Corrosion /83, NACE 1983
17. **“Microstructural Effects on the Corrosion Resistance in a Duplex Stainless Steel in the Wrought and Welded Conditions”**, J Kolts, L H Flasche, D C Agarwal and H M Tawany. Paper No. 190 Corrosion /82, NACE 1982
18. **“Properties and Applications of High Chromium Duplex Stainless Steels”**, P Guha and C A Clark. Proceedings of the 2nd International Conference on Duplex Stainless Steels, St Louis, 1982, (Published by ASM Metals, USA), p. 355.
19. **“Properties and Applications of high Chromium Duplex Stainless Steels”**, P Guha and C A Clark. Proceedings of the 1st International Conference on Duplex Stainless Steels, St Louis, 1982, (Published by ASM), p. 355
20. **“Superplasticity in a Duplex Stainless Steel”**, S K Srivastava. Proceedings of the 1st International Conference on Duplex Stainless Steels, St Louis, 1982, (Published by ASM), p. 1
21. **“Properties of FERRALIUM alloy 255 Duplex Austenitic-Ferritic Stainless Steel for Sour Gas Well Applications”**, J Kolts. Proceedings of the 1st International Conference on Duplex Stainless Steels, St Louis, 1982, (Published by ASM), p. 233
22. **“Evaluation and Application of Highly Alloyed Materials for Corrosive Oil Production”**, B D Craig. Proceedings of the 1st International Conference on Duplex Stainless Steels, St Louis, 1982, (Published by ASM), p. 293
23. **“Physical Metallurgy , Properties, and Industrial Applications of FERRALIUM alloy 255”**, N Sridhar, J Kolts, S K Srivastava and A I Asphahani. Proceedings of the 1st International Conference on Duplex Stainless Steels, St Louis, 1982, (Published by ASM), p. 481
24. **“Weldability of FERRALIUM alloy 255”**, L H Flasche. Proceedings of the 1st International Conference on Duplex Stainless Steels, St Louis, 1982, (Published by ASM), p. 553
25. **“Welding Characteristics of Duplex Steels”**, C A Clark and P Guha. Proceedings of the 1st International Conference on Duplex Stainless Steels, St Louis, 1982, (Published by ASM), p. 631
26. **“Principles Governing the Production of Sound Stainless Steel Castings”**, R Cook and P Guha. Chemistry and Industry, 1981, p. 733
27. **“Welding Duplex Austenitic-Ferritic Stainless Steels”**, D Blumfield, C A Clark and P Guha. Metal Construction, 198, p. 269
28. **“Materials for Pumping Sea Water and Media with high Chloride Content”**, G Pini and J Weber. Sulzer Technical Review No. 2, 1979.

Comparative corrosion resistance table

Environment	Concentration (w/w)	Temperature (°C)	316	FERRALIUM® 255-SD50	Titanium	HASTELLOY® B-3	HASTELLOY® C-276[4]	Carpenter 20Cb-3®	Avesta 2205	Avesta 254 SMO®	INCONEL® 625	INCOLOY® 825	MONEL® 400	Risk of localised corrosion[3]
Cost Range Indication (£/kg)			2-4	4-8	12-16	25-35	16-20	20-25	2-4	4-8	12-16	8-12	8-12	
Acetic Acid	All	to 60°C	●	●	●	●	●	●	●	●	●	●	●	
Acetic Acid	0-50%	Boiling	▲	●	●	●	●	●	●	●	●	●	▲	
Acetic Acid	50-100%	80°C	●	●	●	●	●	●	●	●	●	●	●	
Acetic Acid Vapour	100%	140°C	▲	●	x	●	●	▲	ND	ND	●	●	▲	
Acetic Anhydride	0-100%	to Boiling	●	●	●	▲	●	●	●	●	ND	●	▲	
Acetyl Chloride	100%	20°C	▲	●	●	●	●	ND	ND	ND	ND	ND	ND	if moist
$HNO_3 + H_2SO_4$	50% + 50%	to Boiling	▲	●	x	x	x	●	ND	ND	x	x	x	
$HNO_3 + H_2SO_4$	50% + 20%	80°C	▲	●	ND	ND	ND	ND	●	●	ND	ND	ND	
$H_2SO_4 + HNO_3$	75% + 25%	to Boiling	x	▲	x	x	x	ND	ND	ND	x	x	x	
$HNO_3 + H_3PO_4$	50% + 50%	70-80°C	x	▲	x	x	x	ND	ND	ND	x	x	x	
Alcohols	100%	to Boiling	▲	●	●	●	●	●	●	●	●	●	▲	
Ethanol	All	20°C-BP	▲	●	●	●	●	●	●	●	●	●	▲	
Aluminium Chloride	All	20°C	x	▲	●	●	●	▲	SC	SC	ND	ND	▲	Yes
Aluminium Chloride	5%	100°C	x	▲	●	ND	ND	ND	●	●	ND	ND	ND	Yes
Aluminium Chloride	25%	60°C	x	▲	●	ND	ND	ND	x	▲	ND	ND	ND	Yes
Aluminium Potassium Sulphate (Alum)	All	20°C	▲	●	●	●	●	●	●	●	●	●	▲	
Aluminium Potassium Sulphate (Alum)	All	Boiling	▲	▲	●	x	●	▲	ND	ND	●	●	▲	
Ammonium Carbamate (Urea Process)	40%	to 120°C	▲	●	●	●	▲	ND	ND	ND	●	●	ND	
Ammonium Chloride	All	75°C	▲	●	●	●	●	▲	SC	SC	●	●	▲	Yes
Ammonium Chloride	50%	115°C	▲	●	●	●	●	ND	●	●	●	●	ND	Yes
Ammonium Hydroxide	All	0°C-BP	●	●	●	●	●	●	●	●	●	●	x	
Ammonium Nitrate	All	Boiling	▲	●	●	▲	●	●	●	●	●	●	x	
Ammonium Sulphate	All	70°C	x	●	●	x	●	▲	●	●	●	●	▲	
Ammonium Sulphate	All	20°C-BP	x	●	●	x	●	▲	●	●	●	●	▲	
Aniline	0-100%	20°C	●	●	●	●	●	●	●	●	●	●	▲	
Benzene	100%	100°C	▲	●	●	●	●	●	●	●	●	●	▲	
Bromine (Moist)	Pure		x	ND	●	▲	●	x	ND	ND	●	▲	x	Yes
Carbon Tetrachloride (Dry)	100%	Boiling	▲	●	●	▲	●	●	●	●	●	●	▲	if moist
Citric Acid	All	to Boiling	▲	●	●	●	●	●	●	●	●	●	▲	
Citric Acid	0-70%	Boiling	▲	●	●	●	●	●	●	●	●	●	▲	
Citric Acid + 8% NaCl	5%	140°C	▲	●	●	●	●	▲	ND	ND	ND	ND	ND	Yes
Chlorine (moist gas)	-	20°C	x	ND	●	x	●[5]	x	x	x	x	x	x	Yes
Copper Sulphate + H_2SO_4	10% + 10%	to Boiling	▲	●	●	x	x	●	●	●	ND	ND	ND	
Ethers	100%	20°C	●	●	●	●	●	ND	●	●	●	●	●	
Ether	100%	20°C-BP	●	●	●	●	●	ND	●	●	●	●	●	
Ethyl Chloride (Dry)	100%	to 60°C	●	●	●	●	●	●	●	●	●	●	▲	if moist
Ethyl Chloride (Dry)	100%	BP	●	●	●	●	●	●	●	●	●	●	▲	if moist
Ethylene Chloride (Dry)	100%	20°C	ND	●	●	●	▲	●	●	●	●	●	ND	if moist
Ethylene Chloride (Dry)	100%	20°C-BP	ND	●	●	●	▲	●	●	●	●	●	ND	if moist
Esters	100%	20°C	●	●	●	●	▲	●	●	●	●	●	▲	
Ferric Sulphate ($Fe_2(SO_4)_3$)	0-10%	to Boiling	●	●	●	x	▲	●	●	●	●	●	x	
Ferric Sulphate ($Fe_2(SO_4)_3$)	10%-30%	70°C	▲	●	●	x	●	●	ND	ND	●	▲	x	
Fluorine (Dry gas)	100%	20°C	●	●	x	x	●	●	●	●	●	ND	ND	
Fluorine (Dry gas)	100%	100°C	●	●	x	x	●	●	ND	ND	●	▲	▲	
Formaldehyde	All	20°C-BP	●	●	●	●	●	●	●	●	ND	ND	▲	
Formic Acid	All	66°C	▲	●	●	●	●	x	●	●	●	▲	x	
Formic Acid	100%	BP (100°C)	▲	●	●	●	●	x	▲	●	●	▲	x	
Hydrochloric acid	1%	to Boiling	x	●	▲	●	●	x	SC	SC	●	▲	▲	Yes
Hydrochloric acid	1%	80°C	x	●	▲	●	●	x	▲	●	●	▲	▲	Yes
Hydrochloric acid	1%	Boiling	x	●	▲	●	●	x	x	x	●	▲	▲	Yes
Hydrofluoric Acid	1%	20°C	x	●	x	●	●	x	▲	●	●	●	●	

Environment	Concentration (w/w)	Temperature (°C)	316	FERRALIUM® 255-SD50	Titanium	HASTELLOY® B-3	HASTELLOY® C-276[4]	Carpenter 20Cb-3®	Avesta 2205	Avesta 254 SMO®	INCONEL® 625	INCOLOY® 825	MONEL® 400	Risk of localised corrosion[3]
Cost Range Indication (£/kg)			2-4	4-8	12-16	25-35	16-20	20-25	2-4	4-8	12-16	8-12	8-12	
Hydrofluoric Acid	10%	20°C	x	▲	x	●	●	x	x	▲	●	●	●	
Hydrofluoric Acid	0-100%	20°C	x	ND	x	●	●	x	SC	SC	●	●	●	
Hydrofluoric Acid	1%	40°C	x	ND	ND	●	●	ND	ND	●	ND	ND	●	
Hydrofluoric Acid	0.5%	50°C	ND	ND	ND	●	●	ND	ND	▲	ND	ND	●	
Hydrofluoric Acid	0-100%	50°C	x	ND	x	●	●	x	SC	SC	▲	x	●	
Hydrogen Peroxide	50%	20°C	▲	●	●	x	●	▲	●	●	●	●	▲	
Hydrogen Peroxide	50%	40°C	▲	●	●	x	●	ND	●	●	●	●	▲	
Hydrogen Sulphide (Dry gas)	4%	200°C	●	●	●	●	●	●	●	●	●	●	●	if moist
Hydrogen Sulphide (Dry gas)	100%	to 250°C	●	●	●	●	●	●	SC	SC	●	●	▲	if moist
Hydrogen Sulphide (Moist gas)	-	20°C	▲	●	●	●	●	▲	ND	ND	●	●	x	Yes
Lactic Acid	20%	100°C	x	●	●	●	●	▲	SC	SC	●	●	▲	
Lactic Acid	90%	Boiling	x	●	ND	ND	ND	ND	●	●	ND	ND	ND	
Magnesium Chloride	10-30%	20°C	▲	●	●	●	●	●	●	●	●	●	●	Yes
Magnesium Chloride	5%	Boiling	▲	●	●	●	●	●	●	●	●	●	●	Yes
Nickel Sulphate	All	Boiling	▲	●	●	x	▲	▲	●	●	●	●	▲	
Nitric Acid	0-70%	20°C	●	●	●	x	●	●	●	●	●	●	x	Yes
Nitric Acid	100%	20°C	▲	●	●	x	●	●	ND	ND	●	▲	x	Yes
Nitric Acid	0-40%	70°C	▲	●	●	x	▲	●	●	●	●	●	x	Yes
Nitric Acid	40-70%	70°C	▲	●	●	x	x[8]	●	●	●	●	●	x	Yes
Nitric Acid	0-60%	Boiling	●	●	●	x	x	●	SC	SC	●	●	x	Yes
Nitric Acid	50%	Boiling	●	●	●	x	x	●	●	▲	●	●	x	Yes
Nitric Acid	70%	Boiling	▲	▲	▲	x	x	▲	ND	ND	●	▲	x	Yes
Nitric Acid	65%	Boiling	▲	▲	▲	x	x	▲	▲	▲	●	▲	x	Yes
Oleic Acid	100%	20°C	▲	●	●	▲	▲	●	●	●	●	●	●	
Oxalic Acid	All	20°C	▲	▲	▲	●	●	●	SC	SC	●	●	x	
Oxalic Acid	All	to Boiling	x	▲	x	▲	▲	▲	SC	SC	●	●	x	
Oxalic Acid	40%	75°C	x	●	x	●	●	●	●	●	●	●	x	
Oxalic Acid	50%	Boiling	x	▲	x	▲	▲	▲	x	▲	●	●	x	
Phosphoric Acid	20%	Boiling	▲	●	x	●	●	●	●	●	●	●	x	
Phosphoric Acid	40%	Boiling	▲	●	x	●	●	●	●	▲	●	●	x	
Phosphoric Acid	0-40%	Boiling	▲	●	x	●	●	●	SC	SC	●	●	x	
Phosphoric Acid	50%	Boiling	x	●	x	▲	●	▲	●	●	●	●	x	
Phosphoric Acid	60%	Boiling	x	▲	x	▲	●	▲	▲	▲	●	●	x	
Phosphoric Acid	80%	Boiling	x	▲	x	▲	●	▲	x	▲	●	●	x	
Phosphoric Acid	40-80%	Boiling	x	▲	x	▲	●	▲	SC	SC	●	●	x	
Phosphoric Acid	86%	85°C	●	●	▲	●	●	●	●	●	●	●	x	
Phosphoric Acid	All	to 80°C	●	●	▲	●	●	●	SC	SC	●	●	x	
Phosphoric Acid ('wet' process liquor)[7]	44-55%	80-90°C	▲	●	ND	▲	▲	ND	ND	ND	●	●	x	
Phosphoric Acid ('wet' process liquor)[8]	-	85°C	x	ND	ND	ND	ND	ND	ND	●	●	●	ND	
Picric Acid	All	20°C	▲	●	●	●	●	▲	●	●	●	●	x	
Potassium Chloride	0-30%	to Boiling	▲	●	●	●	●	●	ND	ND	●	●	●	Yes
Potassium Dichromate	All	to Boiling	●	●	●	x	x	●	●	●	●	●	●	
Sodium Chloride	0-10%	to Boiling	▲	●	●	●	●	●	●	●	●	●	●	Yes
Sodium Chloride + 0.1M H_2SO_4 (aerated)	5%	to Boiling	x	●	●	●	●	ND	ND	ND	ND	ND	ND	Yes
Sodium Chloride + 0.5% Oxalic Acid	0-8%	to Boiling	x	●	x	●	●	ND	ND	ND	ND	ND	ND	Yes
Sodium Chloride + 0.5% Citric Acid	0-8%	to Boiling	x	●	●	●	●	ND	ND	ND	ND	ND	ND	Yes

Comparative corrosion resistance table

Environment	Concentration (w/w)	Temperature (°C)	316	FERRALIUM® 255-SD50	Titanium	HASTELLOY® B-3	HASTELLOY® C-276[4]	Carpenter 20Cb-3®	Avesta 2205	Avesta 254 SMO®	INCONEL® 625	INCOLOY® 825	MONEL® 400	Risk of localised corrosion[3]
Cost Range Indication (£/kg)			2-4	4-8	12-16	25-35	16-20	10-13	2-4	4-8	12-16	8-12	8-12	
Sea Water	-	20°C	▲	●	●	●	●	●	●	●	●	●	●	Yes
Seawater saturated with Cl2	-	to 65°C	x	●	●	x	●	x	ND	ND	●	●	x	Yes
Sodium Hydroxide	0-50%	20°C	●	●	●	●	●	●	●	●	●	●	●	
Sodium Hydroxide	All	Boiling	▲	▲	●	●[6]	●[6]	▲	SC	SC	●	▲	●	Yes
Sodium Hydroxide	30%	Boiling	▲	●	●	●[6]	●[6]	▲	●	●	●	▲	●	Yes
Sodium Hydroxide	40%	Boiling	▲	▲	●	●[6]	●[6]	▲	x	▲	●	▲	●	Yes
Sodium Hypochlorite	12-14%	20°C	x	▲	●	●	●	x	ND	ND	▲	●	x	
Sodium Sulphide	60%	20°C	▲	●	●	●	●	●	SC	SC	●	●	●	
Sodium Sulphide	40%	Boiling	▲	●	●	▲	▲	▲	●	●	●	●	●	
Sodium Sulphide	0-50%	Boiling	▲	●	●	▲	▲	▲	●	●	●	●	●	
Sodium Sulphite	50%	20°C	▲	●	●	●	●	●	●	●	●	●	●	
Sodium Sulphite	50%	Boiling	ND	●	●	●	●	ND	●	●	ND	ND	ND	
Sulphuric Acid	20%	40°C	●	●	x	●	●	●	●	●	●	●	●	
Sulphuric Acid	30%	40°C	▲	●	x	●	●	●	▲	●	●	●	▲	
Sulphuric Acid	40%	40°C	x	●	x	●	●	●	x	▲	●	●	▲	
Sulphuric Acid	40-98%	40°C	x	●	x	●	●	●	SC	SC	●	●	▲	
Sulphuric Acid	5-30%	80°C	x	●	x	●	▲	▲	SC	SC	▲	●	x	
Sulphuric Acid	5%	80°C	x	●	x	●	▲	●	●	●	●	●	▲	
Sulphuric Acid	10%	80°C	x	●	x	●	▲	●	▲	●	●	●	x	
Sulphuric Acid	30%	80°C	x	●	x	●	▲	▲	x	x	▲	●	x	
Sulphuric Acid	30-50%	60°C	x	●	x	●	▲	●	x	x	ND	●	x	
Sulphuric Acid	98%	100°C	▲	●	x	●	▲	▲	x	x	ND	●	x	
Sulphuric Acid	98%	150°C	ND	▲	x	x	x	ND	x	x	x	x	x	
Sulphuric Acid (fuming) Oleum	15% SO3	to 80°C	▲	▲	x	x	▲	ND	ND	ND	x	x	x	
Zinc Chloride	All	20°C	▲	ND	●	●	●	▲	ND	ND	●	●	▲	Yes
Zinc Chloride	All	Boiling	x	ND	▲	▲	x	▲	ND	ND	▲	▲	x	Yes

● Excellent corrosion resistance - rate of corrosion less than 0.15mm/yr (see note 1)
▲ Good corrosion resistance under most conditions - rate of corrosion expected to be less than 0.50mm/yr (see note 2)
x Not Recommended
ND Data unavailable
SC Data is supplied for specific concentrations as given in adjacent rows of the table

This table is intended only as a guide as corrosion performance can be affected by precise process conditions and consideration must be made of the possibility of localised rather than general corrosion for the environment indicated. The information given is for pure chemicals and the solvent is water unless stated otherwise. It must be stressed that, whenever possible, plant corrosion tests should be carried out. Samples of FERRALIUM 255-SD50 for this purpose can be supplied on request. Samples of other alloys may be supplied by the Trade Mark holders listed below.

Notes: 1 For Avesta grades only, rate of corrosion is less than 0.1mm/yr. **2** For Avesta grades only, rate of corrosion is between 0.1 mm/yr and 1.0mm/yr. **3** Pitting corrosion/Crevice corrosion/Stress Corrosion/Intergranular corrosion depending on environment. **4** If there is a high iron content, use HASTELLOY C-22®. **5** HASTELLOY C-276® resistant to about 90°C **6** HASTELLOY C-276® and HASTELLOY B-3 susceptible to stress corrosion cracking in hot strong sodium hydroxide. **7** 68.9% phosphoric acid, 4.15% sulphuric acid, 1.85% iron, 5400 ppm fluorides and 2000 ppm chlorides. **8** High corrosion figures found for high concentrations of alloy. **A.** Prices per kg are given as an approximate guide and are correct at the time of publication (August 2001). Note that Ti is 60% density of other materials. **B.** In acid solutions containing oxidising salts, HASTELLOY® B-3 alloy may suffer enhanced corrosion. Guidance should be sought from Haynes International Ltd.

Acknowledgements

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