Stainless Steel & its Industrial Applications

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Discovery of Stainless Steels

First Stainless Steel – 20th Aug 1913

Harry Brearley (1871-1948)

Lee Enfield .303 Rifle

Brearley was working on this type of rifle to solve erosion of gun barrels for
- Royal Small Arms Factory

Brearley 's idea to develop... Heat resistance-Erosion Corrosion
✓Adding high Cr and low C

1913: First Successful Ingot : Cr -12.86% / Mn-0.44% / Si-0.20% / C-0.24%,
No improvement in erosion resistance

Discovery of "Rustless Steel" .. usual etching agents for steel did not etch Cr-containing Fe alloy.

Development of Stainless Steels

- First application for stainless steels was stainless cutlery
- B. Strauss (Germany), developed steel with 0.25% carbon, 20% chromium and 7% nickel; the first austenitic stainless steel for protective tubing for thermocouples and pyrometers
- F.M. Becket (USA) developed high Cr heat resisting stainless steel for furnace troughs

Gateway Arch in St. Louis (304 SS)

Process Plants (Various SS)

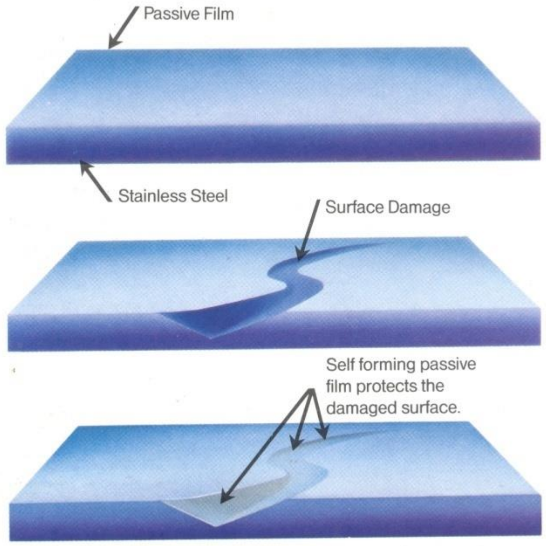
500 MWe PFBR (304/316LN SS)

F-35 Joint Strike Fighter (17-7 PH SS)

What is Stainless Steel

STAINLESS STEELS are iron-base alloys that contain a minimum of about 10.5% Cr, the amount needed to prevent the formation of rust in unpolluted atmospheres

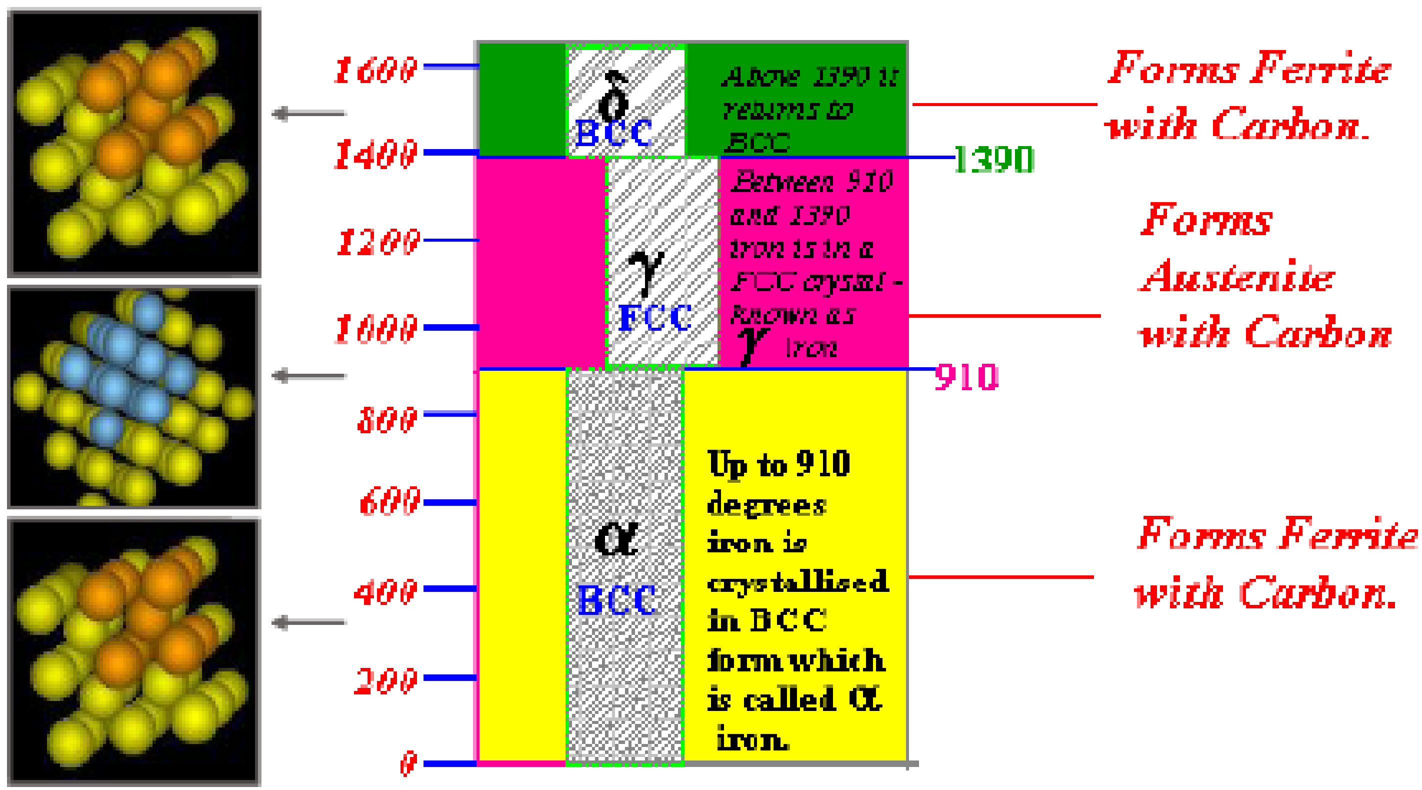
- **Presence of non-rusting thin surface layer provides a 'stainless' nature to steel**
- **Stainless characteristics through the formation of an invisible and adherent chromium- rich oxide film**
- **Oxide film forms and heals itself in the presence of oxygen**
- **Other elements added to improve particular characteristics include nickel, manganese, molybdenum, copper, titanium, silicon, niobium, aluminum etc.**
- **The corrosion resistance and other useful properties are enhanced by increasing chromium content, and the addition of molybdenum, nickel and nitrogen**



Self-repairing property of stainless steel

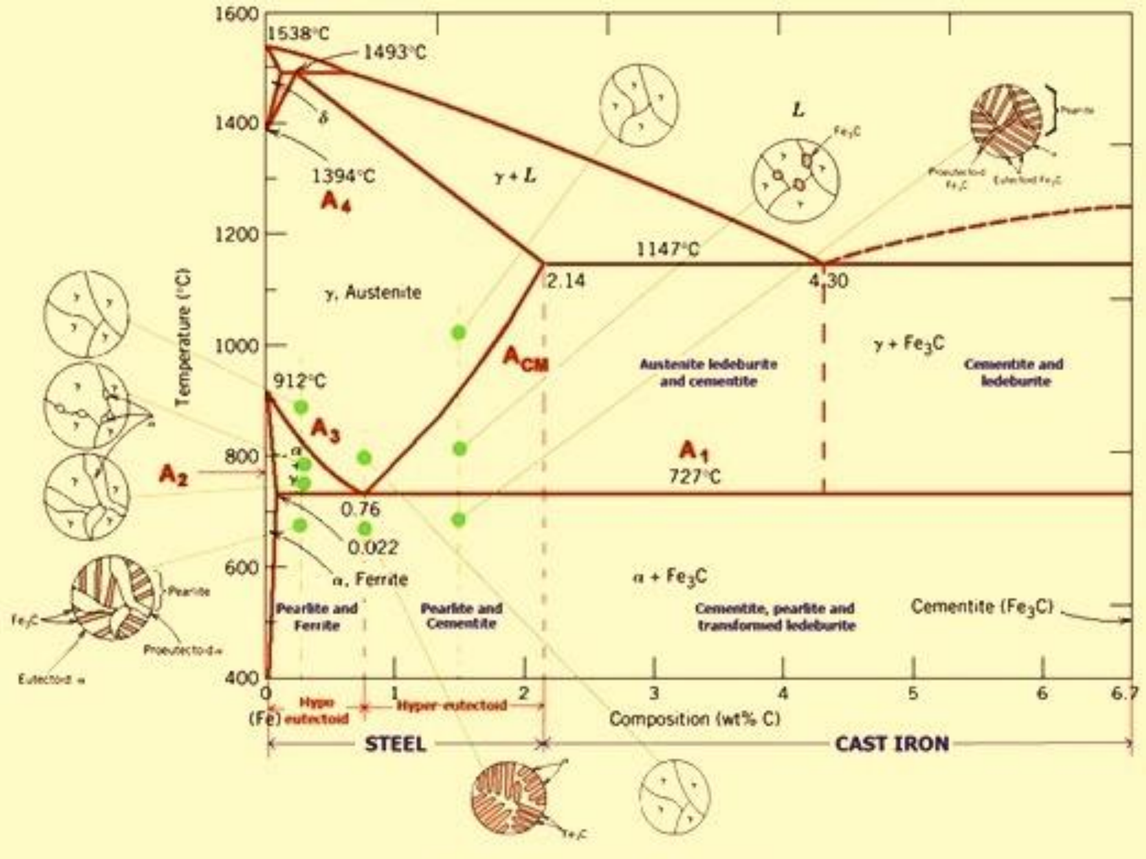
Allotropy of Iron – Genesis for Stainless Steel

Iron changes its structure when heated. Iron has the ability to exist as BCC or FCC depending on the temperature. This ability is called the allotropy of iron



α =alpha γ = gamma δ = delta

Iron-Carbon (Fe-C) diagram



Fe-C phase diagram

Phases present

δ
Bcc structure
Paramagnetic

α ferrite
Bcc structure
Ferromagnetic
Fairly ductile

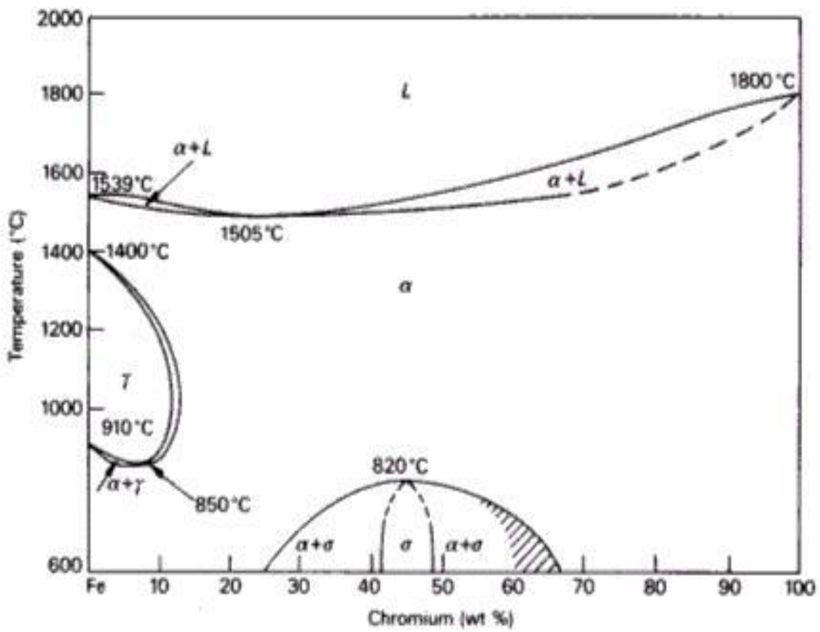
γ austenite
Fcc structure
Non-magnetic
Ductile

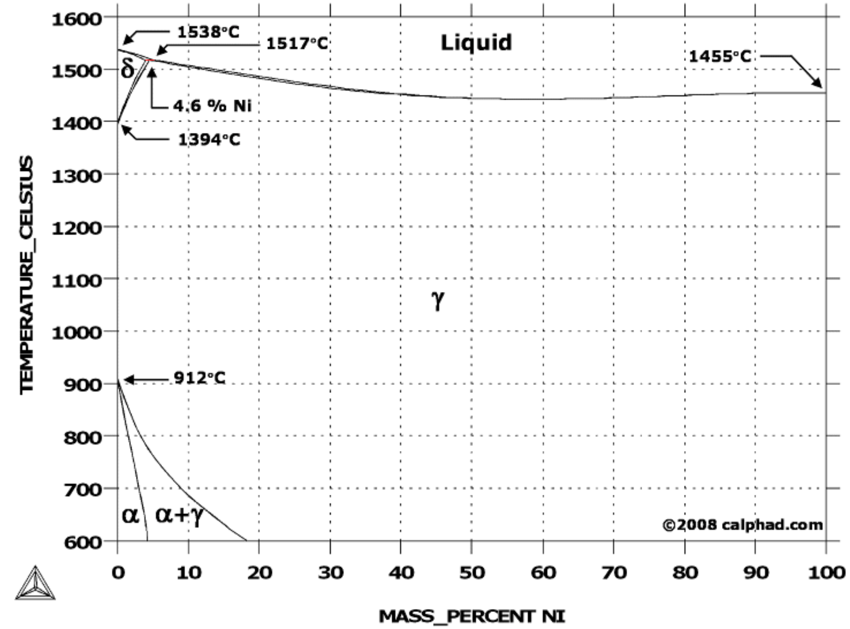
Fe_3C cementite
Orthorhombic
Hard
Brittle

Max. solubility of C in ferrite=0.022% Max. solubility of C in austenite=2.11%

- **Steel is an interstitial solid solution of carbon in iron**
- **Theoretically steel has a maximum of 2.11% carbon**

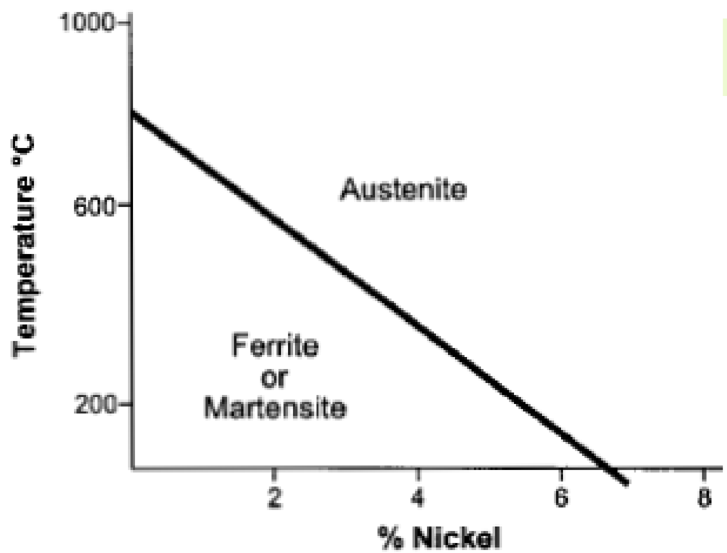
Metallurgy of Stainless Steel





Fe-Cr phase diagram

Fe-Ni phase diagram



Effect of Nickel addition on Fe-Cr alloys

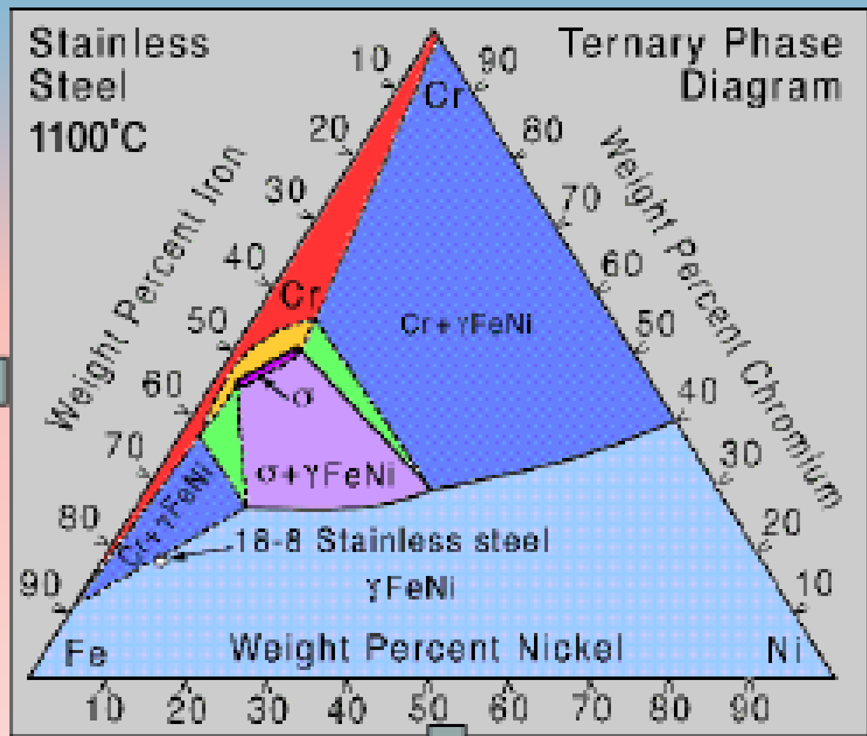
Manifestation of Stainless Steels

Austenitic (65-70%) **Ferritic (20-25%)** **Martensitic (7%)**

Precipitation Hardening (2%) Duplex (1%)

(% of use of 150 types of stainless steels)

Maintain chromium beyond 18%, add nickel minimum 8% to stabilise '<u>austenite</u>' phase; enhance corrosion resistance and toughness



Maintain chromium between 12%-15%, less or no nickel, high C, and transform to '<u>martensite</u>' phase; for enhancing strength and hardenability

Maintain carbon ≤ 0.1%, chromium more than 18%, and NO nickel to arrive '<u>ferrite</u>' structure for achieving strength and moderate corrosion resistance

Types of Stainless Steels

Austenitic

- 300 Series types: Cr and Ni. 200 Series: Cr-Ni with addition of Mn
- Strength can be increased only by cold working
- Nonmagnetic and used in annealed condition
- Exhibit excellent corrosion resistance and good formability

Ferritic

- Ni free alloy and is magnetic
- Cannot be hardened by heat treatment and only moderately hardened by cold working
- Having good ductility and resistance to corrosion and oxidation

Martensitic

- Magnetic and Hardened by heat treatment
- Resist corrosion in mild environments
- Good ductility and drawability

Duplex stainless steels

- Consists of about equal parts of austenite and ferrite in annealed structure
- Highly resistant to chloride stress corrosion cracking, pitting and crevice corrosion
- Exhibit about twice the yield strength as conventional grades

Precipitation-hardening stainless steels :

- Chromium-nickel types, some containing other alloying elements, such as Cu or Al
- Hardened by solution treatment and aging

Types of Stainless Steels (Contd…)

Stainless steels have traditionally been divided into categories depending on their structure at room temperature (decisive effect on properties)

Steel category	Composition (wt%)					Hardenable	Ferro-magnetism
	C	Cr	Ni	Mo	Others		
Martensitic	>0.10	11-14	0-1	-	V	Hardenable	Magnetic
	>0.17	16-18	0-2	0-2			
Martensitic-austenitic	<0.10	12-18	4-6	1-2		Hardenable	Magnetic
Precipitation hardening		15-17	7-8	0-2	Al,	Hardenable	Magnetic
		12-17	4-8	0-2	Al,Cu,Ti,Nb		
Ferritic	<0.08	12-19	0-5	<5	Ti	Not hardenable	Magnetic
	<0.25	24-28	-	-			
Ferritic-austenitic (duplex)	<0.05	18-27	4-7	1-4	N, W	Not hardenable	Magnetic
Austenitic	<0.08	16-30	8-35	0-7	N,Cu,Ti,Nb	Not hardenable	Non-magnetic

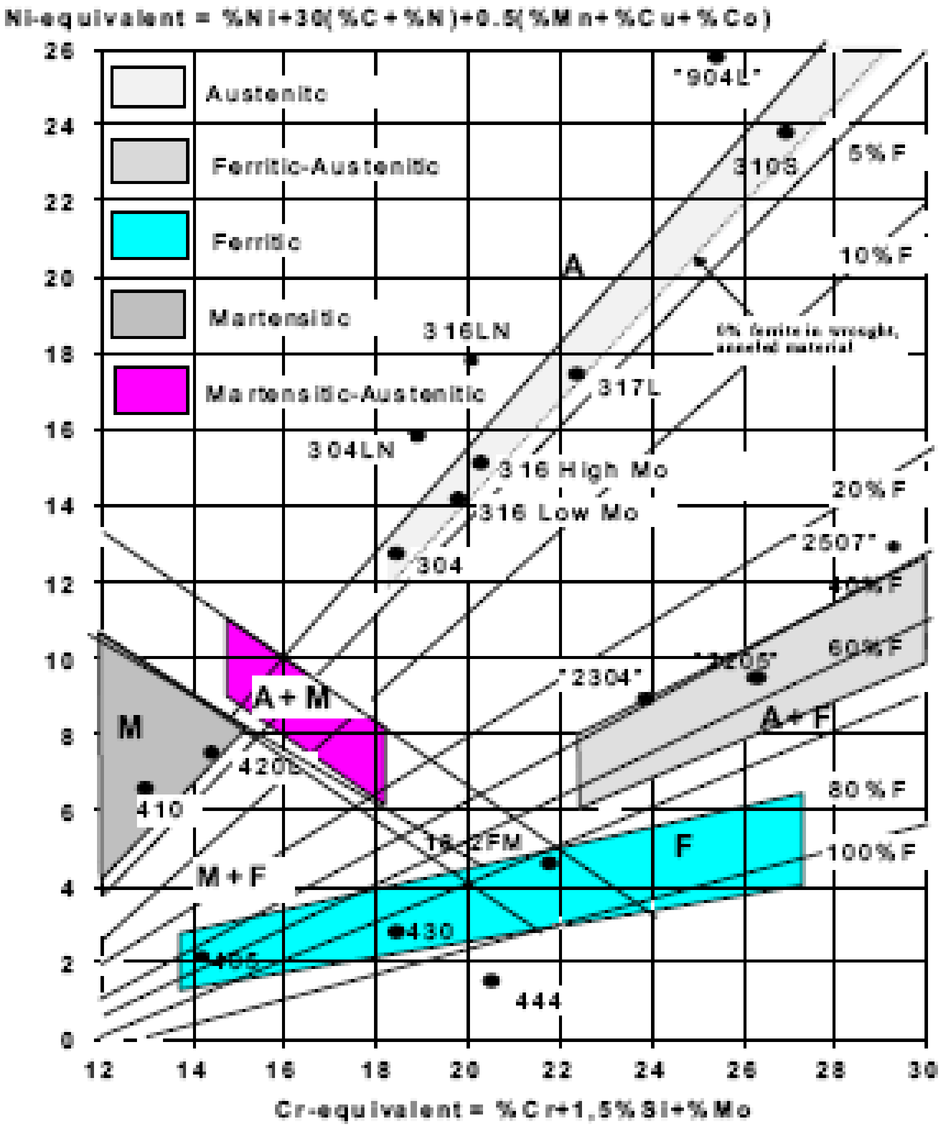
Influence of Alloying Elements

ELEMENT	EFFECT ON STAINLESS STEEL
Chromium	Forms a passive film with oxygen that prevent the further diffusion of oxygen into the surface. Composition needs to contain at least 12 % to be a stainless steel.
Nickel	Increases ductility and toughness. Increase corrosion resistance to acids Addition creates non-magnetic structure.
Molybdenum	Increases pitting and crevice corrosion resistance. Increase resistance to chlorides
Copper	Increase corrosion resistance to sulfuric acid.
Manganese	Substitute for nickel (200 series)
Titanium/ Niobium	Ties up carbon and prevents inter-granular corrosion in welded zone of ferritic grades
Nitrogen	Increase strength and corrosion resistance in austenitic and duplex grades
Silicon	Improves resistance to high temperature scaling
Sulfur	Usually kept low.
Carbon	Usually kept low. Used in martensitic grades to increase strength and hardness

The alloying elements each have a specific effect on the properties. But it is the combined effect of all the alloying elements and, to some extent, the impurities that determine the property

Influence of Alloying Elements (Contd…)

- The Schaeffler- Delong diagram was originally developed for weld metal.
- It describes the structure after melting and rapid cooling.
- This diagram has been found to give a useful picture of the effect of the alloying elements also for wrought and heat treated stainless steel.

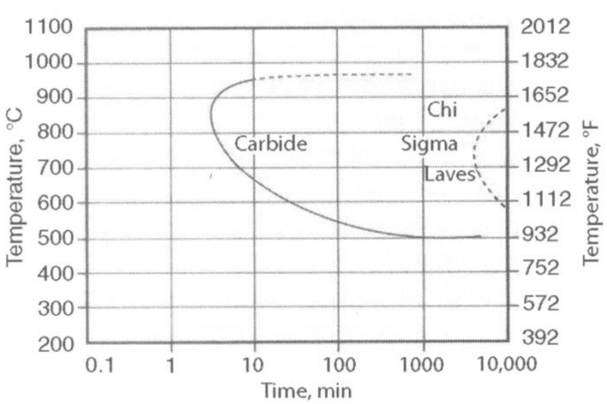


Effect of the alloying elements on the structure of stainless steels

Influence of Alloying Elements (Contd…)

Stainless steels having number of alloying elements (Fe, Cr, Ni, Mn, Si, Mo, Ti, Nb etc) and therefore should have numerous of ancillary intermetallic phases.

- Form by diffusion of substitutional alloying elements (slow process)
- Normally hard and brittle
- Depletion of Cr or Mo from the surrounding matrix causing localized lower corrosion resistance



Precipitation kinetics in 316 stainless steel

Precipitate	Structure	Parameter, A	Composition
NbC	fcc(a)	a = 4.47	NbC
NbN	fcc	a = 4.40	NbN
TiC	fcc	a = 4.33	TiC
TiN	fcc	a = 4.24	TiN
Z-phase	Tetragonal	a = 3.037 c = 7.391	CrNbN
$M_{23}C_6$	fcc	a = 10.57–10.68	$Cr_{16}Fe_5Mo_2C$ (e.g.)
$M_{23}(C,B)_6$	fcc	a = 10.57–10.68	$Cr_{23}(C,B)_6$
M_6C	Diamond cubic	a = 10.62–11.28	$(FeCr)_{21}Mo_3C$; Fe_3Nb_3C; M_5SiC
M_2N	Hexagonal	a = 2.8 c = 4.4	Cr_2N
MN	Cubic	a = 4.13–4.18	CrN
Gamma prime	fcc	a = 3.59	$Ni_3(Al,Ti)$
Sigma	Tetragonal	a = 8.80 c = 4.54	Fe, Ni, Cr, Mo
Laves phase	Hexagonal	a = 4.73 c = 7.72	Fe_2Mo, Fe_2Nb
Chi phase	bcc(b)	a = 8.807–8.878	$Fe_{36}Cr_{12}Mo_{10}$

Influence of Alloying Elements (Contd…)

Most common intermetallic phases:

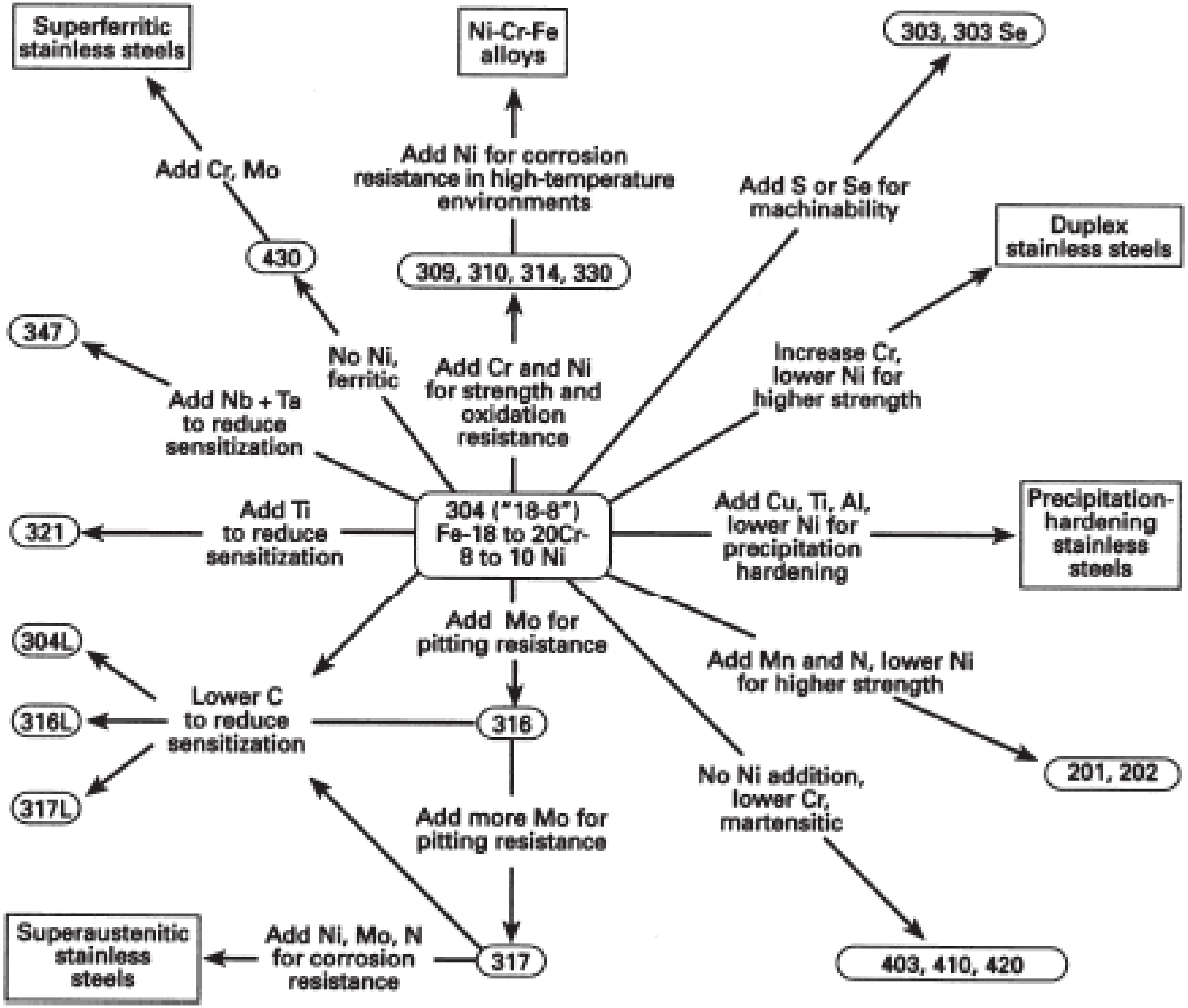
Alpha Prime: Alpha prime is an ordered Fe-Cr phase and is quite brittle. It forms at relatively low temperatures, between 300 and 525°C. This precipitation can cause 475 embrittlement in ferritic or duplex stainless steels and therefore limits their use in this temperature range but not at higher temperature.

Sigma: Sigma is a brittle tetragonal phase richer in Cr and Mo. It forms preferentially at ferritic/austenitic boundaries in the temperature range 600 to 1000°C in alloys more than 18% Cr+Mo. Sigma forms much more rapidly from ferrite than from austenite due to higher diffusion rate of alloying elements in ferrite. This makes a serious issue in ferritic and duplex alloys, which have high Cr and Mo.

Chi: Chi is similar to sigma except it contains more Mo and less Cr and has a cubic structure. It can coexist with sigma and forms in the same temperature range.

Laves Phase: It form at temperature below sigma and above alpha prime, but it takes long times for formation.

Compositional links among stainless steels



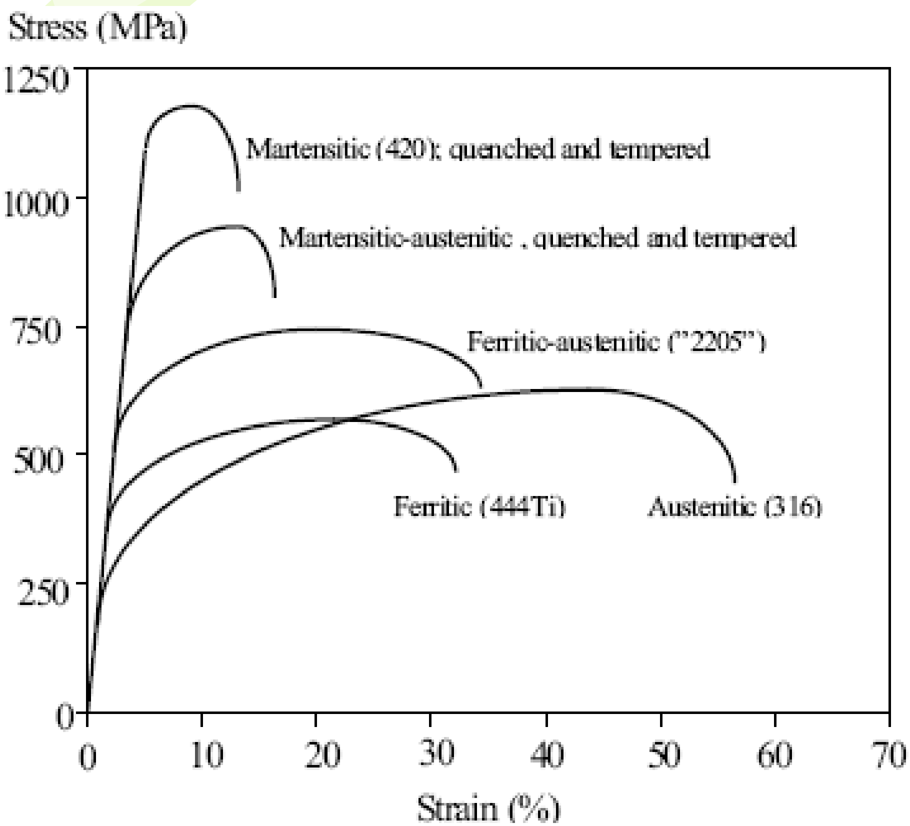
Physical Properties of Stainless Steels

Property	Type of stainless steel			
	Martensitic *	Ferritic	Austenitic	Ferritic-austenitic
Density (g/cm^3)	7.6-7.7	7.6-7.8	7.9-8.2	.8
Young's modulus (N/mm^2) or (MPa)	220,000	220,000	195,000	200,000
Thermal expansion ($x\ 10^{-6}/°C$) 200-600°C	12-13	12-13	17-19	13
Thermal conductivity (W/m°C) 20°C	22-24	20-23	12-15	20
Heat capacity (J/kg°C) 20°C	460	460	440	400
Resistivity (nΩm) 20°C	600	600-750	850	700-850
Ferromagnetism	Yes	Yes	No	Yes

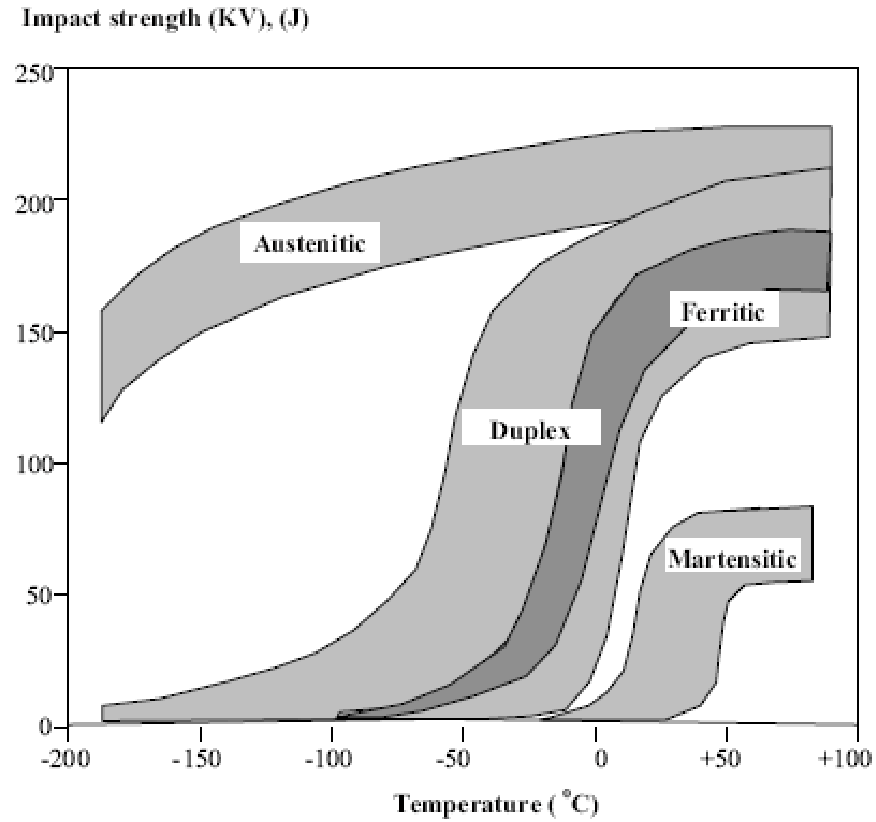
* in the hardened and tempered condition

Austenitic steels exhibit considerably higher thermal expansion than the other stainless steel types. This can cause thermal stresses in applications with temperature fluctuations, heat treatment and welding

Mechanical Properties of Stainless Steels



Typical stress-strain curves for some stainless steels



Impact toughness for different types of stainless steels

Mechanical Properties of Stainless Steels (Contd..)

Martensitic stainless steels are characterised by high strength. Strength is strongly affected by heat treatment. These steels are usually used in a hardened and tempered condition.

Ferritic-martensitic stainless steels have a high strength in the hardened and tempered condition in spite of their relatively low carbon content and good ductility.

Ferritic stainless steels have relatively low yield strength and the work hardening is limited. The strength increases with increasing carbon content, but the effect of chromium content is negligible.

Ferritic-austenitic (duplex) stainless steels have a high yield stress and increases with increasing carbon and nitrogen levels. An increased ferrite content also increases the strength of duplex steels. Their ductility is good and they exhibit strong work hardening.

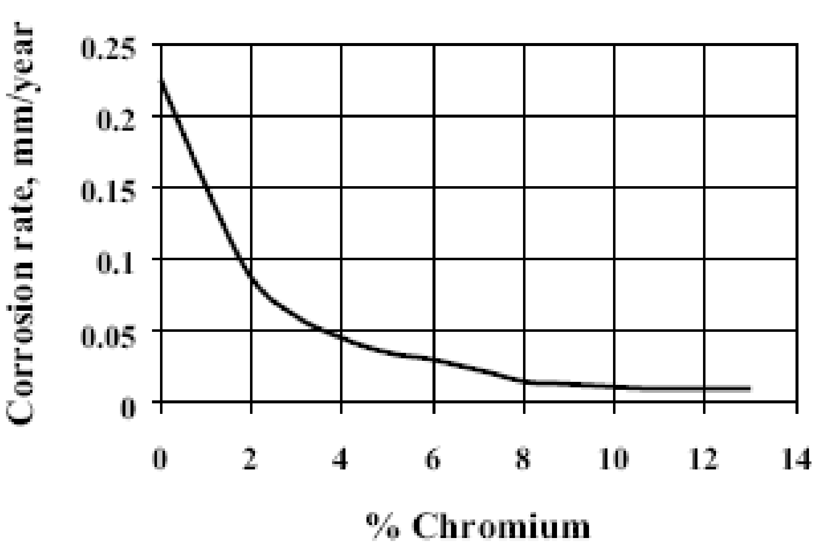
Austenitic stainless steels generally have a relatively low yield stress and are characterised by strong work hardening. The strength of the austenitic steels increases with increasing carbon, nitrogen and to a certain extent molybdenum.

Corrosion Properties of Stainless Steels

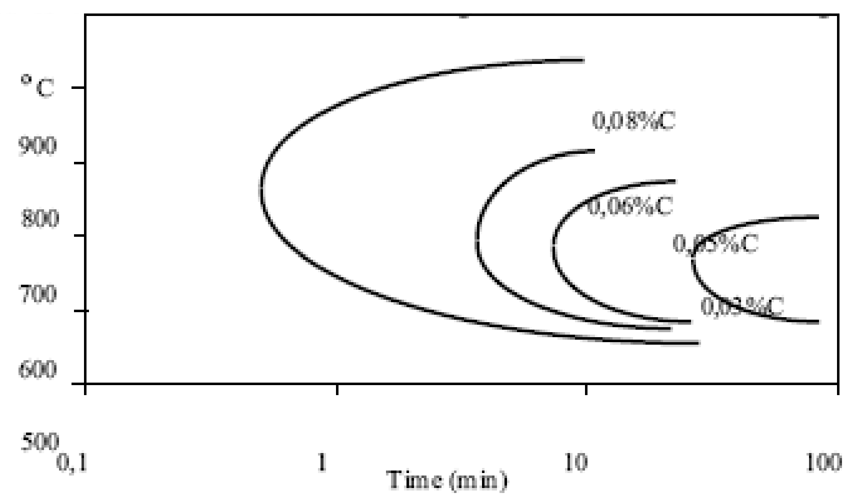
The single most important property of stainless steels and the reason for their existence and widespread use is their corrosion resistance.

Risk for intergranular corrosion can be reduced by decreasing the level of free carbon in the steels. This may be done in either of two ways:

- by decreasing the carbon content
- by stabilising the steel, i.e. alloying with an element (titanium or niobium) which forms a more stable carbide than chromium



Effect of Chromium content on passivity



Time-Temperature-Sensitization diagram for 18Cr-9Ni type steels with different carbon contents

Comparison of Properties of Stainless Steels

Property	Austenitic	Ferritic	Duplex	Martensitic	Precipitation-hardening
Strength	–	+	++	+++	+++
Wear resistance	–	–	+	++	++
Formability	+++	++	++	–	+
Weldability	++	–	++	– –	–
Resistance to general corrosion	++	+	++	–	+
Resistance to pitting corrosion	++	+	++	–	+
Resistance to stress corrosion, chloride-induced	–	++	++	–	–

+ means superior properties, – means lower properties.

Austenitic Stainless Steels

ASTM	EN	C (%)	N (%)	Cr (%)	Ni (%)	Mo (%)	Others (%)
Austenitic steels							
301		≤ 0.15	≤ 0.10	16.0 - 18.0	6.0 - 8.0		
	1.4310	0.05 - 0.15	≤ 0.11	16.0 - 19.0	6.0 - 9.5	≤ 0.8	
303		≤ 0.15		17.0 - 19.0	8.0 - 10.0		S*
	1.4305	≤ 0.10	≤ 0.11	17.0 - 19.0	8.0 - 10.0		S*
304L		≤ 0.030	≤ 0.10	18.0 - 20.0	8.0 - 12.0		
	1.4307	≤ 0.030	≤ 0.11	17.5 - 19.5	8.0 - 10.0		
	1.4306	≤ 0.030	≤ 0.11	18.0 - 20.0	10.0 - 12.0		
304		≤ 0.08	≤ 0.10	18.0 - 20.0	8.0 - 10.5		
	1.4301	≤ 0.07	≤ 0.11	17.0 - 19.5	8.0 - 10.5		
304LN		≤ 0.030	0.10 - 0.16	18.0 - 20.0	8.0 - 12.0		
	1.4311	≤ 0.030	0.12 - 0.22	17.0 - 19.5	8.5 - 11.5		
321		≤ 0.08	≤ 0.10	17.0 - 19.0	9.0 - 12.0		Ti
	1.4541	≤ 0.08		17.0 - 19.0	9.0 - 12.0		Ti
347		≤ 0.08		17.0 - 19.0	9.0 - 13.0		Nb
	1.4550	≤ 0.08		17.0 - 19.0	9.0 - 12.0		Nb
316L		≤ 0.030	≤ 0.10	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0	
	1.4404	≤ 0.030	≤ 0.11	16.5 - 18.5	10.5 - 13.0	2.0 - 2.5	
"316L(hMo)"	1.4432	≤ 0.030	≤ 0.11	16.5 - 18.5	10.5 - 13.0	2.5 - 3.0	
"316L(hMo)"	1.4435	≤ 0.030	≤ 0.11	17.0-19.0	12.5 -15.0	2.5 - 3.0	
316		≤ 0.08	≤ 0.10	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0	
	1.4401	≤ 0.07	≤ 0.11	16.0 - 18.5	10.0 - 13.0	2.0 - 2.5	
"316(hMo)"	1.4436	≤ 0.05	≤ 0.11	16.5 - 18.5	10.5 - 13.0	2.5 - 3.0	
316LN		≤ 0.030	0.10 - 0.16	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0	
	1.4406	≤ 0.03	0.12 - 0.22	16.5 - 18.5	10.0 - 12.0	2.0 - 2.5	
	1.4429	≤ 0.03	0.12 - 0.22	16.5 - 18.5	11.0 - 14.0	2.5 - 3.0	
316Ti		≤ 0.08	≤ 0.10	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0	Ti
	1.4571	< 0.08		16.5 - 18.5	10.5 - 13.5	2.0 - 2.5	Ti

Martensitic Stainless Steels

UNS No.	Type 410 (S41000)	Type 431 (S43100)	Type 440A (S44002)
Composition (%)			
Chromium	11.5–13.5	15.00–17.00	16.00–18.00
Nickel	0.50 max.	1.25–2.50	0.50 max.
Carbon	0.15 max.	0.20 max.	0.60–0.75
Manganese	1.00 max.	1.00 max.	1.00 max.
Silicon	1.00 max.	1.00 max.	1.00 max.
Mechanical properties			
0.2% Proof stress (MPa)	240–1240	620–1270	380–1650
Tensile strength (MPa)	410–1380	720–1520	650–1900
Elongation (%)	25–2	25–10	20–2
Hardness	HB70–HRC45	HRB95–HRC45	HRB95–HRC55

Ferritic Stainless Steels

UNS No.	Type 430 (S43000)	Type 444 (S44400)
Composition (%)		
Chromium	14.0 – 18.0	17.5 – 19.5
Nickel	0.50 max.	1.00
Carbon	0.12 max.	0.025 max.
Manganese	1.00 max.	1.0 max.
Silicon	1.00 max.	1.0 max.
Molybdenum	–	1.75 – 2.50
Nitrogen	–	0.035 max.
Others	–	Ti + Nb = 0.2 + 4 (C+N) min. –0.80 max.
Mechanical properties		
0.2% Proof stress (MPa)	207 min.	310 min.
Tensile strength (MPa)	415 min.	415 min.
Elongation (%)	20 min.	20 min.

Duplex Stainless Steels

	Type			
UNS No.	329 (S32900)	3RE60 (S31500)	SAF2205 223FAL, 22/5 (S31803)	SAF2304 (S32304)
Composition (%)				
Chromium	26.0	18.5	22	23
Nickel	4.5	4.9	5.5	4
Carbon	0.8 max.	0.03 max.	0.03 max.	0.03
Molybdenum	1.5	2.7	3.0	–
Silicon	0.6	1.7	0.8 max.	0.5
Manganese	1.7	1.5	2.0 max.	1.2
Nitrogen	–	–	0.14	0.1
Mechanical properties				
0.2% Proof stress (MPa)	550	450 min.	460 min.	400 min.
Tensile strength (MPa)	720	700 min.	680 min.	650 min.
Elongation (%)	25	30 min.	25 min.	30 min.

Precipitation-hardening Stainless Steels

UNS No.	PH 13–8 Mo (S13800)	17–4 PH (S17400)	17–7 PH (S17700)
	Type		
Composition (%)			
Chromium	12.25–13.25	15.5–17.5	16.8–18.0 PH
Nickel	7.5–8.5	3.0–5.0	6.5–7.5
Carbon	0.05	0.07	0.09
Manganese	0.10	1.0	1.0
Silicon	0.10	1.0	1.0
Others	2.0–2.5 Mo		
	0.9–1.35 Al	3.0–5.0 Cu	
	0.01N	0.15–0.4 Nb+Ta	0.75–1.5 Al
Mechanical properties			
0.2% Proof stress (MPa)	1310–1410min.	515–1170min.	965–1590min.
Tensile strength (MPa)	1380–1520min.	795–1310min.	1170–1650min.
Elongation (%)	6–10min.	10–18min.	1–6min.

Selection of Stainless Steels

Some characteristics for selecting the proper type of stainless steel for specific applications are:

- Corrosion resistance
- Resistance to oxidation, sulfidation
- Strength and ductility at service temperature
- Toughness
- Stability of properties in service
- Suitability for intended fabrication
- Resistance to abrasion, erosion, galling, and seizing
- Suitability for intended cleaning
- Total cost and its effective life
- Product availability

* A suitable steel can be selected for most applications on the basis of experience along with steel manufacturer

Typical Application of Stainless Steels

Type	Typical applications
304/304L	Food-processing industry, paper industry, petrochemical and textile industries. Architectural uses. Cryogenic applications.
253 MA	High temperature components in furnaces.
309	Heat-resistant furnace parts, heater tubes, oil burner parts.
310	Chemical and petroleum industries, heat exchangers, and furnace parts.
316/316L	Chemical and food industries, and sea-water exposure. Better corrosion resistance and creep strength than Types 304 and 304L.
317/317L	Better corrosion resistance and creep strength than Types 316 and 316L because of higher molybdenum content.
321	Ti-stabilised type for fabrication by welding, suitable for intermittent exposure at 400–850°C.
347	Nb-stabilised for intermittent exposure at 400–850°C or subsequent welding.
904L	Heat exchangers, condensers, pipes, tubes, coils in process industries.
254 SMO	For use in severely corrosive environments such as sea-water cooling and pulp-bleach plants.
444	Hot water storage tanks or where resistance to stress corrosion cracking is required.
Duplex types	Hot water storage tanks. Improved resistance to stress corrosion cracking, chemical and paper industries.
PH types	Applications where high strength coupled with good corrosion resistance is required. Marine components.
420	Domestic and industrial cutlery and knives. Cutting blades.
430	Interior architectural trim, domestic articles, stove, and heater components.
440	High temperature valves, and similar components, where resistance to abrasion, oxidation, and corrosion is required.

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