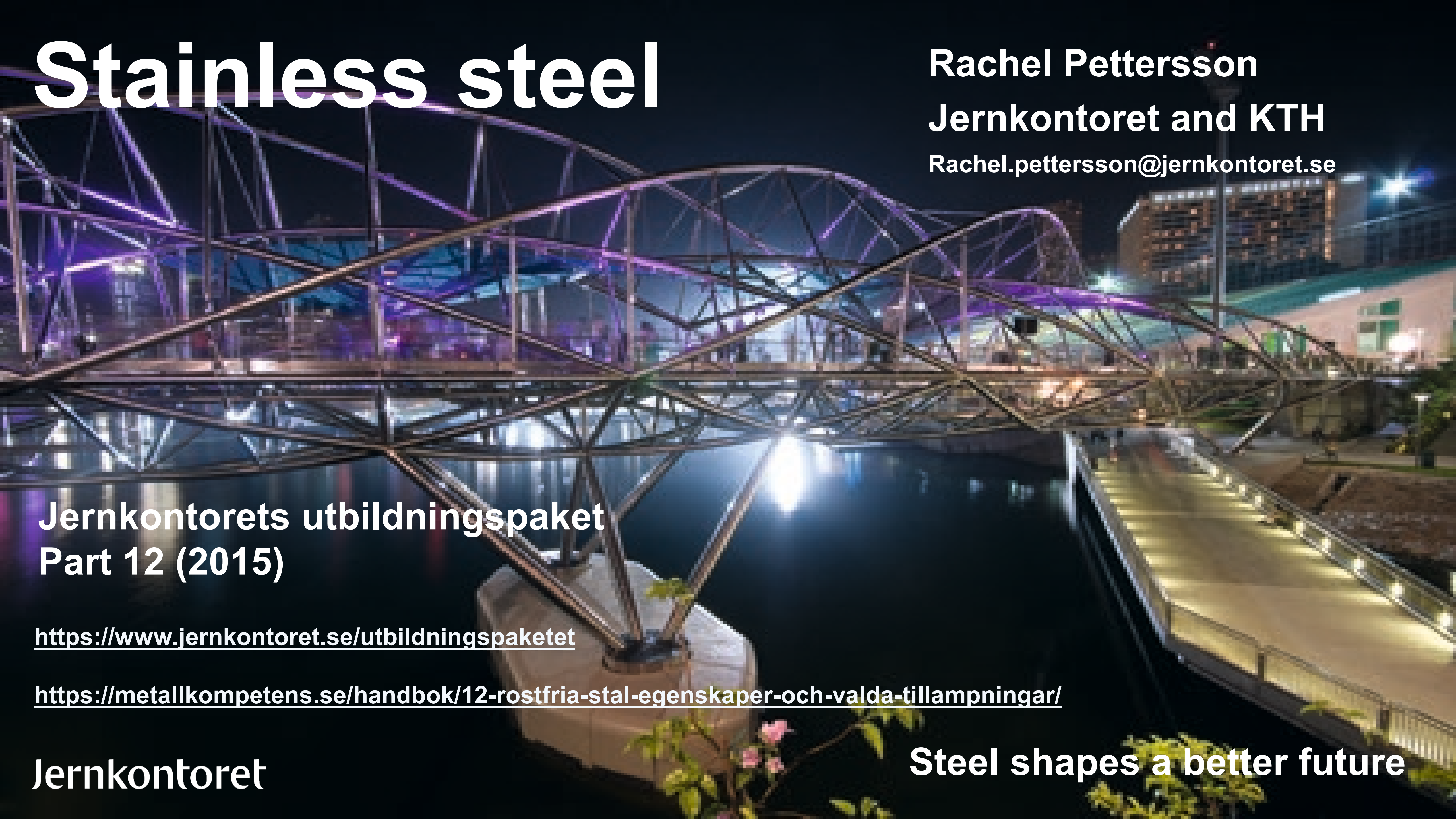

Stainless steel

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Jernkontorets utbildningspaket
Part 12 (2015)

https://www.jernkontoret.se/utbildningspaketet

https://metallkompetens.se/handbok/12-rostfria-stal-egenskaper-och-valda-tillampningar/

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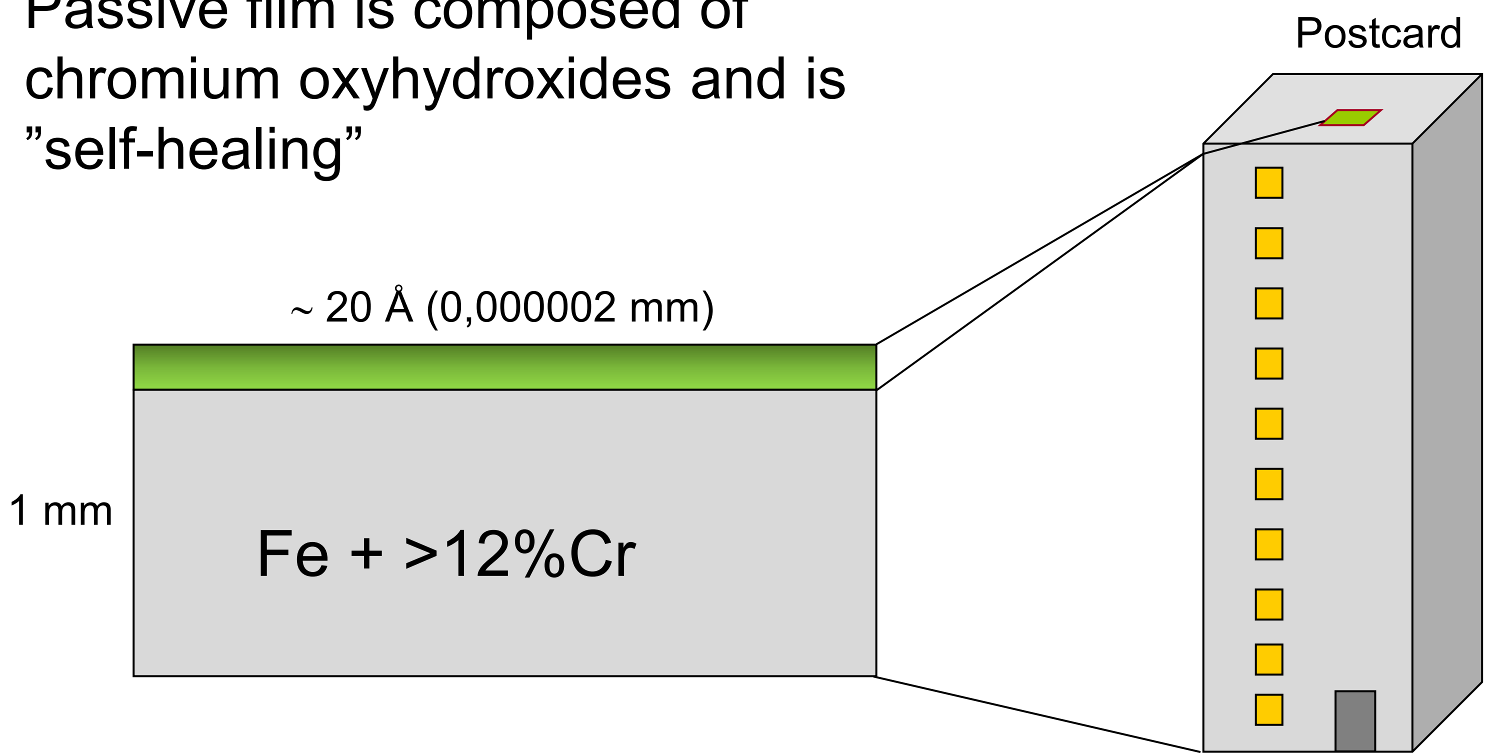
Steel shapes a better future

Stainless steels are protected by a passive film

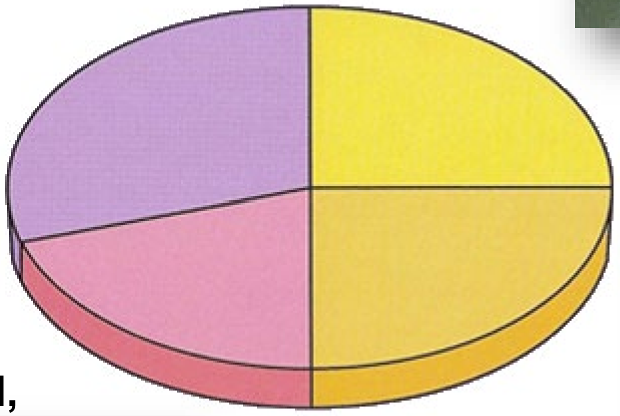
- Iron-base alloys with >12% Cr develop a passive film
- Passive film is composed of chromium oxyhydroxides and is ”self-healing”



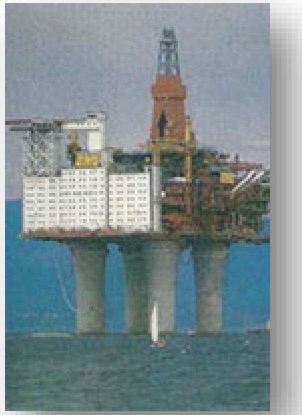
Uses of stainless steels

Transport, energy
P&P, textiles
buildings and general construction
30%

Consumer
products
25%



Chemical, petrochemical,
O&G
20%



Food & drink
25%

Stainless steel in architecture

Lloyds building, London
Built 1978-86
1.5 mm stainless steel
1.4301 (304)

Museum for science & technology, Paris
Diameter 30m
1.5 mm high polished
1.4301

Stainless in wine production and breweries

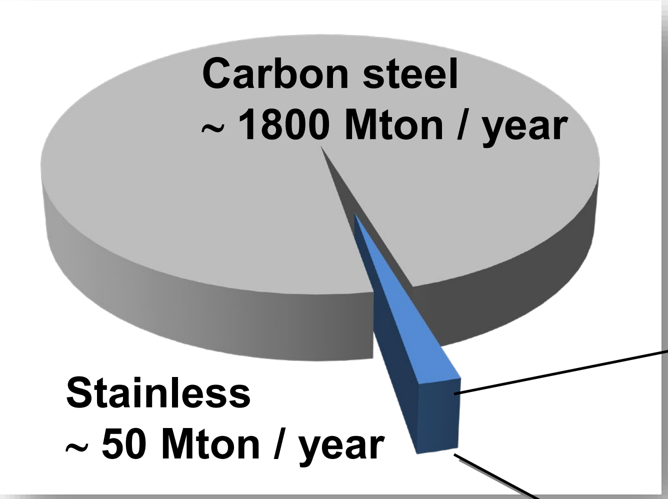
Wine tank in 1.4301

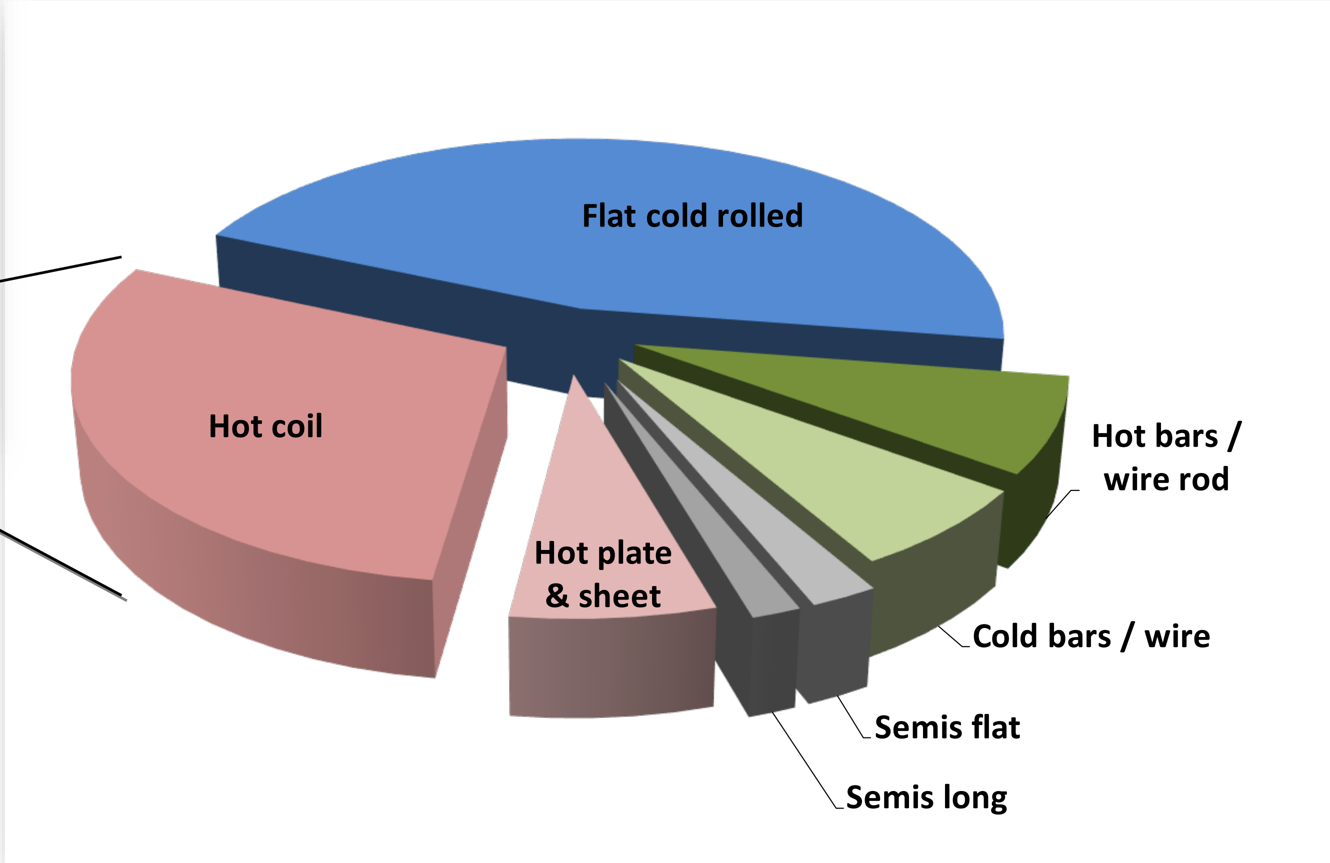
Brewing equipment

Production of stainless steel

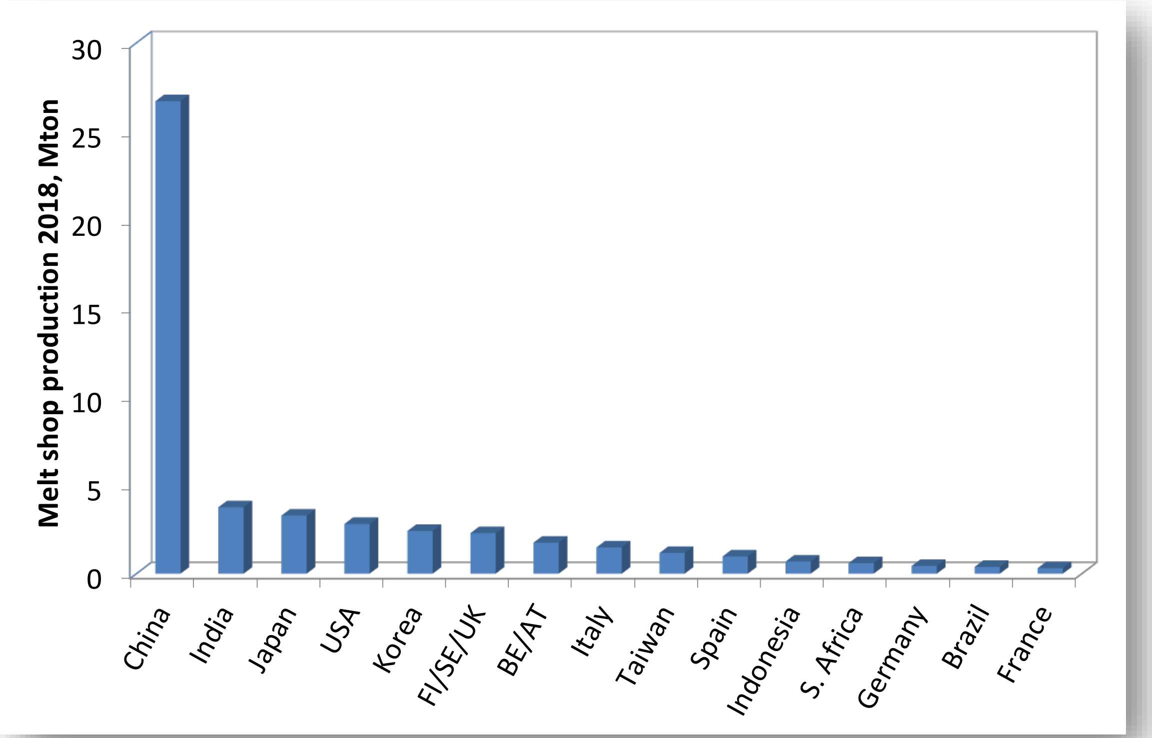
ISSF 2019

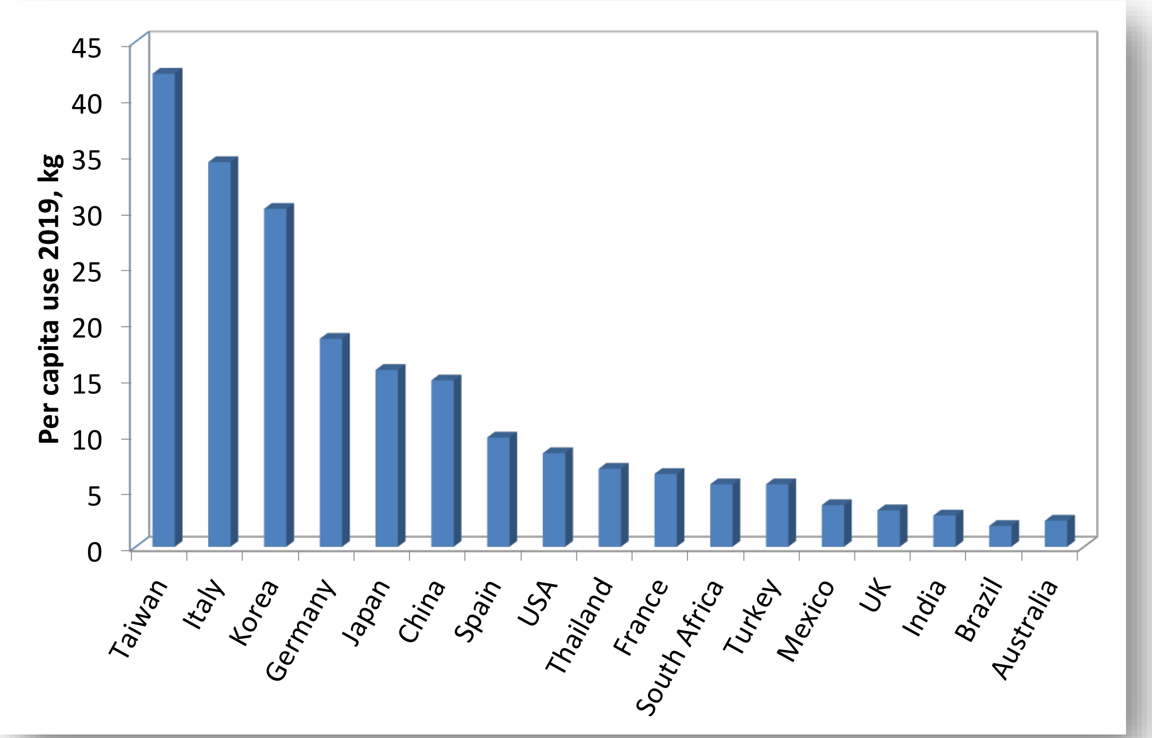
~ 2% of the world steel production is stainless





Production and use of stainless steel





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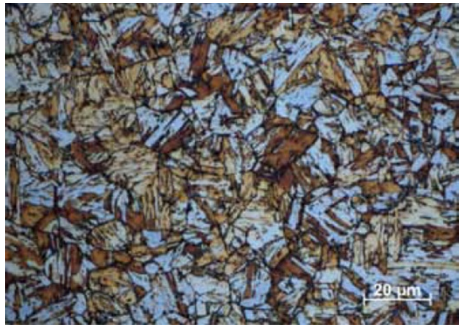
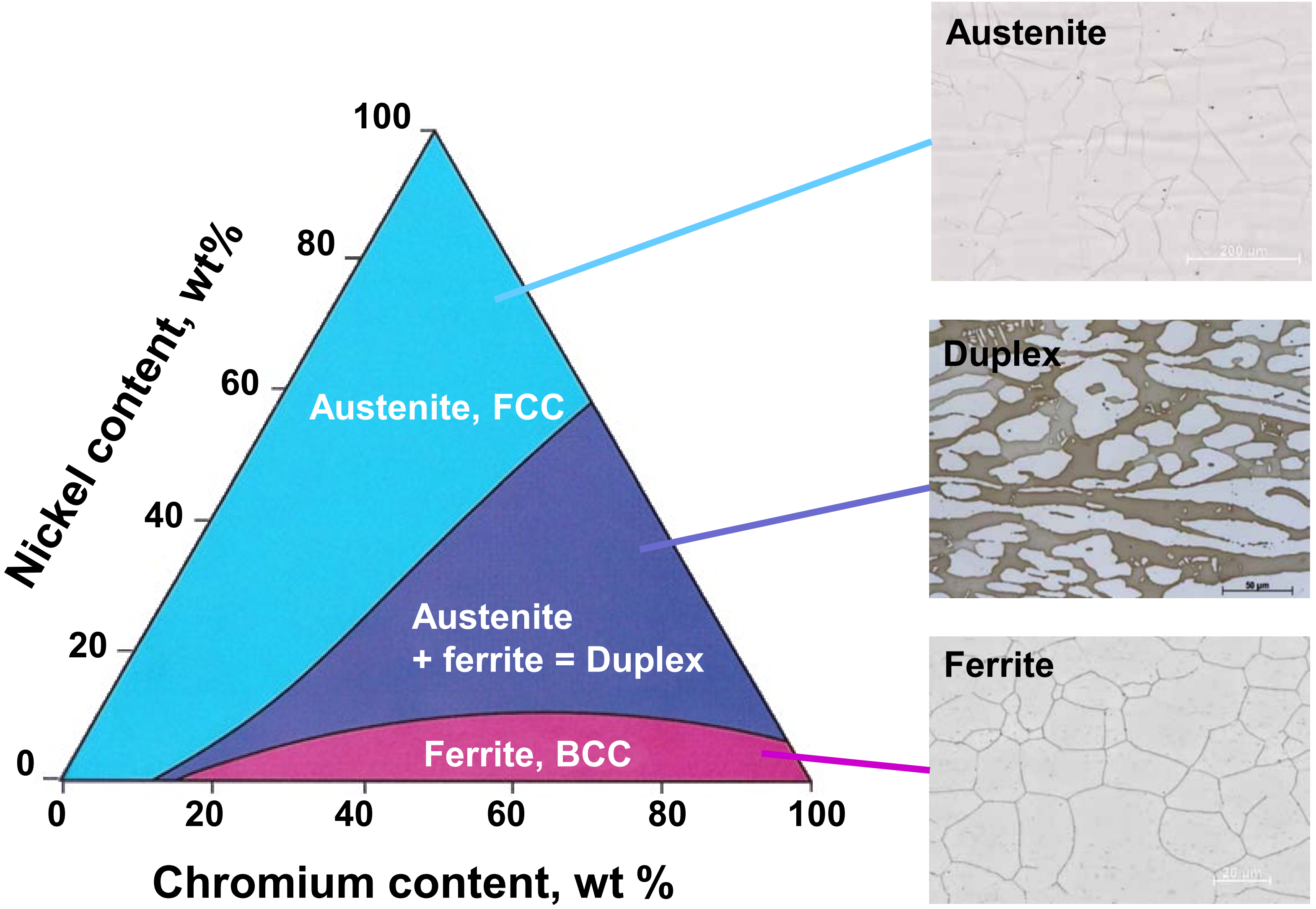
Phase diagrams Fe-Cr-Ni at 1000°C

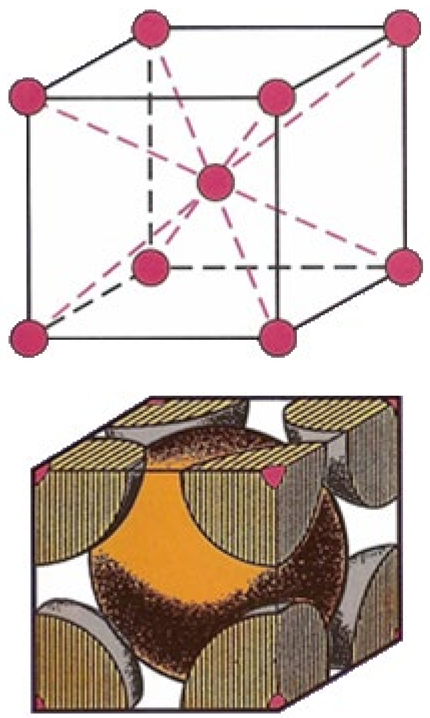
Martensite can form when low alloyed austenitic grades are fast-cooled



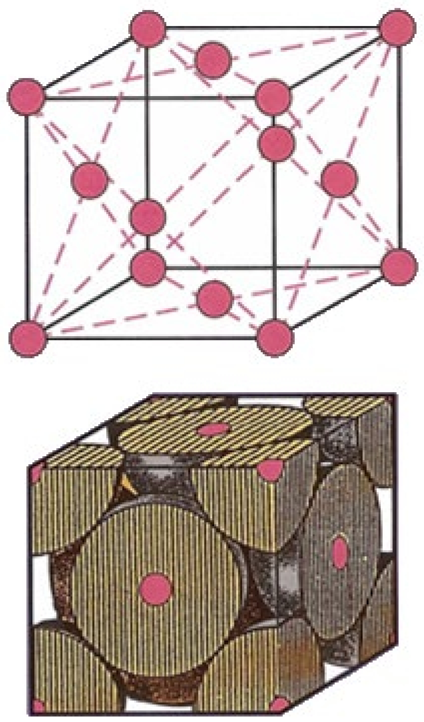


Crystal structure – unit cells

Body centred cubic



Face centred cubic



The red points show the atomic nuclei and the dashed areas in the lower diagrams show the electron orbitals around them.

Effect of alloying elements

Element	Levels (wt%)	Typical levels in austenitic stainless	Effect
Cr	11-25	17	Forms a passive layer with oxygen
Ni	0-40	8-13	Austenite former, improves ductility and toughness
Mn	0.5-8	1.5	Austenite former, replaces Ni in some alloys Increases the solubility of nitrogen
Mo	0-7	0-3	Improves corrosion resistance
Cu	<1.5		Improves corrosion resistance in sulphuric acid
Ti, Nb	<0.5		Form carbides and reduce risk for intergranular corrosion
C	<0.25	<0.05	Austenite former, increases strength and increases risk for intergranular corrosion
N	<0.5	<0.2	Austenite former, increases strength and corrosion resistance

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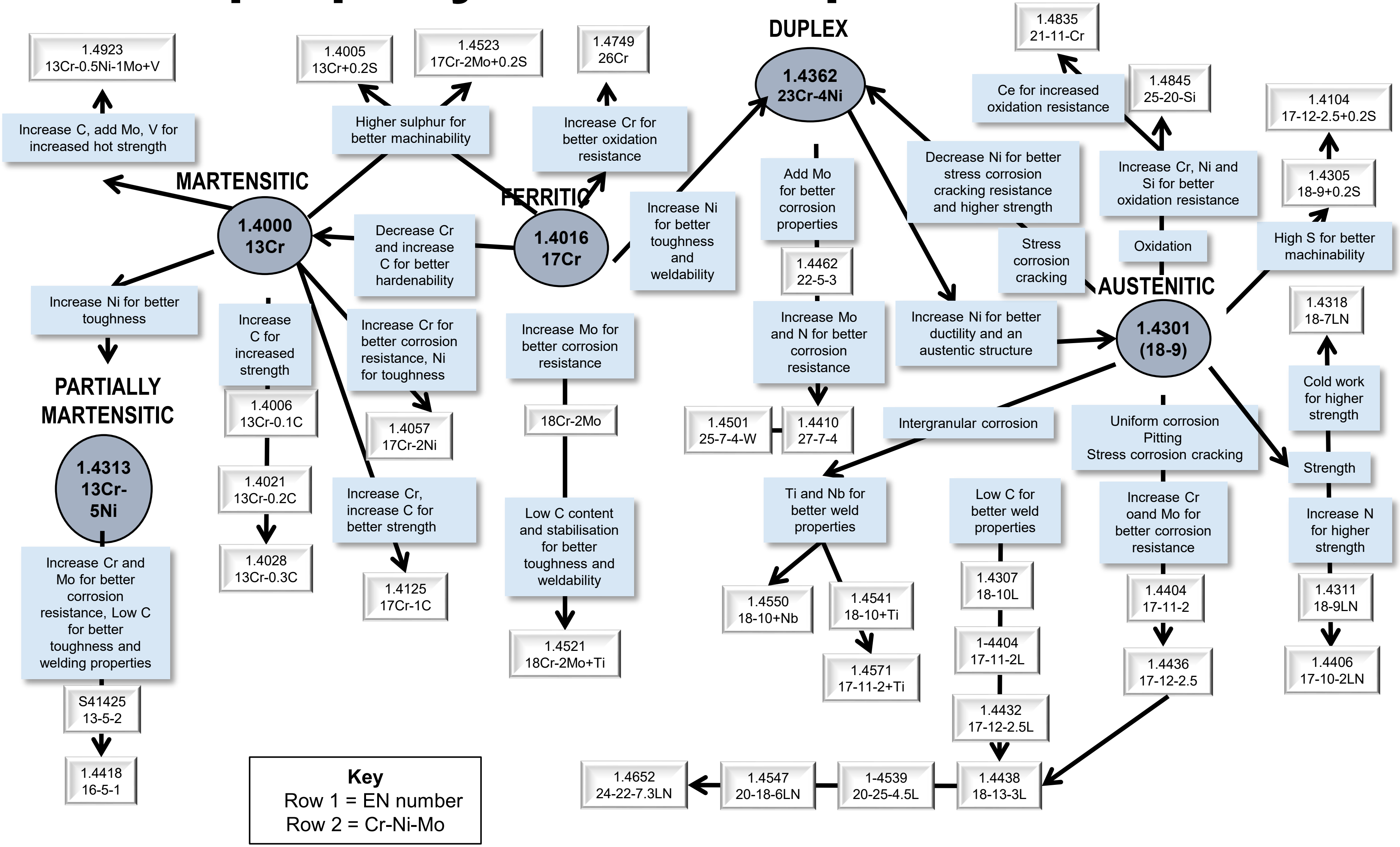
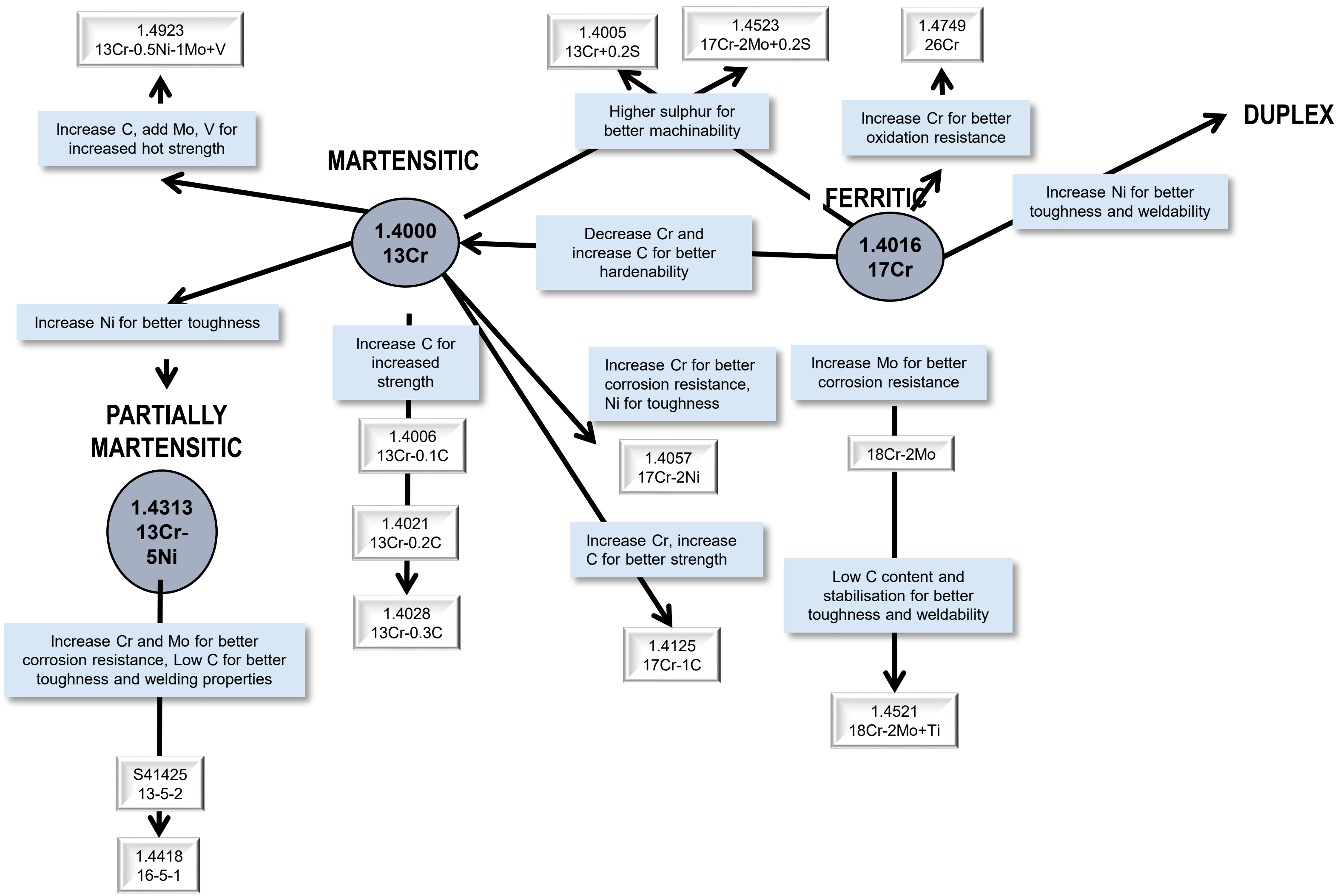
Structure and property relationships



Martensitic and ferritic stainless steel



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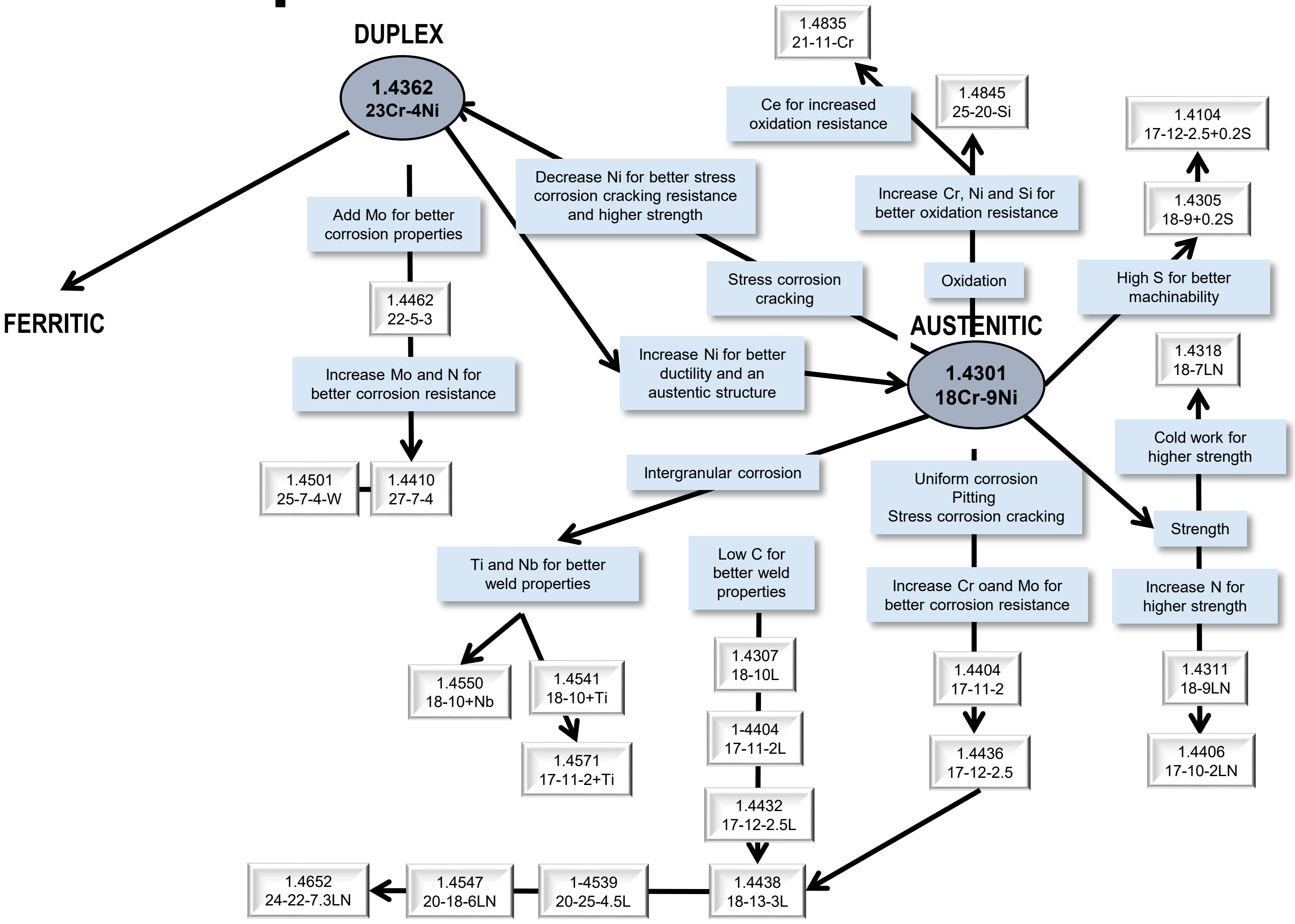
Austenitic and duplex stainless steel



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Some common austenitic and duplex steels

EN	%C	%Cr	%Ni	%Mo	AISI/ Other	UNS	SS
Austenitic							
1.4301	0.04	18	9	-	304	S30400	SS2333
1.4307	0.02	18	9	-	304L	S30403	SS2352
1.4401	0.04	17	10	2.1	316	S31600	SS2347
1.4404	0.02	17	10	2.1	316L	S31603	SS2348
1.4539	0.02	20	25	4.5	”904L”	N08904	SS2562
Duplex							
1.4362	0.02	23	4.8	0.3	"2304"	S32304	SS2327
1.4462	0.02	22	5	3	"2205"	S32205	SS2377
1.4410	0.02	25	7	4	"2507"	S32750	SS2328

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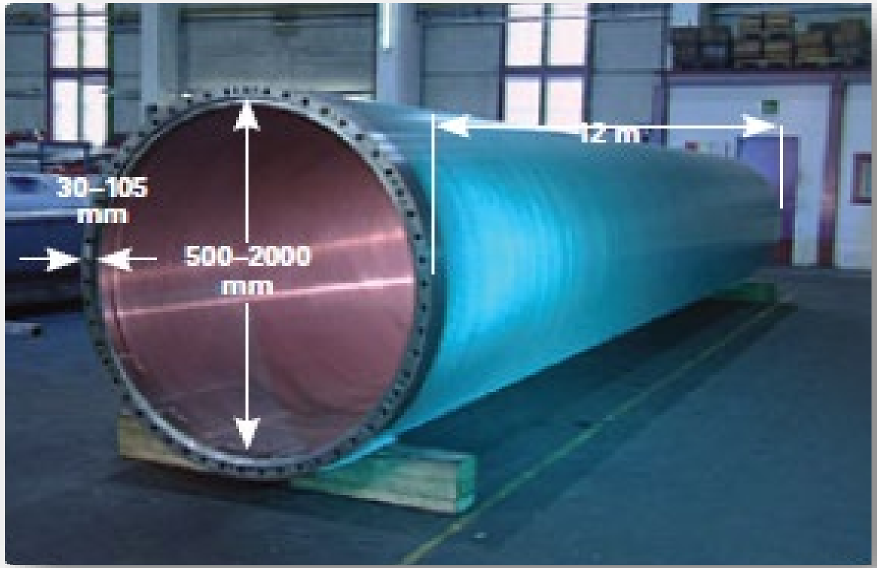
Example Application 1: P&P
- Cellulose Digester

Cellulose digester built in duplex stainless steel 1.4462 (2205)

Example Application 1: P&P
- Suction Rolls

Image: Outokumpu Stainless



Dimensions

Forming

Fatigue Cracking

Often cast but wrought material has better properties.
Designed to withstand corrosion fatigue, which is the most common failure mechanism. Material is duplex stainless steel.

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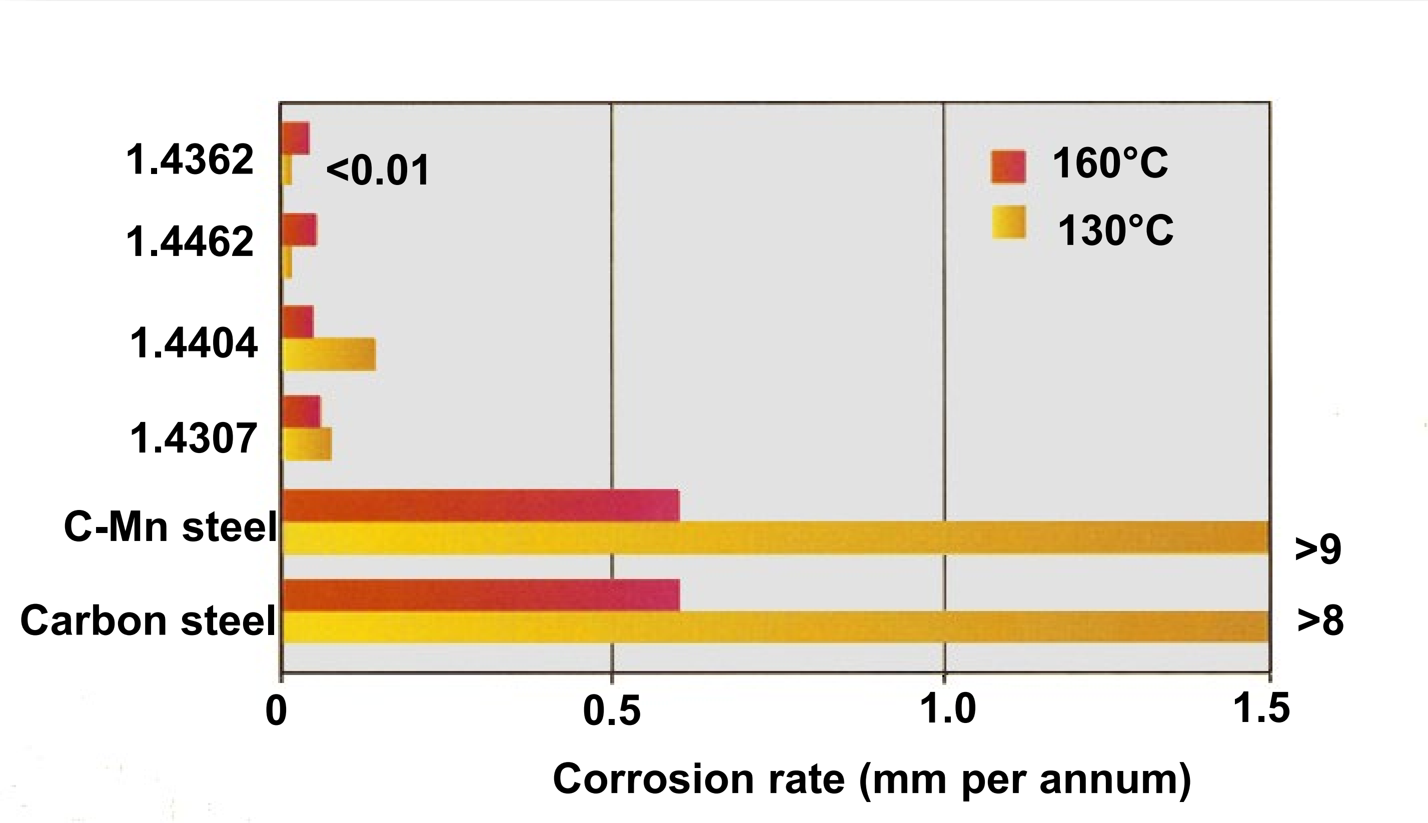
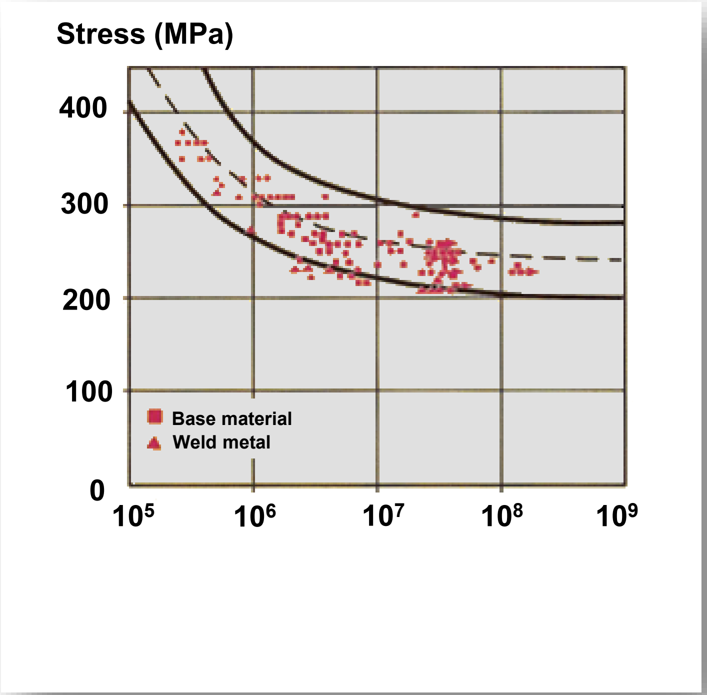
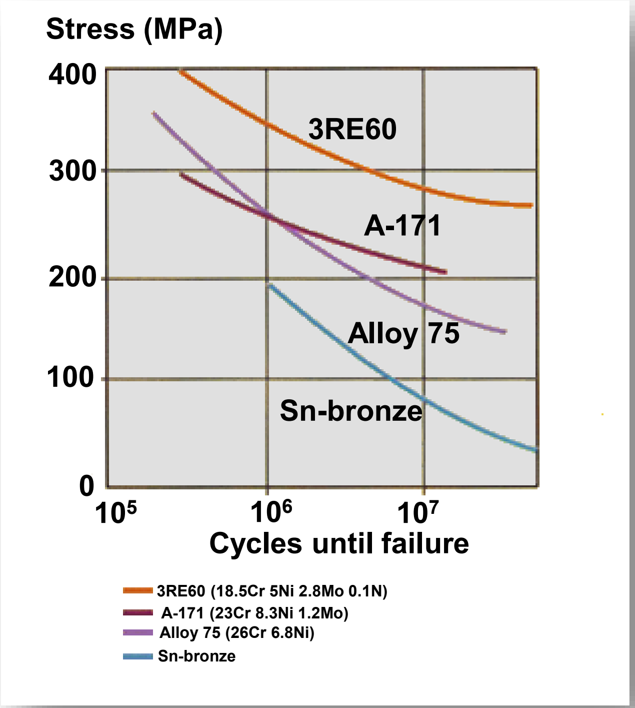
Corrosion rate for different steels in a simulatated sulphate digester environment



Corrosion Fatigue





Wöhler curves in synthetic white liquor for different suction roll materials.
1.4417 (3RE60) is a duplex stainless steel

Environment and testing conditions: rotating bend testing
pH=3.5, 20-400ppm Cl^-, 250ppm SO_4^{2-}, ~1500rpm at RT

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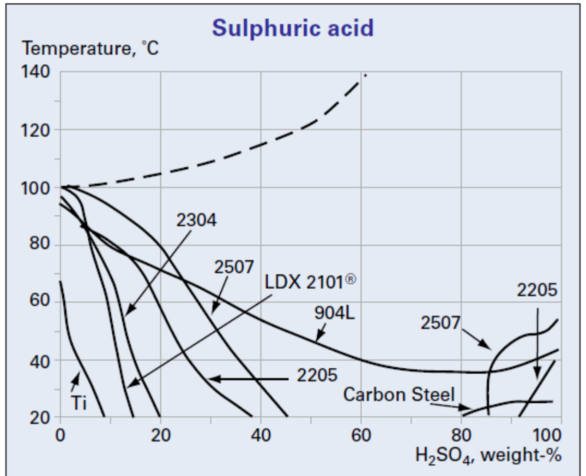
Uniform Corrosion

Corrosion tables give the rate of metal loss

Sulphuric acid
H_2SO_4 — cont.

Conc. %	3	3	5	5	5	5	5	5	10	10	10	10	10	20	20
Temp. °C	85	100 =BP	20	35	60	75	85	101 =BP	20	50	60	80	102 =BP	20	40
Carbon steel	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
13% Cr-steel	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
17% Cr-steel	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
18-2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
18-10	2	2	1	1	2	2	2	2	2	2	2	2	2	[illegible]	[illegible]
17-12-2.5	1	2	0	0	1	1	2	2	0	1	1	2	2	[illegible]	[illegible]
18-13-3	1	2	0	0	0	1	2	2	0	1	1	2	2	[illegible]	[illegible]
17-14-4	1	2	0	0	0	1	2	2	0	0	1	2	2	[illegible]	[illegible]
904L	0	1	0	0	0	0	1	2	0	0	0	1	2	[illegible]	[illegible]
254 SMO®	0	1	0	0	0	0	1	2	0	0	0	0	2	[illegible]	[illegible]
4565	0	1	0	0	0	0	0	2	0	0	0	0	2	[illegible]	[illegible]
654 SMO®	0	0	0	0	0	0	0	2			0	0	1	[illegible]	[illegible]
LDX 2101®	0	1	0	0	0	1	2	2	0	0	0	2	2	[illegible]	[illegible]
2304	0	1	0	0	0	0	0	2	0	0	0	2	2	[illegible]	[illegible]
2205	0	1	0	0	0	0	0	2	0	0	0	1	2	[illegible]	[illegible]
2507	0	1	0	0	0	0	0	1	0	0	0	0	2	[illegible]	[illegible]
Ti	1	2	0	1	1	2	2	2	1	2	2	2	2	[illegible]	[illegible]

0: Corrosion rate < 0,1 mm/year. Material is corrosion resistant
1: Corrosion rate 0,1-1,0 mm/year. Material may be usable
2: Corrosion rate > 1,0 mm/year. Material is not usable



Isocorrosion diagram, 0.1 mm/year, in naturally aerated sulphuric acid of chemical purity. Broken-line curve represents the boiling point.

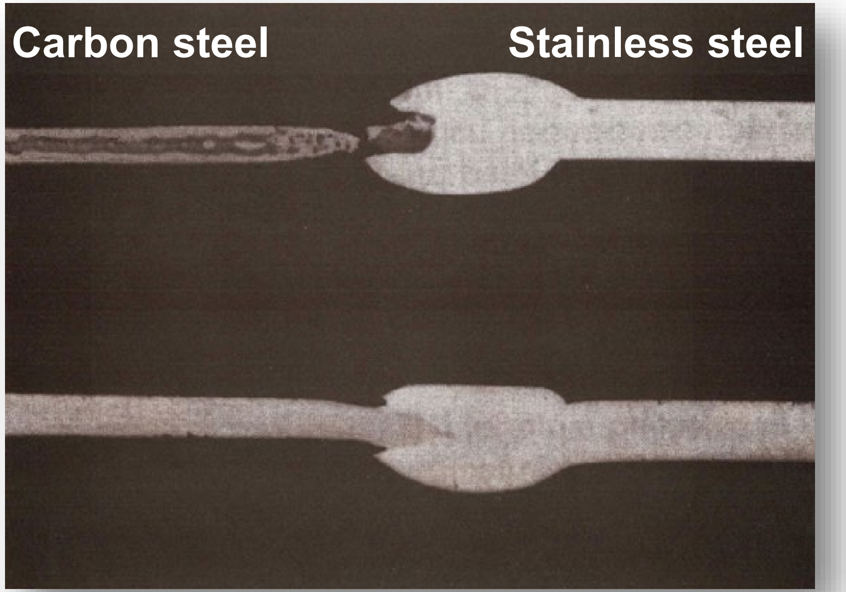
Image: Outokumpu Stainless

Isocorrosion lines show 0.1 mm/year as a function of concentration and temperature for different steel grades.

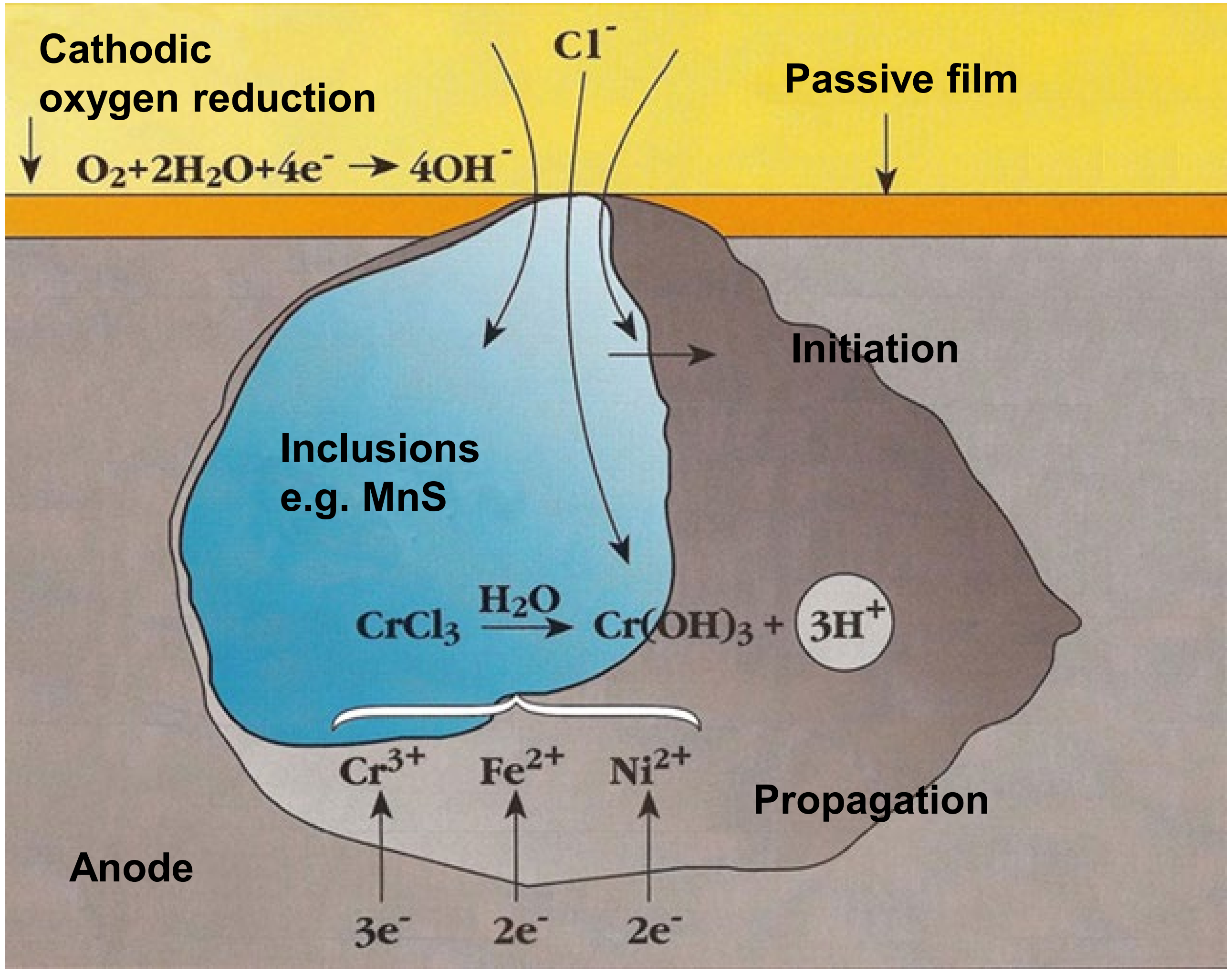
Galvanic corrosion

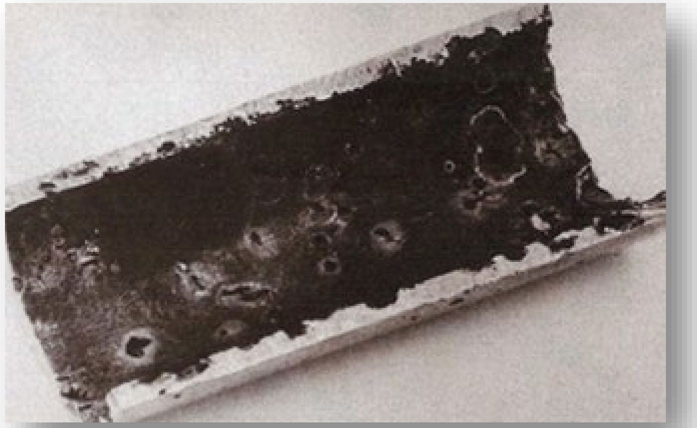
In a weld joint between a stainless and carbon steel

Metall	Potential (V_{SHE}),
Gold	+0.42
Silver	+0.19
Stainless (passive)	+0.09
Copper	+0.02
Tin	-0.26
Stainless (active)	-0.29
Lead	-0.31
Steel	-0.46
Cadmium	-0.49
Aluminium	-0.51
Zinc	-0.86
Magnesium	-1.36



Propagation of pitting corrosion





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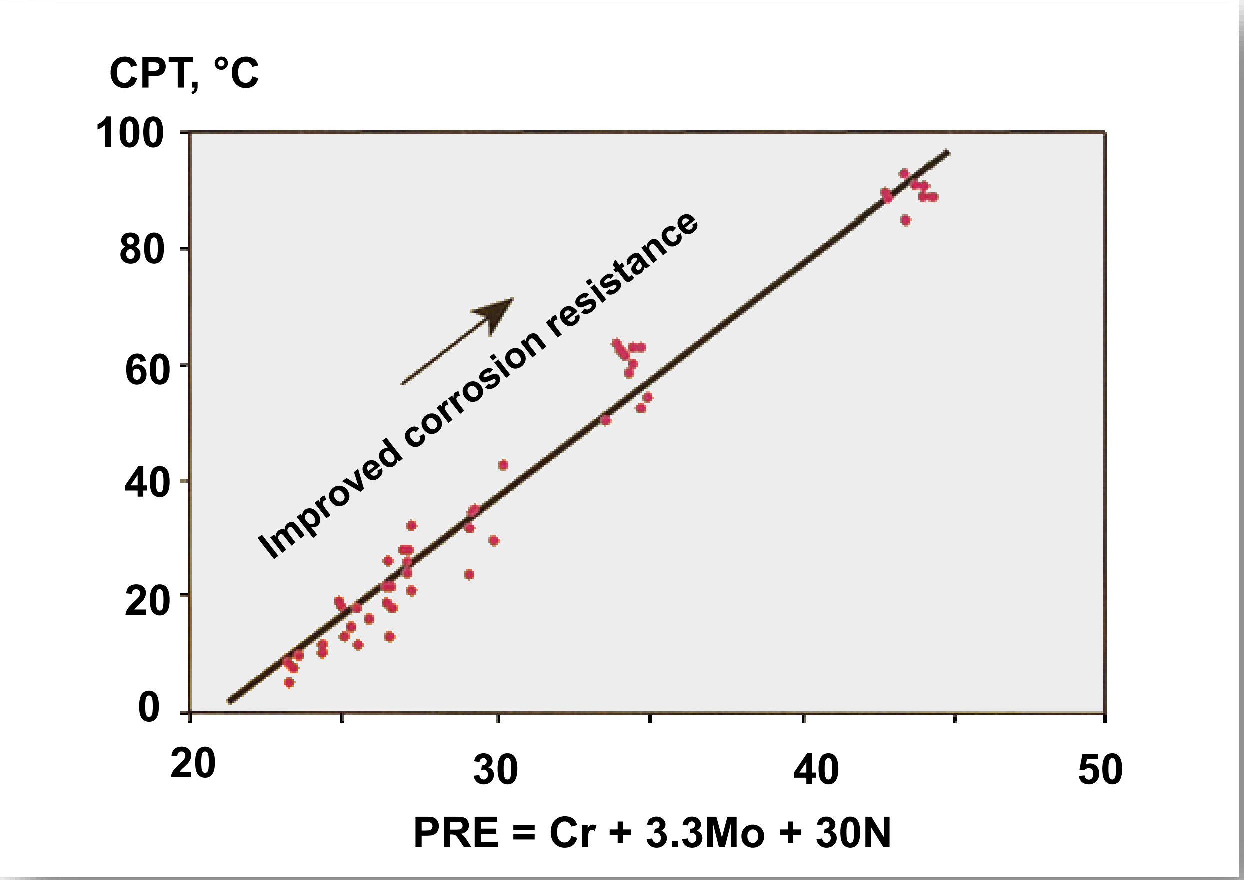
Corrosion resistance vs. PRE

for austenitic stainless steels



PRE = Pitting Resistance Equivalent
Several formulae exist, e.g.
PRE = %Cr + 3.3*(%Mo + 0.5*%W) + 16*%N

CPT = Critical Pitting Temperature

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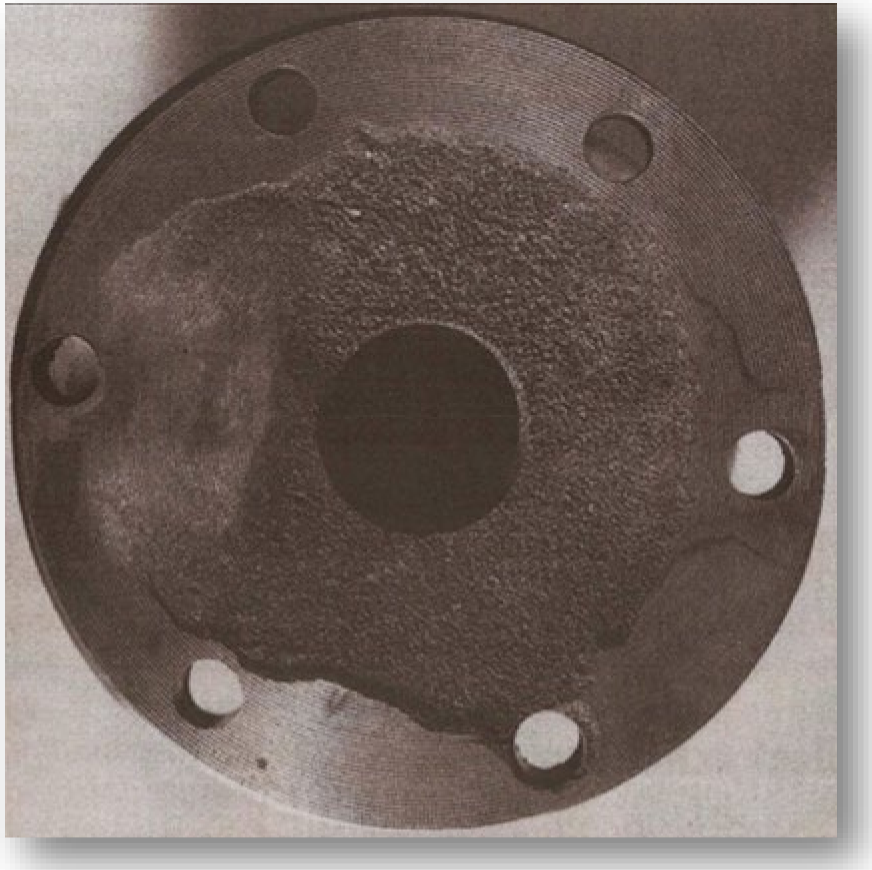
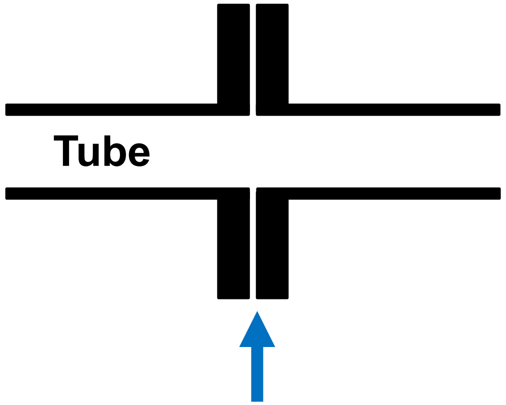
Crevice corrosion



Attack on a flange in high-alloyed stainless steel



Stress corrosion cracking

Stress corrosion cracks from an entrance hole to a black liquor boiler
Alkaline environment with chloride and sulphur at high temperature

Cracks, typically branched, have extended for 4 mm, plate thickness 5 mm

Higher magnification:
crack path is partly intergranular and partly transgranular

Sensitisation

Intergranular corrosion in a pressure vessel after faulty heat treatment which causes precipitation of chromium carbides

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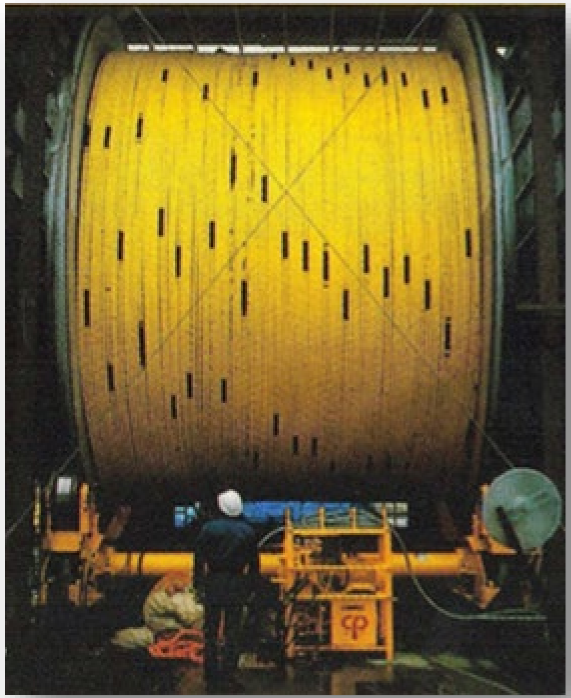
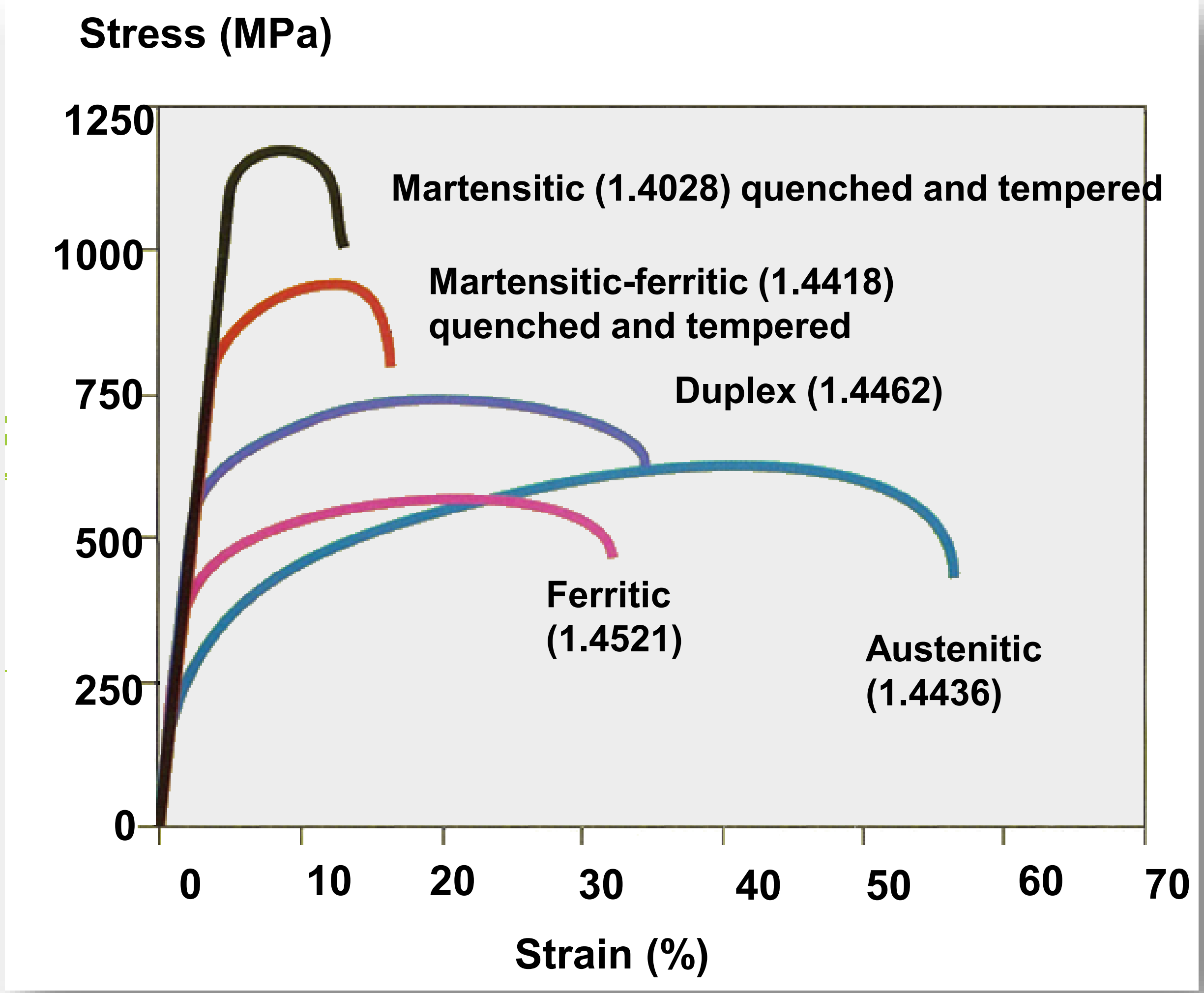
Example Application 2: Umbilicals



Connections which provide seabed oil wells with hydraulics, power, injection fluids etc.

Stress-strain curves



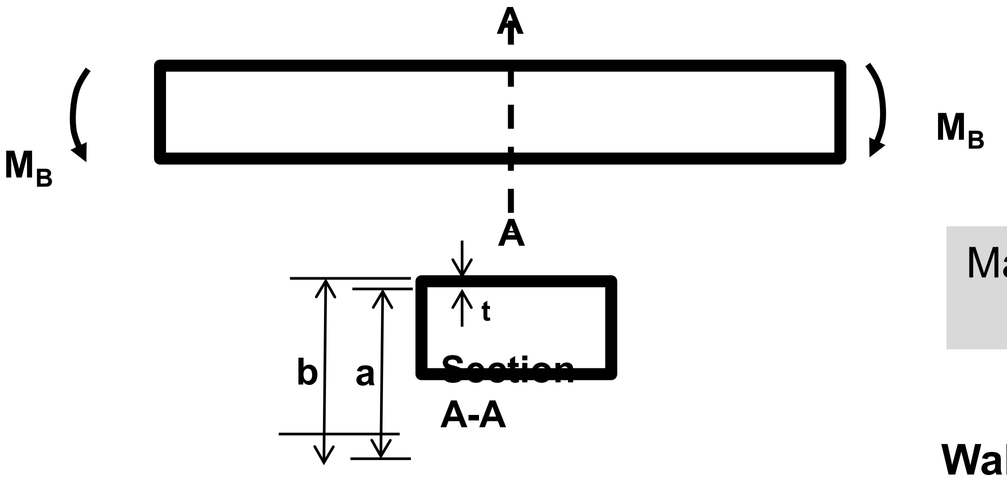
Typical mechanical properties at RT

	EN	AISI/UNS	$R_{p0,2}$ (MPa)	R_m (MPa)	A_5 (%)
Ferritic	1.4000	410S	270	490	30
	1.4016	430	380	520	25
	1.4521	444	360	540	26
	1.4749	446	280	600	20
Martensitic	1.4021	420	500	650	20
(Martensitic-ferritic)	1.4418		700	1000	14
Duplex	1.4362	S32304	450	700	38
	1.4462	S32205	510	750	35
	1.4410	S32750	560	830	35
	1.4501	S32760	550	750	25
Austenitic	1.4301	304	290	600	55
	1.4307	304L	280	580	55
	1.4311	304LN	320	640	55
	1.4541	321	250	570	55
	1.4401	316	280	570	55
	1.4407	316L	280	570	55
	1.4539	N08904	260	600	50
	1.4547	S31254	340	680	50
(Heat resistant)	1.4835	S30815	370	700	50
	1.4845	310S	270	600	50

Example Application 3: Posts & railings

- Lamp posts on the Canary Islands
- Marine atmosphere, high humidity and high chloride concentration
- Galvanised steel corrodes rapidly
- 2000 lamp posts in 1.4404 and some in duplex 1.4462 were installed.
- A lamp post can be considered a conical beam, 4-8 m high.
- Wall thickness, 1.4404 – 2.5 mm and 1.4462 - 2.0 mm
- Weight saving is 20 % or 15 kg for the 8 m high lamp posts.

Example Application 4: Beams

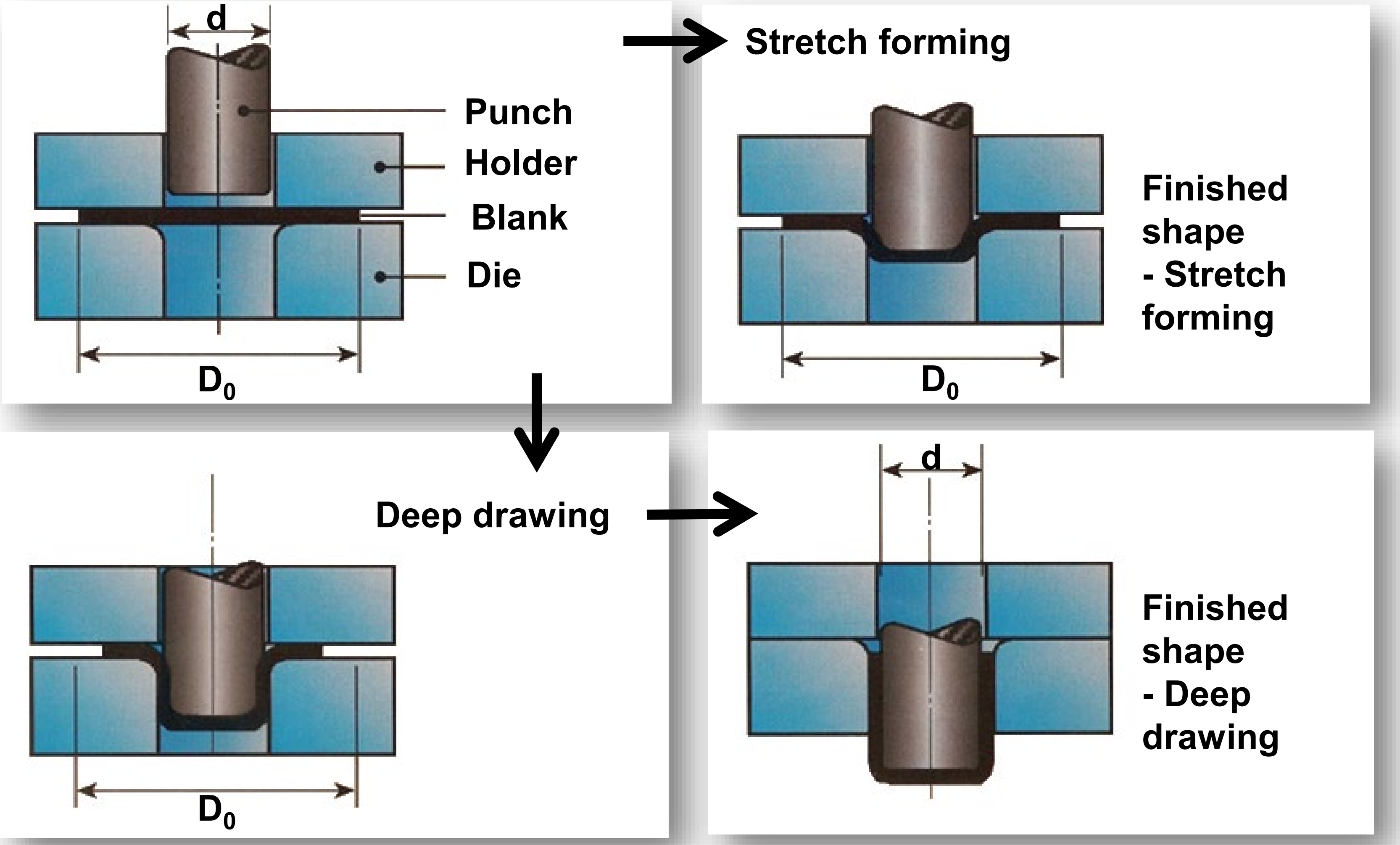


$$\text{Max stress} = \frac{M_B}{W_B} = \frac{M_B}{I / e} = \frac{6\, e\, M_B}{b^4 - a^4}$$

Wall thickness and weight for M_B = 1.53 kNm

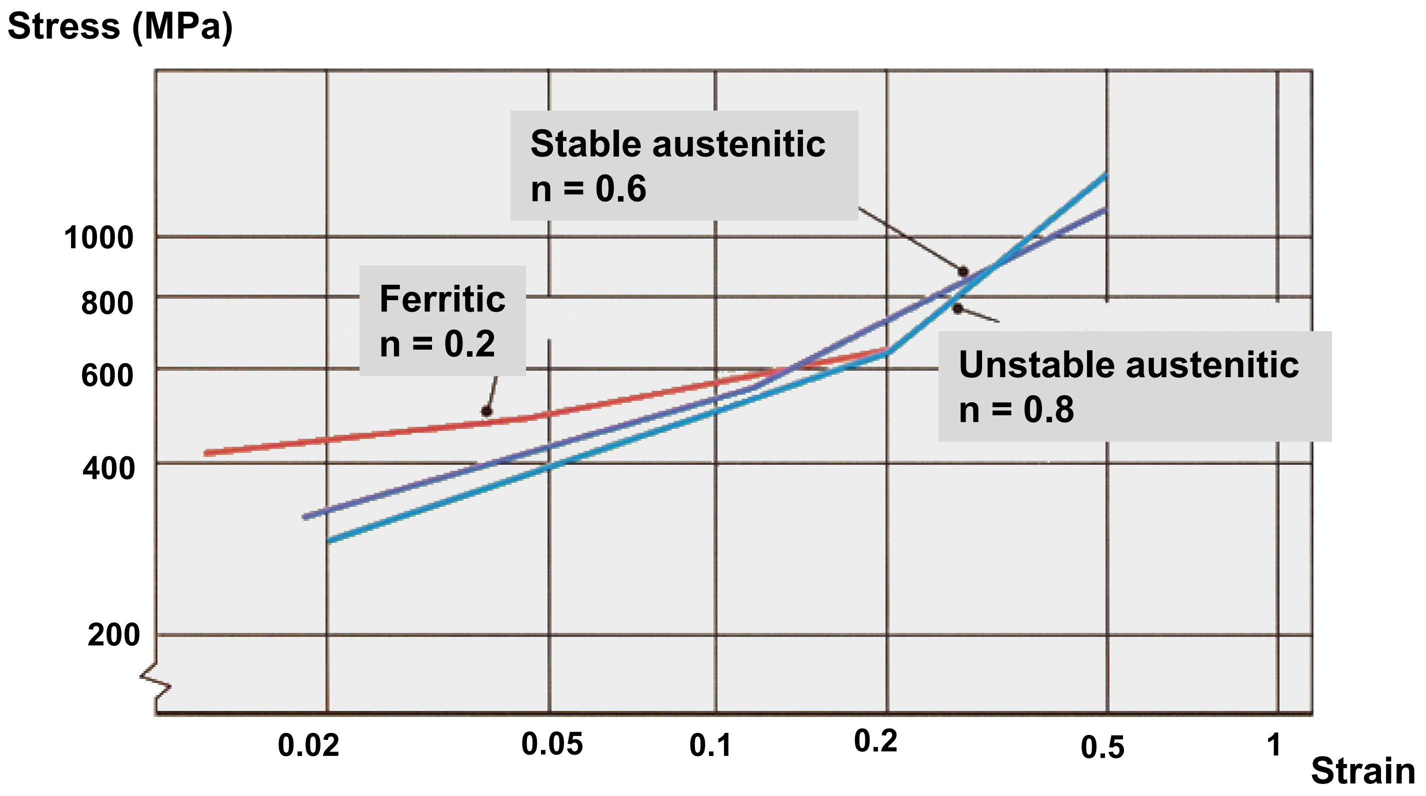
Material	Rp (min) MPa	Thickness mm	Relative weight
1.0425 (C steel)	260	3.6	1
1.4432	210	5.0	1.39
1.4362	400	2.1	0.57
1.4462	480	1.7	0.46

Press forming operations

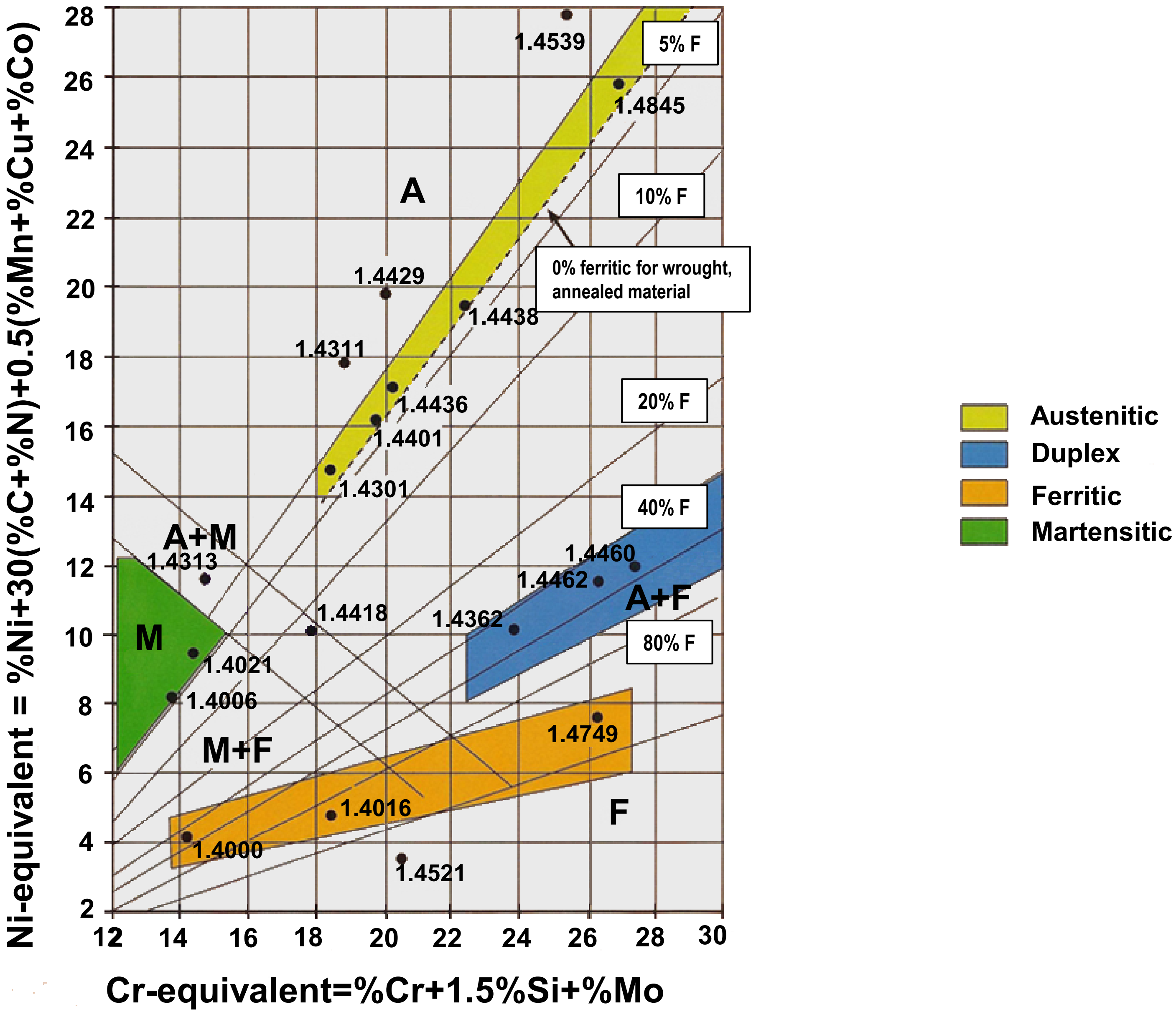


True stress-true strain curve

Comparison between a stable and an unstable austenitic stainless steel and ferritic stainless steel.



Schaeffler-Delong - diagram



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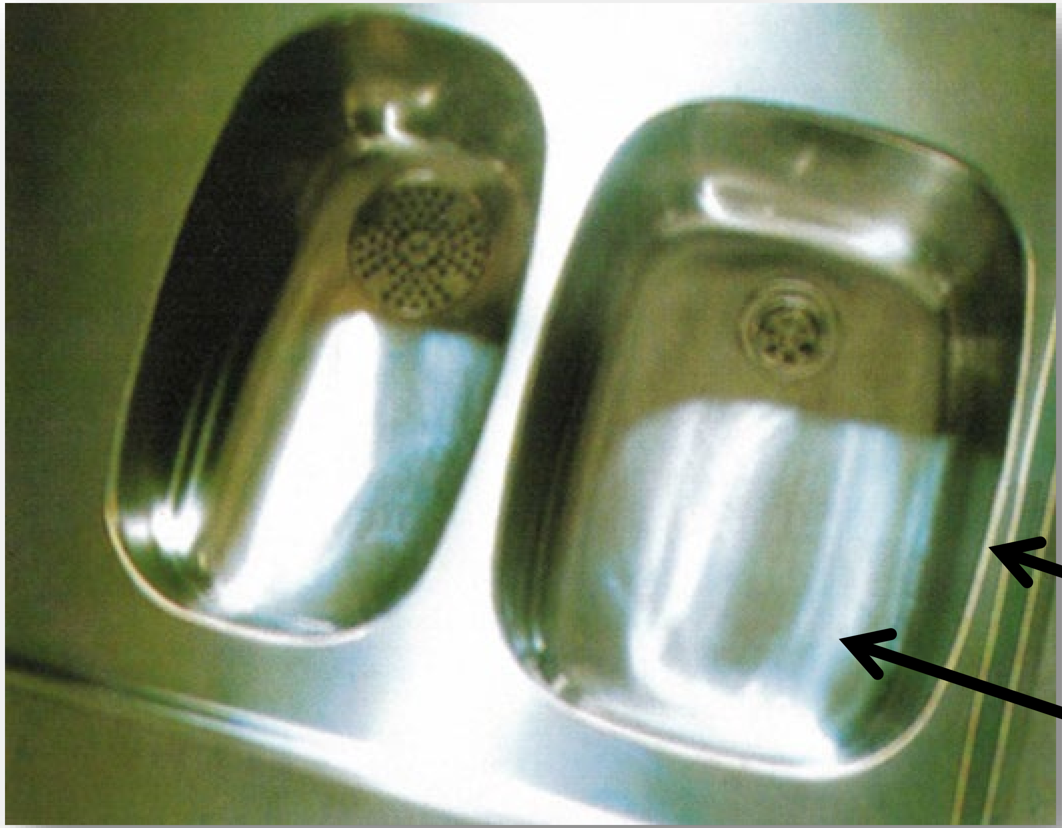
Example Application 5: kitchen sink



Weld

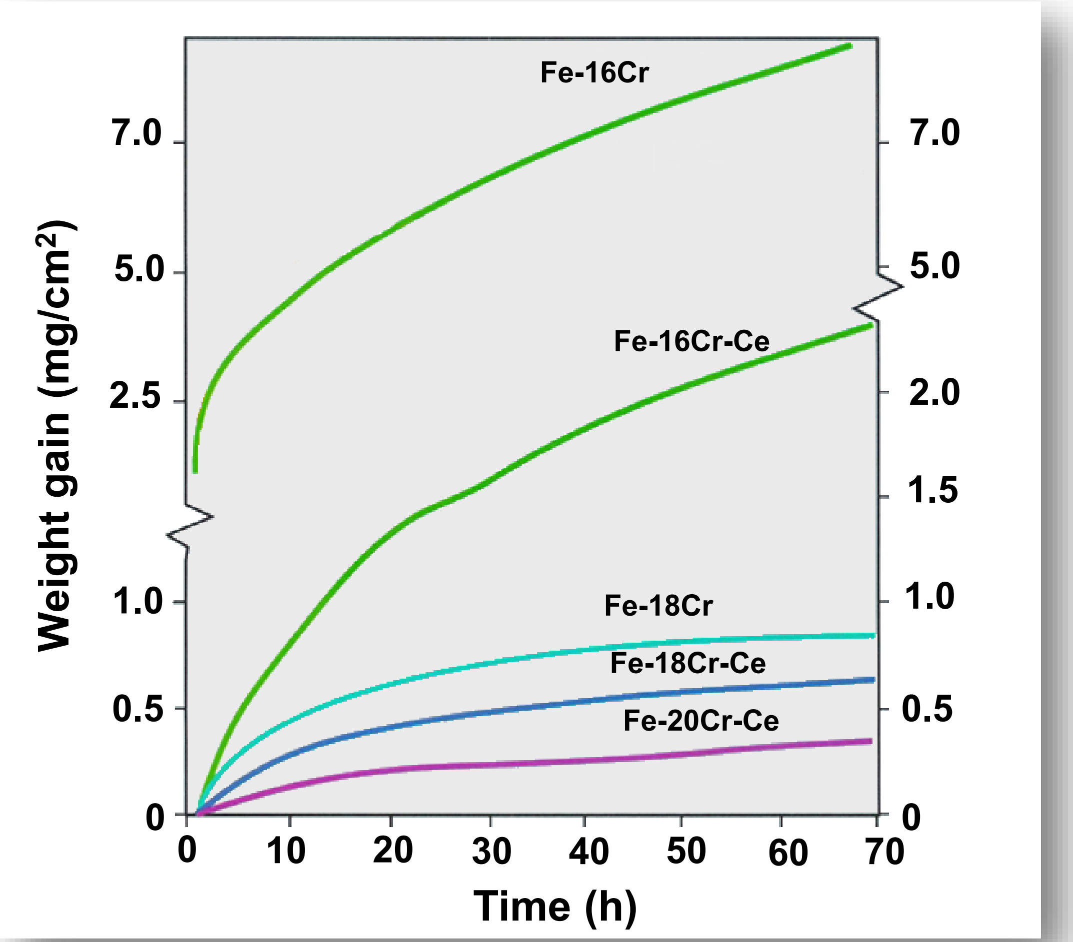
Sink

High demands on formability and weldability
Deep drawn sink with an invisible weld

Austenitic and ferritic high temperature steels

EN	Comm.	Cr	Ni	N	Si	C	Other
Austenitic							
1.4818	153MA	18.5	9.5	0.15	1,3	0,05	Ce
1.4835	253MA	21	11	0.17	1,7	0,09	Ce
1.4854	353MA	25	35	0.15	1.5	0.05	Ce
1.4845	310S	25	20		≤1,5	0,05	
Ferritic							
1.4512	409	11.5			1.0 max	0.03	Ti
1.4509	441	18			1.0 max	0.03	Nb,Ti
1.4742		17.5		0.02	1.0	≤0.12	1 Al
1.4749	446, 4C54	26.5		0.02	0.5	≤0.20	
	Kanthal A1	22			0,3	0,02	5.8Al, Zr
	Kanthal AF	23			0,2	0,04	5,2Al, Zr, Y

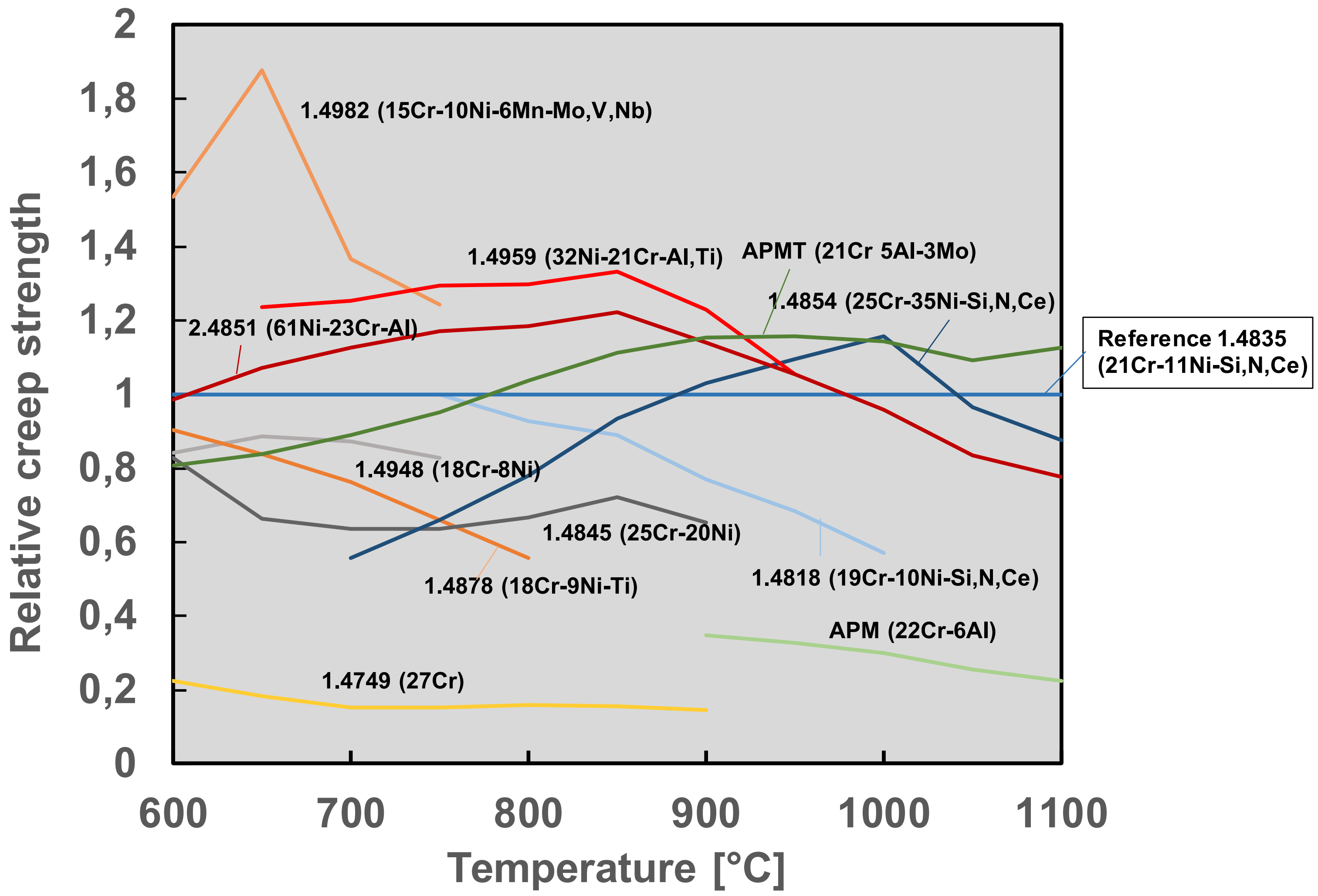
Oxidation resistance – influence of Cr and REM



pO_2=13 kPa

REM = Rare Earth Metals

Creep strength related to 1.4835



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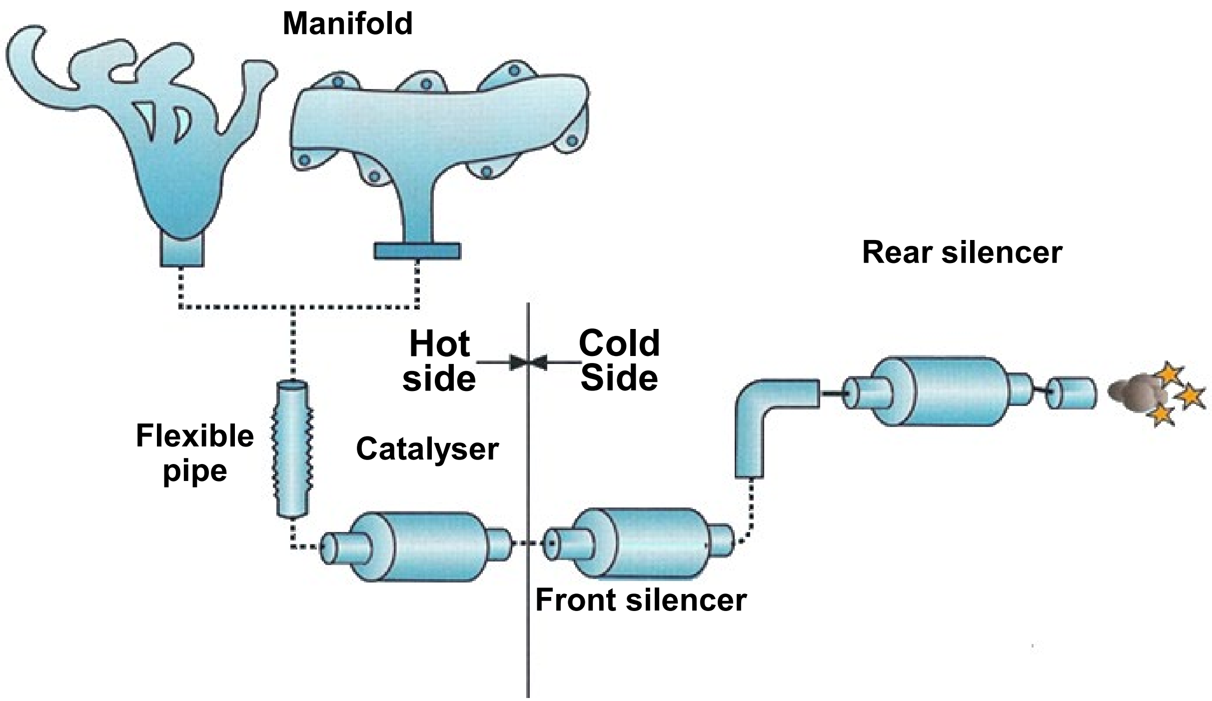
Based on stress data for creep failure in 10 000 hours

Example Application 6: Exhaust system



Oxidation resistance
Hot strength
Embrittlement resistance

Ferritic 13%Cr – Heat resistance 1.4835

Aqueous corrosion resistance (condenstaion, road environment)

Ferritic 13%Cr – austenitic 1.4301

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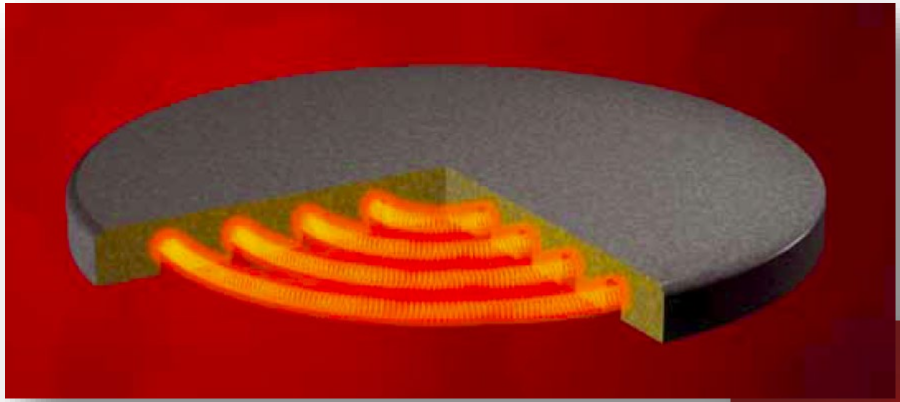
Example Application 7: Heating elements



Resistance heating is used in:

- Ovens and hot plates
- Hairdryers, toasters, irons
- Heaters for buildings
- Industrial furnaces

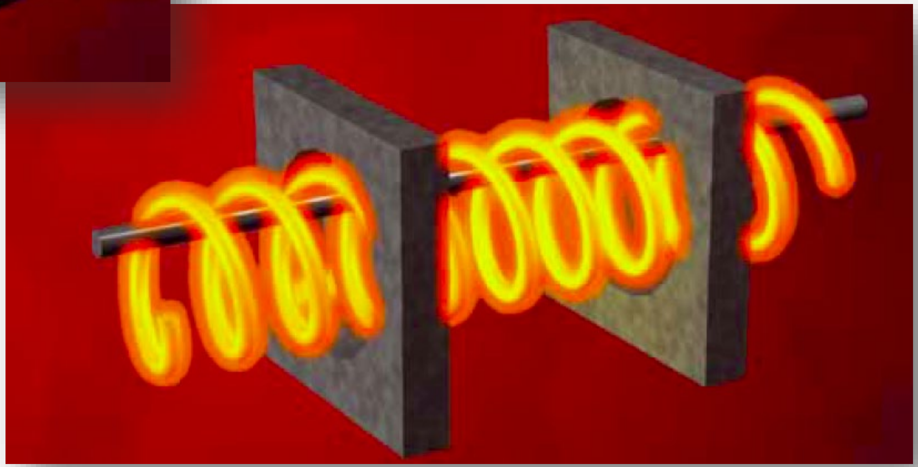


Image: Sandvik

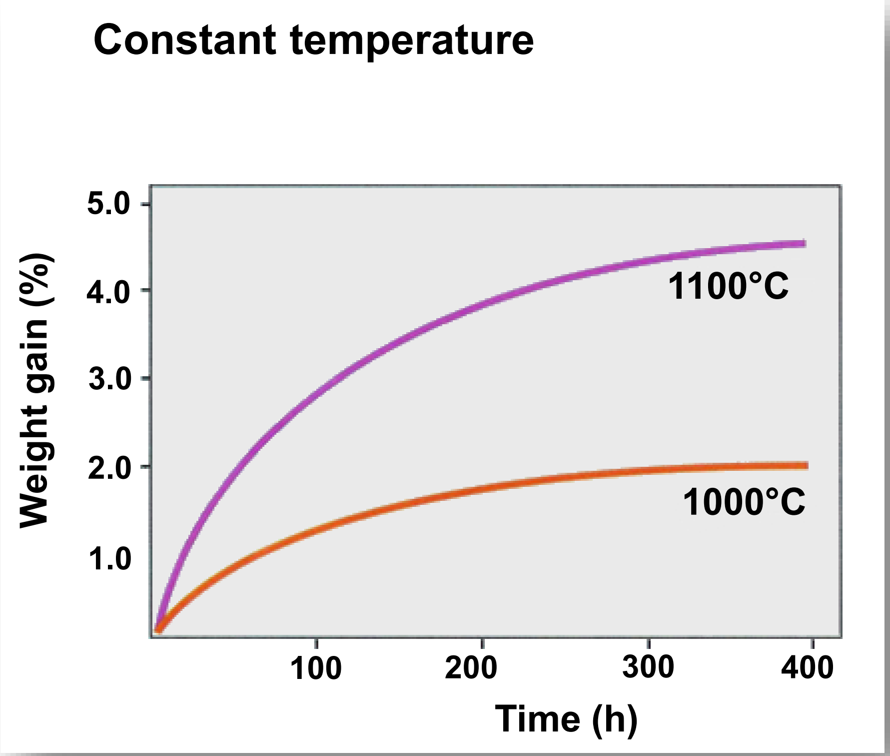
Material must withstand:

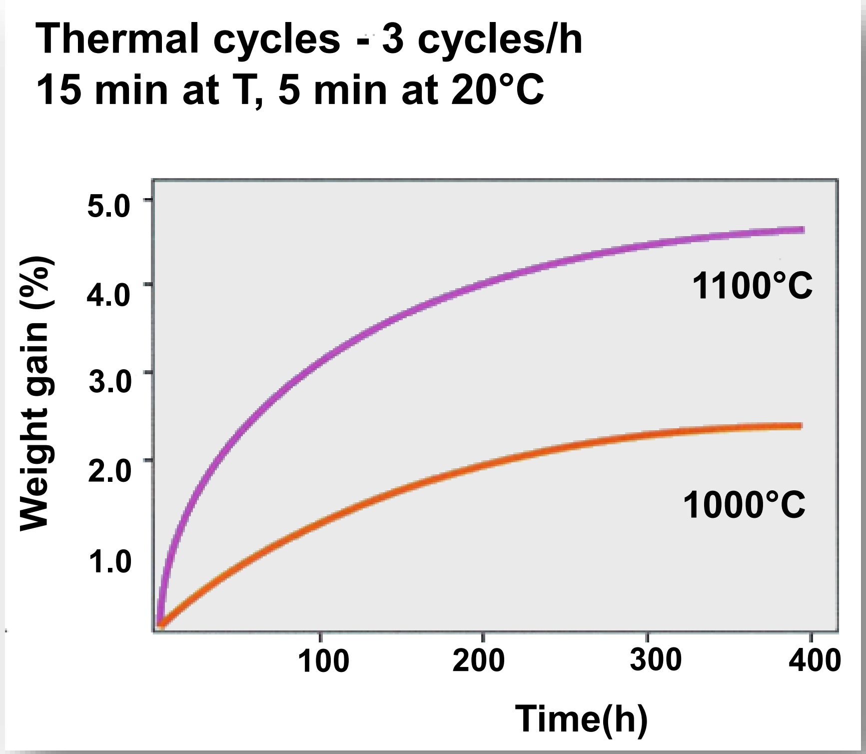
- Oxidation
- Creep – elongation
- Temperature cycles
- Corrosion (steam, chlorides)

Resistance to high temperature oxidation

FeCrAl alloy

Same graph twice





Low weight gain at constant temperature
and in thermal cycling

Physical properties

Property	Martensitic	Ferritic	Austenitic	Duplex
Density [kg/m^3]	7600-7700	7600-7800	7900-8200	7700-7800
Young's Modulus [N/mm^2]	220000	220000	195000	200000
Thermal expansion coefficient [K^{-1}] at 293K (20°C)	$10\text{-}11 \cdot 10^{-6}$	$10\text{-}11 \cdot 10^{-6}$	$15\text{-}17 \cdot 10^{-6}$	$13 \cdot 10^{-6}$
Thermal conductivity [W/mK] at 293K (20°C)	20-30	20-25	12-15	15
Thermal capacity [J/kg K]	460	460	440	440-460
Resistivity $10^9 \cdot [\Omega m^2/m]$ at 293K (20°C)	600	600-750	850	700-850
Ferromagnetic	yes	yes	no	yes