ELI5 Materials

[Sketch]

So this is still a sketch, and it's intended to be a very simple (explain like I'm 5, though sometimes it may be more like ELIPhD) introduction to materials. An ongoing work. Not all content here is original (e.g. images), but because for now it is for personal use only, I haven't included the sources. Unoriginal content will be edited out in a later phase.

First written: Porto, July 2012.

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What You Should Know

FERROUS ALLOYS

1 - Equilibrium Diagram of Fe-C Alloys
1.1 Allotropic varieties of Iron
1.2 Phases and compounds of the Fe-C diagram
1.3 Influence of the alloying elements on the ferritic and austenitic domains

2 - Austenite transformation diagrams
2.1 Influence of the alloying elements
2.2 Influence of austenitizing conditions

3 - Martensitic transformations. Notion of temperament

4 - Fe-C alloys heat treatments

5 - Construction steels
5.1 Carbon steels. Mechanical properties. Heat treatments
5.2 Alloy construction steels. Mechanical properties. Heat treatments
5.3 Some classifications of construction steels
i) Chemical composition
ii) Applications
5.4 Thermochemical treatments: cementation, nitriding and carbonitriding.

6 - Tool Steels
6.1 The classification of tool steels in accordance with AISI-SAE norms
6.2 Hardness and temperability in tool steels
6.3 The austenitizing temperature in tool steels
6.4 Cold working tool steel. Hot-working tool steels and non-deformable steels
6.5 High Speed steels. Heat treatments. Destabilization of austenite in tempering

7 - Stainless Steels
7.1 Structural types; ferritic, austenitic and martensitic steels
7.2 Oxidation. Corrosion. Types of corrosion. Intergranular corrosion in stainless steels
7.3 Heat treatment of stainless steels
7.4 Mechanical properties of stainless steels

8 - Structural Precipitation Steel: Maraging Steels
8.1 Heat treatments
8.2 Mechanical properties. Advantages and limitations of its use

9 - Cast iron. Generalities. Types
9.1 Factors influencing the formation of graphite.
9.2 Gray cast irons. Inoculation. Mechanical properties. Effects of the matrix and of the type of graphite.
9.3 Ductile cast iron. The nodularization treatment. Mechanical properties.
9.4 Malleable cast irons. Thermal treatments. Mechanical properties.

NON-FERROUS ALLOYS

10 - Copper alloys
10.1 Pure copper and its properties
10.2 Copper-zinc alloys: brass. Typology and mechanical properties.
i) Single-phase alloys
ii) Biphasic alloys
10.3 Specific corrosion problems in brass
10.4 Copper-tin alloys (bronzes)
i) Types of bronzes
ii) Bronzes as antifriction materials

11 - Aluminum alloys
11.1 Treatable and non-thermally treatable aluminum
11.2 Structural precipitation hardening processes: duraluminium
11.3 Aluminum for casting. Characteristics and mechanical properties.

12 - Zinc alloys. Magnesium alloys. Types. Mechanical properties. Heat Treatments.

13 - Titanium alloys. Types. Mechanical properties. Heat Treatments. Shape memory alloys.

Properties

Mechanical

- Ductility
- hardness
- Elastic limit
- Ultimate tensile strength
- Elasticity modulus
- Resilience and Toughness
- Crack propagation resistance
- Fatigue resistance
- Impact resistance
- Creep resistance

Thermal

- Specific heat
- Fusion latent heat
- Thermal conductivity
- Thermal expansion
- Melting temperature

Physical

- Density

Electrical and Magnetic

- Conductivity
- Resistivity
- Magnetic permeability
- Magnetic saturation
- etc.

Price

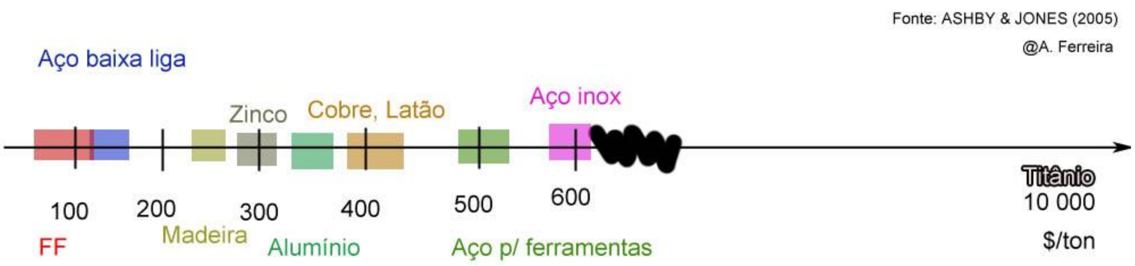
Tabela 1 Preços relativos aproximados por tonelada (continua)

Material	**Preço relativo US$**
Diamante	200 milhões
Platina	5 milhões
Ouro	2 milhões
Prata	150.000
CFPR (mat. 70% do custo; fabr. 30% do custo)	20.000
Cobalto/cermets de carbeto de tungstênio	15.000
Tungstênio	5.000
Ligas de cobalto	7.000
Ligas de titânio	10.000
Ligas de Níquel	20.000
Polimidas	8.000
Carbeto de silício (cerâmica fina)	7.000
Ligas de magnésio	1.000
Náilon 66	1.500
Policarbonato	1.000
Polimetilmetacrilato	700
Magnésia, MgO (cerâmica fina)	3.000
Alumina, Al2O3 (cerâmica fina)	3.000
Aço-ferramenta	500
Polímero reforçado com fibra de vidro – GFPR (mat. 60% do custo; fabr. 40% do custo)	1.000
Aços inoxidáveis	600
Cobre, usinado (chapas finas, tubos, barras)	400
Cobre, lingotes	400
Ligas de alumínio, usinadas (chapas finas, barras)	400
Lingotes de alumínio	300
Latão, usinado (chapas finas, tubos, barras)	400
Latão, lingotes	400
Epóxi	1.000

Tabela 1 (conclusão)

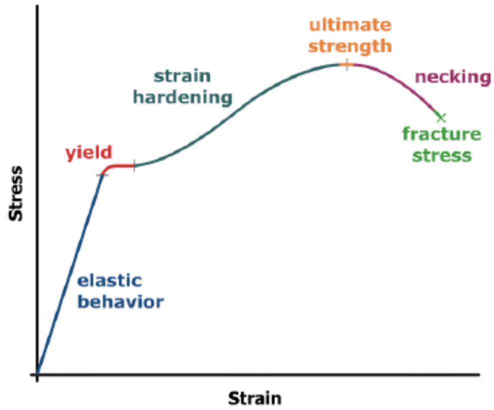
Material	***Preço relativo US$***
Poliéster	500
Vidro	400
Polímeros espumosos	1.000
Zinco, usinado (chapas finas, tubos, barras)	400
Zinco, lingotes	350
Chumbo, usinado (chapas finas, tubos, barras)	250
Chumbo, lingotes	200
Borracha natural	300
Polipropileno (PP)	200
Polietileno (PE), alta densidade	200
Poliestireno (PS)	250
Madeiras duras	250
Polietileno (PEDB), baixa densidade	200
Cloreto de Polivinila ou polivinilcloreto (PVC)	300
Compensado	200
Aços de baixa liga	130
Aço doce, usinado (cantoneiras, chapa, barras)	100
Ferro fundido	90
Ferro, lingotes	70
Madeiras macias	70
Concreto, armado (vigas, colunas, lajes)	50
Óleo combustível	50
Cimento	20
Carvão	20

Fonte: ASHBY & JONES (2005).



Vocabolary

Generic Traction Stress-Strain Curve



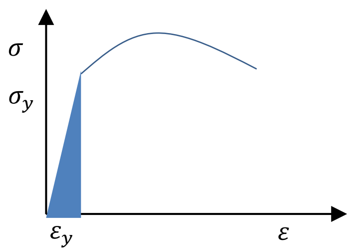
Hardness

The hardness property expresses only a surface property of a body because of the nature of its design. It is, in fact, a measure of resistance to the penetration of a tip (spherical, conical or pyramidal consisting of hard material) offered by the material of the specimen. This property is of particular interest for:

- Evaluating the wear resistance of the material (which is a property dependent on the surface of the body);
- To measure the degree of surface hardening by a heat treatment;
- To roughly estimate the overall mechanical strength of the test specimen material insofar as the mechanical characteristics of its surface are also representative of the characteristics of all body material.

Resilience

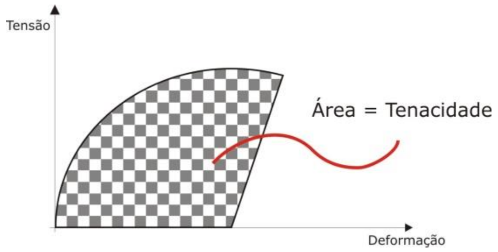
It is the property that a material that absorbs a lot of energy per unit volume in elastic regime has. Particularly important for elastic elements.



$$U_E = \frac{\sigma_y^2}{2E} \qquad [J/m^3]$$

Toughness

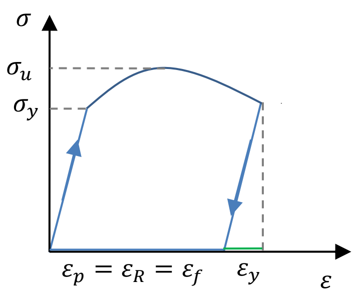
It is the total energy per unit volume of material needed to cause its fracture.

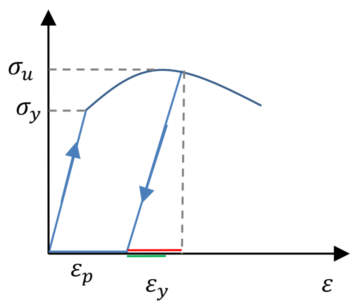


$$U_T = \frac{energy}{volume} = \int_0^{\varepsilon_f} \sigma \, d\varepsilon = \frac{\sigma_y + \sigma_u}{2} \cdot \varepsilon_f \quad [J/m^3]$$

Elastic and Plastic Deformation

Imagine a traction test. When stopping the test or when the specimen ruptures it returns slightly to the original form, reducing ε_y, and remaining with ε_p as a permanent, plastic deformation. Note that if the tests were stopped in the middle, for example, at the tensile strength, ε_y would be larger. When the material breaks, the plastic deformation that it now has, we call it rupture deformation ε_R, or final deformation ε_f.





Fatigue Resistance

Failures of metal components in service are most often due to fatigue caused by cyclical loads. The fatigue fracture presents fragile characteristics and is influenced by several factors such as:

- Stress concentration areas
- Temperature
- Corrosive environment
- Residual stresses and others that depend on the design and manufacturing conditions of the part and the environment. The results of the fatigue tests carried out on the test specimen are only an indication of the in-service behavior of the material of this body, which also depends on many factors not represented in the deflection-rotary, alternating bending and tensile-compression tests.

Cold hardening

Increase in mechanical strength due to going to a stress over the elastic limit σ_y.

Anodization

Is an electrochemical process that converts the metal surface into a decorative, durable, corrosion-resistant, anodic oxide finish.

Machinability

The machinability of a material is a property with critical influence on productivity. It is usually determined as the fitness that a material has to be processed by a cutting tool. Some of the most important characteristics of the material to be cut with effect on the cutting process are: tensile and deformation properties, hardening degree, microstructure, hardness, abrasiveness, chemical composition, thermal conductivity, coefficient of friction, homogeneity and isotropy. The large number of indicators indicates that none of them is totally independent, which is a consequence of the complexity of the phenomenon. Some of the machinability indicators to consider include tool life, roughness and integrity of machined surfaces, productivity, strength and power required for cutting.

The machinability of a material is difficult to quantify. The greater or lesser ability of a material to be machined reflects itself in the surface finish of the workpiece, the length of the cutting tool, the speed and force exerted for machining, and also the capacity to collect the wastes from cutting the workpiece. Knowledge of the material to be machined to succeed in a machining operation is essential. For steel alloys, a general rule is that when the carbon or alloying element content rises, the machinability decreases.

An inverse relation exists between hardness and machinability. When hardness rises the machinability decreases. To increase the machinability some materials, their sulfur content may be increased. However, sulfur reduces the mechanical properties of steels, for example toughness (ability to deform without breaking). Another disadvantage of sulfur is related to surface finish.

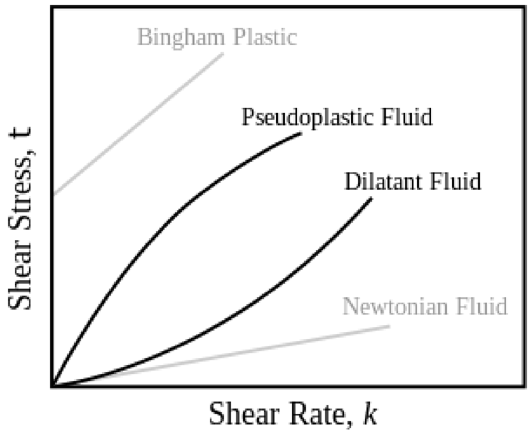
Cold worked steels often have carbon, chromium and vanadium alloys so the carbides in these steels are hard and resistant to abrasion. The hard carbides will, however, reduce the machinability of the steel, generating a high wear of the cutting tool. Selecting the steel grade is not an easy task, the selection of the steel grade is usually done at the design stage, so that the material can be in stock and ready when the project is finished. In many cases, the choice is a compromise between the one who designs it and the one who machines it.

Creep

Creep is the tendency for a material subjected to stresses lower than σ_y to deform over time. Occurs as a result of prolonged exposure to stress. The flow rate generally increases with increasing tension and the temperature at which the material is. This effect generally becomes remarkable for Temp > 30% of Fusion Temperature for metals and > 40-50% for ceramics. Related to the property of viscoelasticity.

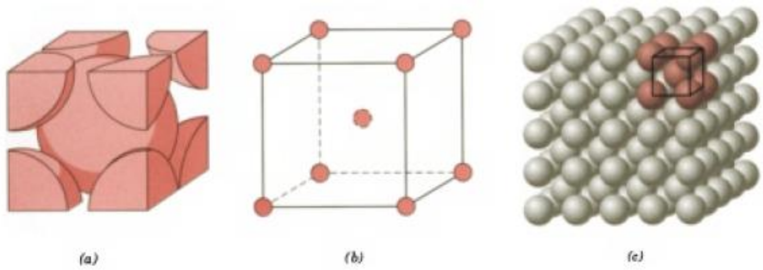
Viscoelasticity

It's the property of materials that exhibit viscous and elastic behavior when deformed. Therefore a viscoelastic material is like a mixture of honey and rubber. When deformed the molecules drag on each other like those of a fluid, with time, but when released, they return a little back as if the honey had some elasticity.



Grain vs Crystal

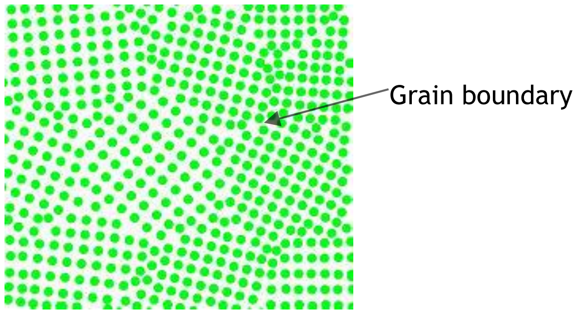
The term grain is more commonly used in metallurgy while the term crystal is more commonly used in the physical-chemical area. However, there is also who says that the crystal is the unitary structure from which the grains are formed.



The crystal would be the cube of image c) and the grain would be the gray cube, a group of crystals. The crystalline structure is thus the spatial organization of the atoms of a crystal.

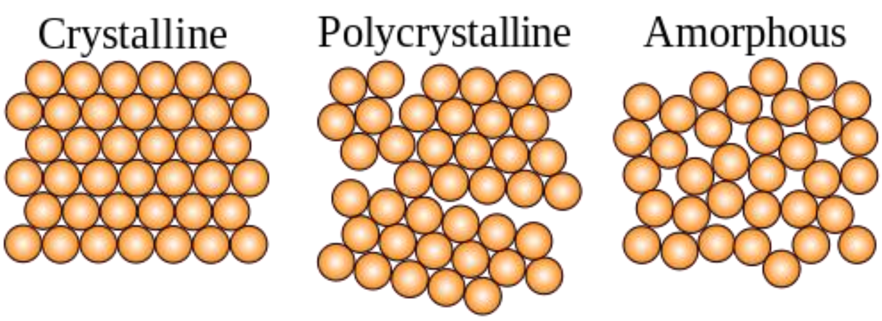
Grain boundaries

They are defects in the crystalline structure of a material of a polycrystalline material. A monocrystalline material only has 1 grain or 1 crystal, and therefore has no grain boundaries.



Amorphous material

It is a material in which atoms are not organized. If cars were atoms, a car park would be a polycrystalline material and a junkyard would be an amorphous material.



Glass Transition

Glass transition is the phenomenon that occurs to an amorphous material, or amorphous regions of a semi-crystalline material in which it goes from hard and relatively brittle to malleable or vice versa and where it undergoes a variation of its viscosity $T_g \approx \frac{T_f}{3}$. In fact this transition does not occur at a single temperature but in a temperature range around T_g (glass transition temperature). Do not confuse with fusion/melting. When melting, the material goes from a state in which the molecules / atoms are arranged (solid) to a state in which they are disorganized (liquid). In the vitreous transition the material is always in a disorganized (amorphous) state. Another difference is that in the glass transition there is no latent heat needed to overcome the transition, but the specific heat of the material increases.

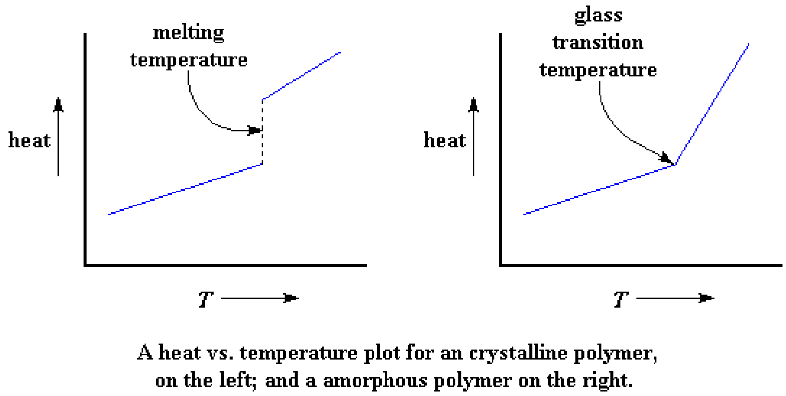


Fig. 1 *Heat vs Temperature for crystalline (left) and amorphous (right) polymers.*

Stress intensity factor and fracture toughness

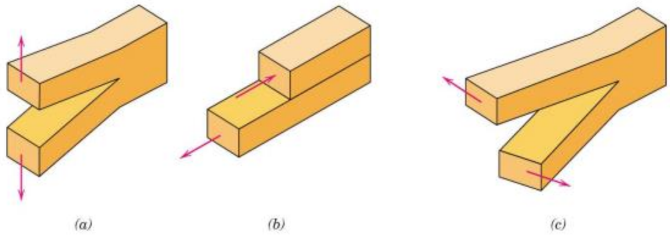


Fig. 2 *Main ways to stress a crack*

For a solid containing only one crack. Mode I is when the surfaces move perpendicular to the plane of the crack, it is called traction mode. Mode II is slip and the 3 is shear. Usually cracks are requested in a mixture of the 3 modes. A crack will propagate when a critical stress value is reached. Similarly, since the stresses in the vicinity of the crack tip can be defined in terms of the stress intensity factor, there is a critical value for this parameter that can be used to specify a fragile fracture condition. This critical value is called the critical stress intensity factor (K_C). For mode I we have

$$K_{IC} = Y \cdot \sigma\sqrt{\pi \cdot a}$$

Y: dimensionless parameter that depends on the geometry (size of failure relative to part, shape of failure)

a: half the length of the crack.

K_{IC} gives us the value of fracture toughness, i.e. the material’s resistance to crack propagation

One can thus know whether the size of the crack is tolerable for a given stress or if the stress is tolerable for a given crack size. This factor, which is a property of the material, tells us the resistance of the material to the propagation of cracks.

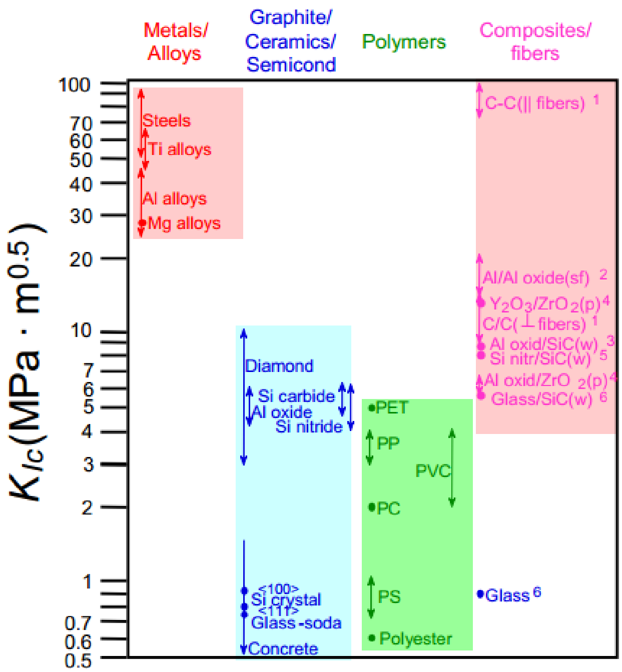


Fig. 3 K_{Ic} of several materials.

If we hold a piece of steel and a piece of polypropylene at the same stress and make an equal crack in both, it is more likely that the PP crack propagates faster (which may lead to the failure of the piece as the resistant section has decreased and the length of the crack increases).

Fragile materials have little plastic deformation before rupture and have low Kc value. Ductile materials have high Kc.

Hardening by precipitation

With the decrease of temperature the solubility of one element in the other decreases and it precipitates. These particles of precipitates act as obstacles to the movement of grains, and as a consequence, increase the mechanical strength of the heat treated alloy.

Tempering

It is a heat treatment that consists in the relief of the internal stresses produced by e.g. quenching, responsible for excessive hardness and fragility of the material. The material after tempering gets better ductility and toughness. Secondary tempering may cause hardening. The treatment consists of heating under A1 temperature followed by slow cooling in air or oil bath.

Martensite

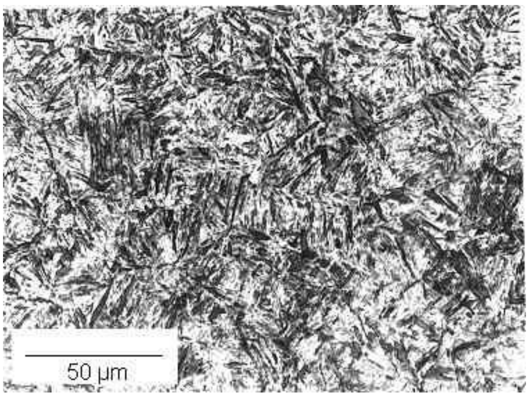


Fig. 4 Martensite under microscope

Hipoeutectoid steel

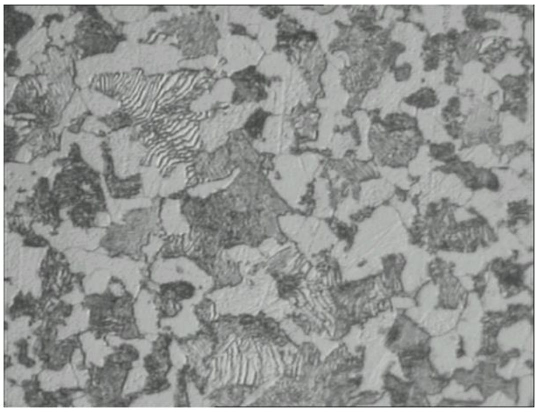


Fig. 5 Hipoeutectoid steel under microscope

Note the pearlite: alternate stripes of ferrite + cementite

Hipereutectoid Steel

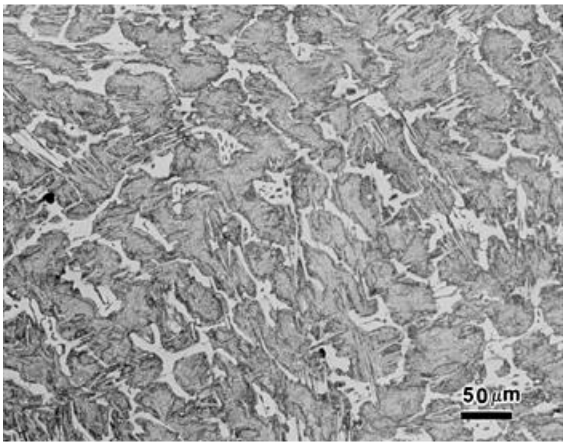


Fig. 6 Hipereutectoid steel under microscope

Notice the same pearlite, but here in the grain boundaries there is cementite (white) instead of ferrite as in the previous image.

Structural Steels

Are steels of low hardness and high ductility, easy to be worked and molded. They are steels for general applications and that allow good finishing and high cutting speeds.

Tool Steels

These are any steels used to make cutting tools, forming tools or any other piece capable of forming a material into a part. They are characterized by high hardness and wear resistance. The great majority of medium and high alloys are quenched in air, so it is not possible to anneal.

High Speed Steels

They are steels whose main application are cutting tools such as drills, scalpels, saws (included in tool steels). The development of these steels allowed for faster cutting speeds, hence the name. They offer high hardness at temperatures up to 500 °C and high wear resistance thanks to alloying elements such as Tungsten, Molybdenum, Vanadium and Chromium which are capable of forming carbides.

Corrosion

is the progressive destruction of a metal by the action of an outside agent.

Electronegativity

The noblest metal is gold and the least is magnesium.

Castability

Ability of a material to be used in casting.

Secondary hardening in tempering

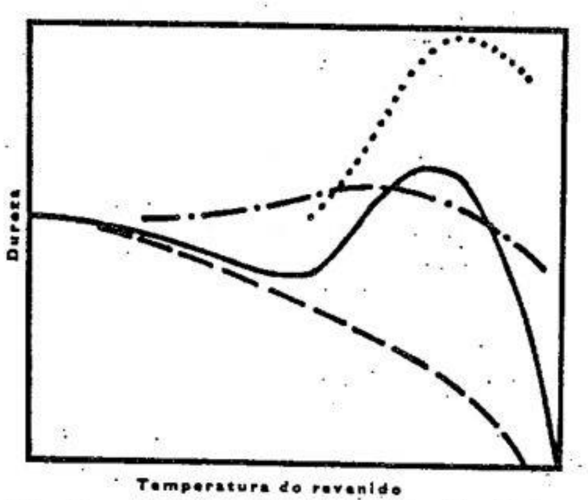


Fig.5 - Influências parciais de vários factores no comportamento ao revenido de um aço rápido.

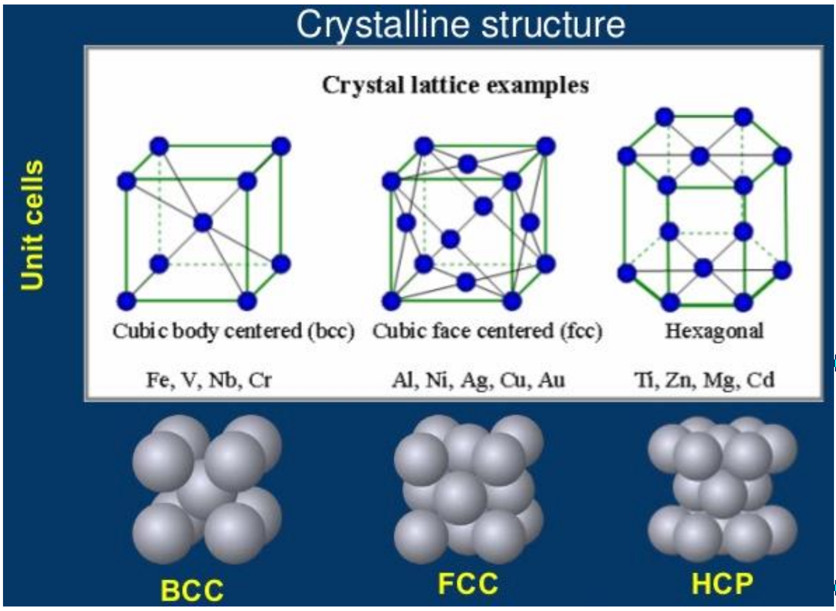
— — — martensite revenida
—.—.— precipitação de carbonetos
.... austenite residual - martensite
——— resposta total ao revenido

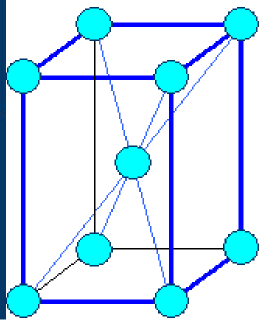
Or secondary quenching, or aging tempering is a hardening process that occurs in tempering due to the transformation of the residual austenite into martensite and due to the precipitation of hardening carbides, the former having more weight in this process.

Aging

It is a heat treatment of hardening and increase of strength applied to certain metallic alloys (generally non-ferrous) which consists in forcing the appearance of a fine precipitate of a second phase in the grains of the first phase, constituting barriers that impede the movement of the grain boundaries and consequently increasing the strength of the alloy. Example Al + Cu.

Crystal structures of engineering materials





Hexagonal close packing (HCP)

Cubic face centered (FCC)

Cubic body centered (BCC)

Body Centered Tetragonal (BCT)

General

Main types of materials

- Metallic
- Polymers
- Ceramics
- Glasses and vitreous materials
- Composites
- Semi conductors
- Biomaterials
- Multifuncional

Metallic Materials

- Good electrical and thermal conductors
- High mechanical strength and ductility
- High shock resistance
- High tenacity

Examples:

- Iron and alloys
- Aluminum and alloys
- Copper and alloys
- Titanium and alloys
- Precious Metals (Gold, Silver)

Polymers

- Cheap
- Easy to conform and fast to achieve final part shape
- Huge variety with very different properties
- Can have very low densities

Examples:

- Polypropylene
- Polyethylene
- Rubber
- Nylon
- Teflon

Ceramics

- High hardness
- High temperature resistance (high melting temperatures and low thermal expansions)
- Great electrical insulators

Examples:

- Clay

- Alumina
- Zirconia
- Carbides
- Nitrides

Glasses and vitreous materials

- Transparency paired with moderate mechanical resistance
- High resistance to degradation through sunlight and environmental chemicals
- High recyclability

Composites

- Can have higher strengths to weight ratio than most other materials
- Very low fatigue issues
- High corrosion resistance
- Highly tailorable to the application

Examples:

- Carbon fiber reinforced polymer
- Concrete
- Fiberglass

Heat Treatments

All heat-treating operations involve the heating and cooling of metals.

Homogenization

Annealing

Normalizing

Hardening

Tempering

Quenching

Solution Heat Treatment

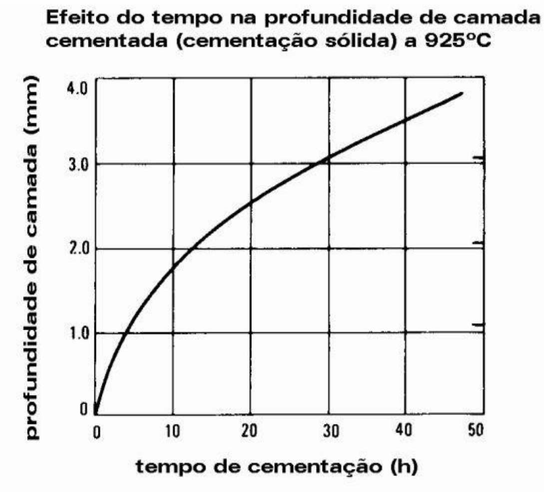
Sintering

I Carburizing

Also referred as case hardening, is a heat treatment process that produces a coating that is resistant to wear. This heat treatment is applied to low carbon steel parts which by nature are not that resistant to wear, after they are machined. This way it's possible to have a tough core, easily machinable, or made of a cheaper material, and a hard surface.

This heat treatment is achieved by heating the parts in a furnace with a controlled atmosphere where carburizing gases are present. After this the parts will be quenched. Either right away or after slow cooling and re-heating.

- It is not considered carburized surface when the carbon content gets lower than 40% of that of the surface. At the surface, generally there's 0.9 – 1.1 %C.
- Temperature of carburizing is 870-930ºC.
- Hardness of surface between 650-800 HV.
- The longer the part stays in the atmosphere the deeper the carburized surface becomes.
- Generally have 2 mm thickness.



Quando se pretende um máximo de tenacidade e dureza

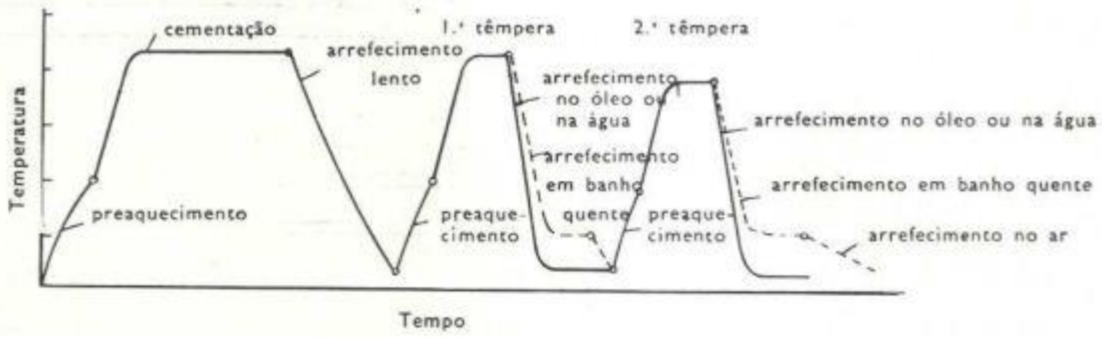


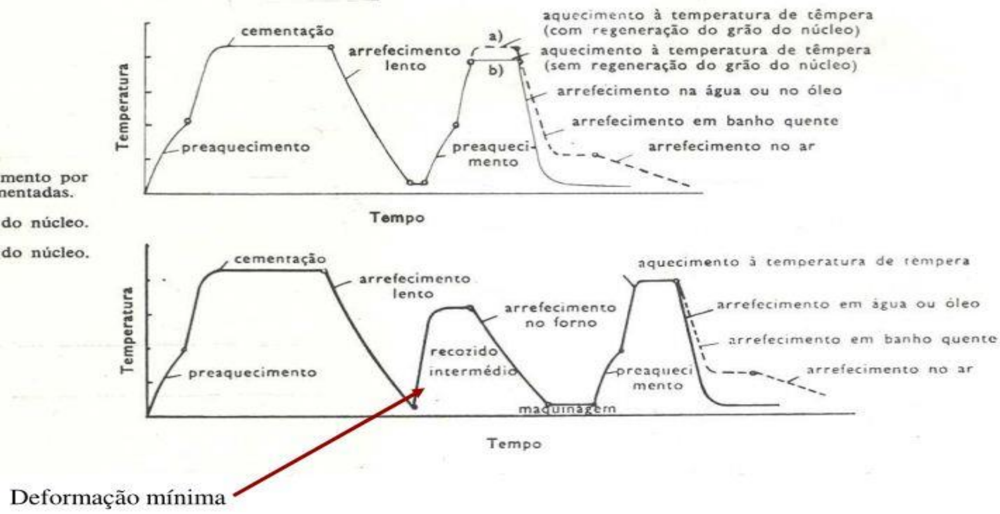
Fig. 74 — Têmpera dupla com regeneração do grão do núcleo.

Fig. 72 — 3 hipóteses de tratamento por têmpera simples de peças cementadas.

a) Com regeneração do grão do núcleo.

b) Sem regeneração do grão do núcleo.

c) Com recozido intermédio.



I Nitriding

- Regular thickness of up to 1 mm.
- Surface gets a lot harder than carburizing (1000 HV)
- Before nitriding it is required quenching and tempering
- No further heat treatments required after nitriding
- Considerably increases fatigue resistance, which comes from the fact that the nitrided surface expands itself causing compression tension in the matrix.
- Temperature of this treatment occurs between 500-580ºC
- Cooling in oven / air
- The superficial layer is very thin and has very little tenacity

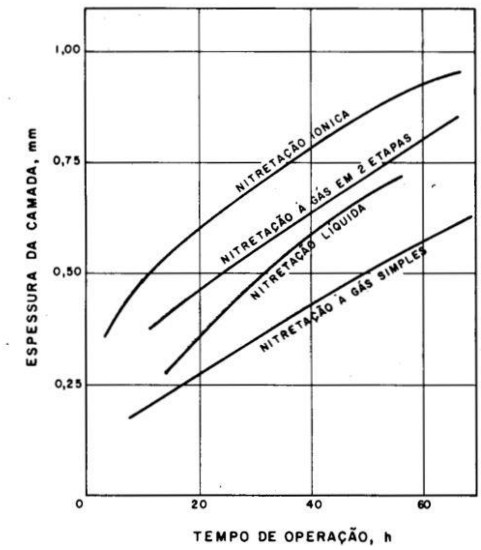


Fig. 7 *Operation time of the different methods of nitriding and the resultant surface thickness.*

Carbonitriding

- Thermochemical treatment that promotes a superficial enriching of carbon and nitrogen. Used for parts that require very hard superficial hardness, high contact fatigue resistance and subject to moderate superficial loads.
- For very hard surfaces with ~ 0.1 mm of thickness.
- Can be applied to any steel

Mechanical Construction Steels

Steels for heat treatment

Non-alloyed / carbon steel

- Small parts and subject to low loads
- 0.1-0.6%C

Alloyed

- Almost all contain chromium
- Usually come pre-heat-treated (quenched + tempered)
- Medium to big parts, subject to medium to high loads
- Advantages of these steels:
  - Higher hardenability, which allows even big parts to be hardened to the nucleus
  - Can be quenched in air, oil or water
  - Higher range of temperatures for heat treatments, allowing for heating with less chance of overheating.

Steels for carburizing

- 0.1-0.25%C
- Carbon steels
  - Low sized parts, general, common uses
- Alloyed
  - Bigger parts, higher loads
  - Lower wear, higher tenacity (gears, bearings, …)

Steel for springs

- High elasticity
- High fatigue resistance
- For springs that work in high temperatures → high temperature resistant steels

Stainless Steel

General Properties

- Chromium > 12% and Carbon < 1%, so it doesn't form carbides (which reduces chromium's effect).
- Chromium is the alloying element that has the biggest impact in oxidation corrosion resistance because it's the one that forms a protective layer (chromium oxide) which protects the interior of the material from oxidation progression. Nickel can be added to further increase this protection as it encourages generation of the chromium oxide layer and gives it more stability.
- In oxygenless environments, when the Cr_2O_3 layer is damaged, it won't form again, so the corrosion resistance is left to other elements (Ni, Mo, Cu, Si).

Stainless steel types

According to their chemical composition:

- Cr
- Cr + Ni
- Cr + Ni + Mb
- Special alloys

According to their structure:

Ferritic (400 series):

- Max 0.2 %C
- Normal max 18% Cr (unusual max 30% Cr)
- Good corrosion resistance and plastic formability
- Used mostly in coatings as they have same dilatation coefficient as normal steels
- Not heat treatment hardenable (due to low carbon content are hard to quench)
- Bad to weld

Austenitic (300 series):

- Max 0.1 %C
- 15-26% Cr + 7-25% Ni
- The best in terms of corrosion resistance
- The best in terms of weldability, because the chromium gets redissolved after welded caused corrosion.
- Amagnetic
- Not heat treatment hardenable
- In knifes the meaning of 18/10 ou 18/8 means the % of Cr and Ni.

Martensitic (400 series):

- 0.15-1 %C according to their Cr content (up to 17%) in order to be possible to obtain martensitic structure by quenching
- Heat treatment hardenable
- Good compromise between mechanical strength and corrosion resistance
- Used in drills and scalpels
- Heat treatments: Annealed 1-2h at ~ 800ºC, quenched at air or oil. Tempering revenido:
    - 200 - 350ºC, for high mechanical resistance or stress relief or
    - 600 - 700ºC, for high ductility and tenacity in detriment of mechanical resistance.

Types of corrosion in stainless steels

Salt water can cause formation of rust in simple stainless steels (without Nickel). Even nobler Cr-Ni stainless steels can oxidize, just slower.

Corrosion resistant steels only forms if:

- The passive layer does not form (contact corrosion)
- The passive layer is damaged (intergranular corrosion, uniform, alveolar, galvanic)

Contact

Uniform

- Corrosion uniformly attacks the whole surface of the piece

Alveolar

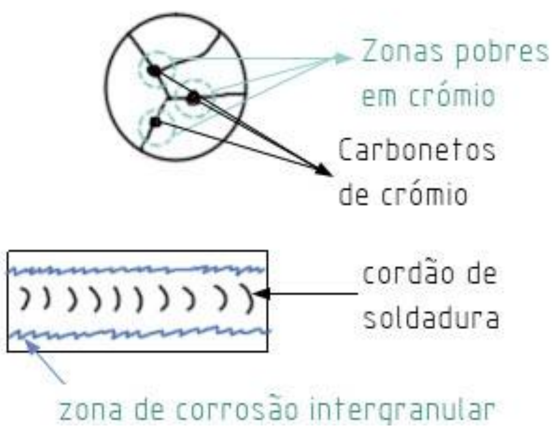
- Craters / dots form in the surface
- Frequently in chloride rich environments (e.g. sea water)
- Hard to detect
- **Molybdenum** is very good to avoid alveolar corrosion because it helps to repair the protective layer. Even then sometimes it is necessary to resort to other elements like titanium.

Galvanic or electrolytic

- Galvanic corrosion occurs when different metallic materials come in contact with each other and are impregnated with an electrolyte. The less noble material is attacked and goes into the solution. Corrosion resistant steels are noble compared to most other metallic materials.
- How to avoid?
    - Use the same material in different parts
    - isolate the different materials so as to avoid such contact

Intergranular

- Occur in grain contours
- They result from the precipitation of chromium carbides in grain contours when the steel passes through the critical temperature of 500-600ºC. The area immediately surrounding it is depleted in chromium and susceptible to corrosion.
- Typical corrosion in welding
    - In welding it is possible to see the precipitation of Chromium carbides by its brownish color.



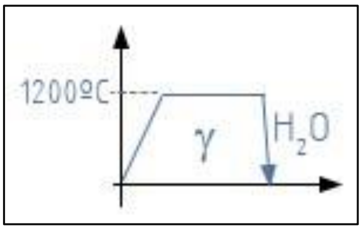
Solutions:

A priori

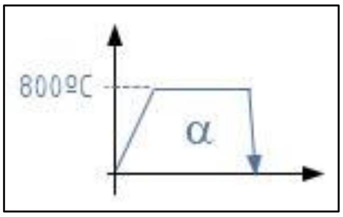
- Use extra low carbon (ELC) steels
  - Half of %C normal stainless steels (0.03% max.) (less carbon, less chance of carbides forming)
  - Lower elastic limit, which can be solved with cold hardening
  - Are more expensive
- Steels stabilized with N Aços estabilizados Niobium or Titanium
  - Ti e o Nb have more affinity with the carbon than Chromium, so they don't let the chromium form as many carbides.
  - Cheaper than ELC

A posteriori

For **austenitic steels** quench at 1200ºC (hiperqueching) to redissolve chromium in steel. Rapid cooling prevents precipitation of chromium (which would cause distortions in the mesh).



For **ferritic steels** it's not possible to raise the temperature so much (and redissolve the chromium in the steel, only difusion is possible). So in the end we only manage to make the steel semi-stainless. For this reason austenitic steels are the best for welding. Quench at



Corrosion under stress

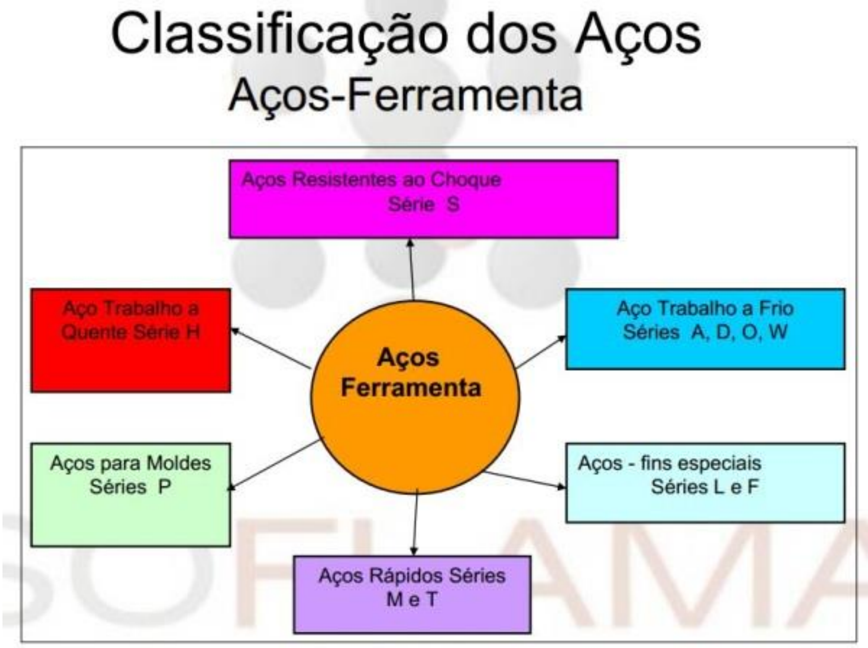
Phenomenon of deterioration of materials caused by the joint action of mechanical stresses (residual or applied) and a corrosive medium

- They arise due to internal / external stresses in the material, and can allow corrosion to move into the inside of the piece.
- When the steel is under tension if there are cracks in the surface layers (i.e. in the protective layer) the stresses promote a quicker crack propagation.

Erosion-corrosion

- It is the wear of the protective film that exposes the steel to new corrosion
- Frequent in surfaces of tubes with fluids at high speeds
- Solutions:
  - Oxygenate the fluid artificially
  - Add more Chromium
  - Change the shape of the tube
  - Reduce the flow rate

Tool Steels



AISI-SAE Norms

W Series

(quenched in water)

- 0.6% - 1.4% C
- You can add
  - Chromium: + quenchability, + wear resistance
  - Vanadium: + tenacity (because of finer + grain)

O Series

(for cold working, quenched in oil)

- 0.9% - 1.1% C
- Derivatives of the series W, with small additions of alloying elements (Cr, Mo, V, W, which allows them to be tempered in oil)
- Less distortions and cracks

A Series

(for cold working, quenched in air)

- 0.9 - 1.1% C
- Higher wear resistance due to higher carbon content.

S Series

(shock resistant)

- 0.5 %C → moderate wear resistance
- Main alloying elements are Si, Cr, W
- Moderate quenchability

- Cr or Mb can be added for higher quenchability
- High tenacity and fatigue

D Series

(for cold working, for good dimensional precision)

- 1.5 - 2% C
- 10 - 12% Cr

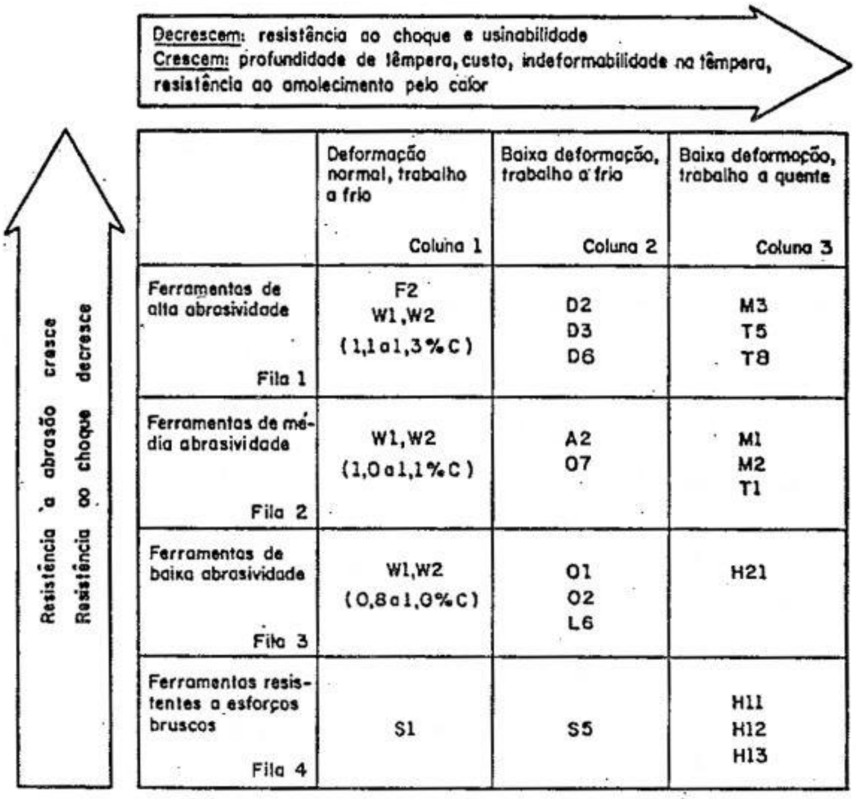
(high quenchability and wear resistance)

- Can be quenched in air, secondary hardening in tempering

H Series

(hot)

- ~ 0.5% C, ~ 4% Cr, some W or Mo
- For tools that achieve temperatures around 550 ºC. For that it's needed Cr, W, or Mb (same used in high speed steels)
- High resistance to creep
- High machinability


Decrescem: resistência ao choque e usinabilidade
Crescem: profundidade de têmpera, custo, indeformabilidade na têmpera, resistência ao amolecimento pelo calor
Resistência 'a abrasão cresce
Resistência ao choque decresce

	Deformação normal, trabalho a frio — Coluna 1	Baixa deformação, trabalho a frio — Coluna 2	Baixa deformação, trabalho a quente — Coluna 3
Ferramentas de alta abrasividade — Fila 1	F2 W1,W2 (1,1 a 1,3%C)	D2 D3 D6	M3 T5 T8
Ferramentas de média abrasividade — Fila 2	W1,W2 (1,0 a 1,1%C)	A2 O7	M1 M2 T1
Ferramentas de baixa abrasividade — Fila 3	W1,W2 (0,8 a 1,0%C)	O1 O2 L6	H21
Ferramentas resistentes a esforços bruscos — Fila 4	S1	S5	H11 H12 H13

High Speed Steels

T Series

(T from Tungsten)

- 18% W which forms many carbides of difficult dissolution, and which are the main hardeners
- 4% Cr
- High resistance to tempering
- May contain Vanadium which promotes the formation of said carbides

M Series

(M from Molibdnedium)

- 8% Mb as hardening agent
- 4% Cr
- They make up 80% of high speed steel, the T series the rest.
    - + 30% cheaper than T series
    - + Lightly tougher
    - – They decarbonize easily so the heat treatment has to take that into account
    - – Narrower service temperatures

Properties of High Speed Steels

- Hardness (wear resistance, good cutting power)
- Resistance to tempering
- Can work at 500-600 °C without appreciable hardness decrease
- Can be quenched in air
- Supplied in the soft annealed state
- Temperature of quenching as high as possible to dissolve as much carbon and alloying elements as possible. Have in mind that the the grain does not grow too much which could compromise the tenacity and result in an increase of residual austenite.

On the resistance to tempering: When working, the surfaces of dies used in hot forming are subject to high temperatures, in which tempering can occur again. Therefore, in order to promote improved heat resistance, these phenomena must be retarded and thus the resistance to tempering becomes critical.

Maraging Steels

General

More like Iron-Nickel alloys (15 % < Ni < 25 %). Carbon is actually seen as an impurity.

Most common maraging steels:

- 18 % Ni: Martensitic
- 20% Ni: Martensitic
- 25% Ni: Room temperature austenitic

Characteristics

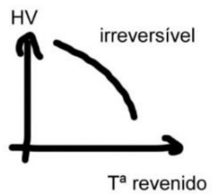
- Good resistance
- Good resilience
- Good toughness
- Used in the manufacture of parts that require good mechanical characteristics, in which it is of interest that they have a low weight (moving parts, lower E. kinetics)
- Also used in parts that must be welded (18% are the best in this aspect) and should have excellent mechanical characteristics and dimensional stability.

Manufacturing

First, the steel is formed until homogenization of the alloying elements and formation of austenite (generally at 800 °C). Followed by (quench) rapid cooling to 200 °C for formation of the martensitic structure. At this point, the parts are usually machined and welded, as this is where the best conditions for such processes are obtained. Then aging treatment is performed, which consists of tempering between 425 °C and 510 °C and is when precipitation hardening occurs and consequent increase of mechanical resistance.

Maraging martensite is naturally obtained unlike steel which has to be cooled quickly.

Table 1 *Comparison of steel's martensite and maraging steel's martensite.*

Fe-Ni martensite	Fe-C martensite
- Natural martensite - Isothermal (banho de sais) - BCC crystaline structure - low hardness, high toughness - tempering increases hardness because the other alloying elements precipitate with Ni; reversible tempering.	- Artificial martensite - athermal - BCT crystaline structure - high hardness, low ductility, low toughness (depends on C%) - 

Hardening of martensite leads to structural precipitation, i.e., it is in the zones of instability that the precipitation of Fe-Ni + alloying elements compounds incoherent with the matrix happens.

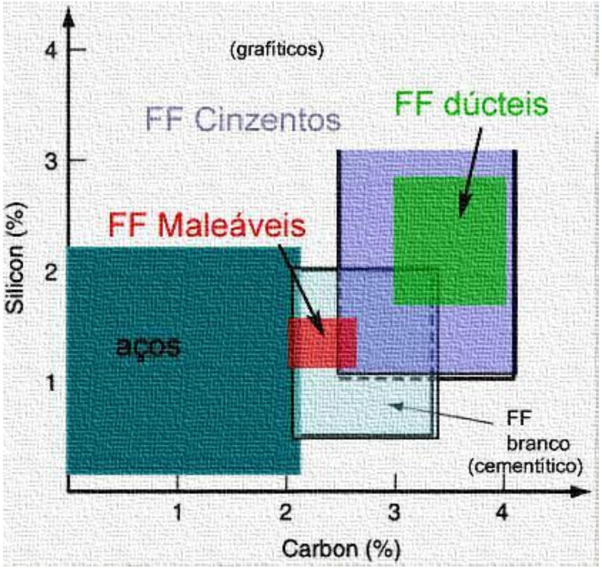
Heat treatments

- Solution annealing / homogenization / diffusion

- At a temperature above the line Af (end of martensite transformation into austenite during aging). With this treatment it is intended to homogenize the alloy, all in the austenitic phase, and to homogenously dissolve all the hardening elements.
- The machining is always done after this heat treatment, since the hardness is low until the structural tempering is done (the hardness of the martensite only depends on the C% which is very low, so the hardness is also very low)

- Treatment of austenite transformation in martensite (only for alloys with 25% Ni in which we have austenite at room temperature)
  - 4h at ~700 °C, Nickel carbides precipitate. By decreasing the amount of Nickel in the matrix, consequently Ms and Mf increase, becoming then possible to obtain martensite at room temp
  - In the end do cold hardening
  - Allow hot working to be performed
  - Allow surface hardening, work well with nitriding
- Structural tempering - has as purpose the hardening of the structure by precipitation, and is carried out at around 470ºC. The cooling rate has no influence.
  - The precipitation of compounds occurs without deformation in the structure resulting in good dimensional accuracy

Cast Iron

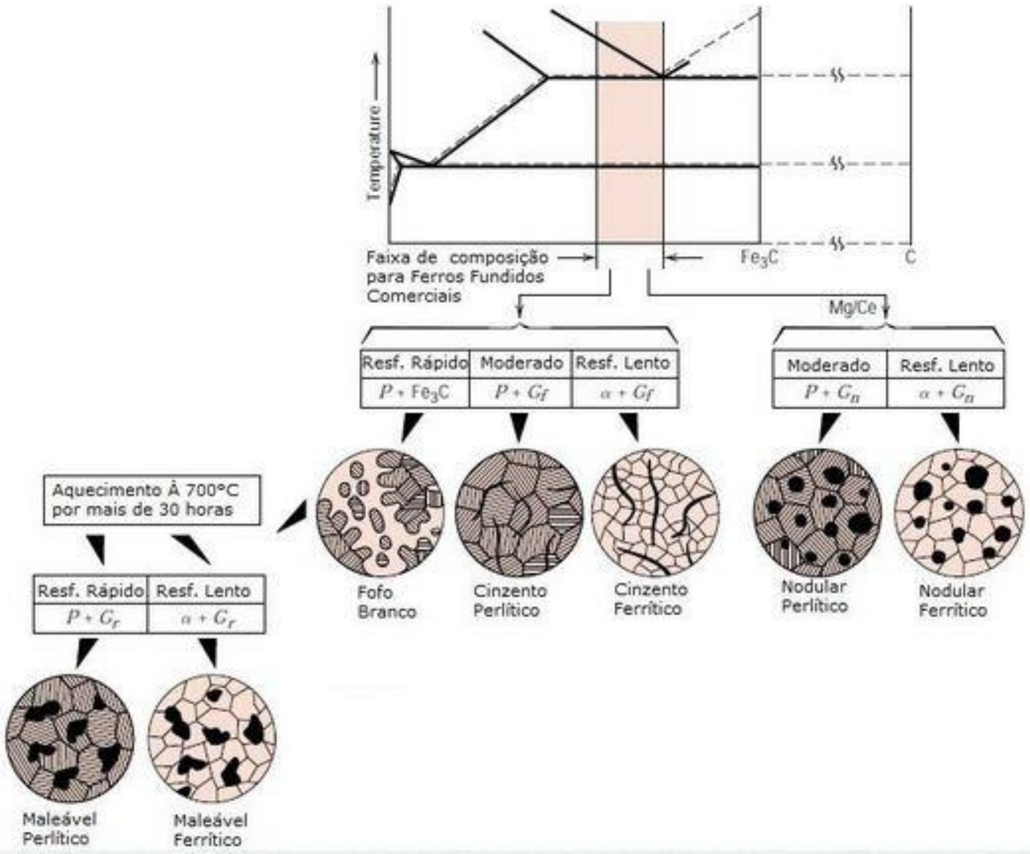


- 2.01-6.67 % Carbon, 1-3 % Silicon
  See Smith's book.

- White
- Graphitic
    - Grey
    - Ductile
    - Maleable (obtained from heat treating the white cast iron)
        - White nucleus
        - Black nucleus

Factors that influence the formation of graphite (**grafitizantes**) or cementite (**carborígenos**):

	Grafite	**Cementite**
Chemical composition	Si, C, Al	Cr, Mo, V, W
Cooling speed	Slow	Quick
	Adding powders of Fe, Si, Ca, that favor graphite	Rarely is cementite favored as it is very hard and fragilizes the rest of the material



White

- Carbon precipitates as cementite.
- Very hard and brittle, low toughness and ductility
- Rarely used, are passing materials (used to produce malleable FF)

Grey

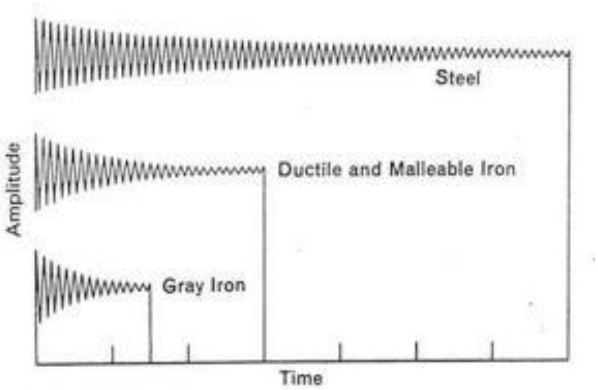
- Phase rich in carbon: graphite
- Good castability – graphite dilates during cooling which contradicts the material contractions in the mould
- Behaves differently when subject to traction and compression, as the graphite works as a micro emptiness, $\sigma_y(compression) = 3\ a\ 5x\ bigger\ than\ \sigma_y(traction)$
- Can contain minimal quantities of cementite (precipitates from ferrite)

Inoculation consists of introducing Fe-Si or Si-Ca in the liquid cast iron just before the pouring of certain additions such as granulates. These granules provide the germinating power of the bath for graphite.

Form when the carbon content of the alloy exceeds the amount that dissolves in the austenite, precipitating in the form of graphite lamellae.

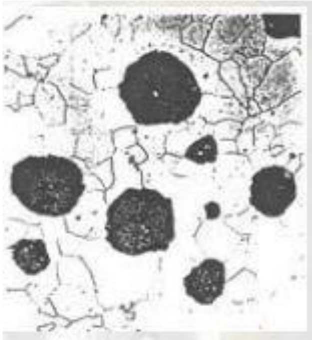
Fig. 8 Graphite lamellae

- Silicon from 1 to 3% to promote graphite formation.
- Cheap
- Good machinability, good hardness levels and good wear resistance and vibration damping capability.
- There can't be too much lamelles of graphite because that results in poor mechanical properties such as low ductility low σ_y and σ_u
- Influence of cooling rate on matrix formation:
  - Fast cooling results in pearlitic matrix
  - Slow cooling results in ferritic matrix
  - Moderate cooling results in a mixture of the two. speed
- Cannot be plasticly formed. Need to be cast and machined.
- Classes
  - 10 (100MPa UTS) – hiper, a lot of graphite.
  - …
  - 40 (400MPa UTS) – hipo, few grafite.



Ductile

- Spheroidal or nodular graphite - improves ductility (lamellar graphite has a factor of higher which increases the risk of cracks)
- Good castability, machinability, wear resistance, mechanical strength, ductility, deformability and quenchability.
- They admit bainitic quenching or even martensitic quenching
- The only cast irons that compete with steel.



Treatment of **nodularization** (which allows the obtaining of graphite in a nodular / spheroidal form)

- Addition of nodular elements (e.g. Magnesium) to the liquid cast iron, which reduce the levels of Sulfur and Oxygen, which are impediments to the formation of spherical nodules.
- After nodularization there is a tendency to form cementite to inoculate to prevent that from happening.

Types of ductile cast irons:

- Pearlitic: by addition of Cu, Ni, Sn
- Ferritic: obtained only by heat treatment
- Ferritic – Pearlitic

Less common

- Austenitic
- Aciculares
    - Bainitic
    - Martensitic

Malleable

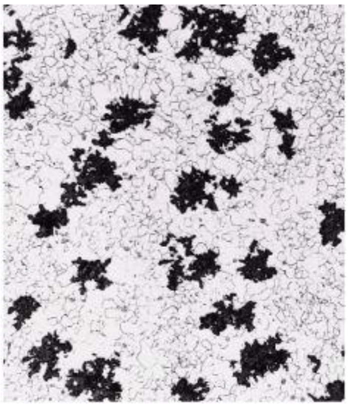
Obtained from heat treating white cast irons

Chemical composition

Fe (%)	C (%)	Si (%)	Mn (%)	S (%)	P (%)
remaining	2.16-2.9	0.9-1.9	0.15-0.25	0.02-0.2	0.02-0.15

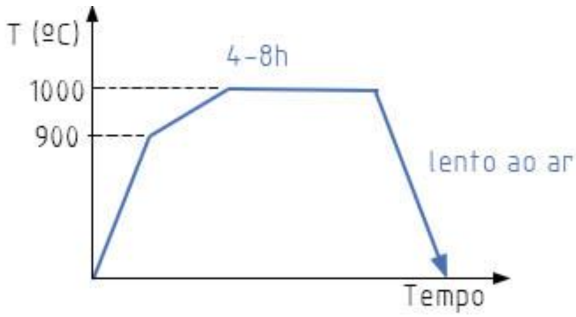
- Mechanical strength between that of grey and ductile: $200 < \sigma_y < 500 \text{ MPa}$
- Obtaining malleable cast iron is done through a 2 step heat treatment:
    - 1 – **graphitization**, melted parts are heated above eutectoid temperature, staying at constant temperature for 2- 20h, the white cast iron's cementite transforms into austenite and graphite.
    - 2 – cooling, in which the austenite becomes one of 3 possible matrices depending on the cooling rate: ferritic (in the oven), pearlitic (in the air) or martensitic (in oil).

Process



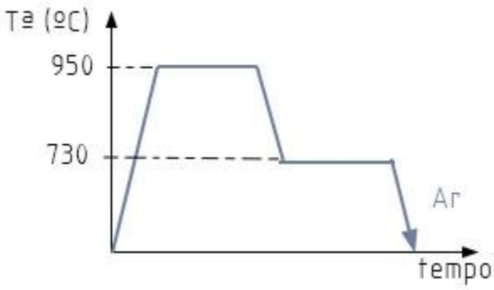
Formation of malleable cast iron by decarbonization:

- Elimination of cementite by decarbonization (elimination of carbon content of white cast iron)
  - White color, due to the essentially ferritic composition
  - parts are placed in boxes with oxidizing medium
  - decarbonization occurs at the surface
    - small parts only decarbonisation occurs
    - In large parts graphitization occurs inside



Formation of malleable cast iron by graphitization:

- Transformation of cementite into graphite
  - Graphite nodules (black color) of variable sizes (see image) are formed in a ferritic matrix
  - use of boron, higher temperatures, and shorter stages
  - perlite does not form
  - 1st step: Fe_3C (ϒ) → Graphite
  - 2nd step: Fe_3C(P) → Graphite



Applications

Aluminum

Properties

- Low density
- 2nd most malleable metal (1st is gold)
- Non-toxic (and why it's used as sheets to wrap food for example)
- Good ductility (CFC structure)
- Good corrosion resistance (due to Al_2O_3 that naturally forms when exposied to air)
- Most abundant metal on Earth's crust
- σ_y between 20MPa (pure) and 600MPa (alloys)
- Good thermal and electrical conductivity
- Amagnetic
- Low rigidity $E_{Aço} = 3 \cdot E_{Al}$
- Fusion temperature ≈ 600ºC
- Infinitely recyclable, and low temperature of fusion for that (compared to steel or Ti for example)

Specific parameters:

$\frac{E}{\rho}$ (specific rigidity) ≈ to steel's

$\frac{\sigma_y}{\rho}$ (specific strength) > steel's

Another consideration is buckling. For the same weight and yield strength, with aluminum you get a thicker part. This means more resistance to buckling. In airplanes, for example, it is not convenient to reinforce steel plates (instead of aluminum plates) so that they resist buckling.

Classification

Nomenclature of xxx(x) series

The different types of aluminum alloys are called by numbers, some have 4, others have 3. In both cases, the first number refers to the main alloying element.

1st no.	Main Alloy Element	Properties	~ UTS (MPa)	Heat treat.
1	> 99% Al	Very weak mechanically, but great corrosion resistance and electrical conduction.	130	
2	Cu	Copper is added to aluminum to make it harder, less ductile and will reduce resistance to corrosion. High strength, high performance over range of temperatures. Used in aerospace. Hard to weld.	306	x
3	Mn	One of their first uses was pots and pans, and they are the major component today for heat exchangers in vehicles and power plants. Their moderate strength, however, often precludes their consideration for structural applications.	200	
4	Si	Silicon, when added to aluminum, reduces its melting point and improves its fluidity when molten. These characteristics are desirable for filler materials used for both fusion welding and brazing. Consequently, this series of alloys is predominantly found as filler material.	280	?
5	Mg	When adding magnesium to aluminum, its strength is considerably increased. It is also hardened when submitted to strain. This makes it more ideally suited for sheets and plates.	240	
6	Mg + Si	It has improved ductility and is heat-treatable. These characteristics make it ideal for aluminum extrusions.	240	x
7	Zn	These alloys are often used in high performance applications such as aircraft, aerospace, and competitive sporting equipment. Out of all other series, this is the most resistance to fatigue, hence its use in aircraft.	410	x
8	Tin			
9	other			

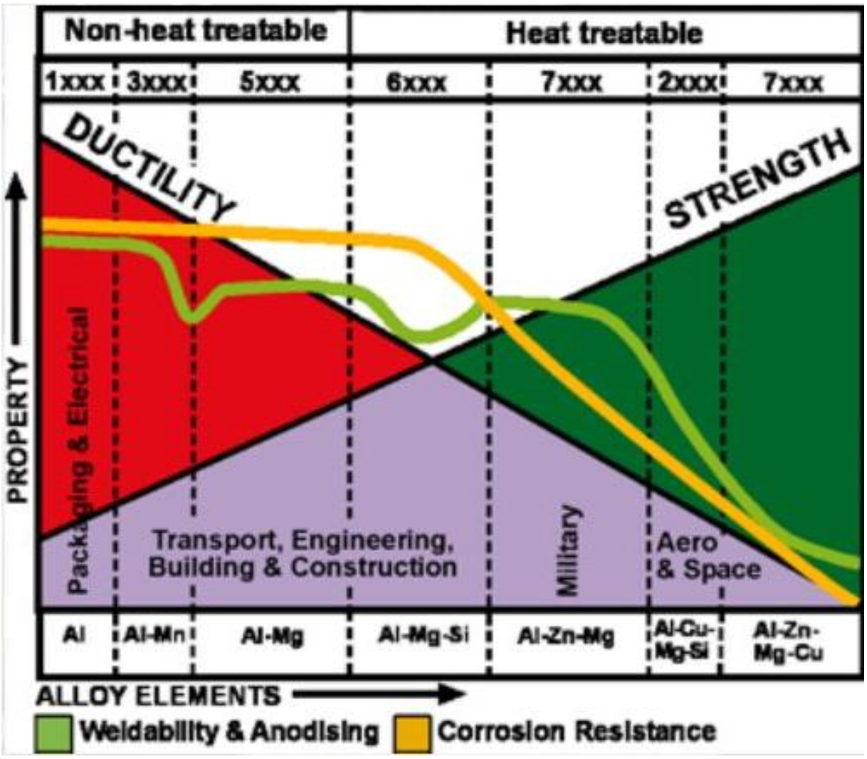


Fig. 9 Main properties of Aluminum XXXX series.

These alloying elements harden the Al by precipitation or by solid solution.

Because Al alloys are not as resistant to corrosion as pure Al, we can work around that issue by coating them with pure Al or by anodization.

Duraluminum

- Brand name for Al with concentration of 4% Cu, 0.7% Mn, 0.4% Mg.
- Heat treatable.
- Oldest and most used Al alloy.
- Tensile strength comparable to low %C steel.

A note about Cu as an alloying element of Al:

Copper is the main alloying element for Al. Its percentage as an alloying element in Al ranges from 4% for plastic forming until 8% in alloys for casting.

Heat treatments

A note on heat treatments and the difference between heat-treatable and non-heat-treatable Al alloys.

The increased strength of both Aluminum types is initially obtained by alloying the aluminum with additions of other elements. Further increase in strength of these alloys is obtained through various degrees of cold working or strain hardening. Cold working or strain hardening is accomplished by rolling, drawing through dies, stretching or similar operations where area reduction is obtained.

Contrary to their brothers, heat-treatable Al alloys exhibit increased solubility of their alloying element with an increase in temperature. Because of this, it is possible to produce significant additional strengthening to the heat-treatable alloys by subjecting them to elevated temperatures, to over-saturate them at lower temperatures, quenching, and, when applicable, precipitation heat-treatment known also as artificial aging.

Homogenization is the heat treatment process that redistributes the precipitating element(s) evenly through the part. For many alloys the homogenizing temperature is just under the melting point. Once the whole part reaches the homogenizing temperature it is allowed to cool slowly, resulting in a part that has a uniform internal structure ready to take advantage of other heat treatment processes or cold working.

For example, when casting aluminum alloys, the outside edge in contact with the mold cools first, forming a skin of aluminum crystals, also known as grains. As the cooling process continues towards the center, the casting has regions of pure aluminum near the skin and other regions near the center, where the alloying element(s) precipitate out and lock crystal regions in place. This results in areas where the casting is soft and others that are strong.

Annealing doesn't need heating the alloy at such a high temperature as homogenizing. This causes recrystallization, where the original crystalline structure reforms and easy slip planes are evident again. Unlike many heat treatment processes, the rate of cooling after annealing is not critical.

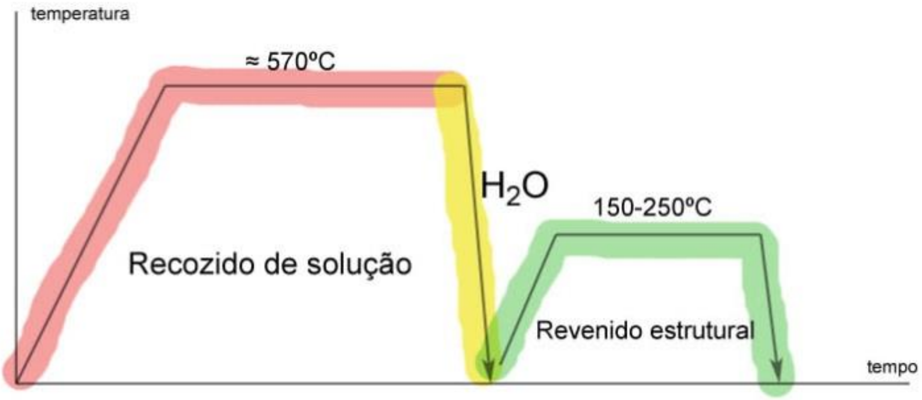
The process of shaping aluminum alloys causes the grain structures to slide against one other, along areas known as slip planes. After a while there are less easy slip planes, and increased force is required to shape the part. This state is referred to as work hardened. The annealing process resets the crystalline structure and creates a new batch of unused slip planes, making it easy to work the part again.

Solution heat treatment

1st step – Annealing to dissolve the copper homogenously.

2nd step - Quenching

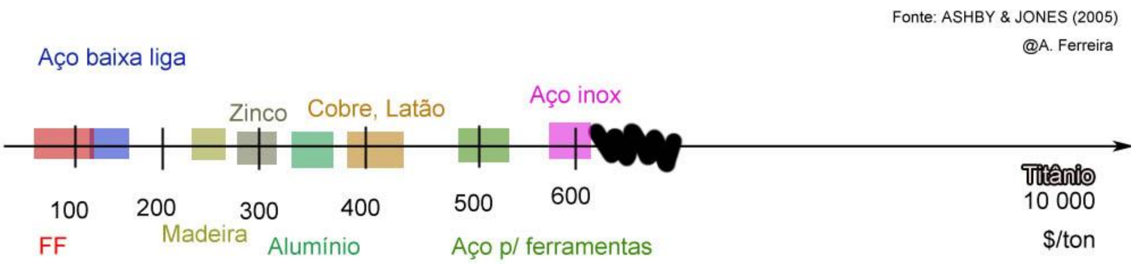
3rd step – Natural aging or artificial aging aka precipitation hardening. This step is necessary for the precipitates to form. The time the aging takes depends on whether its natural (room temperature) or artificial (higher temperature) and the massiveness of the piece that is being treated. The bigger and thicker the more time it will take.



Copper

Pure

- Excellent thermal and electrical conductivity, widely used in the electrical industry.
- Corrosion resistant (form oxide film)
- CFC, thus good ductility (50-60% elongation), which, together with the high conductivity that causes micro-soldering between the tool and the material, causes poor machinability (bad finishing).
- Low σ_y (40-50 MPa)
- To harden and lower conductivity: add small amounts of alloying elements such as Nickel and Zinc
- Higher service temperatures (and fusion temperatures: approx 1000ºC) than Al and Mg (main competitors), for which qe will be preferable in terms of fluency.



Brass (Cu and 5-50% Zn).

Up to 3% lead to improve machinability. Both these and the bronzes are part of the class of coppers with high alloy content. The addition of Zinc has two general effects that have as a combined effect the improvement of the machinability of the brass relative to pure Copper:

- σ_y = approx 150 MPa → easy to machine
- Lowered thermal conductivity → improves the microwelding issue

Brass is good for brazing (welds in which the material to be joined does not mix with the added metal). We can braze steels with brass (brass beta is ideal).

α-brasses (monophasic / red)

- Zn < 35%
- + ductility, + cold hardenability
- Eg:
    - "Commercial bronze" 10% Zn - gold color, ornaments, hardware
    - "Red brass" 15% - idem
    - "Brass for cartridges" 30%. Good mechanical strength + excellent ductility, tubes, heat exchangers

α+β brasses (biphasic / yellow)

- 35% < Zn < 45%
- + hot forming
- Biggest advantage is good machinability
- “Metal Muntz”, 40% Zn, used in mechanical construction, good for forged components, heat exchangers

β brasses

- 45% < Zn < 50%
- Used for brazing
- Not for mechanical construction

Comparison	Monophasic brasses	Biphasic brasses
Ductility	+	- (only ductile when hot)
Mechanical strength	-	+ β is the harder phase
Castability	-	+
Machinability	- (bad finishings)	+
Corrosion resistance	-	- micro galvanic corrosion

Dezinficação dos latões (perda de zinco): Como as fases alfa e beta têm electronegatividades diferentes, o zinco sendo menos nobre perde massa, e ocorre a dezinficação. Nota-se pelas manchas vermelhas de Cobre puro.

Solução: acrescentar Arsénio (em solução sólida não é tóxico) em pequenas quantidades, <0,1%, ajuda a resistir à corrosão dezincificada. Al e Sn também poderão ajudar.

Corrosão micro galvânica: duas ligas em contacto elétrico com grau de nobreza diferente. A liga menos nobre sofre perdas de massa devido à presença da outra.

Nos latões pode ocorrer esse tipo de corrosão na presença de águas sulfurosas e atmosferas com pouco Oxigénio. A solução é usar latões monofásicos ou juntar menos de 0.1% de Arsénio, Alumínio ou Estanho.

Bronze (Cu + 1 to 10% Sn)

General characteristics of bronze

- excellent resistance to atmospheric and marine corrosion
- optimum castability
- good wear resistance, moderate hardness
- Good weldability
- good ductility (cold) (alpha) or hot (beta), gamma and delta phases have poor ductility and elongation.
- Delta bronze has anti-friction and anti-seizure capabilities, which are used in bearings and bearings in lubricated rotating shafts.
- Copper is expensive, tin even more
- Excellent corrosion resistance including salt water
- Better mechanical resistance than brass
- Used in sculptures because in addition to the excellent anti-corrosion properties, on cooling they expand slightly filling all the details of the sculpture.
- As the % in Tin increases, so do the hardness and properties associated with mechanical strength without appreciable drop in ductility. In addition it can be worked in cold to further increase the hardness.
- Lead provides self-lubricating / anti-rubbing properties to bronze, but is no longer so much used for environmental reasons.
- Excellent castability, weldability and ductility

Bronze metallurgic phases

- alfa (CFC), until 7% Sn - cold working
- beta e gama, >7%Sn - hot working
- delta, 5-10% Sn - anti-friction and anti-seizing

Types of bronzes

1. **Mechanical Construction bronzes (Gun Metal) 8-10% Sn**

They were used in cannons, nowadays they are used in gears and bearings. They are not suitable for salt water, they resist but not very well.

2. **Universal bronze: 5% Tin, 5% Zinc, 5% Lead**

The presence of two different phases leads to the creation of thin layers of oil in the softer alpha zones, which helps prevent seizing (adhesion from one part to another).

3. **Phosphorous bronzes (Tin between 6% and 14% + 0.1% and 0.6% of Phosphorus).**

The best to resist salt water. Balance between machinability and castability. Also used in casting.

4. **Bronzes de alto teor em chumbo, entre 4 e 5%.**

Used in valves

5. **Bronzes de alto teor de estanho (aprox 30%)**

- Elevada heterogeneidade estrutural
- Segregações

- Más propriedades mecânicas
- Bom timbre, usados p/ sinos

Note on tin:

Due to its relatively low mechanical strength, tin cannot be used as a mechanical building material or as a structural component in general, but as an alloying element in copper, it increases mechanical strength and resistance to corrosion, forming the so-called tin bronzes . Due to the remarkable anti-friction characteristics of tin-containing alloys (lead-tin, copper-tin and aluminum-tin, these materials are widely used in sliding bearings (bimetallic and trimetallic systems) the tin is only used under conditions in which its most relevant characteristics, such as high corrosion resistance, high ductility and low melting point, can be better utilized.

Magnesium

Density comparable to composites. Fights with Aluminum in uses that require low density materials (see Smith p.560) -> aeronautics, textile machines with parts that move at high speeds

Pyrophobic properties: fireworks

It is very electronegative (nobleness grade very low) which makes it so that it very easily is subject to galvanic corrosion.

To increase its mechanical strength it's usual to add Aluminum or Zinc which harden by solid solution.

Low resistance to corrosion.

Low ductility (HCP) and mechanical strength (hardness, fatigue, creep)

Requires special manufacturing processes

Titanium

Pure

- Fusion temperature = 1700ºC, Service temperature until 500ºC without creep issues.
- Steel, aluminum and titanium comparison

	E (MPa)	σ_y (MPa)	Density (kg/m3)
Steel	210	600 soft steel	7800
Titanium	140	1600	4300
Aluminium	70	600	2700

Properties:

$\frac{E}{\rho}$ (specific rigidity) generally higher than steel's.

$\frac{\sigma_y}{\rho}$ (specific strength) much higher than steel's and higher than aluminum's.

- High corrosion resistance, particularly in oxidant environments because of its high affinity with oxygen, with who it quickly forming a superficial oxide layer.
- Óxido fragiliza o material, qualqer pancada faz soltar o óxido, expondo-o a nova corrosão.
- The quick oxide formation brings problems to welding, which makes it necessary to use welding where no oxygen contacts the titanium (e.g. by using Argon)

Uses

- Structures with critical specific strenghts
- Severe corrosive environments
- Resistência fadiga-corrosão: os dois processos facilitam-se entre si
- Amagnetic uses
- 60% of its alloys are used in aeronautic and aerospace.

Structure

- at 20ºC it is HCP fase α
- at 883ºC undergoes alotropic transformation: BCC fase β

Alloyed

- Alphagene elements: Al, Sn, O
- Betagene elements: Fe, Cr, V

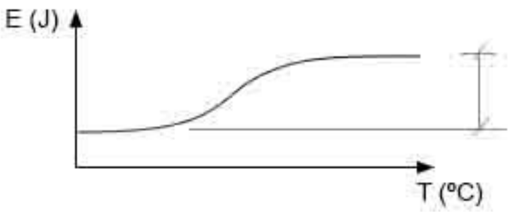
Monophasic alloys

- Good weldability (without oxygen)
- Good ductility

Bifasic alloys

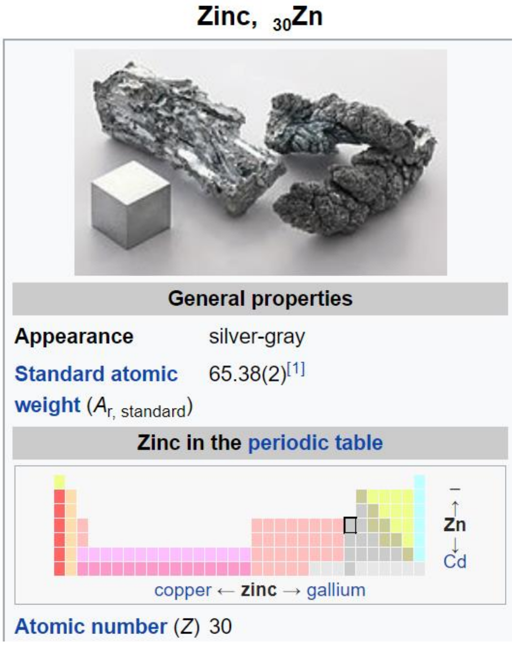
- More resistant
- Less ductile
- Poor weldability

Titanium alloys have a ductile-fragile transition less marked than steels':



Ductile-fragile steps very close to each other

Zinc



Some properties

- Fusion temp = 400 °C
- Normal price = 3.3€/kg
- Hexagonal close packing structure, so it has limited plasticity at room temperature.
- Recrystallizes at room temperature, so it can't be hardened by cold hardening
- Density = 7150 kg/m3

Uses

In decreasing order of importance:

Galvanization

Galvanization = coating of iron or steel to give it corrosion resistance. The most common for of galvanization is hot-dip, where the parts are submerged in melted zinc. As long as a coating of zinc exists above the iron or steel, it will be protected from corrosion.

Galvanization is a more expensive but more durable corrosion resistance method than paint. It's also better for harsh environments, as the zinc bonds itself much more strongly to the steel than paint does and has higher abrasion resistance.

Zamak alloys

In Zamak alloys – main alloying elements are aluminum, copper, and magnesium). Zamak 3 (there are other numbers) is the most widely used zinc alloy in North America and is usually the first choice when considering zinc for die casting for a number of reasons.

1. Excellent balance of desirable physical and mechanical properties
2. Superb castability and long-term dimensional stability
3. Excellent finishing characteristics for plating, painting, and chromate treatments

4. Excellent damping capacity and vibration attenuation in comparison to aluminum die cast alloys
5. Excellent dimensional precision.

However they need to be coated because are susceptible to corrosion. Even then, they are very weak for outdoor use to UV, temperature change, salt, which will make the coating to come off in a matter of weeks, months. This coating is also prone to be scratched by other harder metals.

***Table** 2 Mechanical Properties of Zamac 3*

Tensile Strength (MPa)	Yield Strength (0.2%) (MPa)	Impact Strength (J)	Shear Strength (MPa)	Hardness (B)	Elongation (%)
283	221	58	214	82	10

Alloying Element

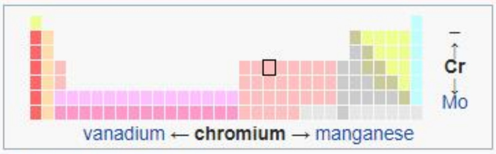
Zinc is used as an alloying element in Brass, Aluminum, Copper.

Chromium

Chromium, $_{24}$Cr

General properties	
Appearance	silvery metallic
Standard atomic weight ($A_{r,\ standard}$)	51.9961(6)[1]

Chromium in the periodic table



Atomic number (*Z*) 24

Chrome plating

Shape Memory Alloys

Reversible martensitic transformation of thermoelastic type.

- 50% Titanium, 50% Niquel
- Copper / Zinc / Niquel or Aluminum (próxima dos latões)

The memory effect can be

- Simple
    - Mechanical deformation in the martensitic state
    - When it goes to the austenitic phase, goes back to normal
- Reversible

Reversible temperature transformation between -110ºC and 110ºC

$$\alpha\ (BCT) \xrightarrow{T_{tr}} \gamma\ (FCC)$$

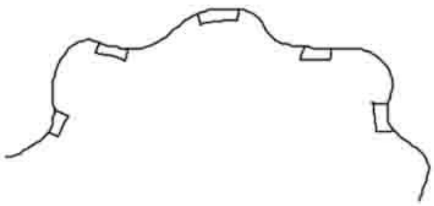
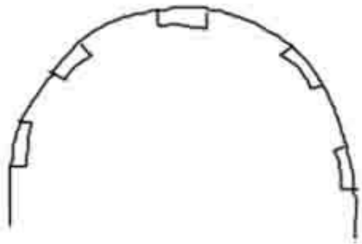
Natural martensite
* Low rigidity

* Low strength

Cold ($T<T_{transition}$): alloy takes on temporary shape, can be molded

Hot ($T> T_{transition}$): alloy returns to natural shape

Dental braces usually use Nitinol, a shape memory allow which has excellent biocompatibility.

Cold (20ºC)		Hot (37ºC)
	At 37ºC it's above the transition temperature so they assume their natrual shape	

Uses

-

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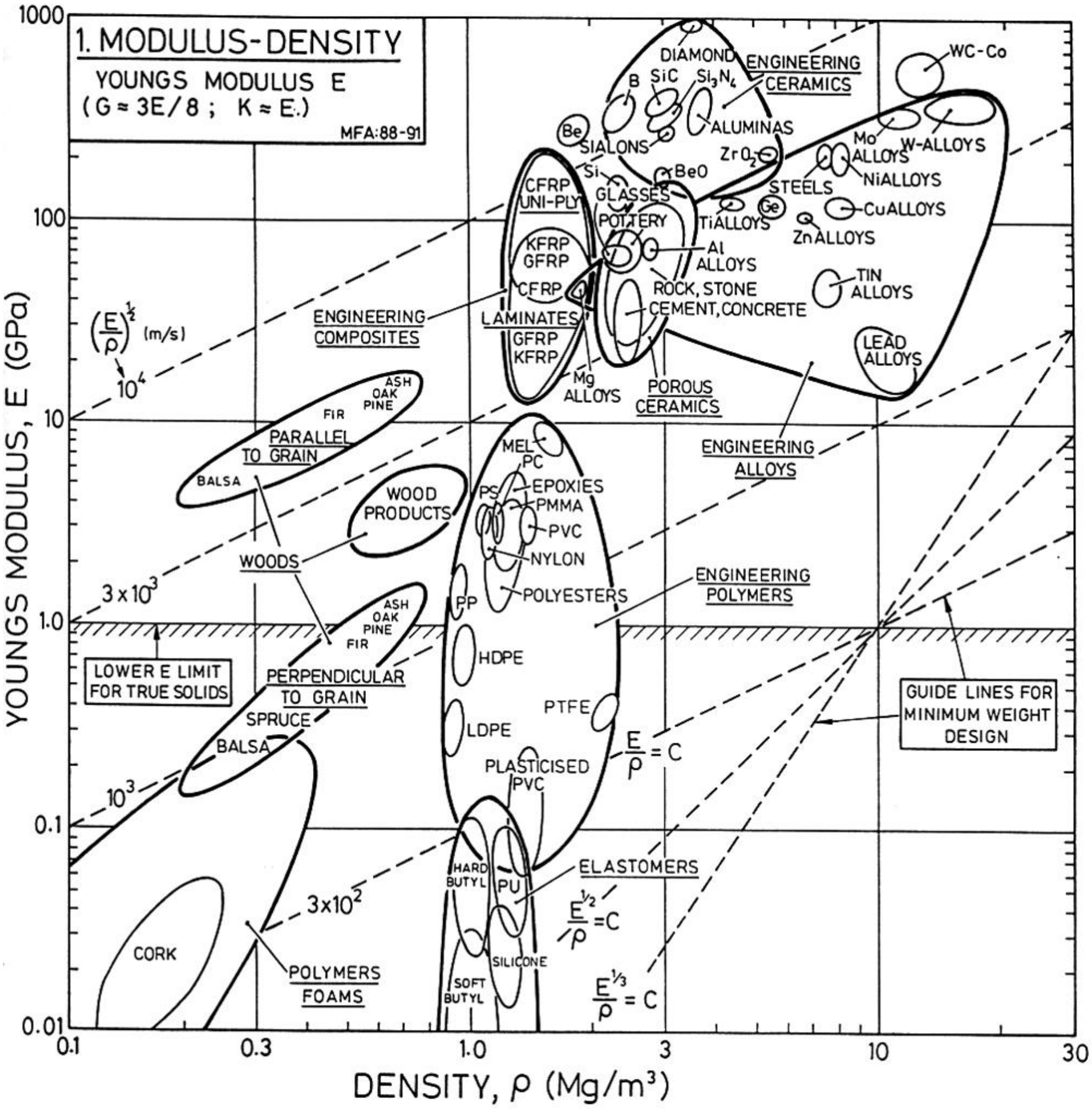
Anexes

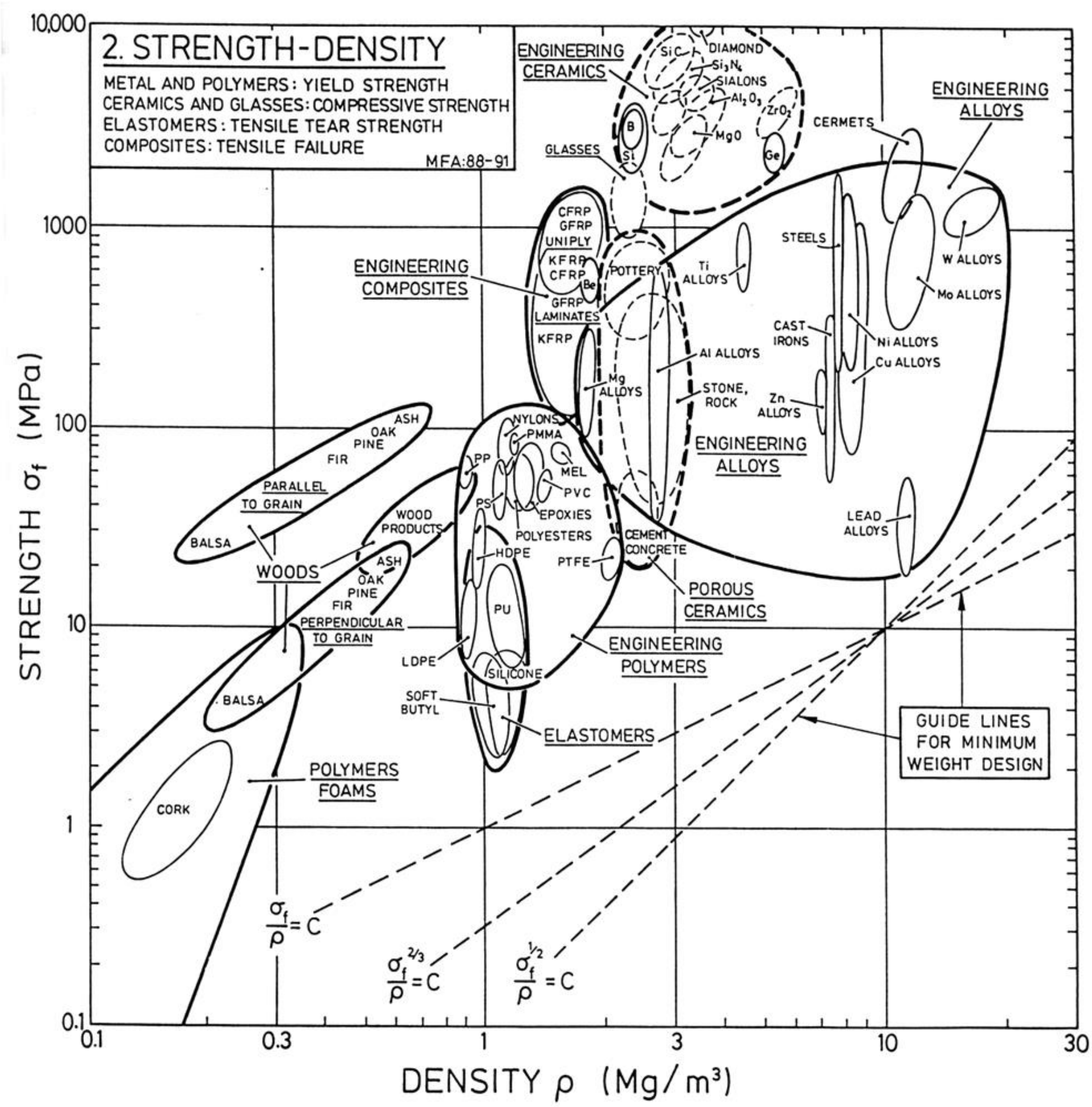
Influence of alloying elements in properties of metals

Influência na Propriedade	Elemento									
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al
Aumento da Resistência	●	●	●		●				●	
Aumento da Dureza	●	●	●		●					
Aumento da Resistência ao Impacto						●				
Redução da ductilidade	●		●	●						
Aumento da Resistência em altas temperaturas								●		
Aumento da Temperabilidade							●	●		
Ação Desoxidante		●			●					●
Aumento da Resistência à Corrosão							●			
Aumento da Resistência à Abrasão							●			
Redução da Soldabilidade	●									

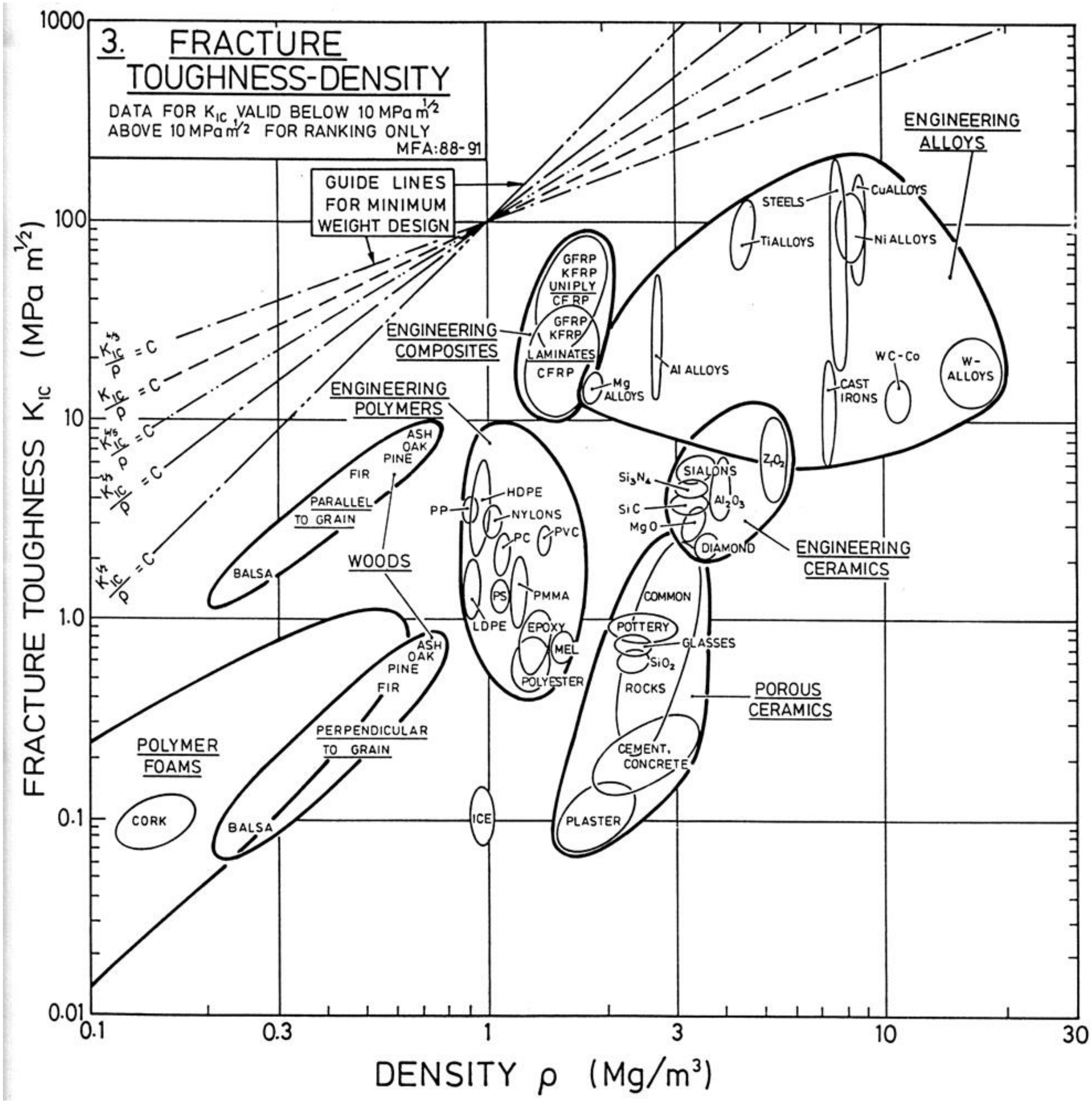
Modulus vs Density



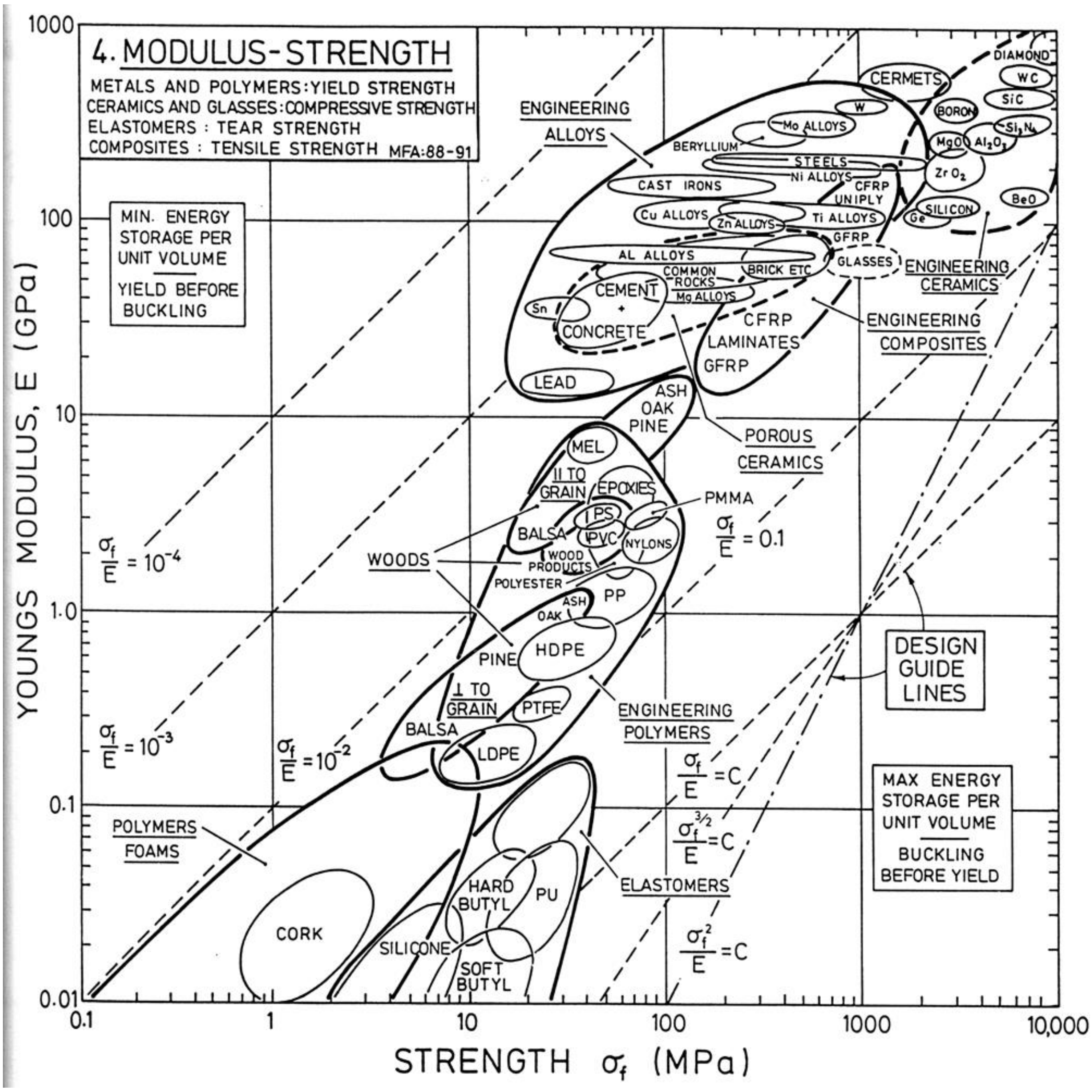
Strength vs density



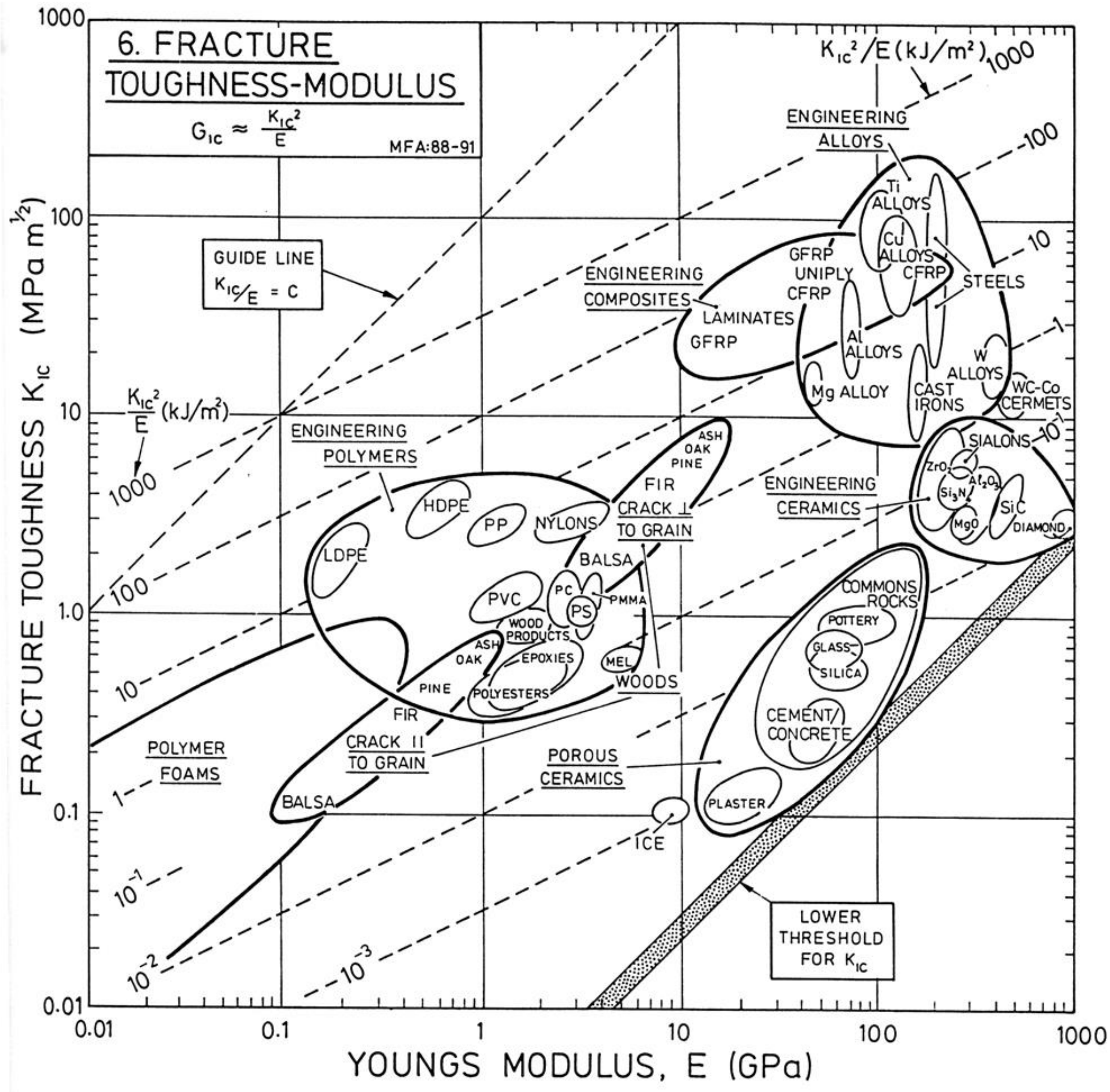
Fracture toughness vs density



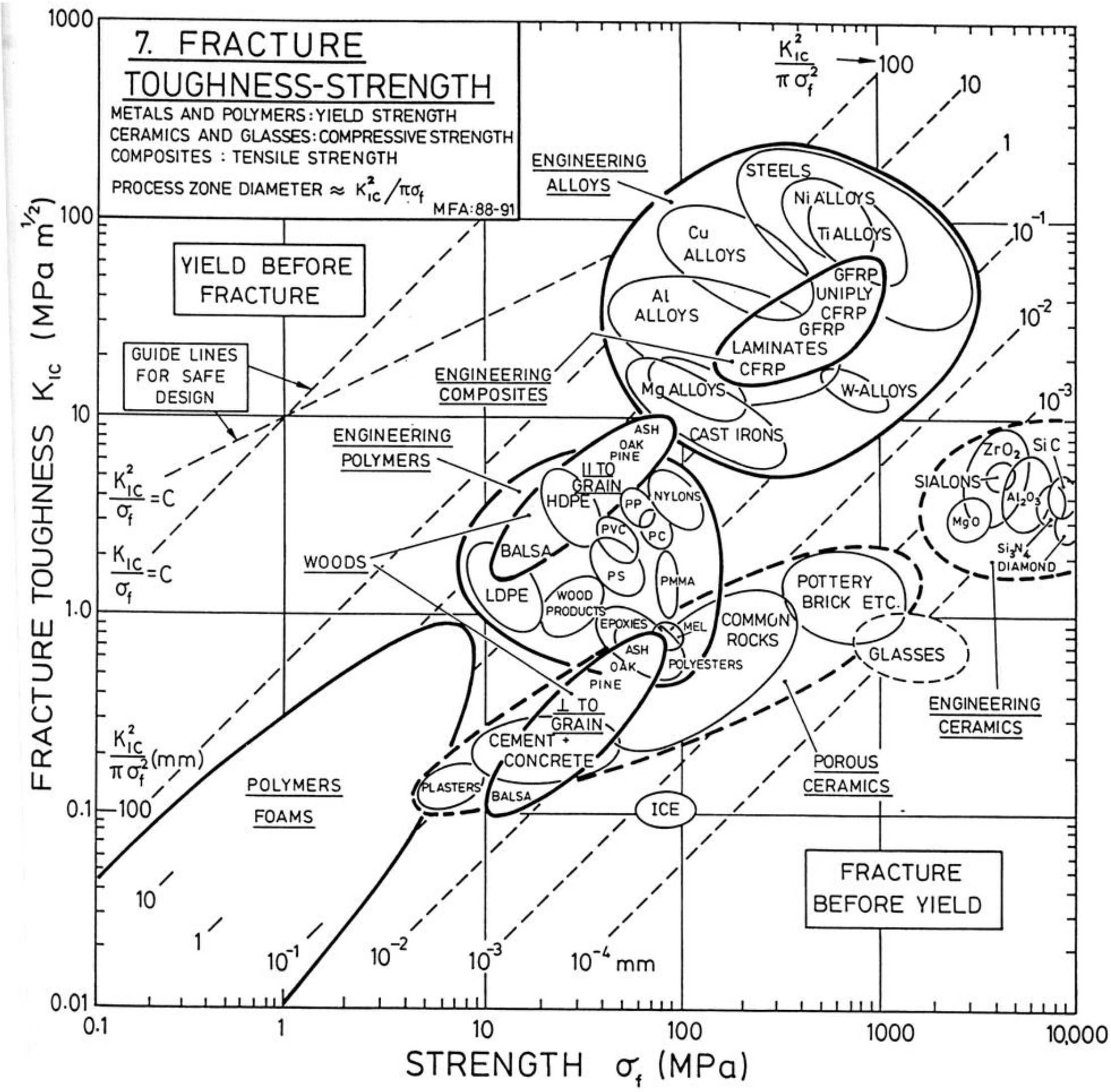
Young's modulus vs strength



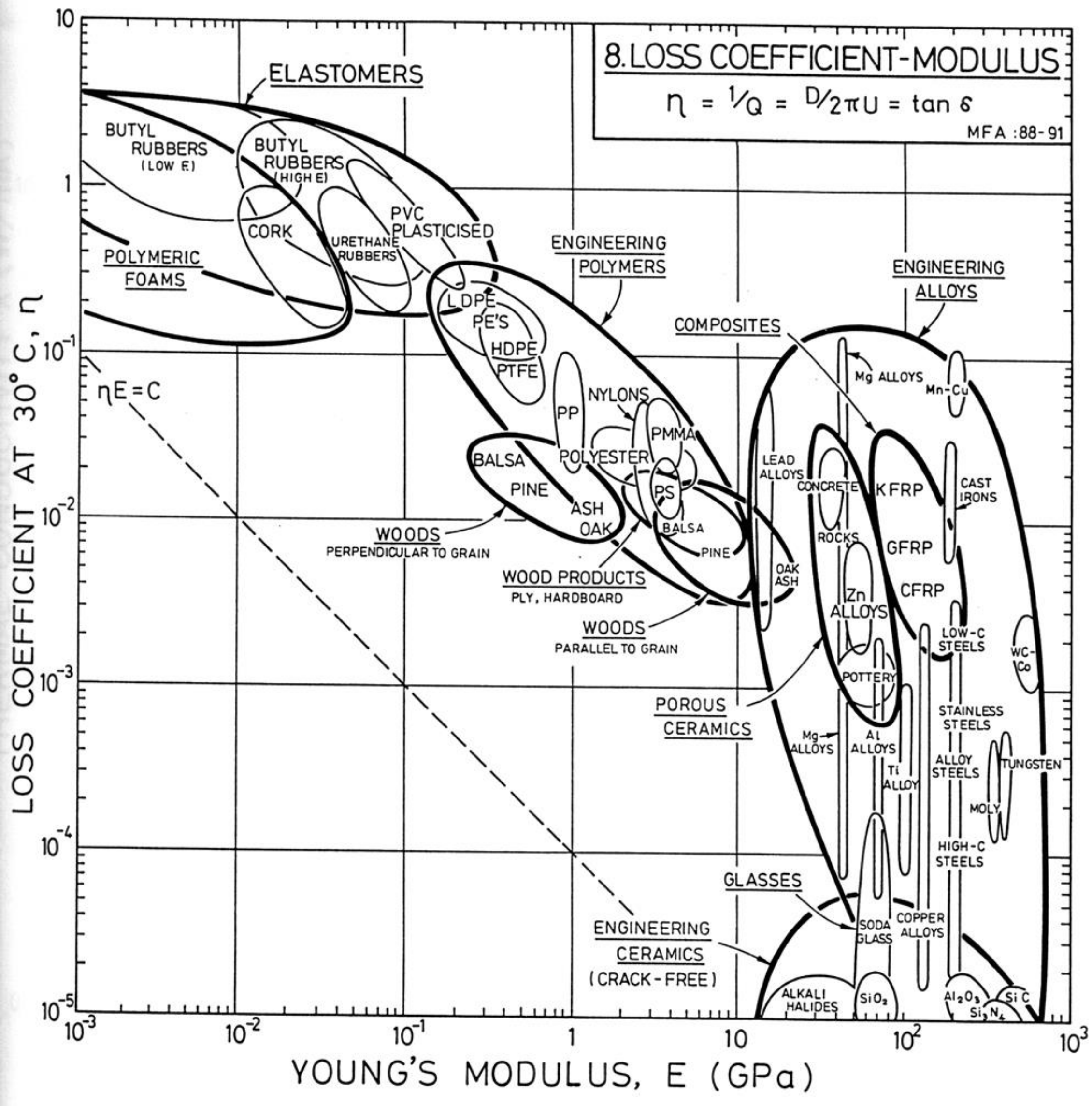
Young's modulus vs Fracture toughness



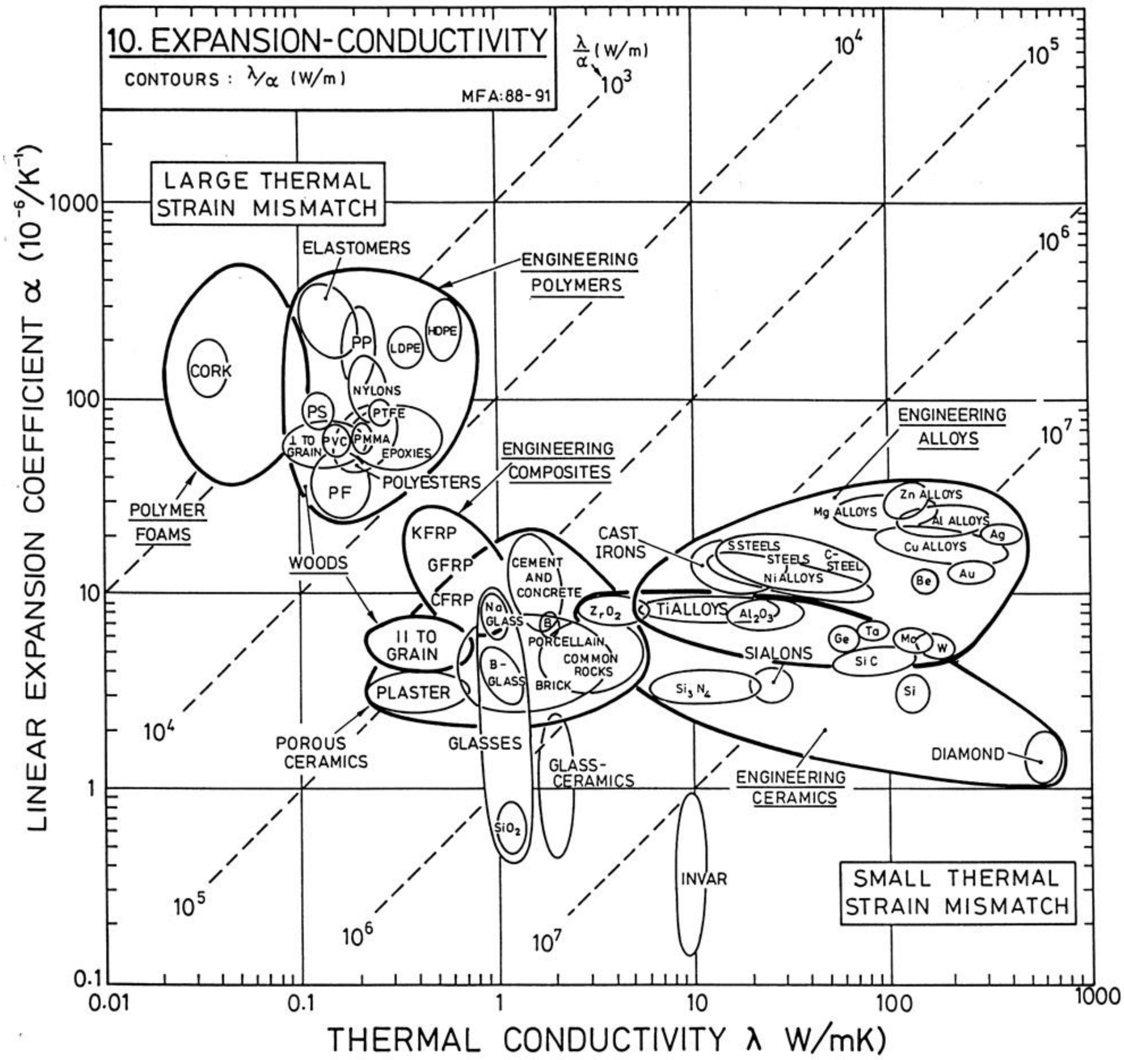
Fracture toughness vs strength



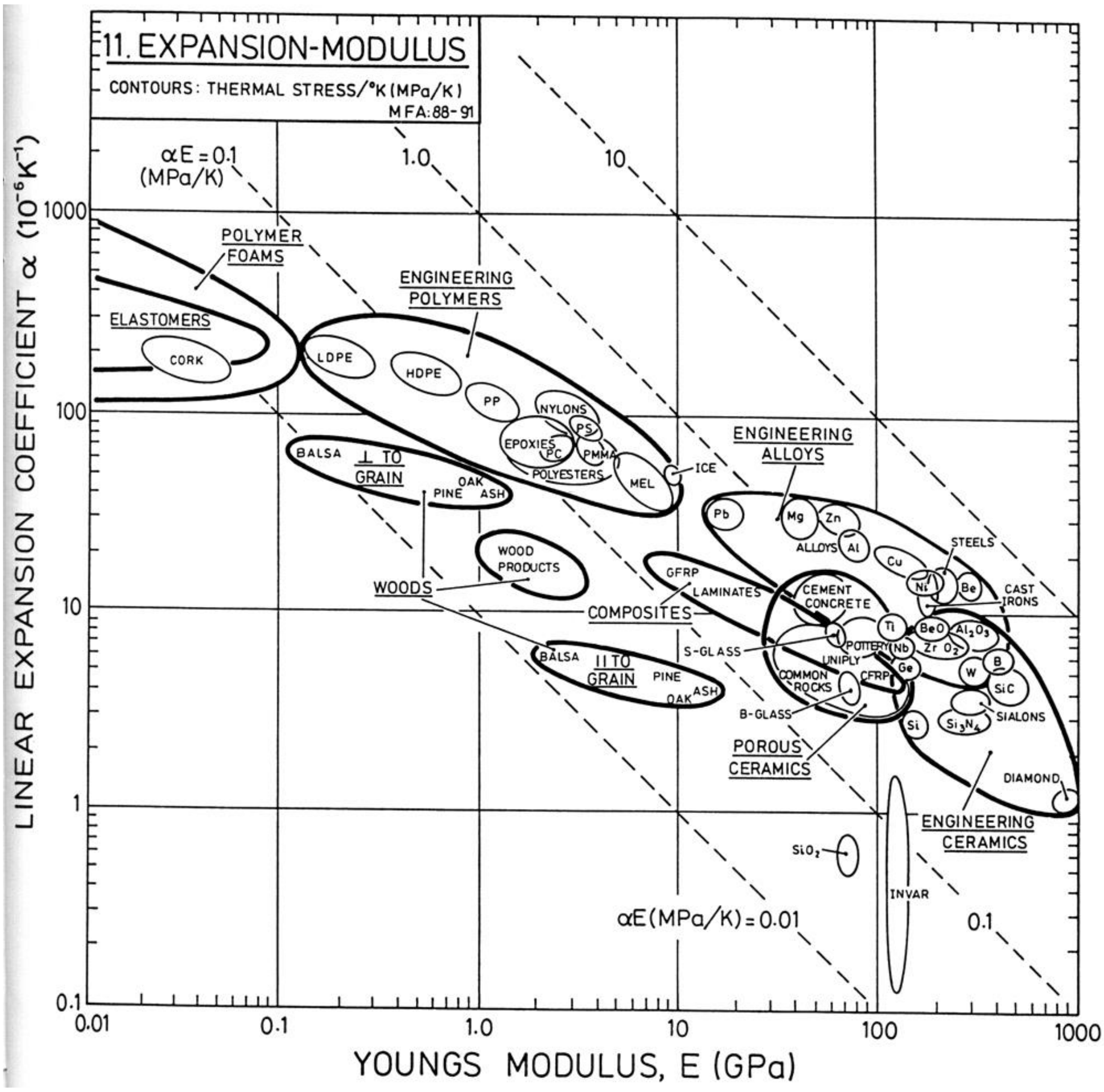
Loss coefficient vs Young's Modulus



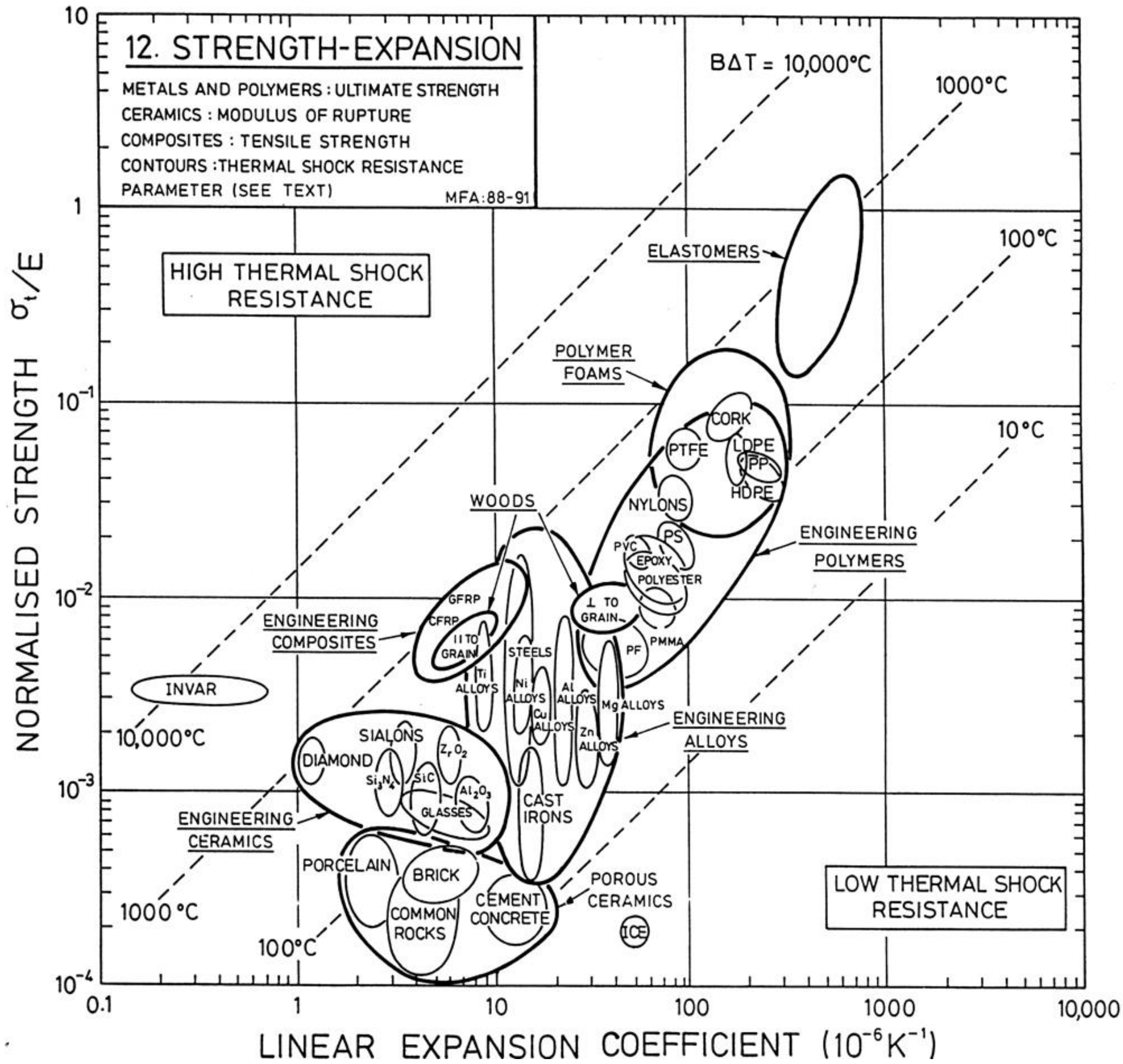
Thermal conductivity vs linear expansion coefficient



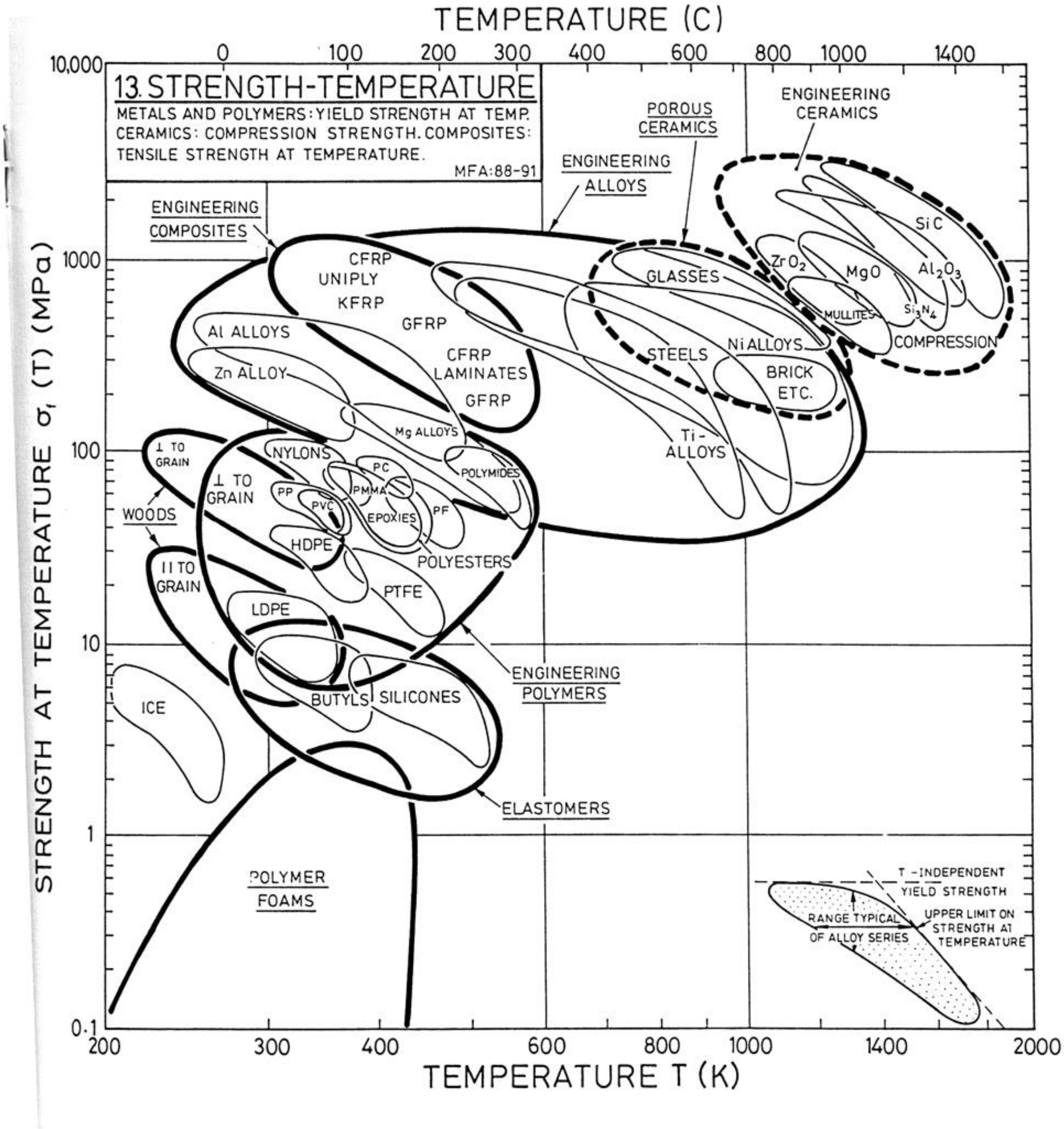
Linear expansion coefficient vs Young's Modulus



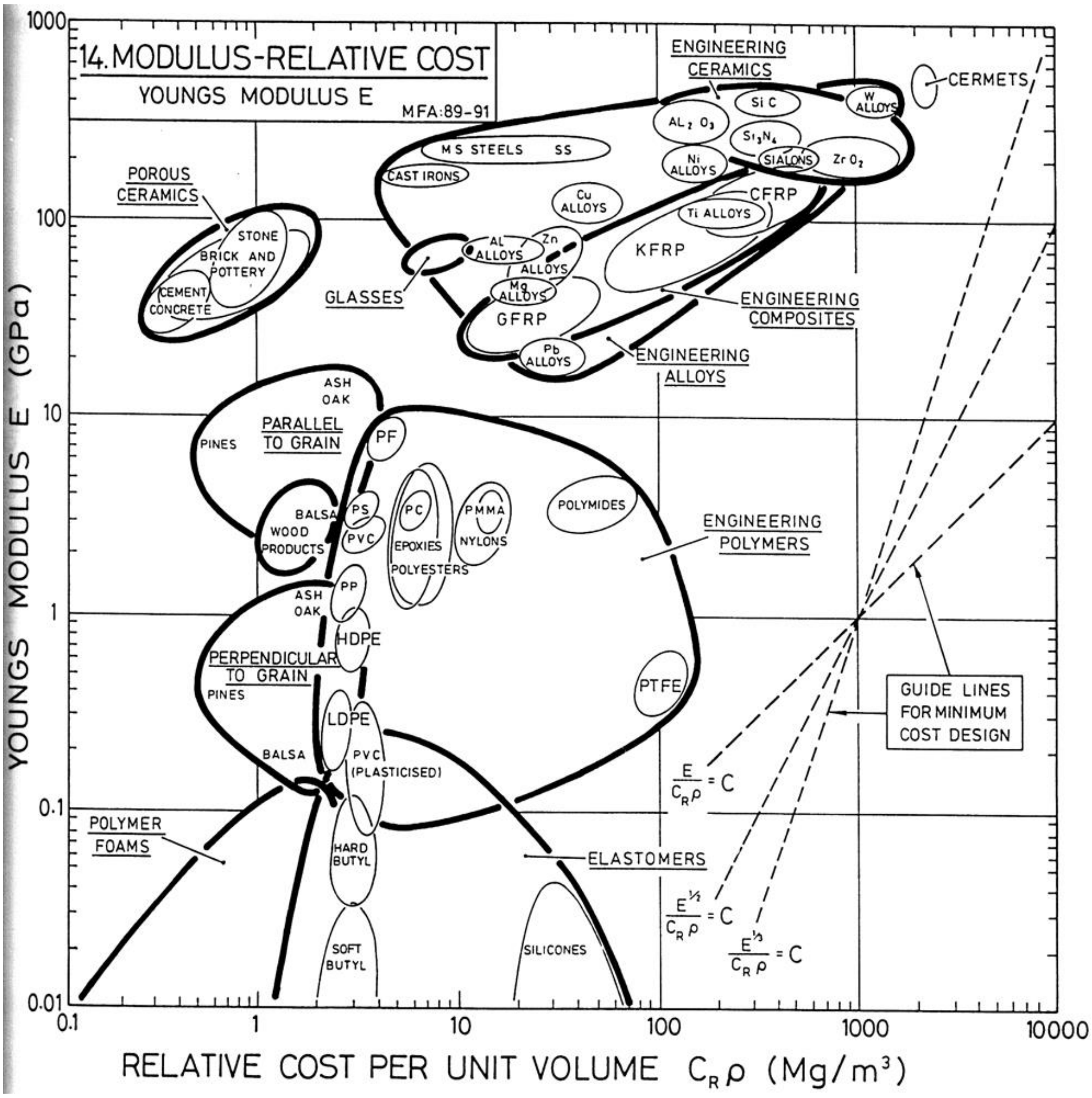
Normalized Strength vs Linear expansion coefficient



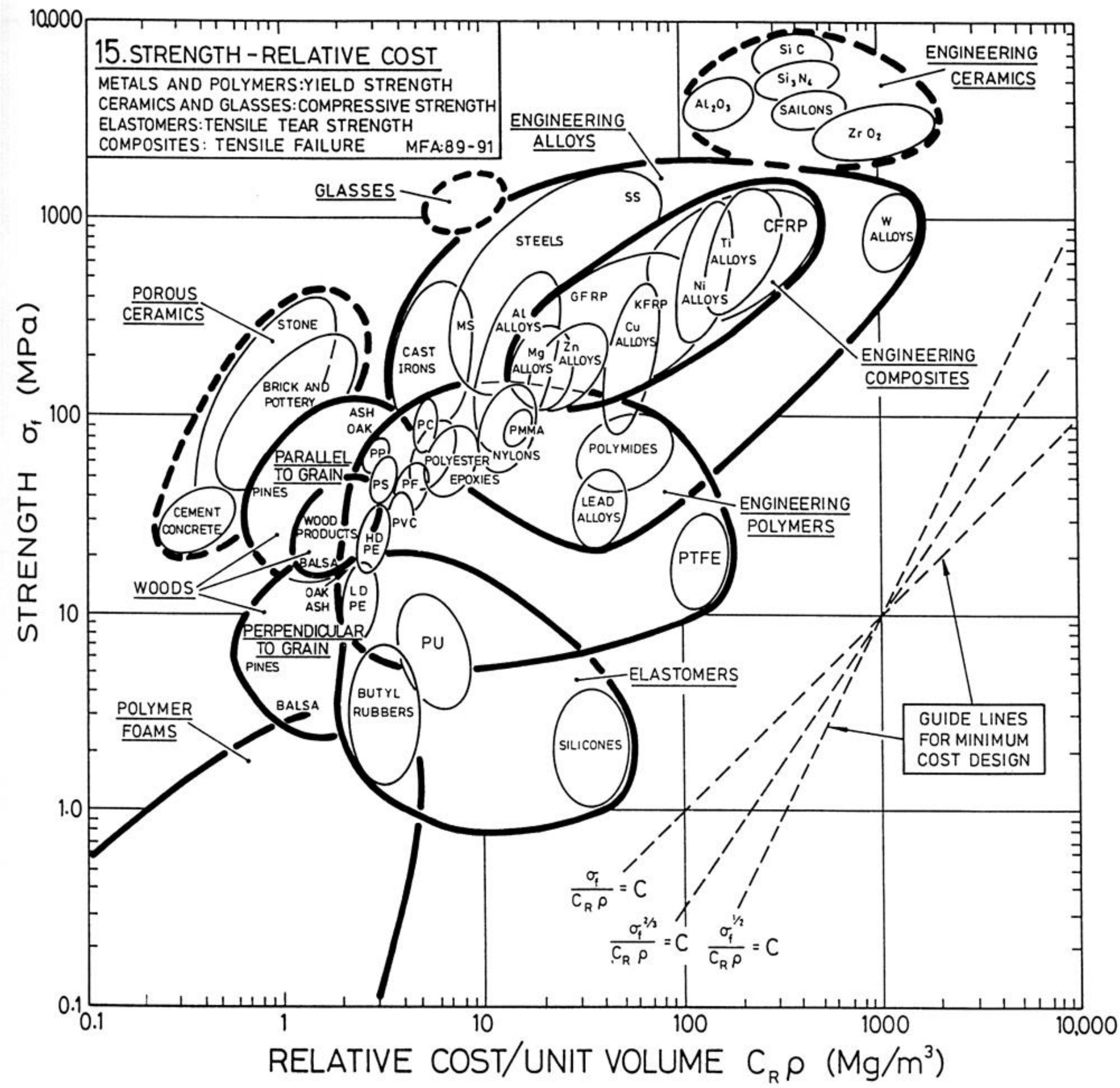
Strength at temperature vs temperature



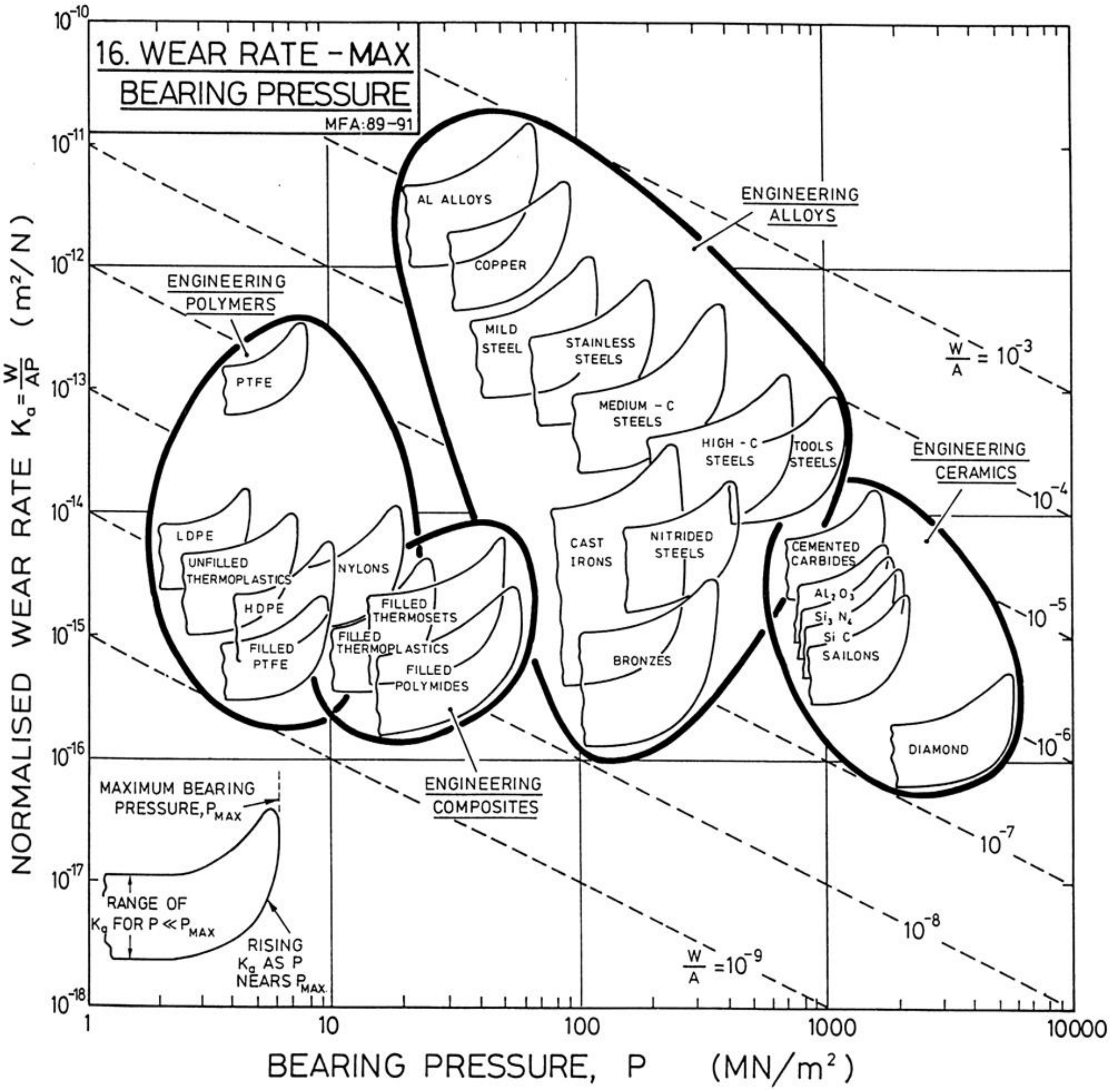
Young's Modulus vs Relative cost per unit volume



Strength vs Relative Cost per unit volume



Normalized wear rate vs bearing pressure



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