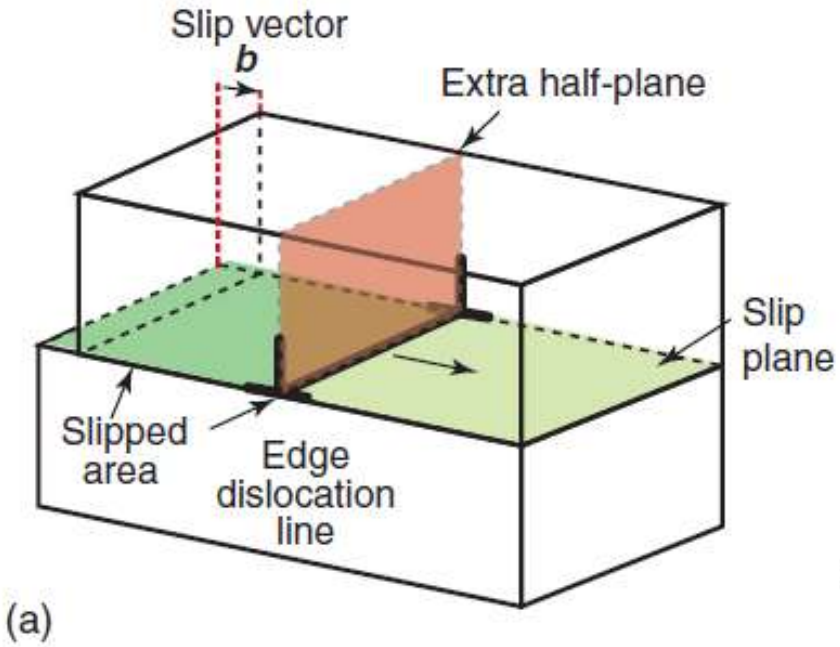
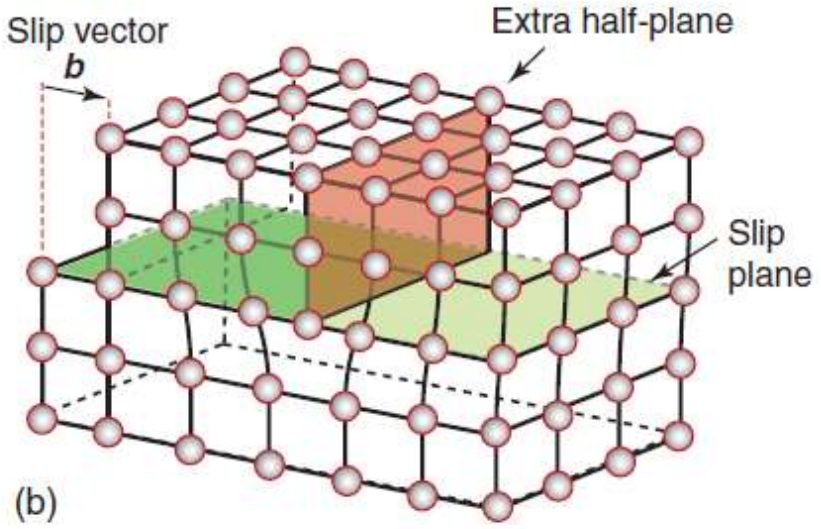
TEMA 5. Deformación Plástica y endurecimiento de metales

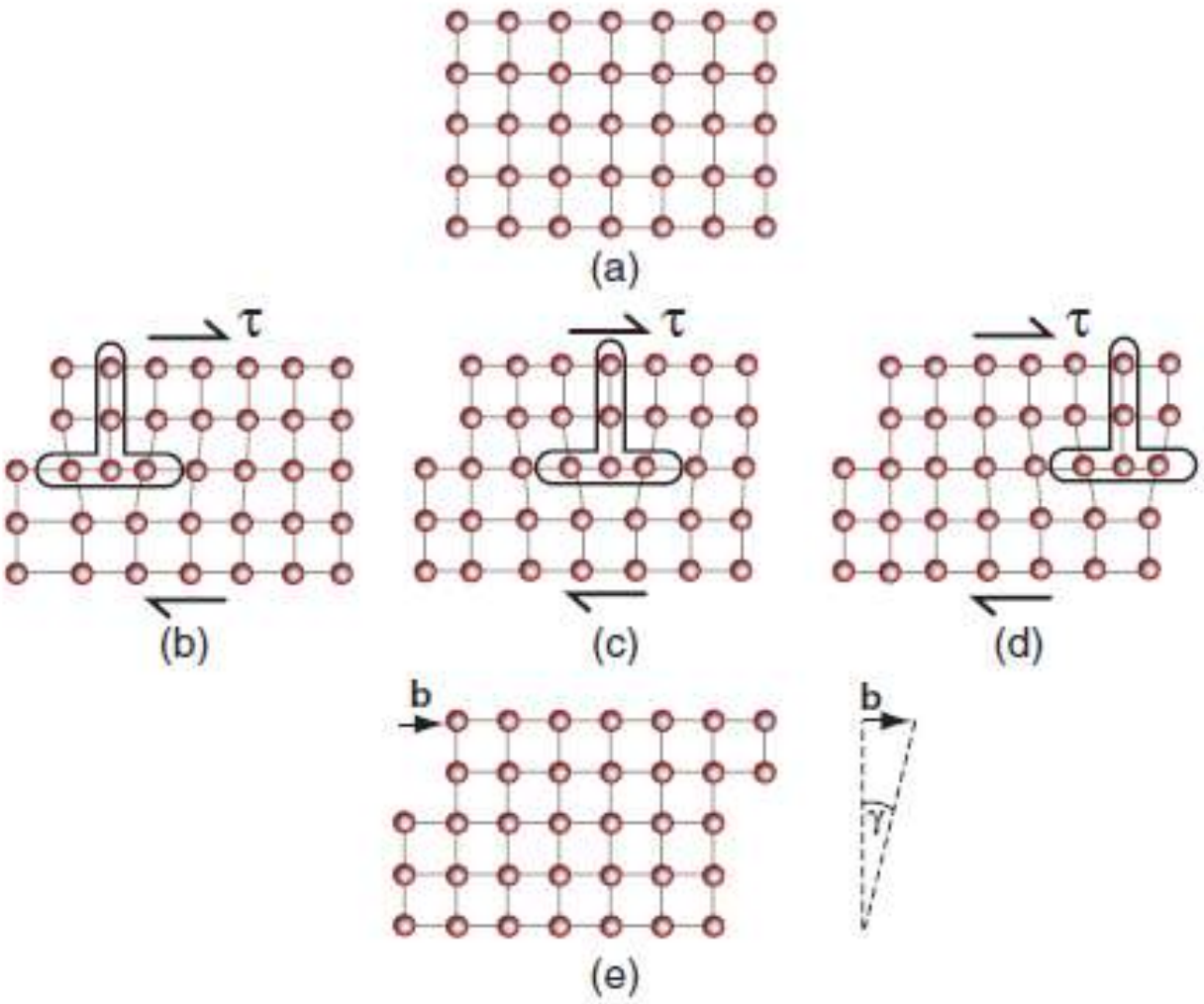
- Procesos Industriales de Endurecimiento de metales
- Relación de Hall-Petch
- Endurecimiento por precipitación

Dislocaciones

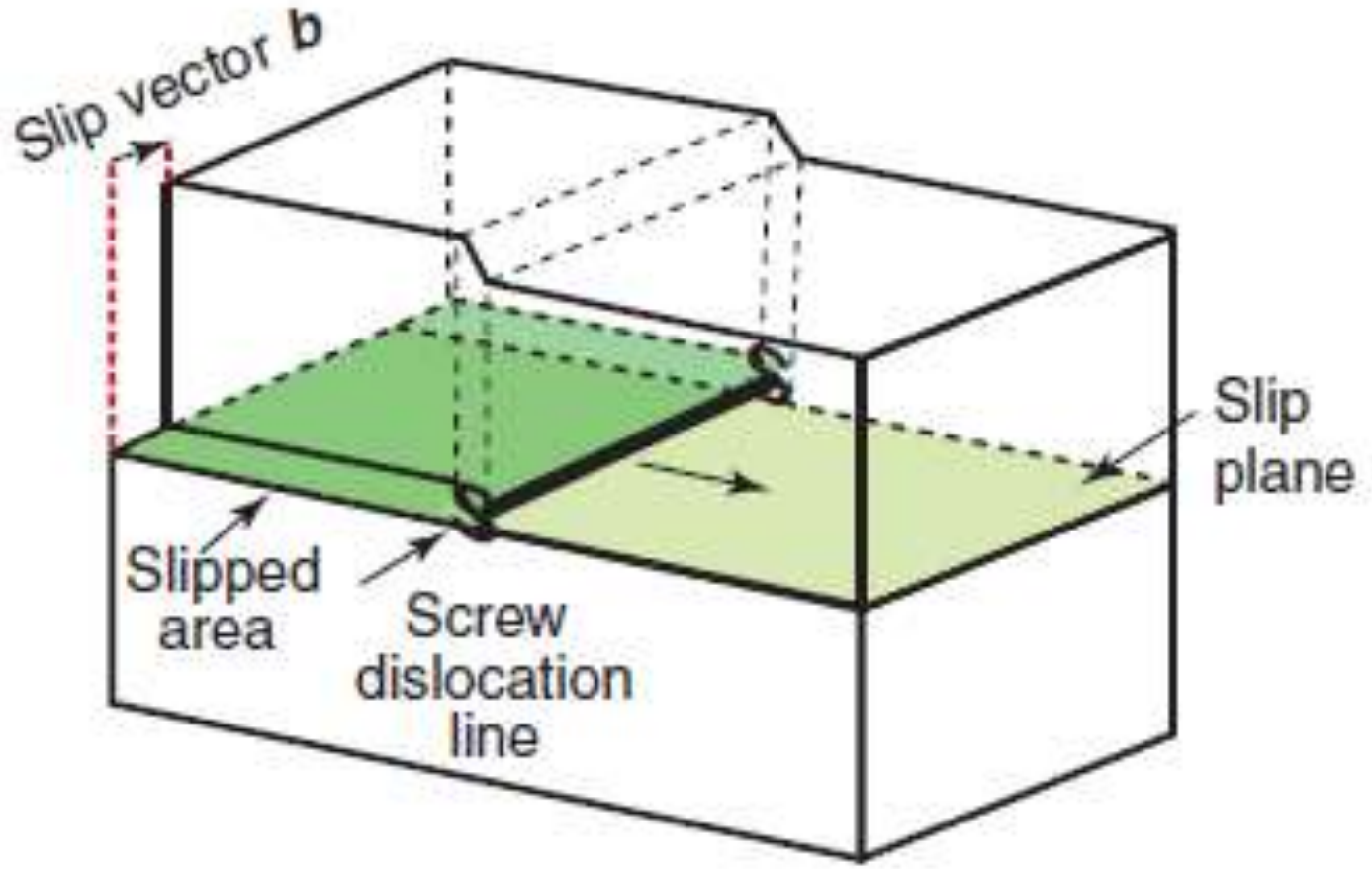




Movimiento de una dislocación



Dislocación de tornillo

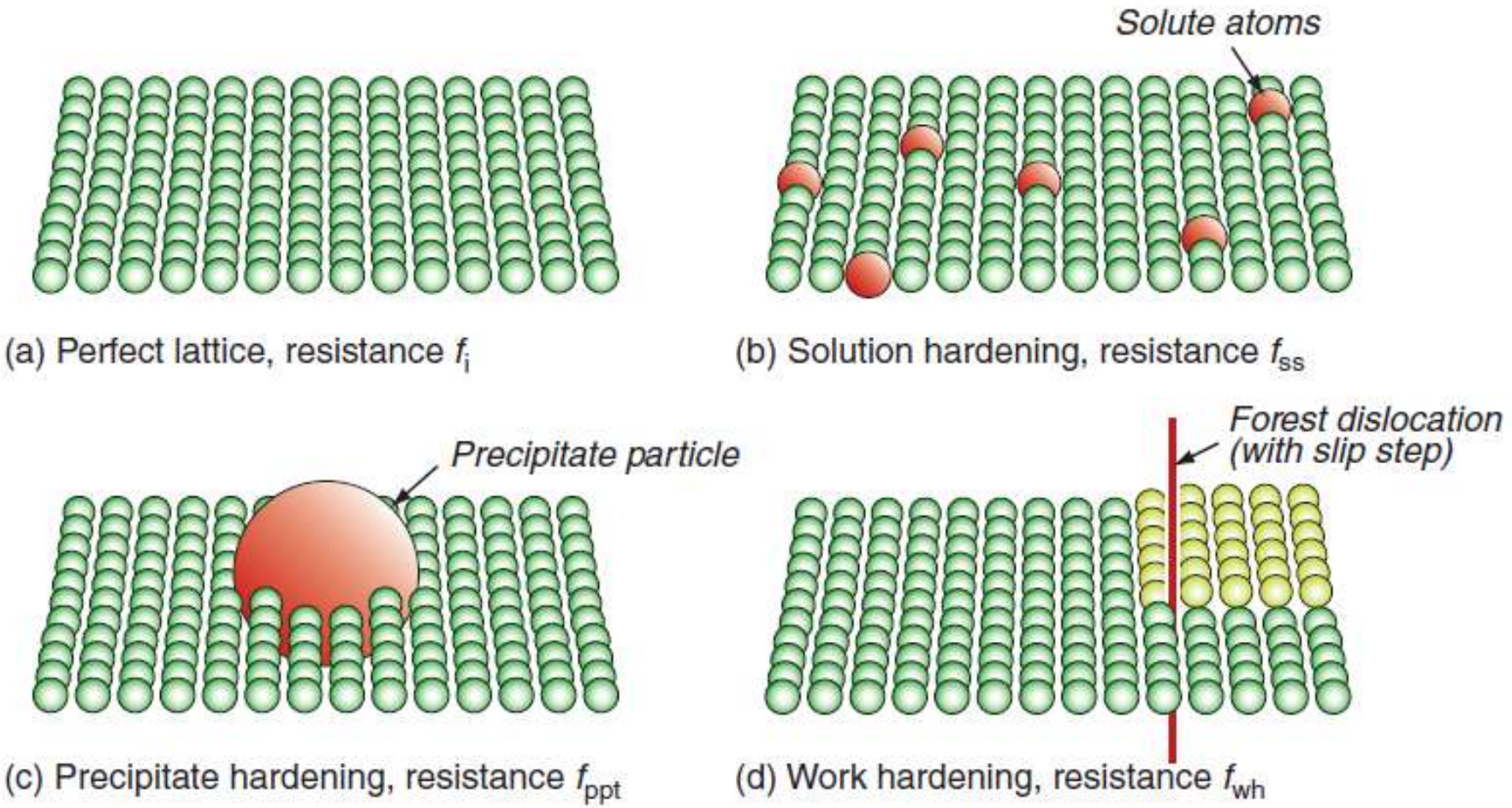


Las dislocaciones siempre están presentes en los Materiales:

- Un material recocido (baja densidad de dislocaciones) puede contener más de 1000 km de dislocaciones por milímetro cúbico

- Un material fuertemente deformado en frío puede alcanzar los 10 millones de km de dislocaciones por milímetro cúbico

Endurecimiento de metales



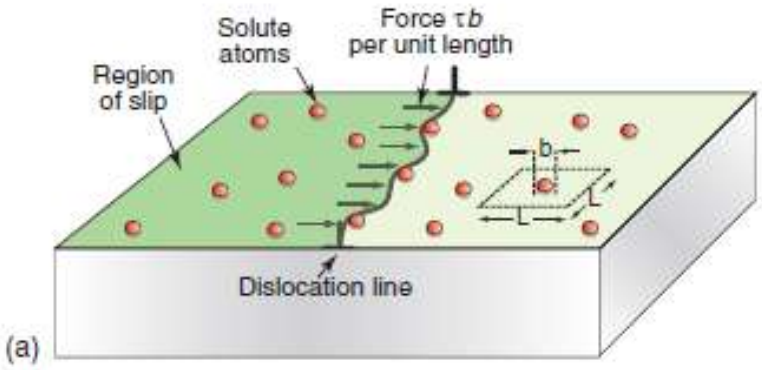
(a) Perfect lattice, resistance f_i

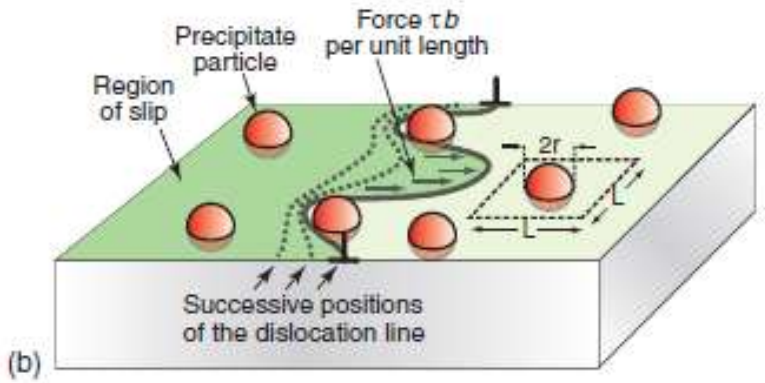
(b) Solution hardening, resistance f_{ss}

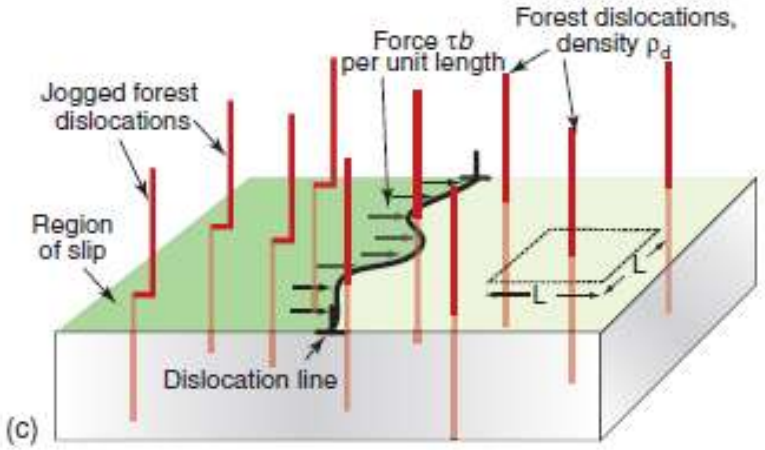
(c) Precipitate hardening, resistance f_{ppt}

(d) Work hardening, resistance f_{wh}

Endurecimiento de metales







Procesos Industriales de Endurecimiento de metales

Alloy	Typical uses	Solution hardening	Precipitation hardening	Work hardening
Pure Al	Kitchen foil			✓✓✓
Pure Cu	Wire			✓✓✓
Cast Al, Mg	Automotive parts	✓✓✓	✓	
Bronze (Cu–Sn), Brass (Cu–Zn)	Marine components	✓✓✓	✓	✓✓
Non-heat-treatable wrought Al	Ships, cans, structures	✓✓✓		✓✓✓
Heat-treatable wrought Al	Aircraft, structures	✓	✓✓✓	✓
Low-carbon steels	Car bodies, structures, ships, cans	✓✓✓		✓✓✓
Low alloy steels	Automotive parts, tools	✓	✓✓✓	✓
Stainless steels	Pressure vessels	✓✓✓	✓	✓✓✓
Cast Ni alloys	Jet engine turbines	✓✓✓	✓✓✓	

Symbols: ✓✓✓ = Routinely used. ✓ = Sometimes used.

Endurecimiento por reducción del tamaño de grano

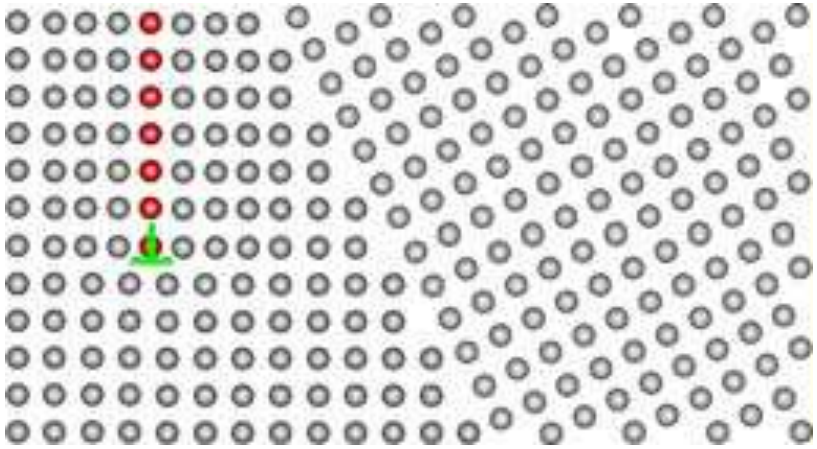
- Una dislocación se desliza por un plano cristalográfico concreto.

- Si dos granos contiguos poseen distinta orientación cristalográfica será muy difícil que una dislocación pase de uno de ellos a otro, tanto por el cambio de orientación como por la distorsión que supone la junta.

- Cuantas más juntas de grano existan en un material más difícil será que las dislocaciones se muevan por él.

Endurecimiento por reducción del tamaño de grano

Frenado de una dislocación al pasar de un grano (A) a otro (B)



grano A grano B

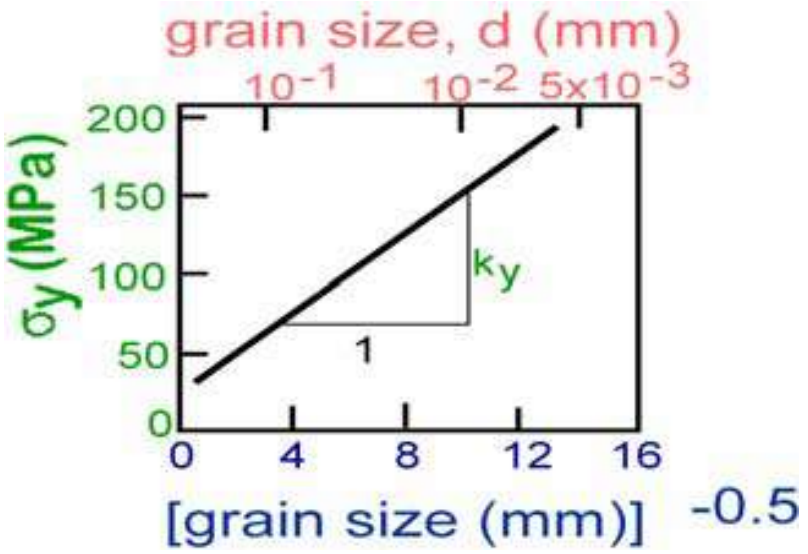
Efecto del Tamaño de Grano en el endurecimiento

Los materiales metálicos generalmente aumentan su resistencia a la fluencia según la expresión:

$$\sigma_y = \sigma_o + k_y d^{1/2}$$

Relación de Hall-Petch

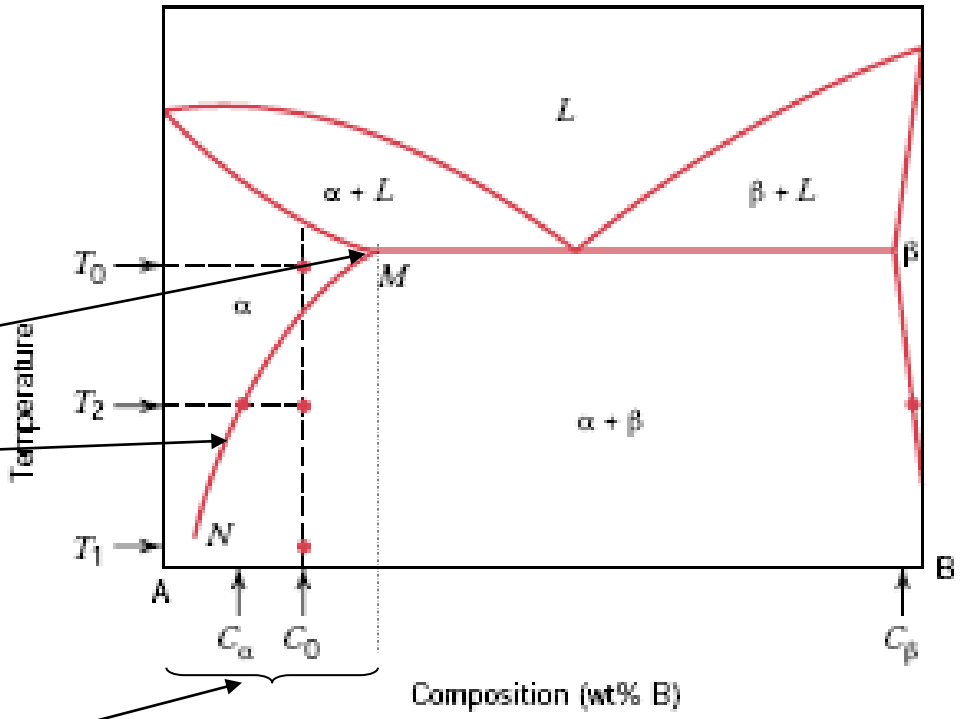
Latón (70%Cu + 30%Zn)



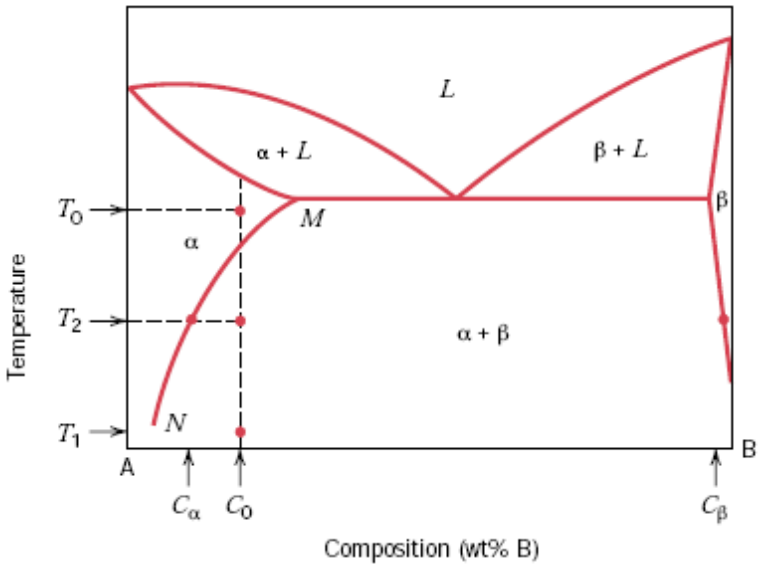
Tratamiento térmico de precipitación

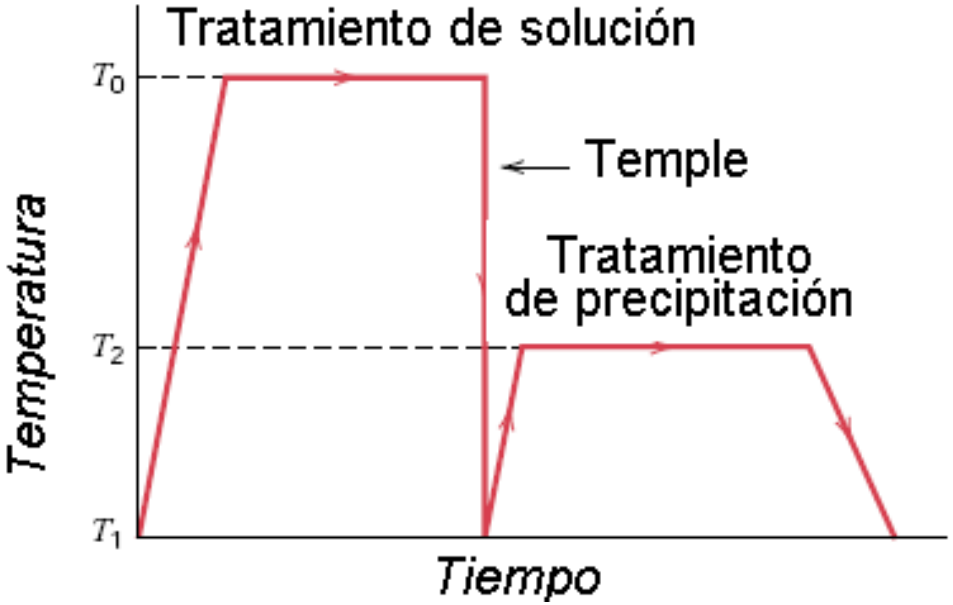
Requisitos del diagrama de fases. (necesarias mas no suficientes)

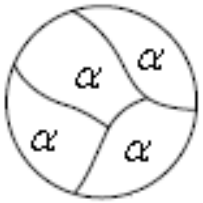
1. Solubilidad máxima de un elemento en el otro apreciable (punto M)
2. Marcado cambio del limite de solubilidad con la temperatura (línea MN)
3. La composición de la aleación a endurecer debe ser menor que la solubilidad máxima (en el rango 100% A y el pto.M)



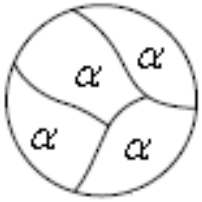
Endurecimiento por precipitación



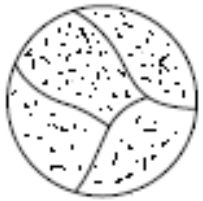


@ T_0 → 

Solución sólida homogénea

@ T_1 → 

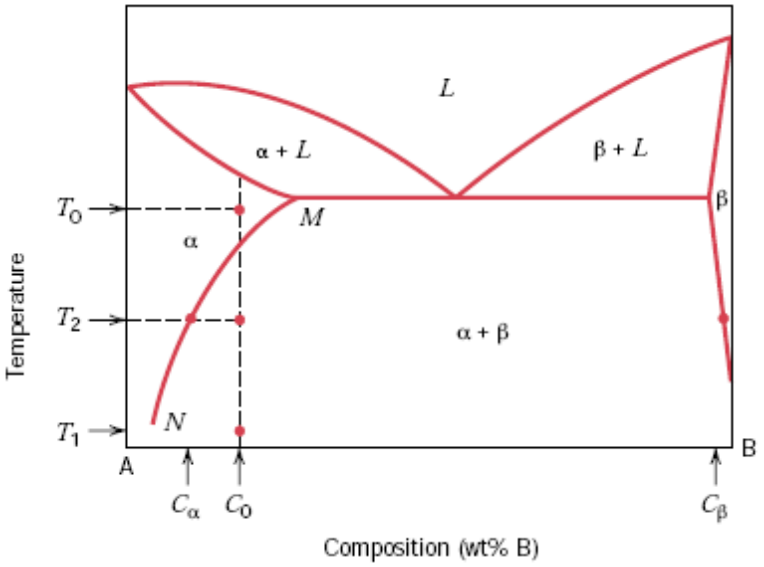
Solución sólida sobresaturada

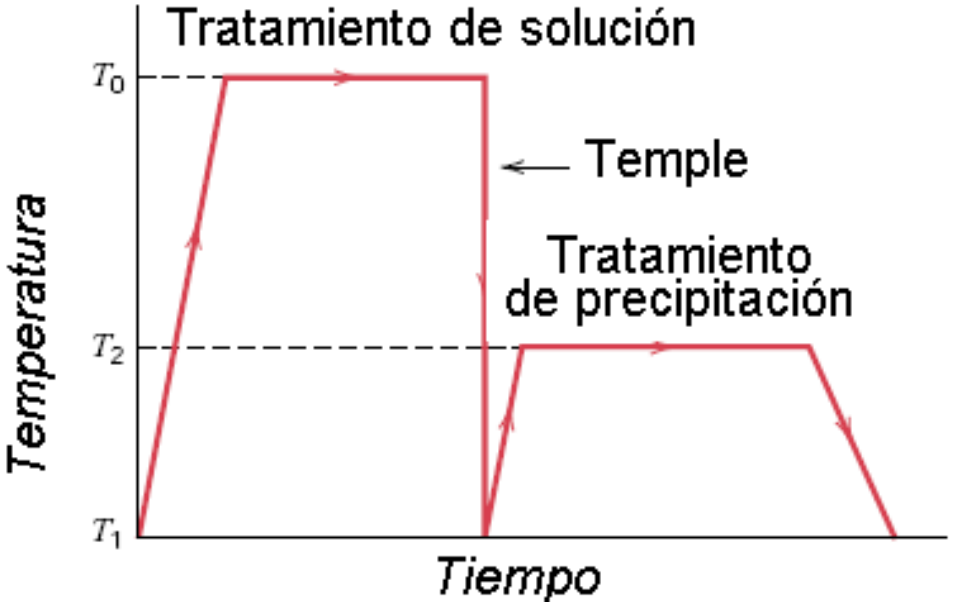
@ T_2 → 

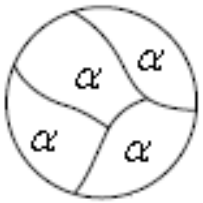
Matriz α con precipitados

La microestructura dependerá del tiempo y de la temperatura T_2

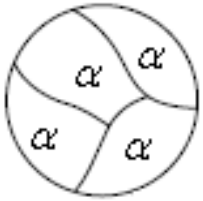
Endurecimiento por precipitación



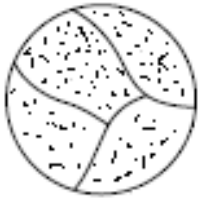


@ T_0 → 

Solución sólida homogénea

@ T_1 → 

Solución sólida sobresaturada

@ T_2 → 

Matriz α con precipitados

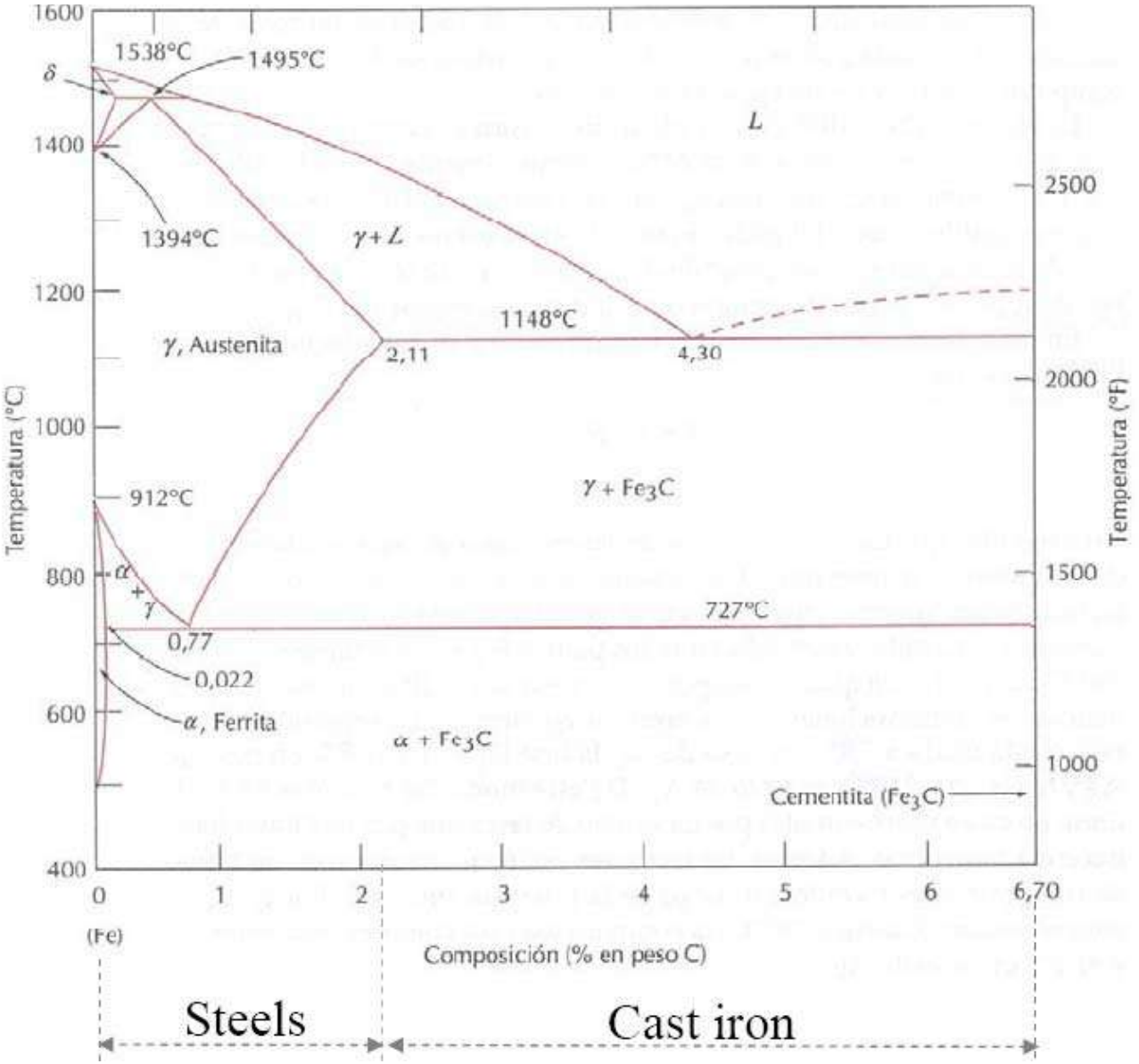
La microestructura dependerá del tiempo y de la temperatura T_2

TEMA 6. Aleaciones de base hierro

- Tipos de Acero
- Nomenclatura de los tipos de acero
- Aceros Inoxidables y sus aplicaciones
- Fundiciones y sus aplicaciones

Aleaciones Ferrosas

- Aceros al carbono
- Aceros aleados
- Fundiciones
- Aceros inoxidables



Aceros al Carbono

Aleaciones de Fe-C con algo de Mn (0.30-0.95%) para mejorar la resistencia

Aceros bajos en carbono (C<0.2%)	→	Poca resistencia, mucha ductilidad (body panels in cars)
Aceros medios en carbono (0.2%<C<0.5%)	→	Más resistentes, menos dúctiles (ejes, engranajes)
Aceros de alto carbono (0.6%<C<0.95%)	→	Alta resistencia, baja ductilidad (muelles, matrices, cuchillas)

Aceros al Carbono

Aceros bajos en carbono (C<0.2%)

Aceros al Carbono

Aceros medios en carbono (0.2%<C<0.5%)

Aceros al Carbono

Aceros de alto carbono (0.6%<C<0.95%)

Aceros al Carbono

Table 9.3 Typical mechanical properties and applications of plain-carbon steels

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
1010	0.10 C, 0.40 Mn	Hot-rolled	40–60	276–414	26–45	179–310	28–47	Sheet and strip for drawing; wire, rod, and nails and screws; concrete reinforcement bar
		Cold-rolled	42–58	290–400	23–38	159–262	30–45	
1020	0.20 C, 0.45 Mn	As rolled	65	448	48	331	36	Steel plate and structural sections; shafts, gears
		Annealed	57	393	43	297	36	
1040	0.40 C, 0.45 Mn	As rolled	90	621	60	414	25	Shafts, studs, high-tensile tubing, gears
		Annealed	75	517	51	352	30	
		Tempered*	116	800	86	593	20	
1060	0.60 C, 0.65 Mn	As rolled	118	814	70	483	17	Spring wire, forging dies, railroad wheels
		Annealed	91	628	54	483	22	
		Tempered*	160	110	113	780	13	
1080	0.80 C, 0.80 Mn	As rolled	140	967	85	586	12	Music wire, helical springs, cold chisels, forging die blocks
		Annealed	89	614	54	373	25	
		Tempered*	189	1304	142	980	12	
1095	0.95 C, 0.40 Mn	As rolled	140	966	83	573	9	Dies, punches, taps, milling cutters, shear blades, high-tensile wire
		Annealed	95	655	55	379	13	
		Tempered*	183	1263	118	814	10	

Designación SAE de aceros

SAE designation	Type
1xxx	Carbon steels
2xxx	Nickel steels
3xxx	Nickel-chromium steels
4xxx	Molybdenum steels
5xxx	Chromium steels
6xxx	Chromium-vanadium steels
7xxx	Tungsten steels
8xxx	Nickel-chromium-vanadium steels
9xxx	Silicon-manganese steels

EN steel number	EN steel name	SAE grade	UNS	DIN	BS 970	UNI	JIS
			Carbon steels				
1.1141 1.0401 1.0453	C15D C18D	1018		CK15 C15 C16.8	040A15 080M15 080A15 EN3B	C15 C16 1C15	S15 S15CK S15C
1.0503 1.1191 1.1193 1.1194	C45	1045		C45 CK45 CF45 CQ45	060A47 080A46 080M46	C45 1C45 C46 C43	S45C S48C
1.0726 1.0727	35S20 45S20	1140/1146		35S20 45S20	212M40 En8M		
1.0715 1.0736	11SMn37	1215		9SMn28 9SMn36	230M07 En1A	CF9SMn28 CF9SMn36	SUM 25 SUM 22
1.0718 1.0737	11SMnPb30 11SMnPb37	12L14		9SMnPb28 9SMnPb36	230M07 Leaded En1A Leaded	CF9SMnPb29 CF9SMnPb36	SUM 22L SUM 23L SUM 24L

Aceros aleados

Necesidad:

•Mejora en las propiedades mecáncicas (alta resitencia con buena ductilidad/tenacidad)

•Mejora de la resitencia a la oxidación/corrosión

Desarrollo de aleaciones a medida según los requerimientos:

•Adición de aleantes (Mn, Ni, Cr, Mo, W, V, Co, B, Cu, Al, Pb, Ti, Nb)

•Tratamientos térmicos

Aceros aleados

Table 9.4 Principal types of standard alloy steels

13xx	Manganese 1.75
40xx	Molybdenum 0.20 or 0.25; or molybdenum 0.25 and sulfur 0.042
41xx	Chromium 0.50, 0.80, or 0.95, molybdenum 0.12, 0.20, or 0.30
43xx	Nickel 1.83, chromium 0.50 or 0.80, molybdenum 0.25
44xx	Molybdenum 0.53
46xx	Nickel 0.85 or 1.83, molybdenum 0.20 or 0.25
47xx	Nickel 1.05, chromium 0.45, molybdenum 0.20 or 0.35
48xx	Nickel 3.50, molybdenum 0.25
50xx	Chromium 0.40
51xx	Chromium 0.80, 0.88, 0.93, 0.95, or 1.00
51xxx	Chromium 1.03
52xxx	Chromium 1.45
61xx	Chromium 0.60 or 0.95, vanadium 0.13 or min 0.15
86xx	Nickel 0.55, chromium 0.50, molybdenum 0.20
87xx	Nickel 0.55, chromium 0.50, molybdenum 0.25
88xx	Nickel 0.55, chromium 0.50, molybdenum 0.35
92xx	Silicon 2.00; or silicon 1.40 and chromium 0.70
50Bxx*	Chromium 0.28 or 0.50
51Bxx*	Chromium 0.80
81Bxx*	Nickel 0.30, chromium 0.45, molybdenum 0.12
94Bxx*	Nickel 0.45, chromium 0.40, molybdenum 0.12

Aceros aleados

Aceros aleados

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
Manganese steels								
Nickel (1.83%)-chromium-molybdenum steels								
4340 (E)	0.40 C, 1.83 Ni, 0.90 Mn, 0.80 Cr, 0.20 Mo	Annealed Tempered*	108 250	745 1725	68 230	469 1587	22 10	Heavy sections, landing gears, truck parts
Nickel (0.55%)-chromium-molybdenum steels								
8620	0.20 C, 0.55 Ni, 0.50 Cr, 0.80 Mn, 0.20 Mo	Annealed Normalized	77 92	531 635	59 52	407 359	31 26	Transmission gears
8650	0.50 C, 0.55 Ni, 0.50 Cr, 0.80 Mn, 0.20 Mo	Annealed Tempered*	103 250	710 1725	56 225	386 1552	22 10	Small machine axles, shafts
	*Tempered at 600°F (315°C).							
	0.55 Mn, 0.25 Mo	Normalized	83	573	53	366	29	chain pins, shafts, roller bearings
4820	0.20 C, 3.50 Ni, 0.60 Mn, 0.25 Mo	Annealed Normalized	99 100	683 690	67 70	462 483	22 60	Gears for steel mill equipment, paper machinery, mining machinery, earth-moving equipment

Aceros aleados

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
Nickel (1.83%)-chromium-molybdenum steels								
4340 (E)	0.40 C, 1.83 Ni, 0.90 Mn, 0.80 Cr, 0.20 Mo	Annealed	108	745	68	469	22	Heavy sections, landing gears, truck parts
		Tempered*	250	1725	230	1587	10	
Nickel (0.55%)-chromium-molybdenum steels								
8620	0.20 C, 0.55 Ni, 0.50 Cr, 0.80 Mn, 0.20 Mo	Annealed	77	531	59	407	31	Transmission gears
		Normalized	92	635	52	359	26	
8650	0.50 C, 0.55 Ni, 0.50 Cr, 0.80 Mn, 0.20 Mo	Annealed	103	710	56	386	22	Small machine axles, shafts
		Tempered*	250	1725	225	1552	10	

*Tempered at 600°F (315°C).

Aceros Inoxidables

Se utilizan fundamentalmente por su resistencia a la corrosión.
Adición de Cr ⟶ Oxido superficial que protege de la corrosión

Inoxidables ferríticos (BCC)
12%<Cr<30%

→ Resistentes a corrosión y altas temperaturas
Elementos de construcción

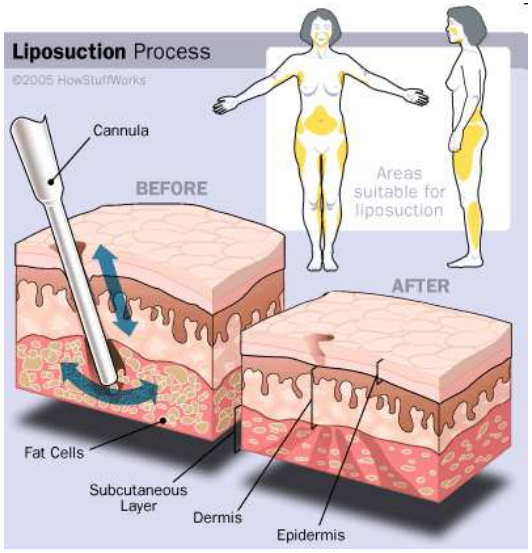
Inoxidables martensíticos
12%<Cr<17% + 0.15-1% C

→ Capacidad de endurecimiento
Rodamientos, útiles quirúrgicos

Inoxidables austeníticos
16%<Cr<25% + %7<Ni<20%

→ Excelente resistencia a la corrosión
Industria química

Aceros inoxidables



Aceros inoxidables

Alloy number	Chemical composition (wt %)*	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation in 2 in (%)	Typical applications
Ferritic stainless steels								
430	17 Cr, 0.012 C	Annealed	75	517	50	345	25	General-purpose, nonhardenable; uses: range hoods, restaurant equipment
446	25 Cr, 0.20 C	Annealed	80	552	50	345	20	High-temperature applications; heaters, combustion chambers
Martensitic stainless steels								
410	12.5 Cr, 0.15 C	Annealed Q & T†	75	517	40	276	30	General-purpose heat-treatable; machine parts, pump shafts, valves
440A	17 Cr, 0.70 C	Annealed Q & T†	105 265	724 1828	60 245	414 1690	20 5	Cutlery, bearings, surgical tools
440C	17 Cr, 1.1 C	Annealed Q & T†	110 285	759 1966	70 275	276 1897	13 2	Balls, bearings, races, valve parts

Aceros inoxidables

Alloy number	Chemical composition (wt %)*	Condition	Tensile strength		Yield strength		Elongation in 2 in (%)	Typical applications
			ksi	MPa	ksi	MPa		
Austenitic stainless steels								
301	17 Cr, 7 Ni	Annealed	110	759	40	276	60	High work-hardening rate alloy; structural applications
304	19 Cr, 10 Ni	Annealed	84	580	42	290	55	Chemical and food processing equipment
304L	19 Cr, 10 Ni, 0.03 C	Annealed	81	559	39	269	55	Low carbon for welding; chemical tanks
321	18 Cr, 10 Ni, Ti = 5 × %C min	Annealed	90	621	35	241	45	Stabilized for welding; process equipment, pressure vessels
347	18 Cr, 10 Ni, Cb (Nb) = 10 × C min	Annealed	95	655	40	276	45	Stabilized for welding; tank cars for chemicals
Precipitation-hardening stainless steels								
17-4PH	16 Cr, 4 Ni, 4 Cu, 0.03 Cb (Nb)	Precipitation-hardened	190	1311	175	1207	14	Gears, cams, shafting, aircraft and turbine parts

*Balance Fe.
†Quenched and tempered.

Fundiciones

Aleaciones ferrosas con 2-4% C y 1-3% Si

Diseñadas para ser fundidas, solidifican contrayendo poco

Amplia gama de durezas. Se pueden alear para obtener resistencia a desgaste, compresión y corrosión.

Table 9.13 Chemical composition ranges for typical unalloyed cast irons

Element	Gray iron (%)	White iron (%)	Malleable iron (cast white) (%)	Ductile iron (%)
Carbon	2.5–4.0	1.8–3.6	2.00–2.60	3.0–4.0
Silicon	1.0–3.0	0.5–1.9	1.10–1.60	1.8–2.8
Manganese	0.25–1.0	0.25–0.80	0.20–1.00	0.10–1.00
Sulfur	0.02–0.25	0.06–0.20	0.04–0.18	0.03 max
Phosphorus	0.05–1.0	0.06–0.18	0.18 max	0.10 max

Source: C. F. Walton (ed.), *Iron Castings Handbook*, Iron Castings Society, 1981.

Fundiciones

Fundiciones

Table 9.14 Typical mechanical properties and applications of cast irons

Alloy name and number	Chemical composition (wt %)	Condition	Microstructure	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
Gray cast irons									
Ferritic (G2500)	3.4 C, 2.2 Si, 0.7 Mn	Annealed	Ferritic matrix	26	179	. . .		. . .	Small cylinder blocks, cylinder heads, clutch plates
Pearlitic (G3500)	3.2 C, 2.0 Si, 0.7 Mn	As-cast	Pearlitic matrix	36	252	. . .		. . .	Truck and tractor cylinder blocks, heavy gear boxes
Pearlitic (G4000)	3.3 C, 2.2 Si, 0.7 Mn	As-cast	Pearlitic matrix	42	293	. . .		. . .	Diesel engine castings
Malleable cast irons									
Ferritic (32510)	2.2 C, 1.2 Si, 0.04 Mn	Annealed	Temper carbon and ferrite	50	345	32	224	10	General engineering service with good machinability
Pearlitic (45008)	2.4 C, 1.4 Si, 0.75 Mn	Annealed	Temper carbon and pearlite	65	440	45	310	8	General engineering service with dimensional tolerance specified
Martensitic (M7002)	2.4 C, 1.4 Si, 0.75 Mn	Quenched and tempered	Tempered martensite	90	621	70	438	2	High-strength parts; connecting rods and universal joint yokes
Ductile cast irons									
Ferritic (60-40-18)	3.5 C, 2.2 Si	Annealed	Ferritic	60	414	40	276	18	Pressure castings, such as valve and pump bodies
Pearlitic	3.5 C, 2.2 Si	As-cast	Ferritic-pearlitic	80	552	55	379	6	Crankshafts, gears, and rollers
Martensitic (120-90-02)	3.5 C, 2.2 Si	Martensitic	Quenched and tempered	120	828	90	621	2	Pinions, gears, rollers, and slides