METALS FOR SUSTAINABLE MANUFACTURING

Solidification, casting and cast alloys

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Reminders: fabrication of metals

Cast alloys → obtained from the melt (typically brittle/difficult to be worked). Ex. cast irons, some Al alloys

Wrought alloys → shaped using hot or cold working (amenable to mechanical deformation). Ex. steels.

Fabrication methods:

Casting → a totally molten metal is poured into a mold cavity having the desired final shape.

Hot (cold) working → a solid metal is shaped by mechanical plastic deformation applying an external force or stress. Hot working is done at T above recrystallization.

Reminders: casting methods

Sand casting → a two-piece mold is formed by packing sand aroung a pattern that has the shape of the intented casting.

Die casting → a two-piece permanent steel mold is used. The liquid metal is forced into the mold under pressure at relatively high velocity and pressure is maintained during solidification

Investment (or lost-wax) casting → pattern made of wax or plastic (low melting T). Around the pattern the solid mold is formed from a liquid slurry (plaster of Paris). The mold is then heated and the wax is burned out, leaving the mold cavity of the desired shape.

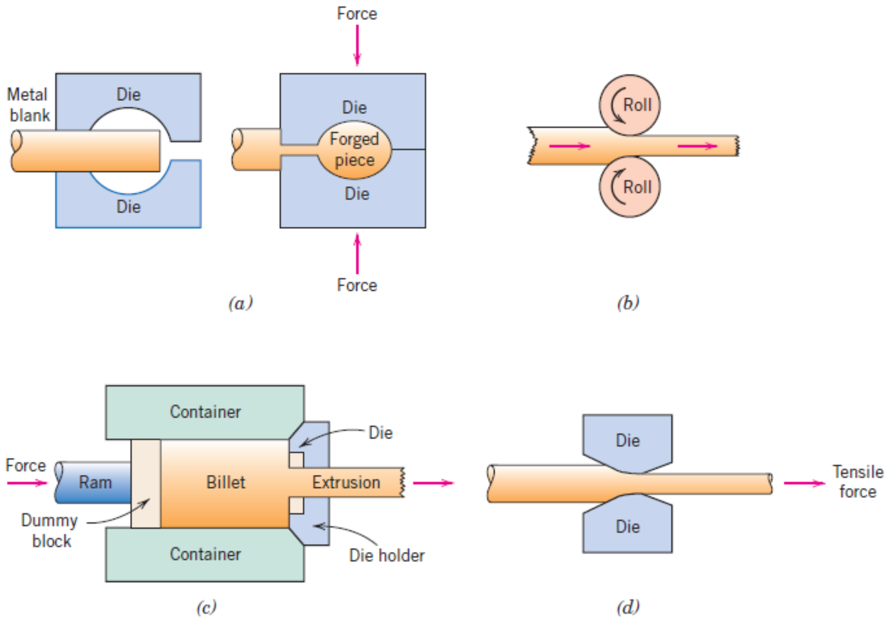
Lost foam casting → similar to investment casting, but a foam of polystyrene is used instead of wax.

Continuous casting → casting + hot rolling

Reminders: hot and cold working methods

a) Forging → a force (successive blows or continuous squeezing) is applied to two or more die halves having the finished shape.

b) Rolling → a piece of metal is passed between two rolls. A reduction of thickness is obtained from the compressive stresses exerted by the rolls. For sheets, strips, foils.



c) Extrusion → a bar of metal is forced through a die orifice by a compressive force. The extruded piece emerges with the desired shape and reduced section. For rods, wires, tubing.

d) Drawing → pulling of a metal piece through a die having the tapered bore by means of a tensile force. For rods, wires, tubing.

Casting: how is undercooling limited?

Nucleation within melt enhanced by ***inoculants*** to get grain refining. Inoculants limit supercooling and the development of dendrites. Inoculants are alloys or compounds added to melt in powder form and °/$_{\circ\circ}$ amount.

Mechanism of inoculation not always known. Examples include:

- local high content of an element (Si from FeSi in cast iron);

- formation of compounds (Al_3Ti from TiB_2 in Al castings);

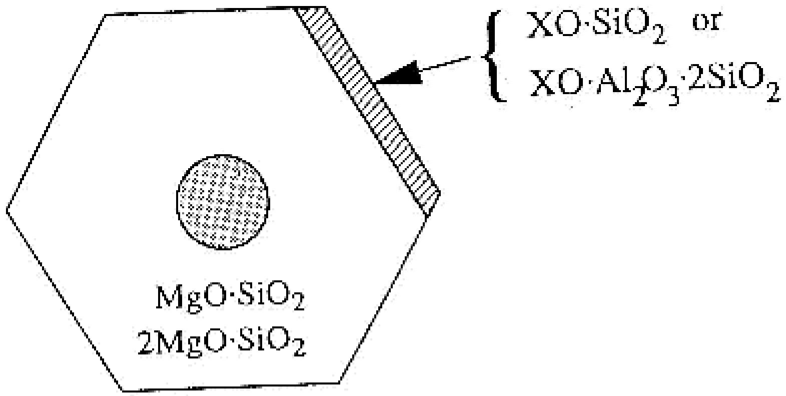
- dispersed solid substrates (e. g. Ru or Ir in cast Au-alloys).

Effectiveness often referred to low interfacial energy with solidifying phase (lattice match) but also chemical reaction, roughness,…

Modifiers

Modifiers are used together with inoculants to modify the shape of graphite crystals. Ex. Mg, Ce. Several mechanisms of nucleation and growth have been proposed and may operate.

An example of mechanism of spheroidization: Mg-silicate particle collects more impurity atoms, graphite nucleates and grows on facetes.



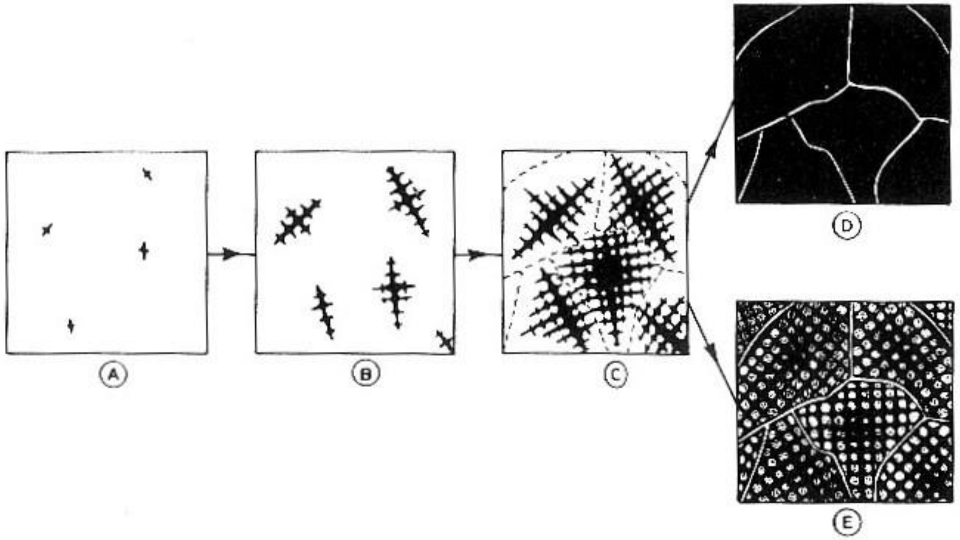
Mg treatment + inoculants
X denotes Ca, Sr, Ba

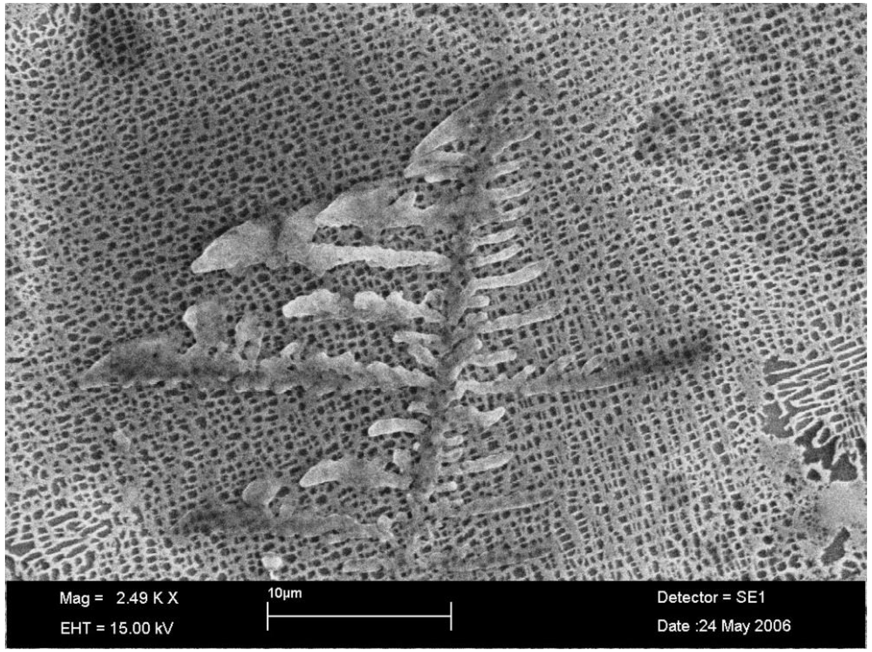
100x

Effects of dentrites

Pure metals: dendrites extend and form grains. They disappear.

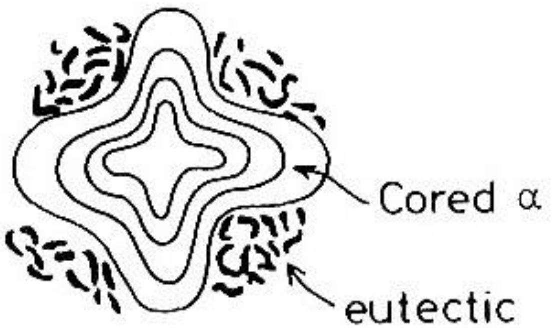
In alloys (including metals with impurities) solutes are segregated in the interdendritic zones which solidify later and at lower T. They are revealed in polished sections by etching.

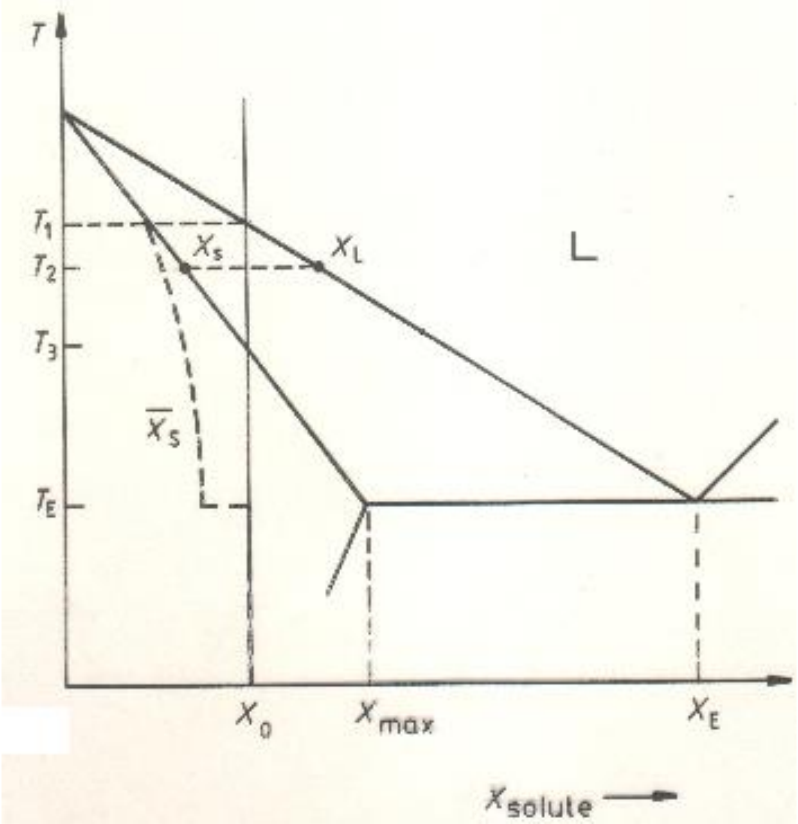




Effects of dentrites

Each dendrite has gradient of solute from the inside out. Nucleus is poor in solute (T_1); successive layers solidify with progressively larger concentration of solute (T_2). No time for homogenization because diffusion in the solid is slow compared to processing times and solute is rejected into melt.



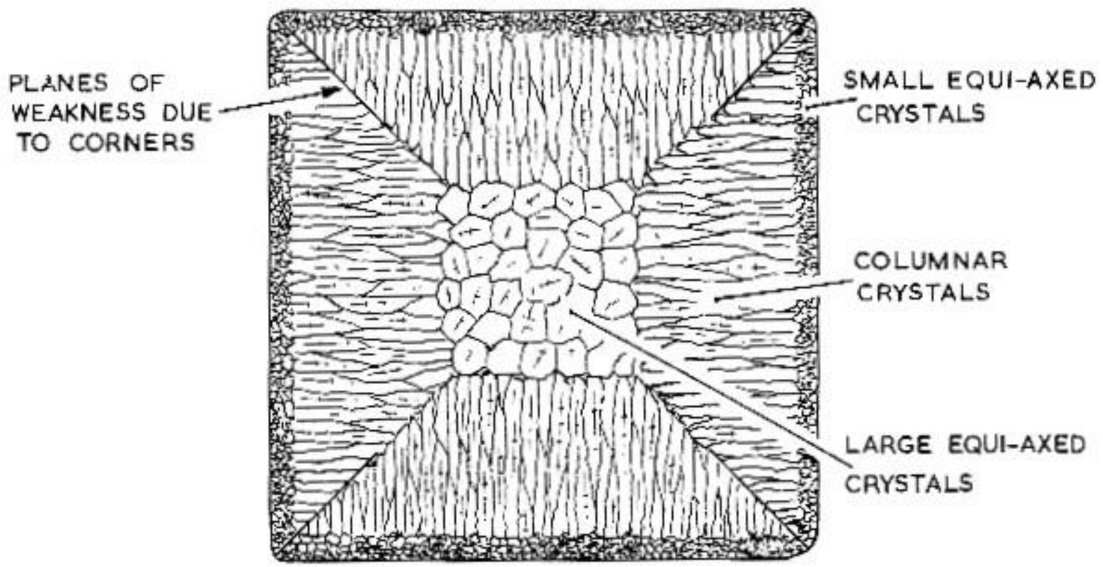


Out of equilibrium microstructures occur: cored primary phase according to Scheil eq. and eutectic.

Ingot solidification

Outer Shell: high frequency of nucleation (fine crystals) due to contact with cold mould. Dendrites then develop: they interact with each other during growth and form columnar crystals (growth of secondary arms disfavoured by the release of latent heat).

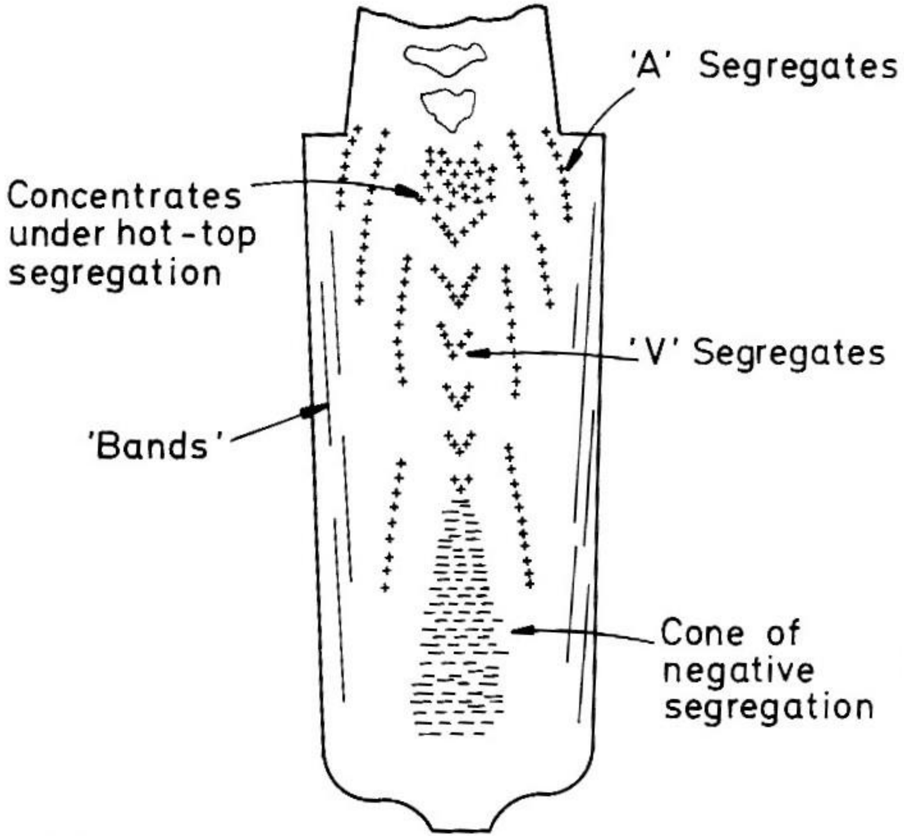
Central part: equiaxic large crystals because of lower nucleation rate and growth on dendrite fragments.



Micro-, macro-segregation and shrinkage

Segregation of solutes between dendrites arms is called ***micro-segregation***. ***Macro-segregation*** occurs on the scale of the ingot due to movement of liquid masses.

It is due to variation in the density of the melt which flows in regions where shrinkage occurs (V), convective motion of liquid, crystals falling by gravity (-). The regions that solidify late will be enriched in solute (+).

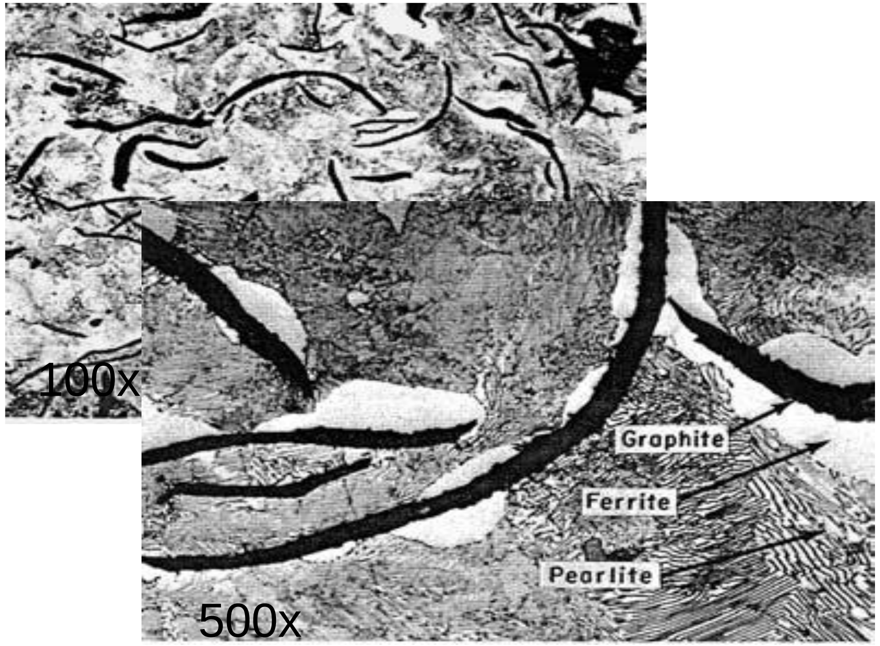


Cast alloys: cast irons

Gray iron → separate graphite flakes in ferrite or pearlite matrix. Good dumping properties.

Nodular/ductile cast iron → Mg(Ce) added to molten iron to spheroidise graphite (e. g. formation of Mg-silicate). Low levels of minor elements such as S and P present. Strong and ductile (similar mech properties of steels).

White iron → cementite in ferrite or pearlite matrix. Low Si content and high cooling rates. Hard and brittle.

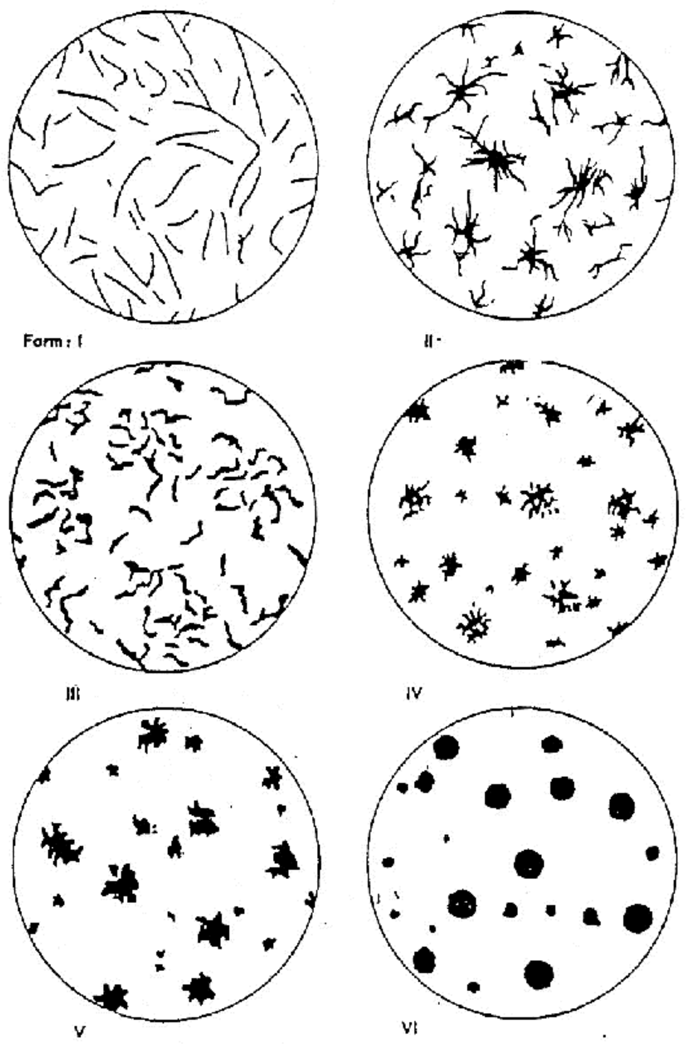


Cast irons

Low amount of modifier (~ 1 °/$_{\circ\circ}$) used to produce ***Compact Graphite Iron*** (CGI) with *vermicular (wormlike) graphite crystals*. Ductile and malleable. Microstructure in between gray and nodular cast iron.

Graphite shapes are conventionally classified as seen in microscopy: *flaky, spiky, vermicular, rosettes, nodules*.

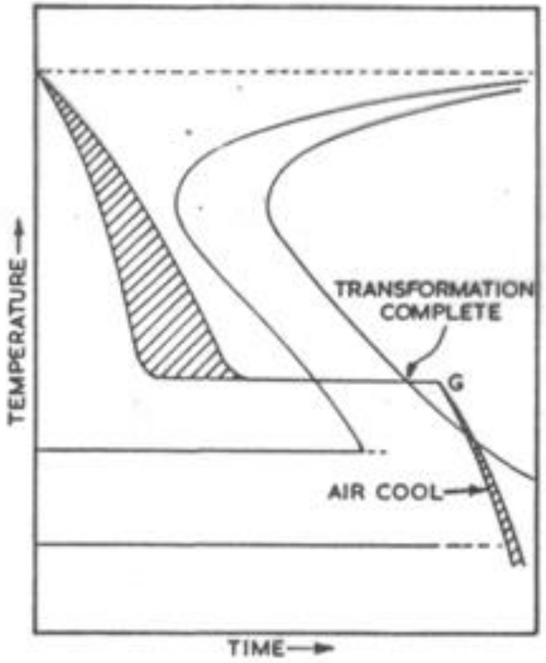
Classification of graphite shapes



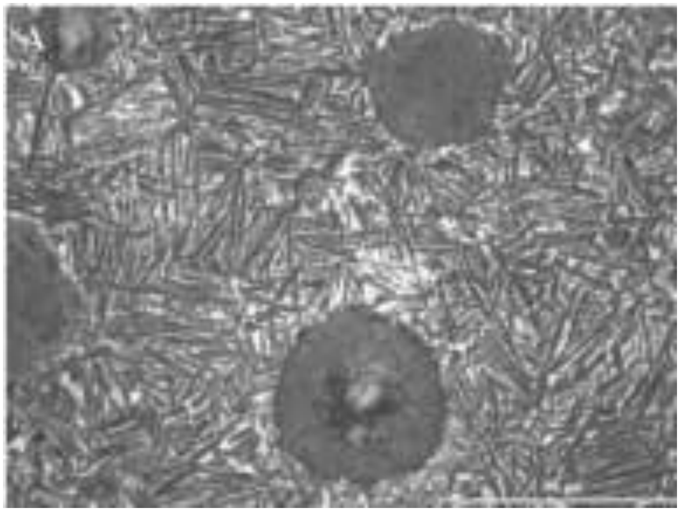
Cast irons: austempered ductile iron (ADI)

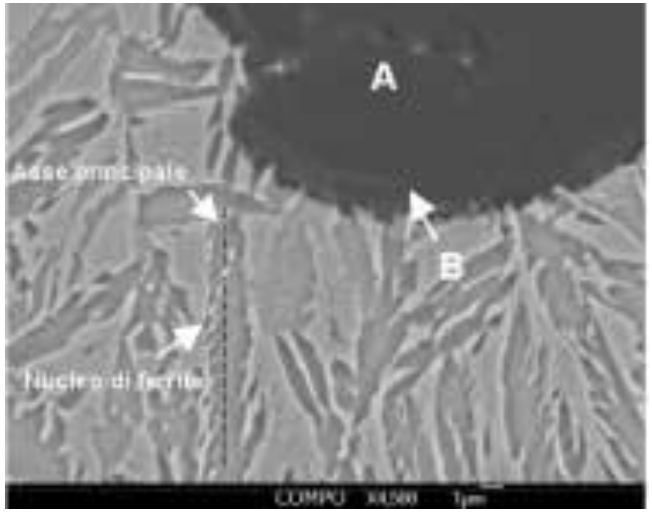
The graphite is spheroidized (A + rim B).

Austenite is transformed above M_s. Acicular bainitic ferrite is formed (arrows). C is rejected into austenite grains. The C-enriched austenite has M_s at low temperature. Austenite is retained.



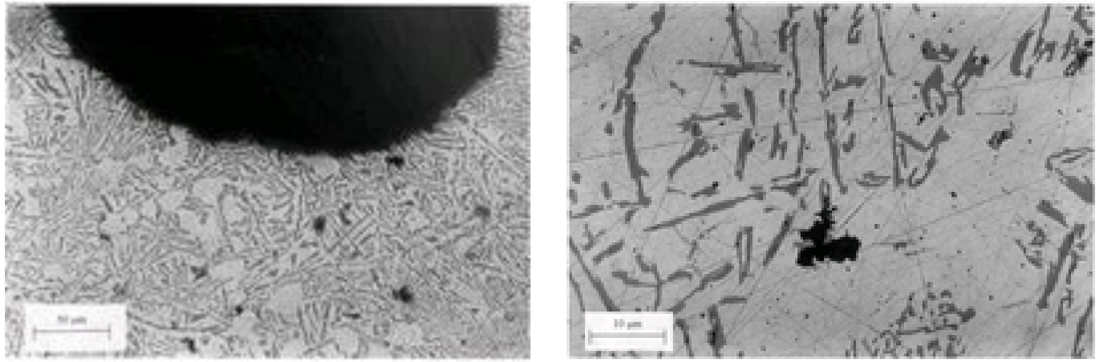
AUSTEMPERING





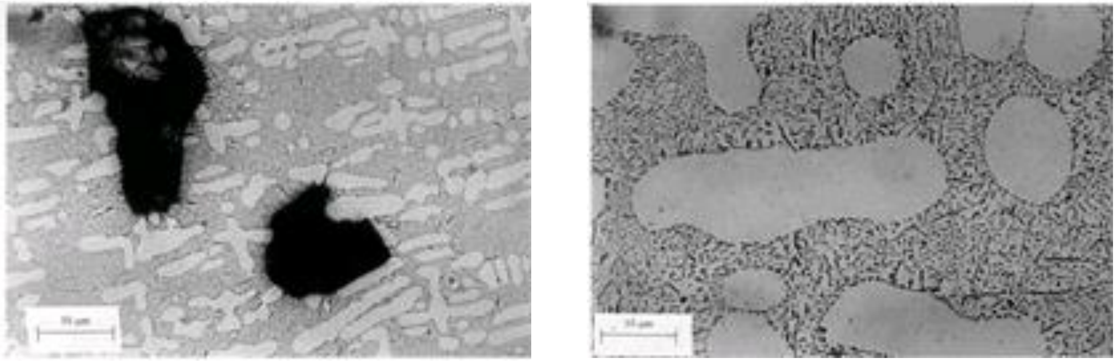
Aluminium alloy castings

The addition of silicon to aluminum reduces melting temperature and improves fluidity



Al-12Si

(plate-like eutectic)

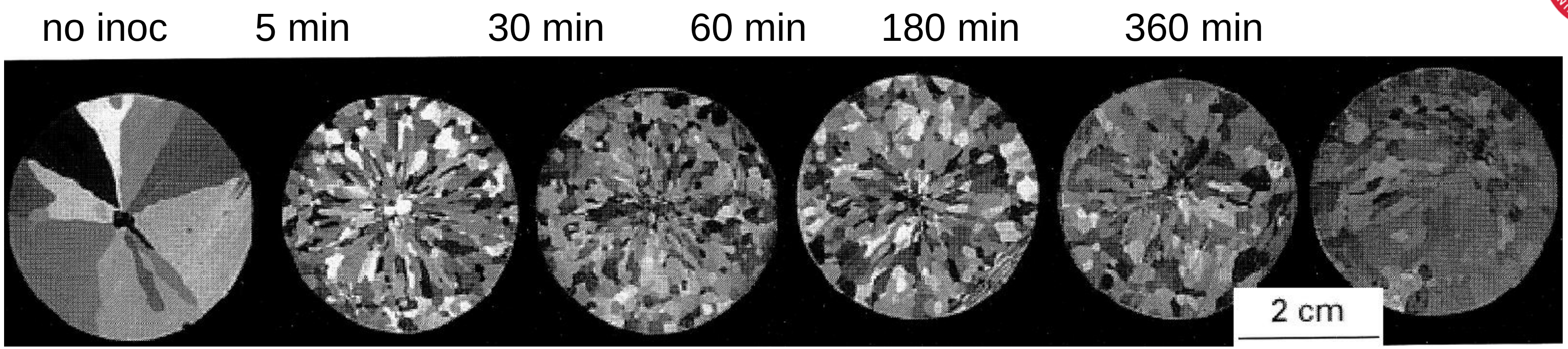


Al-12Si-0.02Na

(finer eutectic microstrucure, fibrous eutectic)

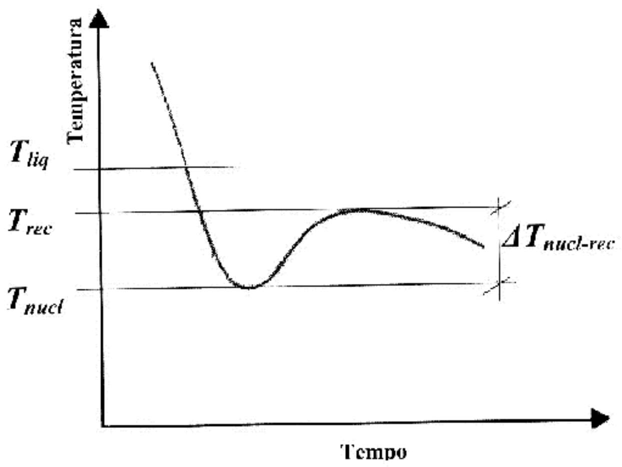
Alloy for engine block: 7-8 Si, 3-4 Cu, 0.25-0.35 Mg, 0.0-0.4 Fe, 0.5 Mn, 0.00-0.25 Ti, 0.25 Zr, trace Sr

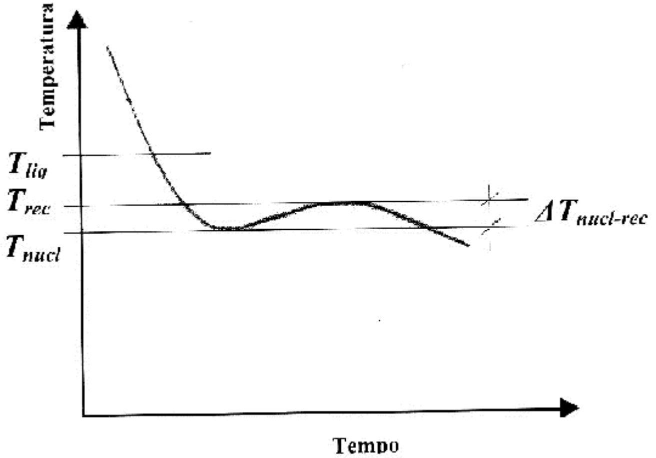
Inoculation of Al with Al-Ti-B



Example of grain size of commercially pure Al for increasing time after inoculation showing grain refining and fading of effect.

Thermal analyses of not inoculated and inoculated Al.





Mechanism of inoculation

Al-Ti-B contains primary Al, Al_3Ti, TiB_2. $\{0001\}$ planes of Al_3Ti have been shown to be active for heterogeneous nucleation of Al. Various hypotheses have been put forward for explanation:

- TiB_2 surrounds Al_3Ti preventing its dissolution in the melt;
- Al_3Ti is entrapped in cavities of TiB_2 particles;
- Al_3Ti is «adsorbed» on faces of TiB_2 particles.

The later seems to explain most the experimental facts concerning refining and fading.

Note that Al-Ti-B not very effective in Al-Si alloys because of formation of Ti-silicides. Al-B inoculant can be used.