Between 316L and titanium in seawater cooled PHE

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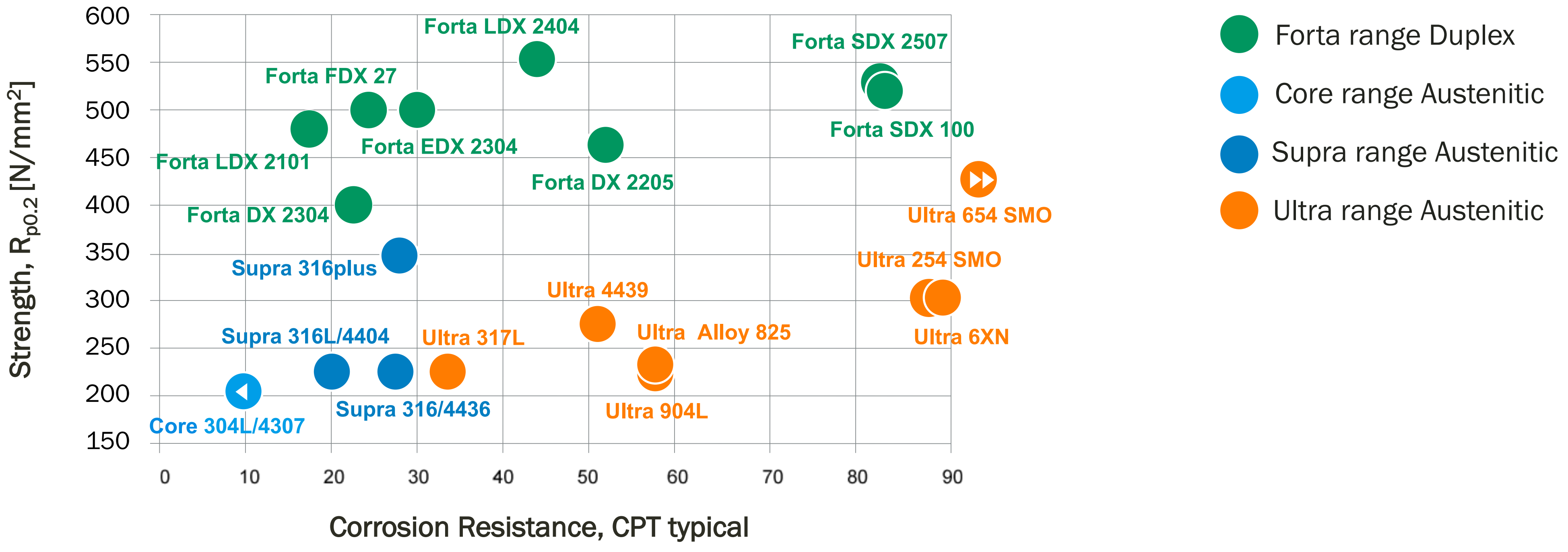
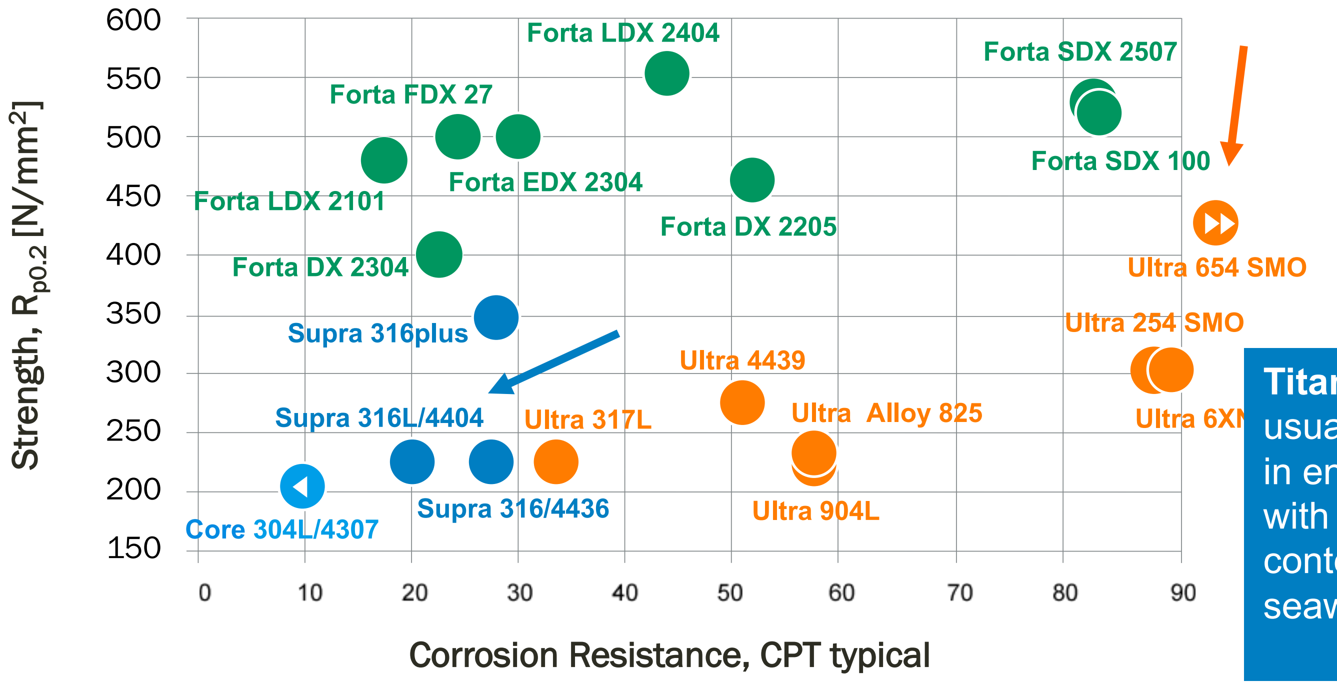
Seawater

- Neutral chloride solution
  - Chloride level: 18,000 – 30,000 ppm
- Corrosion mechanisms
  - Localized corrosion: pitting and crevice
  - Stress Corrosion Cracking (SCC)
- Biofilm formation
  - Temperature dependent
  - Affects the performance of the materials

Critical Pitting Temperature



Critical Pitting Temperature



Titanium alloys are usually very good in environments with high chloride content, such as seawater.

But there is a big gap between 316L and Titanium. Why not considering Ultra 654 SMO as an intermediate solution.

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General Characteristics – 654 SMO belongs to the Ultra range

- Austenitic structure
- For use in a wide temperature range
- Very good resistance to uniform corrosion
- Good to exceptionally good resistance to pitting and crevice corrosion (PRE 28 to 56)
- Very good resistance to stress corrosion cracking
- Excellent formability
- Good weldability
- Non-magnetic

Ultra 654 SMO

- Benefits of utilizing Ultra 654 SMO

Grade	Price indication
316L	Base
Ultra 654 SMO	8x more
Ultra Alloy 625	12x more
Titanium Gr. 4	15 - 20x more

- Its higher mechanical strength combined with good elongation result in strong and light heat exchangers
- Its corrosion resistance in chloride rich environments is higher than Alloy 625, similar to C-276

Ultra 654 SMO is better and more cost-effective than Titanium and the most traditional nickel alloys.

Typical chemical composition

Steel grade	EN	UNS	C	Cr	Ni	Mo	N	Other
Ultra 654 SMO	**1.4652**	**S32654**	**0.010**	**24**	**22**	**7.3**	**0.5**	**3.5Mn, Cu**
Ultra 254 SMO	1.4547	S31254	0.010	20	18	6.1	0.20	Cu
Alloy 31	1.4562	N08031	0.015	27	31	6.5	0.2	2Mn, Cu
Alloy 625	2.4856	N06625	0.030	22	Min 58	9	-	3.5 Nb+Ta
Alloy 22	2.4602	N06022	0.010	21	Min 50	13	-	3W, 2.5Co
Alloy C-276	2.4819	N10276	0.010	16	Min 52	16	-	3.5W, 2.5Co
Titanium Gr. 4	3.7065	R50700	0.080	-	-	-	0.05	O, Fe, H

Ultra 654 SMO has lower Ni & Mo content → better price stability

Physical properties

Steel grade	Density [kg/dm3]	Thermal conductivity [W/mºC] at 20 º	Electrical resistivity [μΩm] at 20 ºC	Modulus of elasticity [GPa] at 20 ºC	Thermal expansion [*10^{-6}/˚C] at 20 -100ºC
Ultra 654 SMO	**8.0**	**11**	**0.78**	**190**	**15**
Ultra 254 SMO	8.0	14	0.85	195	16.5
Alloy 31	8.1	11.7	1.03	198	14.3
Alloy 625	8.5	9.8	1.25	209	12.5
Alloy 22	8.7	9.4	1.14	206	12.4
Alloy C-276	8.9	10.6	1.25	208	11.7
Titanium Gr. 4	4.5	17.2	0.1	103	8.6

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Mechanical properties

Steel grade	$R_{p0.2}$ [MPa]	$R_{p1.0}$ [MPa]	R_m [MPa]	A_{50} [%]
Ultra 654 SMO	**≥ 430**	**≥ 470**	**≥ 750**	**≥ 40**
Ultra 254 SMO	≥ 300	≥ 340	≥ 650	≥ 40
Alloy 31	≥ 276	≥ 310	≥ 650	≥ 40
Alloy 625	≥ 330	-	≥ 730	≥ 35
Alloy 22	≥ 310	≥ 335	≥ 690	≥ 45
Alloy C-276	≥ 280	≥ 300	≥ 730	≥ 25
Titanium Gr. 4	≥ 480	-	≥ 550	≥ 15

Ultra 654 SMO → Strength combined with formability

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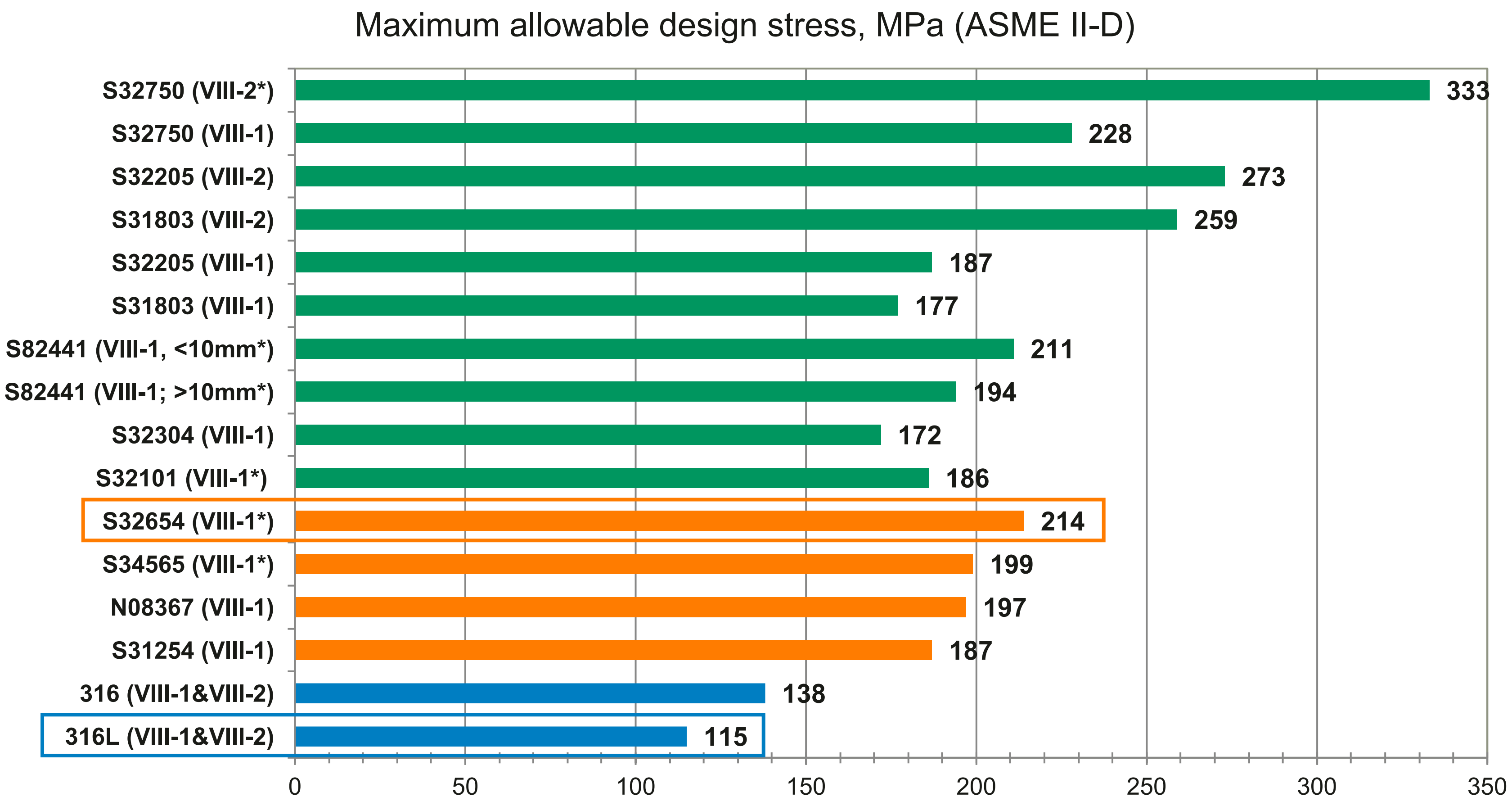
Stainless steels in heat exchanger



Ti Gr. 1 68 MPa
Ti Gr. 2 98 MPa
Ti Gr. 3 128 MPa
Ti Gr. 4 ? MPa

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Ranking of different steel grades

- The relative resistance to pitting and crevice corrosion can be illustrated in different ways

- Critical pitting and crevice corrosion temperatures (CPT and CCT)
    - Commonly used for stainless steel
    - ASTM G48E (CPT)
    - ASTM G48F (CCT)
    - ASTM G150 (CPT)
    - Some limitations for Ni-base materials

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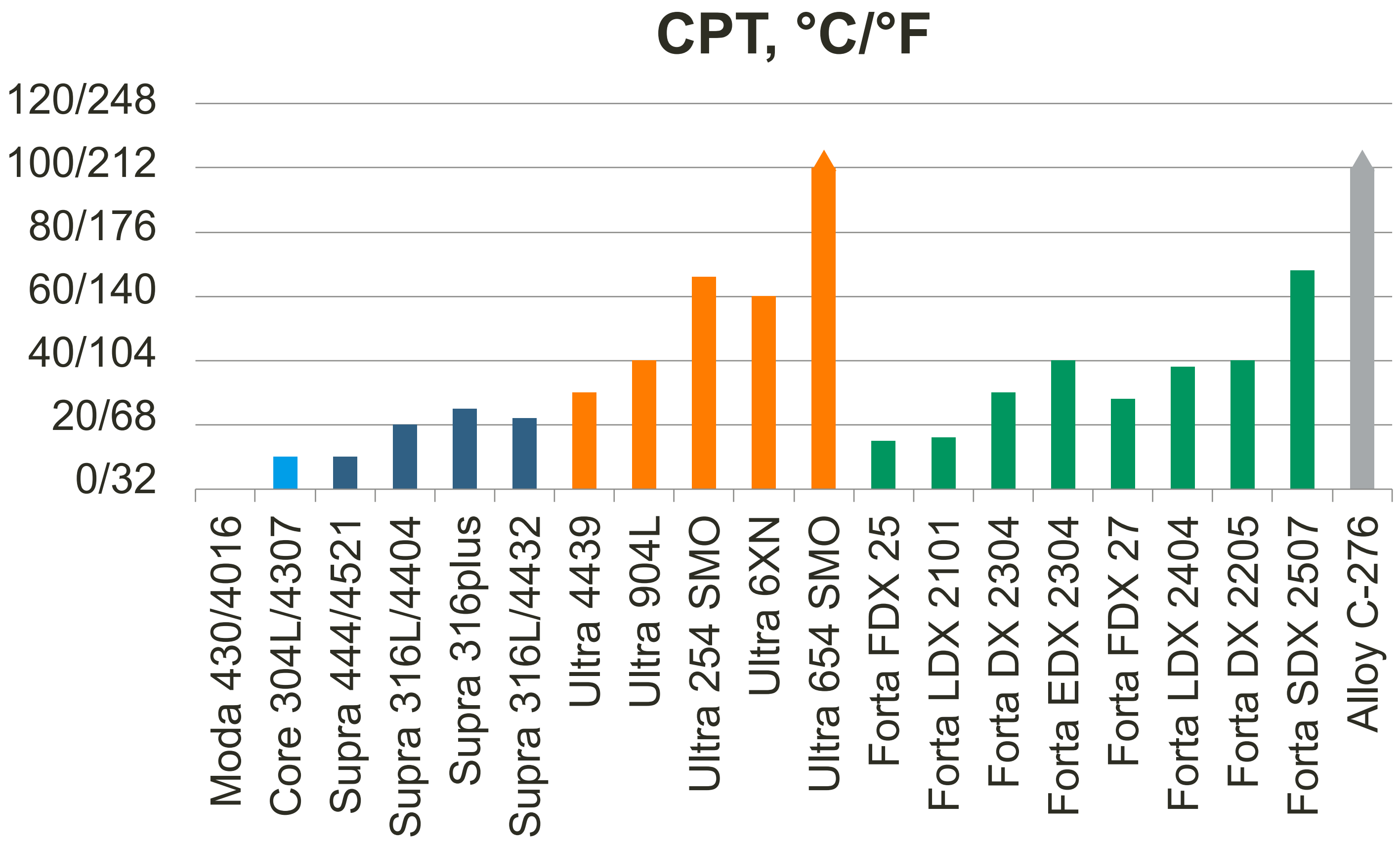
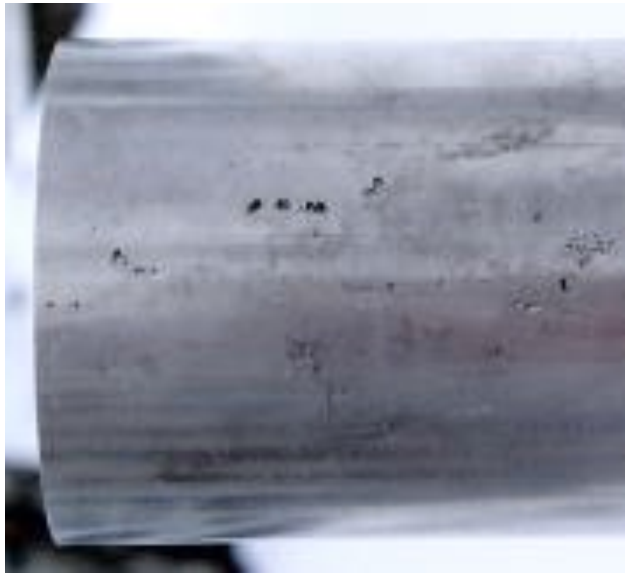
Resistance to pitting corrosion – CPT ASTM G48E





Chlorides penetrate through chromium oxide layer

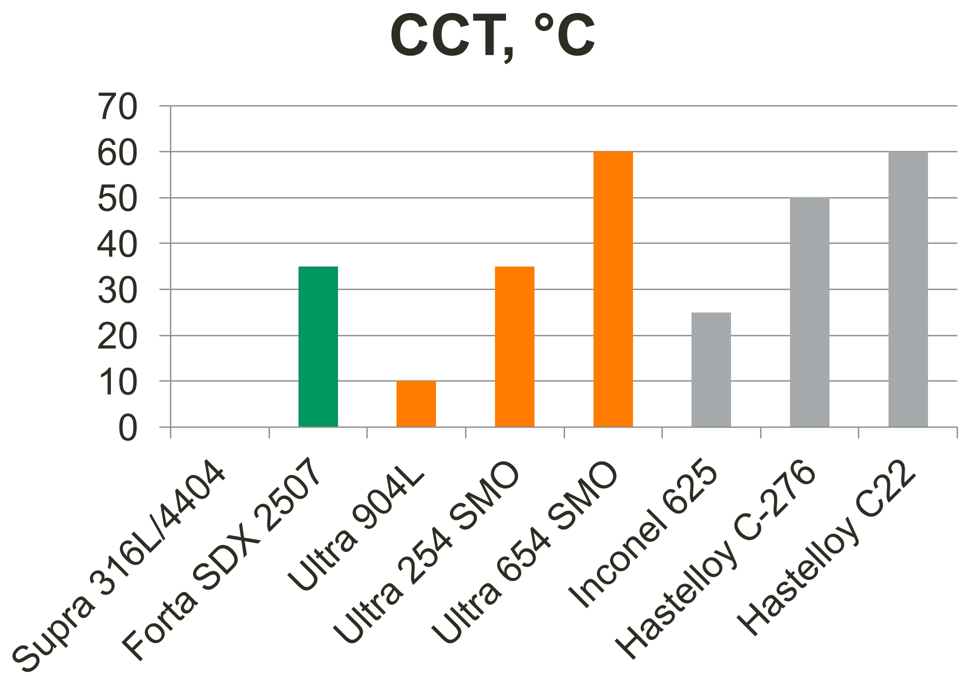
Critical Pitting Temperatures (CPT)

- Test on dry ground surfaces (120 grit)

Steel grade	ASTM G48 E	Green Death
	CPT (°C)	CPT (°C)
Ultra 254 SMO	65	60
Ultra 654 SMO	**>BP**	**90**
Alloy 625	**90**	**75**
Alloy C-276	>BP	100
Alloy 22	>100	-

ASTM G48: 6% $FeCl_3$ + 1% HCl, 24h
Green death: 11.4% H_2SO_4 + 1.2% HCl + 1% $FeCl_3$ + 1% $CuCl_2$, 24h
BP: Boiling Point

CCT ASTM G48 F *)



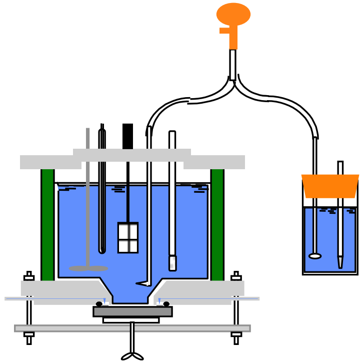
- CCT – Critical Crevice corrosion Temperature
- Standardised ranking test method
- The higher the CCT, the higher resistance to crevice corrosion

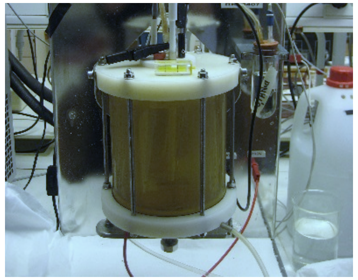
*) Testing condition: 6% $FeCl_3$ + 1% HCl, 24h, 1.58 Nm

CPT ASTM G150

- 1 M NaCl, 700 mVSCE, temperature ramp 1°C/min
- 3 M NaBr: modified ASTM G150

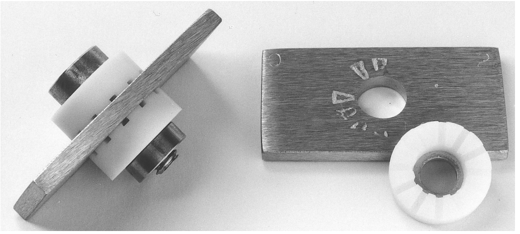
Alloy	1 M NaCl	3 M NaBr
Ultra 254 SMO	85	32
Ultra 654 SMO	**>90**	**85**
Alloy 31	>90	52
Alloy 625	**>90**	**52**
Alloy C-276	>90	81
Alloy 22	>90	68



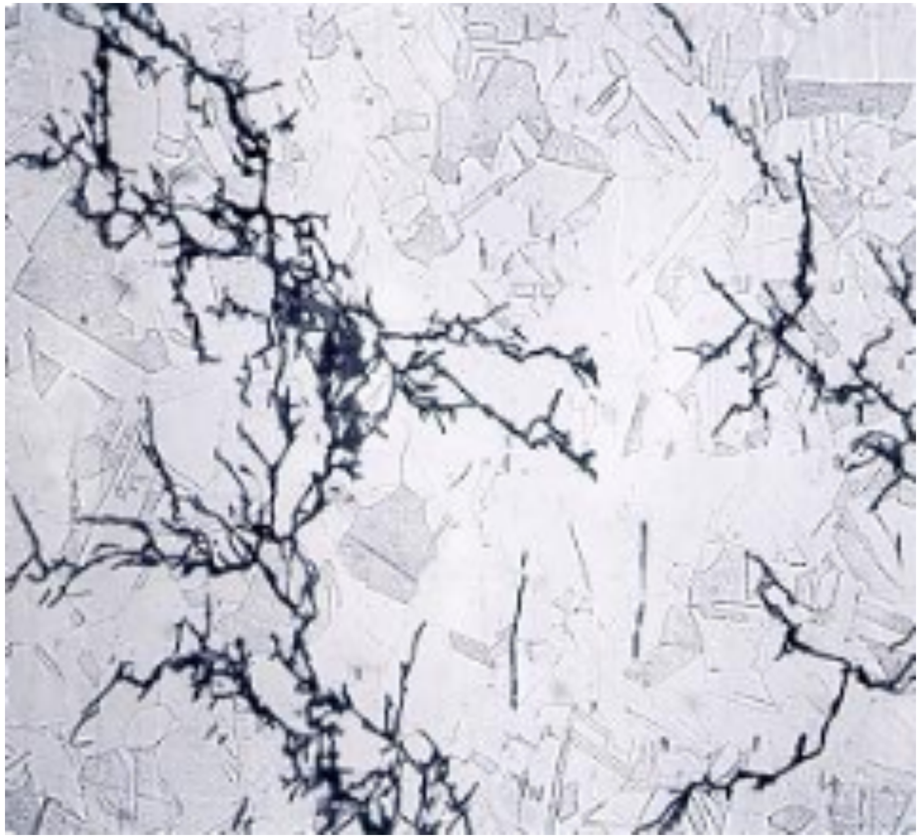


Crevice corrosion test – 6% $FeCl_3$, 50 °C, 1.58 Nm, 500 h

Alloy	Number of attacks (max 24)
Ultra 254 SMO	22
Ultra 654 SMO	**0**
Alloy 31	24
Alloy 625	**24**
Alloy C-276	20
Alloy 22	24



Stress Corrosion Cracking (SCC)



Standard austenitic stainless steels, e.g. 304 or 316 are sensitive to SCC

For increased resistance:

+Ni

- Ultra 904L
- Ultra 254 SMO
- Ultra Alloy 825
- Ultra 654 SMO

Austenitic stainless steels with high content of Ni and Mo

-Ni

- Forta LDX 2101
- Forta DX 2304
- Forta LDX 2404
- Forta DX 2205
- Forta SDX 2507

Two phase structure

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ISO 15156-3 Alloy requirements for sour service

Material type/ individual alloy		Max. temp. [°C]	Max. pH_2S [bar]	Max Cl^- [mg/l]	pH
AUSTENITIC STAINLESS STEELS	Austenitic stainless steels	60	1	1)	1)
		2)	2)	50	2)
	S31600	93	0.102	5000	≥ 5.0
	S31603	149	0.102	1000	≥ 4.0
	(%Cr + 2 x %Mo > 30) or PREN < 40	60	1	1)	1)
		2)	2)	50	2)
	PREN > 40	121	7	5000	3)
		149	3.1	5000	3)
		171	1	5000	3)
DUPLEX STAINLESS STEELS	30 < PREN ≤ 40, Mo ≥ 1.5	232	0.1	1)	1)
		2)	2)	50	2)
	40 ≤ PREN ≤ 45	232	0.2	1)	1)
		2)	2)	50	2)

1) Any combination of chloride concentration and *in situ* pH occurring in production environments
2) These materials have been used without restrictions on temperature, pH_2S or *in situ* pH in production environments.
3) The *in situ* pH values occurring in productions environments are acceptable.

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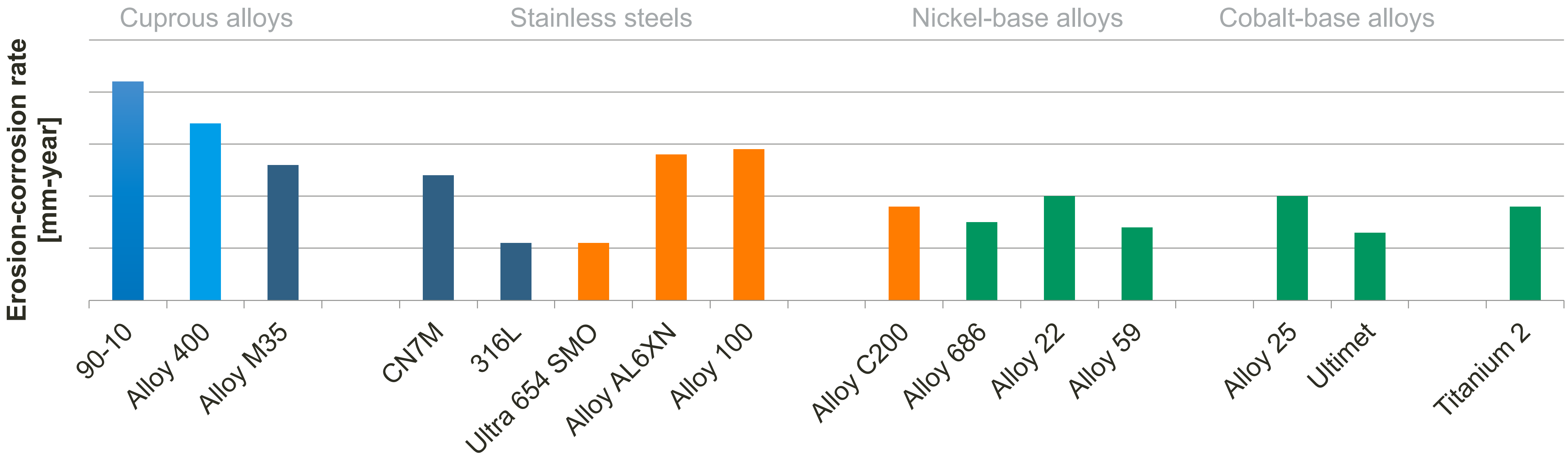
Erosion Corrosion

- Relative erosion-corrosion rates for candidate valve materials tested in seawater



Fabrication of higher alloyed Ultra range products

Formability

- Very good formability, suitable for all forming processes available for stainless steel
- Higher yield strength compared to conventional austenitic steel grades – increases springback and demands higher forming force

Machining

- Due to their high alloy content, work hardening and toughness – right choice of tools, tool settings and cutting speeds is key to manage typical machining operations such as turning, milling and drilling

Welding

- Well suited for welding using methods for conventional austenitic steels
- More sensitive to hot cracking due to their fully austenitic structure – use low heat input
- Solidification after welding may cause redistribution of elements – segregation of molybdenum – can impair corrosion resistance in certain environments
- Use fillers with higher molybdenum content than base metal

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Field testing experience

Plate heat exchanger:

- Sea water – North Sea – Salinity of 3.3 – 3.6%
- ~45, 50, 60 and 70ºC
- 2 ppm continuous chlorination
- ≥3 months

- Ultra 254 SMO suffered crevice corrosion at 45ºC
- C-276 suffered shallow crevice corrosion and transpassive corrosion at 45ºC
- Ultra 654 SMO was resistant to crevice corrosion at 70ºC

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Product program

Cold rolled coils

Thickness [mm]	Width [mm]
6.00 – 3.71	1,000 – 500
3.70 – 3.01	1,000 – 150
3.00 – 2.50	1,000 – 48
2.49 – 1.50	1,000 – 36
1.49 – 0.40	1,000 – 25

No quarto plate available.
For thicker gauges, cladding should be no issue.

Thank you for listening!

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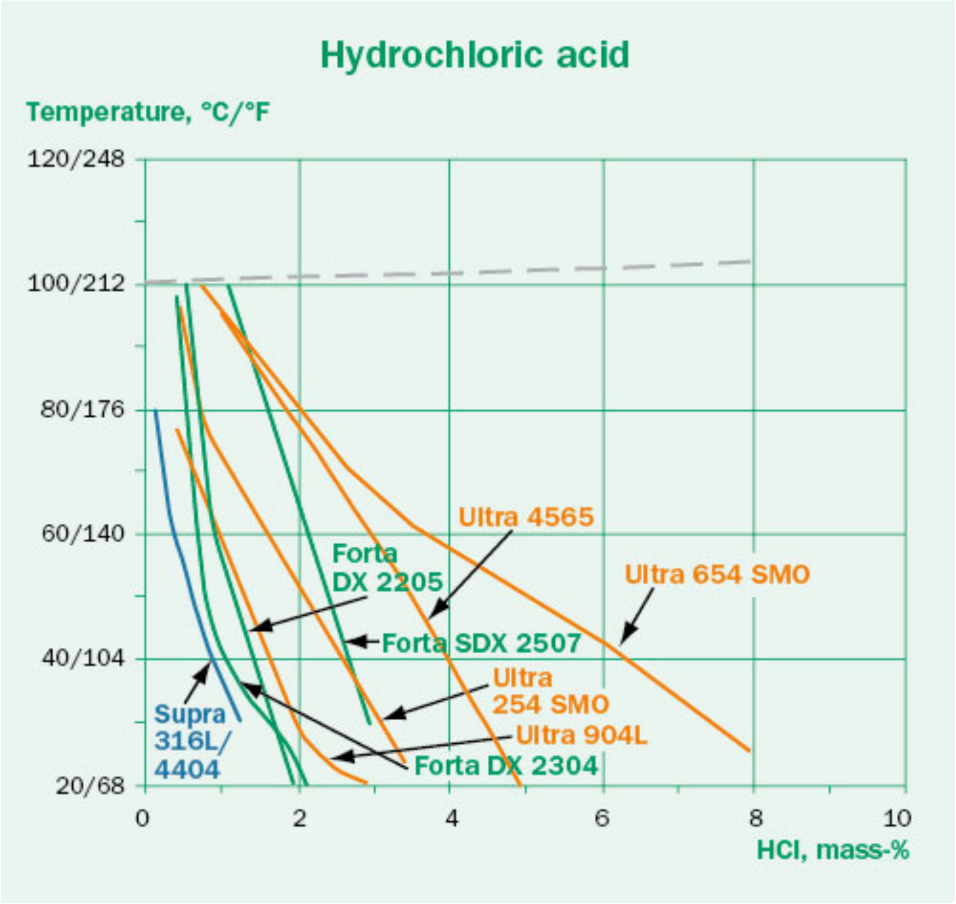
Backup slides

Resistance in Hydrochloric acid, HCl



- In non-oxidizing acids like HCl the use of most stainless steels is limited to relatively low concentrations and temperatures
- Ultra 654 SMO has the highest resistance of stainless steels
- Nickel alloys perform better

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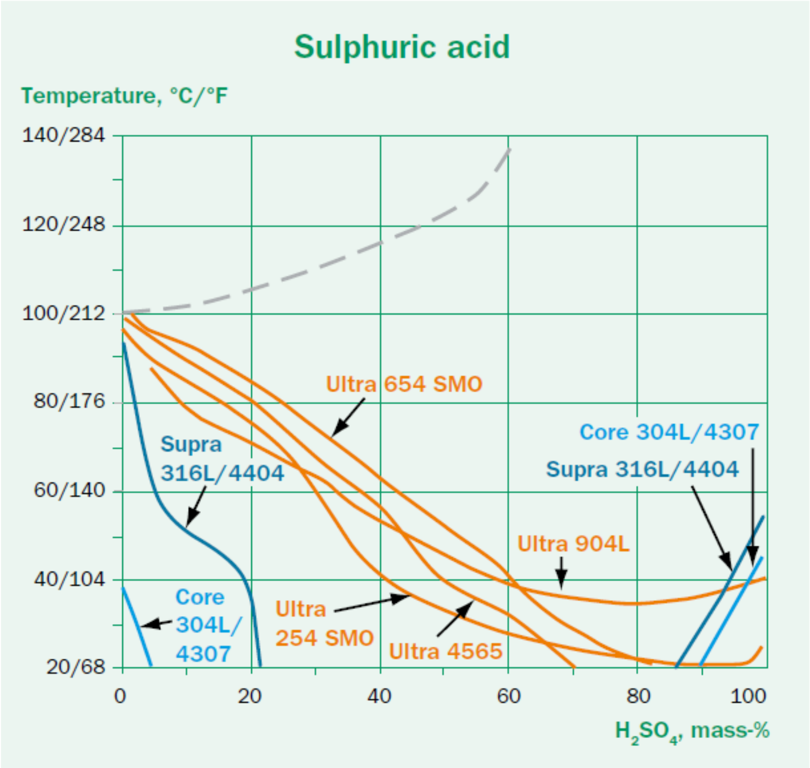
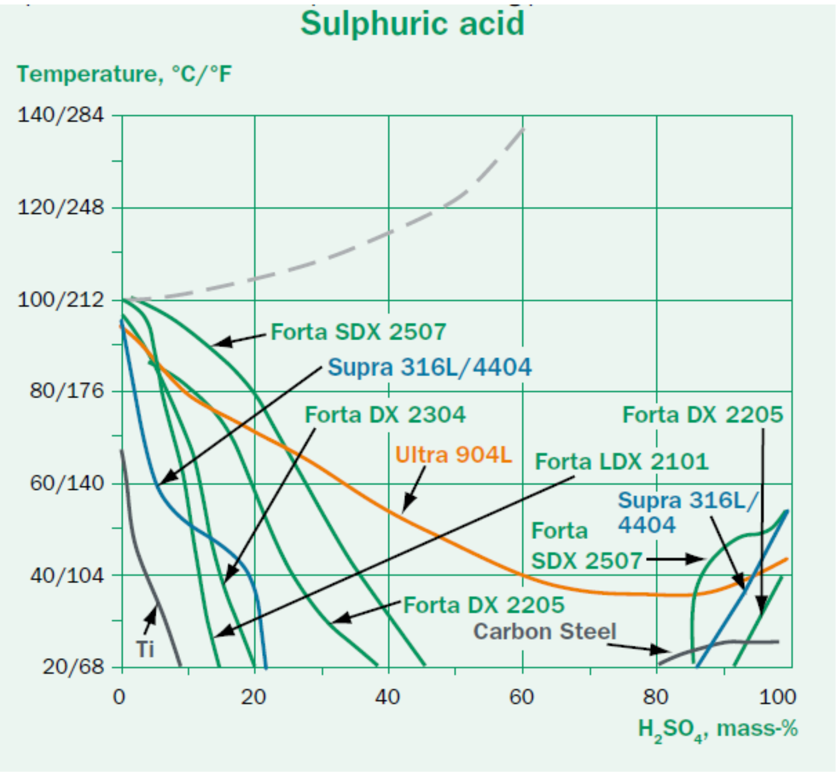
Resistance to Sulfuric Acid, H_2SO_4





The acid is reducing at low and intermediate concentrations, but oxidizing when concentrated

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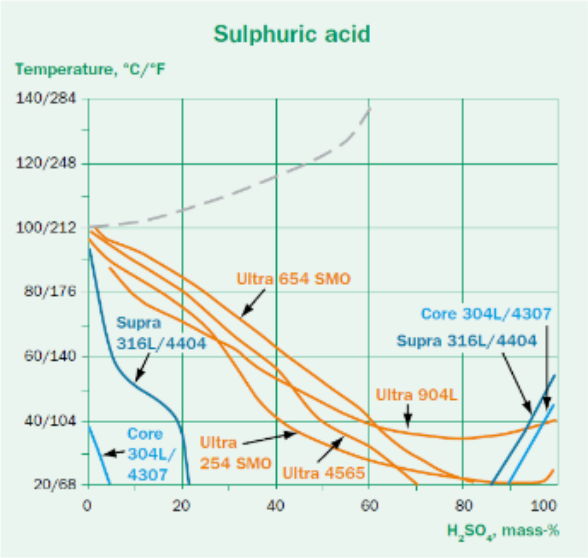
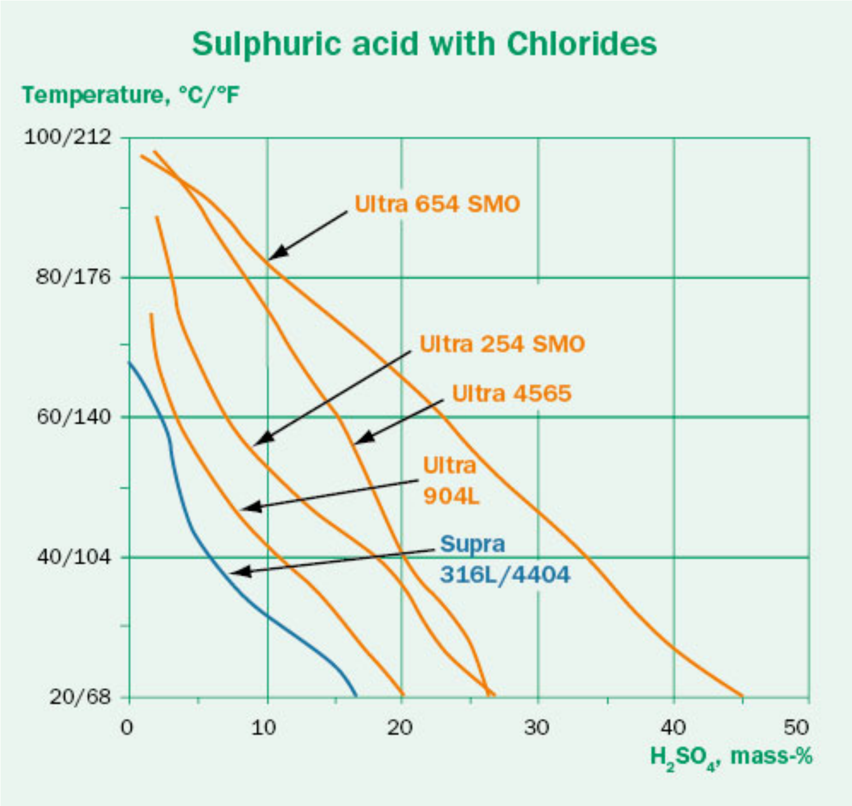
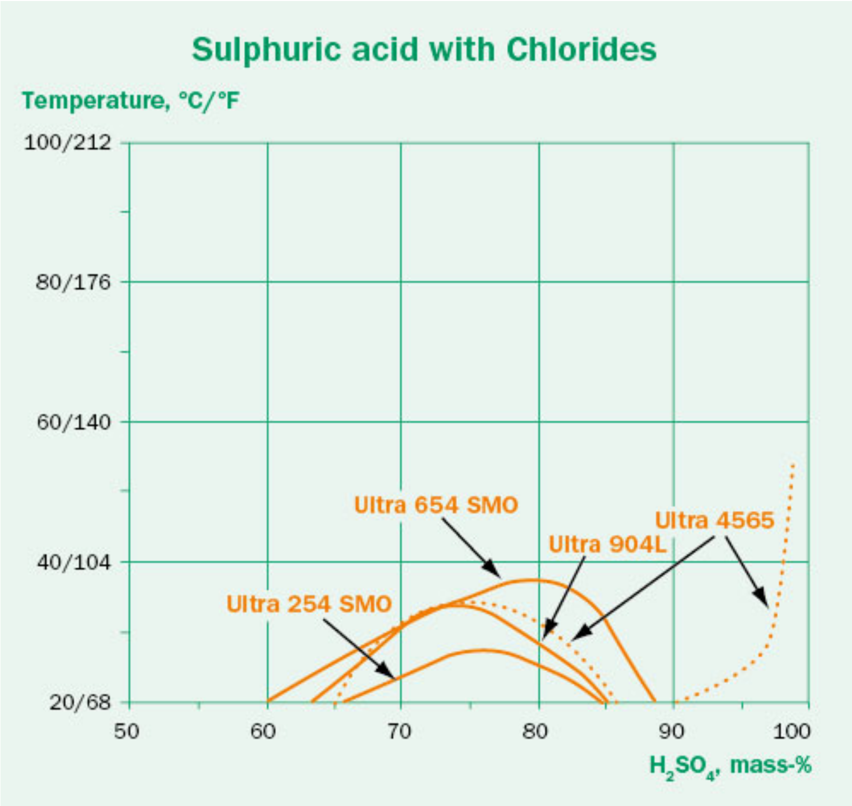
Resistance to Sulfuric Acid with Chlorides



2000 ppm Chlorides



2000 ppm Chlorides



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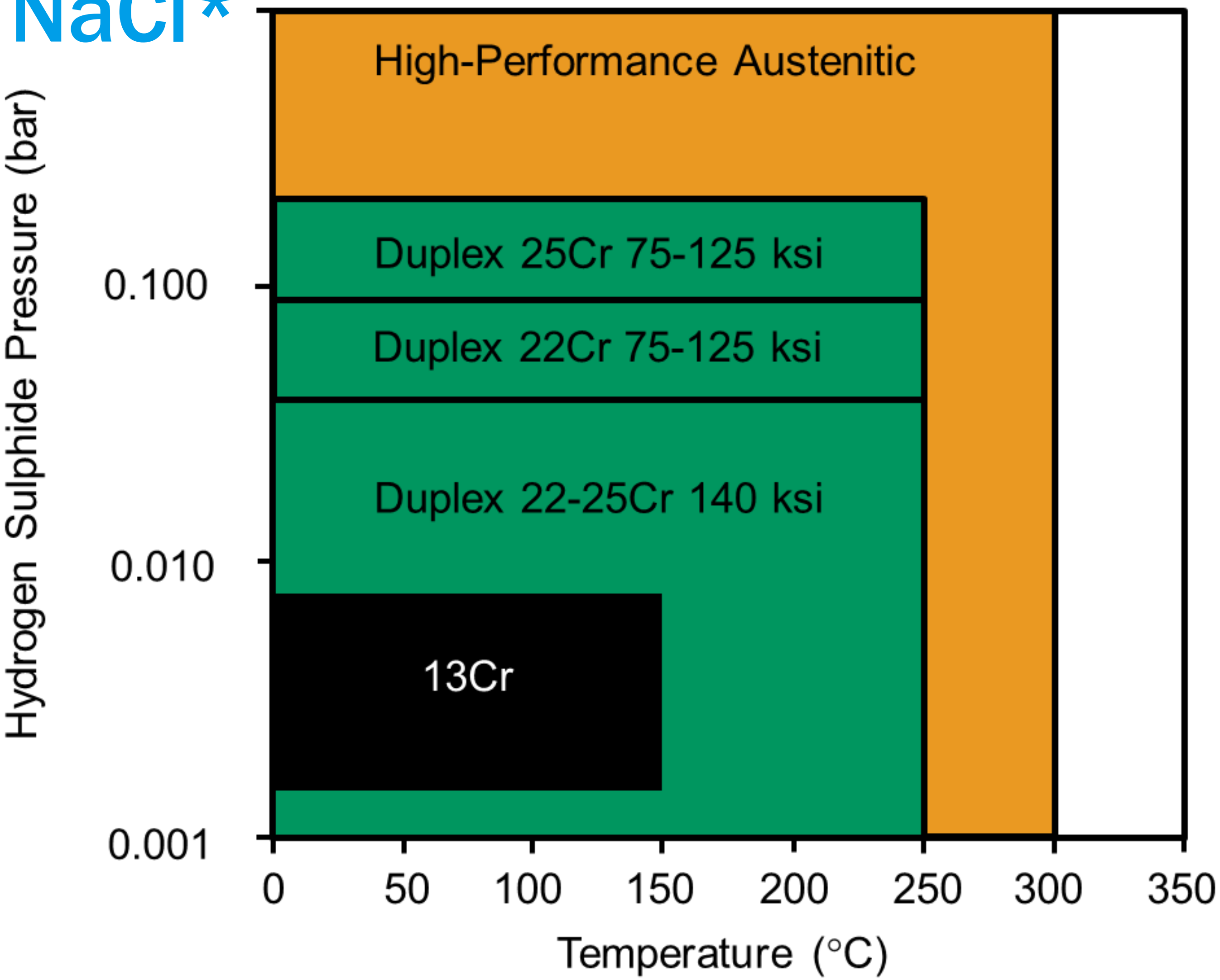
Indicative applicability range in sour environment containing NaCl*



*NaCl = 50g/l

Source: Based on graph Figure 66, Nickel Development Institute, Reference Book Series No 11 021

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