Aalto University
School of Engineering

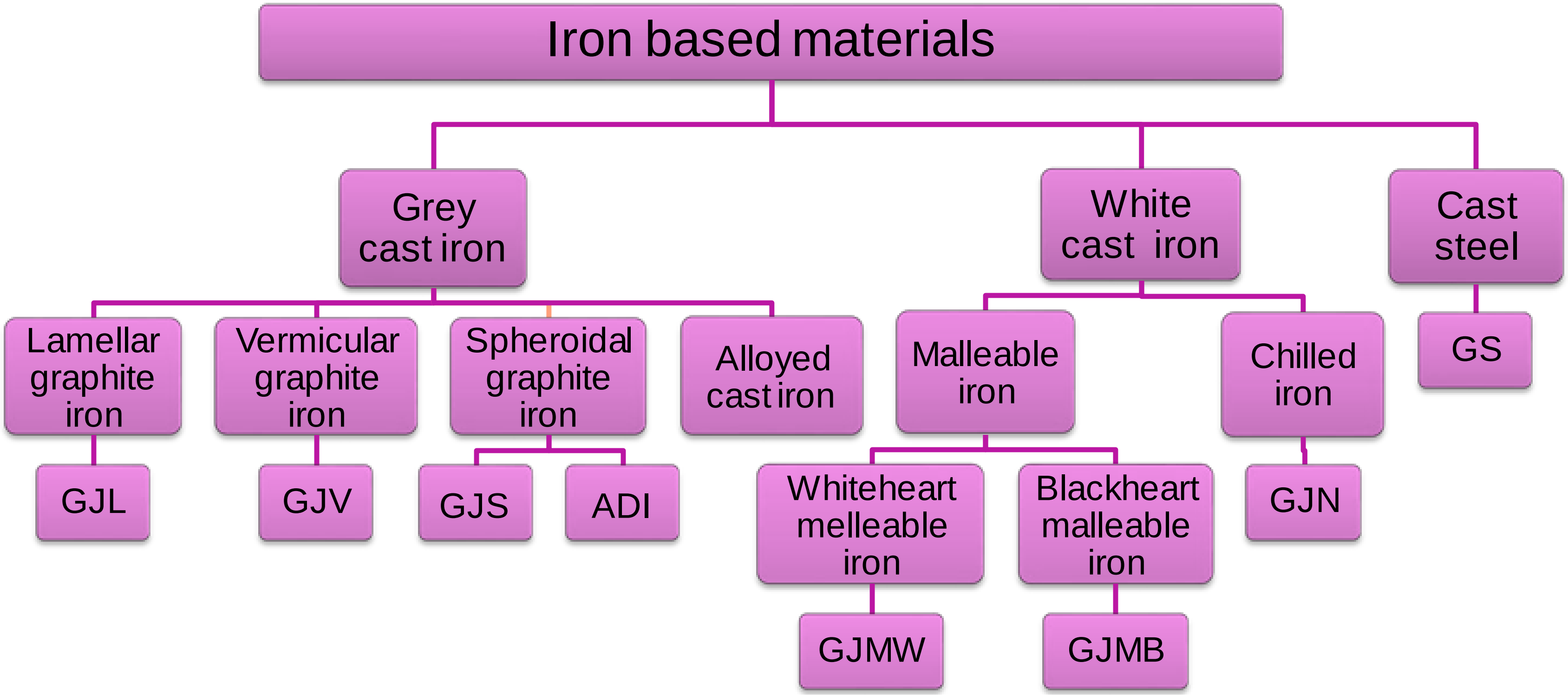
Cast Materials

Prof. Juhani Orkas

Overview

- **Ferrous - Iron based cast materials**
  - Grey iron – Lamellar graphite cast iron
  - Nodular iron – Spheroidal graphite cast iron – Ductile cast iron
  - White cast iron and other alloyed cast irons
  - Cast steels and iron based superalloys
- **Nonferrous cast materials**
  - Aluminium alloys
  - Magnesium alloys
  - Titanium alloys
  - Copper alloys
  - Nickel-base alloys

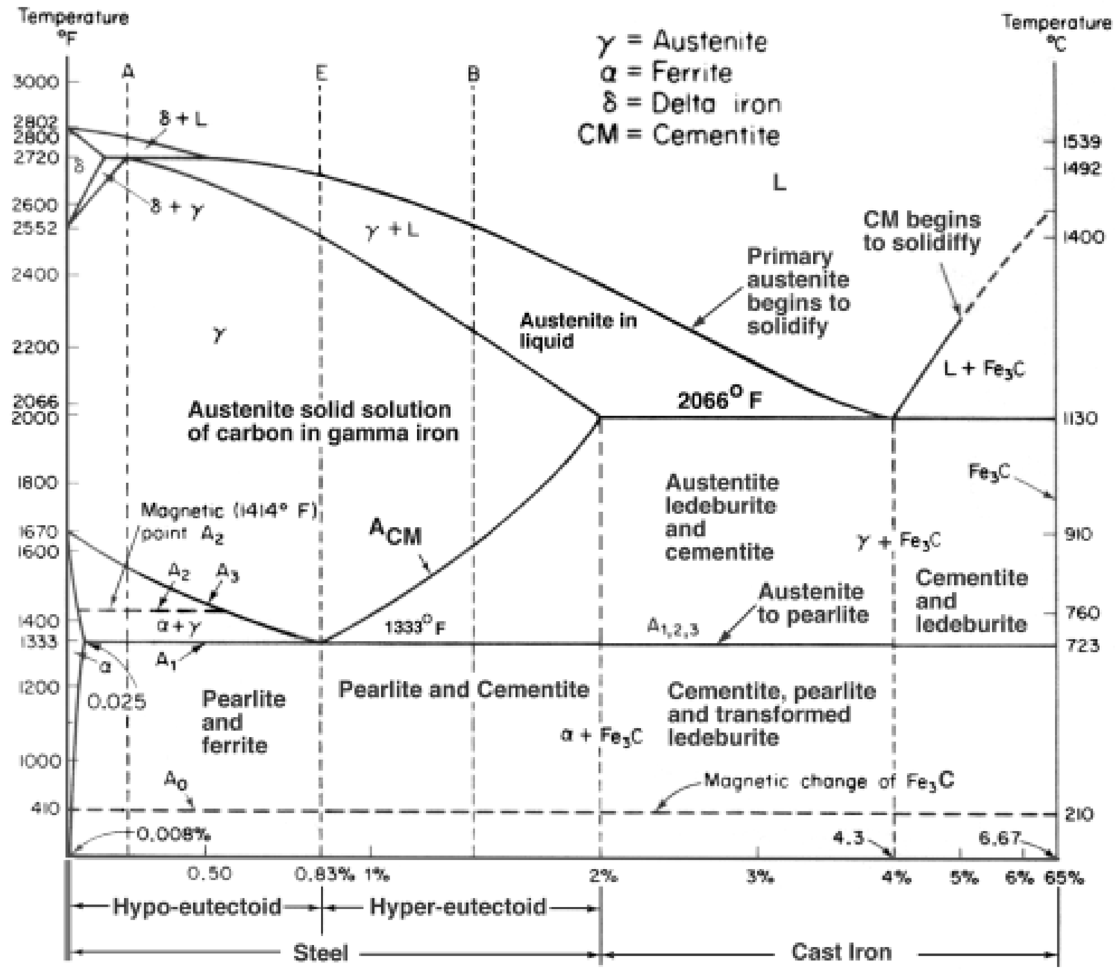
Classification of iron based materials



http://www.hoffmann-group.com/download/de/zhb_2006_2007/teil/web_pdf/053-093.pdf

Iron-carbon phase diagram

- **Cast iron**
  - **C > 2,06 %**
- **Grey cast iron**
  - Stable system
  - Fe-C
  - Iron-graphite
  - Si, Ti, Al
- **White cast iron**
  - Metastable system
  - Fe-Fe_3C
  - Iron-cementite
  - Mn, Cr, Mo

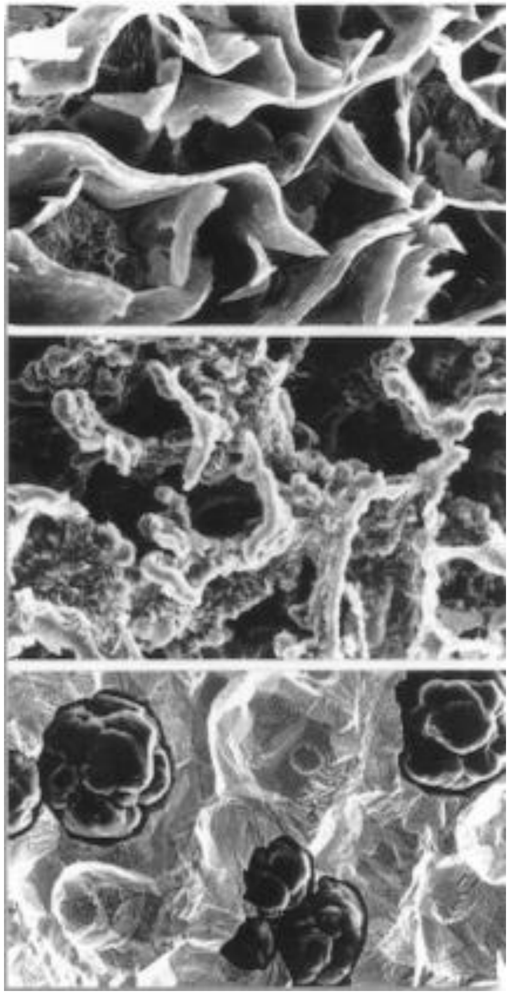


Cast irons

- **Carbon is mostly precipitated as Graphite**
  - Grey color at the fracture surface
- **Silicon**
  - Graphite stabilizing
- **Compressive strength higher than tensile strength (~2:1)**
  - No bond between Iron and Graphite
- **Good machinability**
  - Graphite-matrix interface – interruptions in microstructure
  - Carbon lubricates cutting tools, easing machinability
- **Designation system: GJ(Symbol) - R_m**

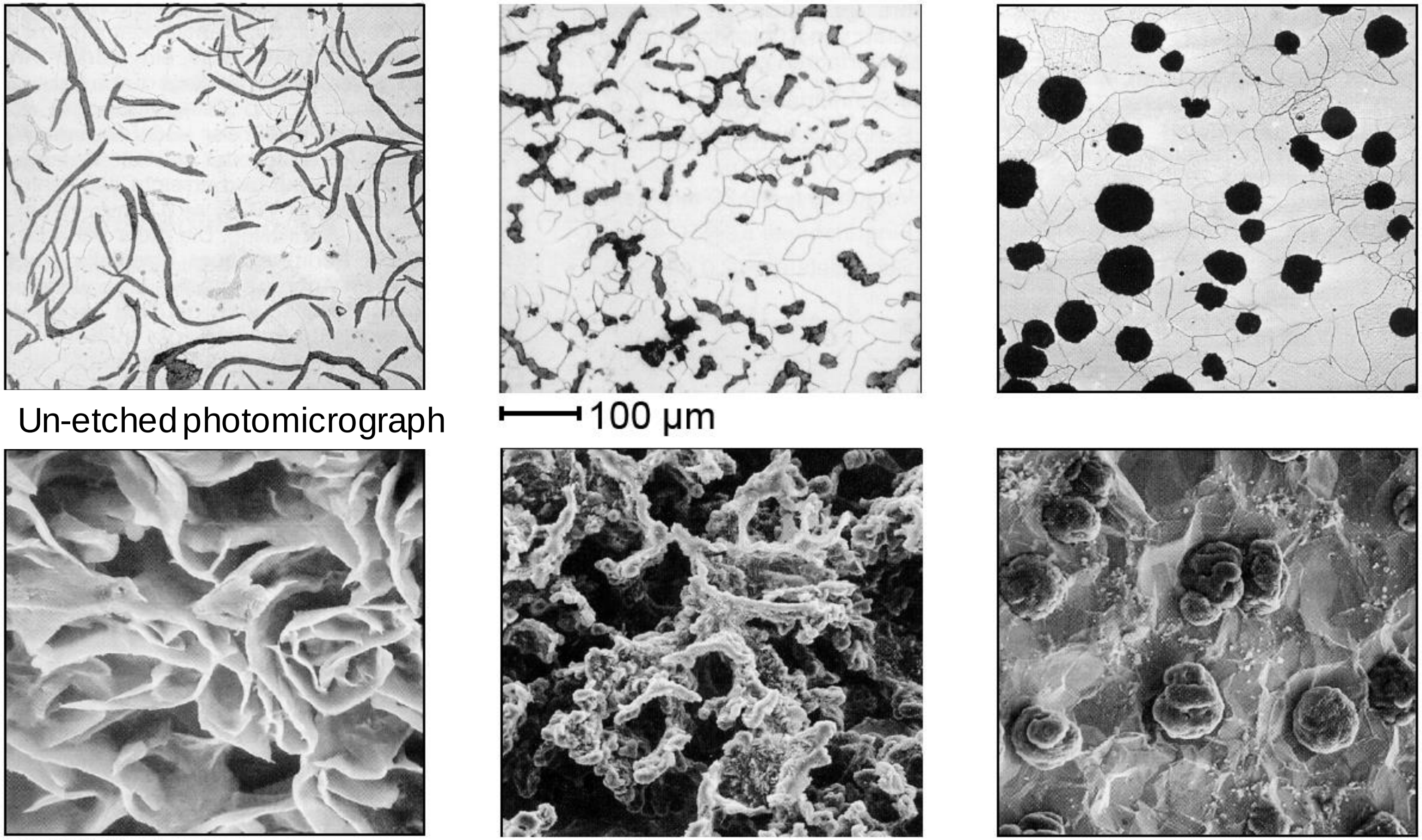
Cast irons - Overview

- **Lamellar graphite iron (GJL)**
  - Pressure and wear-resistant
  - Corrosion-resistant
  - Good damping characteristics
  - Low tensile strength and elongation at fracture
  - Low cost
- **Vermicular graphite iron (GJV)**
  - Between GJL and GJS
  - Low thermal expansion
- **Spheroidal graphite iron (GJS)**
  - Ductile and Nodular
  - High tensile strength and elongation at fracture



Wikipedia: Datei:GGV-GGG.jpg

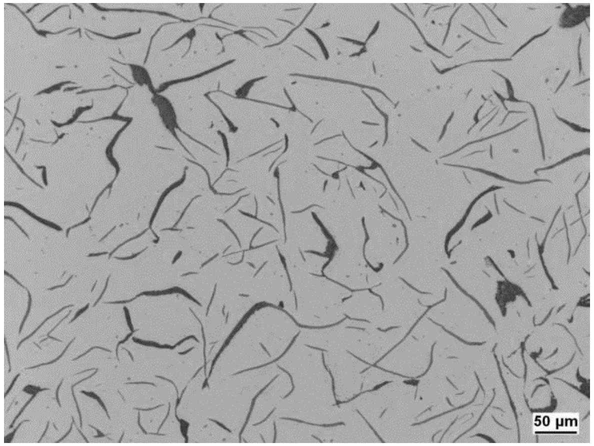
Cast irons - Overview



Quelle: CLAAS GUSS

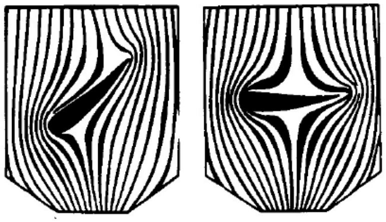
http://mciron.mw.tu-dresden.de/lut/vorlesung/script_ft1/FT1%20VL%20%202%20Gu%C3%9Ftechnik.pdf

Lamellar graphite iron - GJL



EN GJL-250

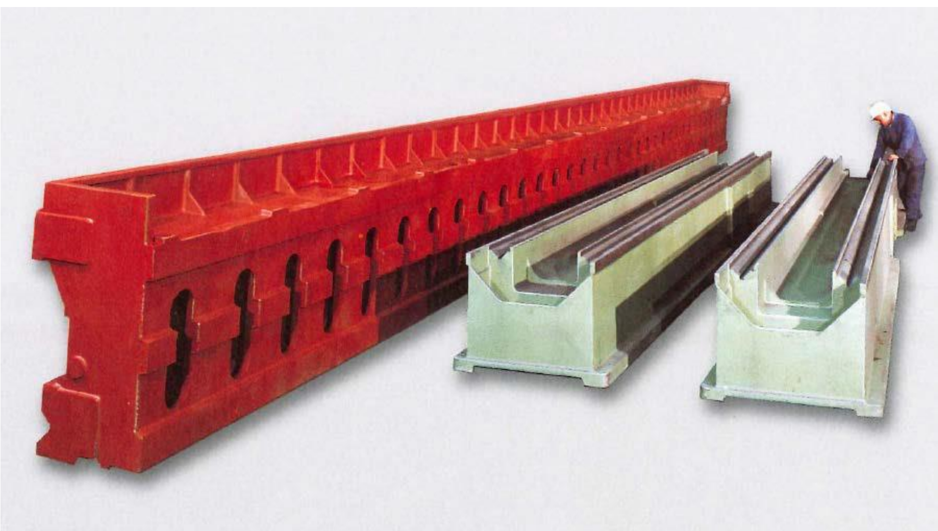
- **Ferritic-pearlitic microstructure**
  - $R_m \leq 400$ MPa
  - Poor toughness
  - Good compressive strength
- **Cooling conditions affects microstructure**
  - Tensile strength depends on wall-thickness
  - Higher strength in thin walls
- **Very good damping capacity (Vibration)**
  - GJL : GJS : Steel 1 : 1,8 : 4,3
- **Notch-sensitive**
  - High tension gradient at graphite flakes
- **Good frictional properties**
- **Very good melt fluidity**

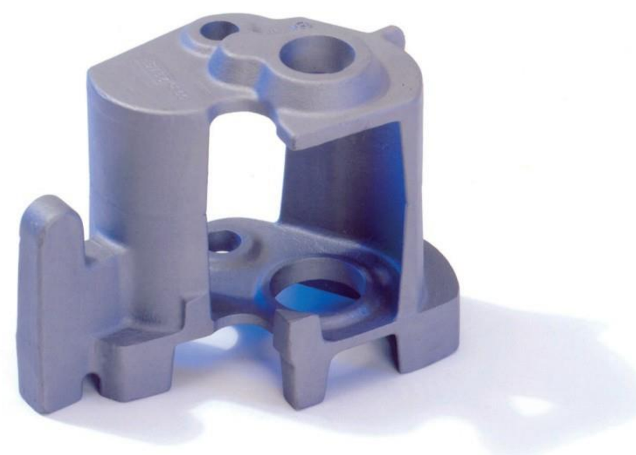


http://www.htw-aalen.de/gta/de/eisenguss/eisenguss.htm

Lamellar graphite iron - GJL

- Bed for machine tools
  - EN GJL-250 /-300
  - Up to 12,8 m
- Gearbox for a printing machine
  - EN GJL-250

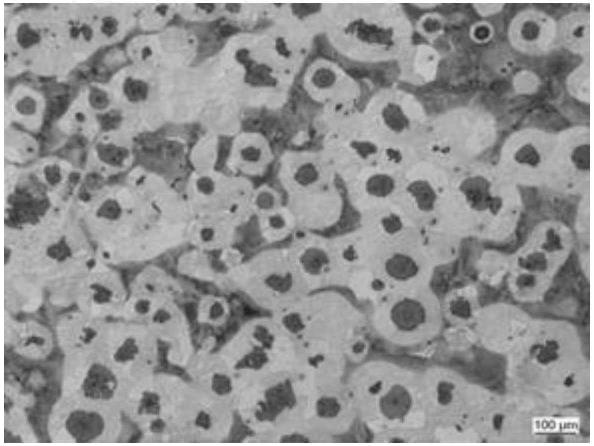




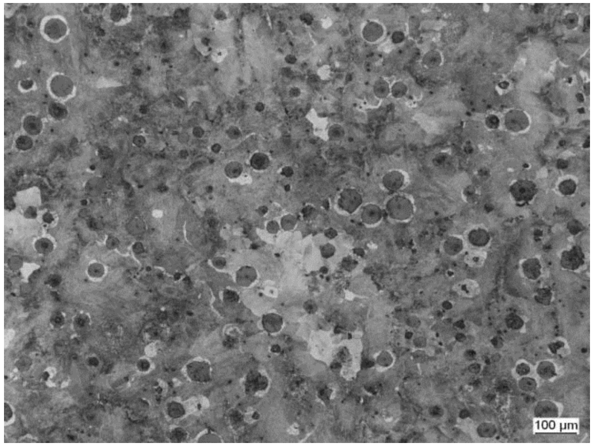
www.claasguss.de/pdf/psst_ant_5_2007.pdf

Spheroidal graphite iron - GJS

- **Add magnesium or cerium**
  - Spheroidal graphite
- **Ferritic-pearlitic structure**
  - $R_m \leq 800$ MPa
  - Moderate toughness
- **Less Notch-sensitive than GJL**
  - Average tension gradient at graphite spheres
- **Moderate damping capacity**
- **For mechanically stressed parts**



EN GJS-500

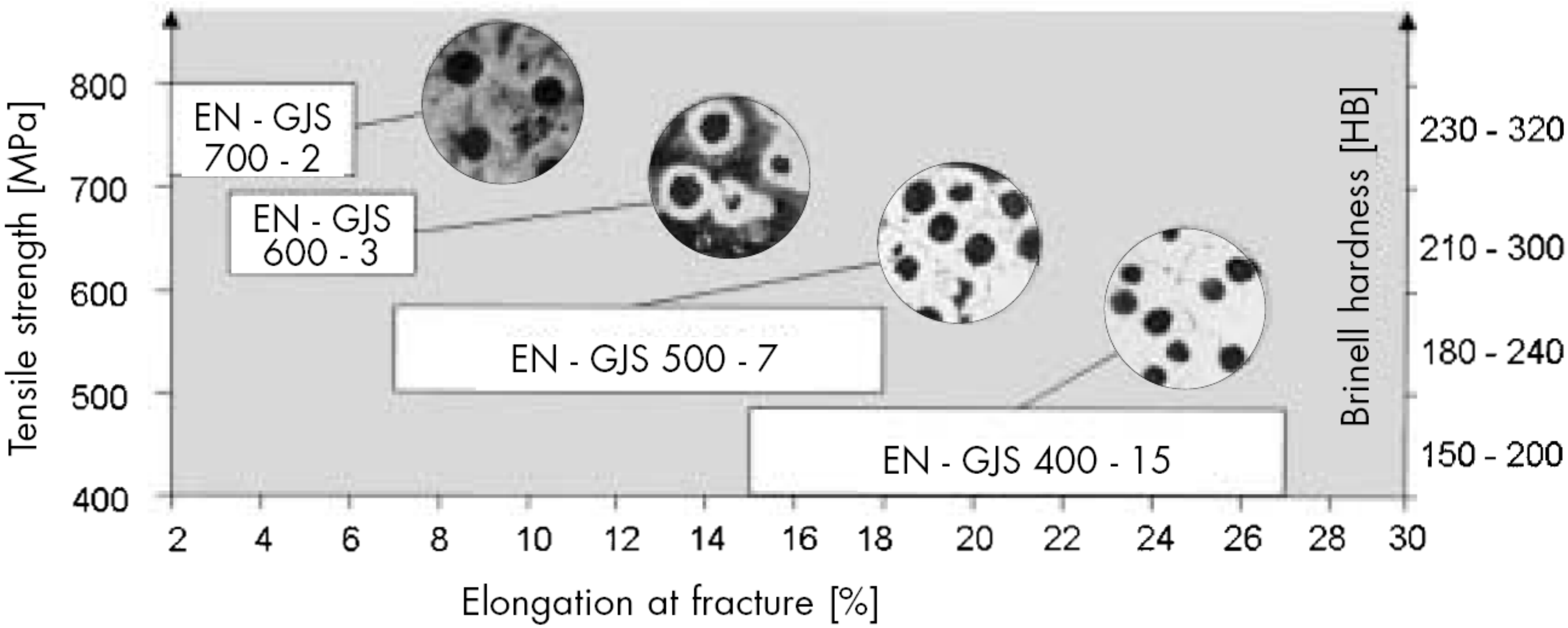


EN GJS-700

http://www.htw-aalen.de/gta/de/eisenguss/eisenguss.htm

Spheroidal graphite iron - GJS

- **High C- and Si-level**
  - Low strength and Brinell hardness
  - High elongation at fracture



http://www.claasguss.de/html_e/pdf/THBl2_engl.pdf

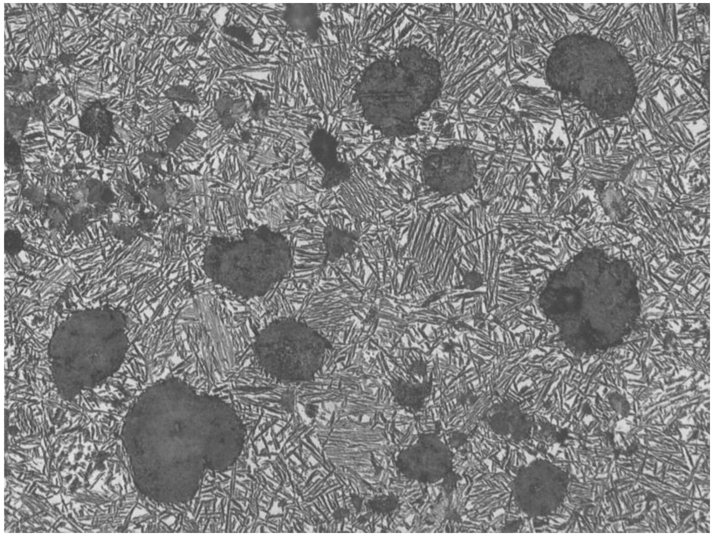
Spheroidal graphite iron - GJS

- **Cylinder block for marine diesel engine**
  - EN GJS-400-18U
  - 9 x 2.84 x 3.35 m
  - 81‘450 kg
- **Rotor hub (1.5MW)**
  - EN GJS-400-18U-LT
  - 3.128 x 2.7 x 2.1 m
  - 8’400 kg

http://www.fwh.de/produkte.html

Austempered ductile iron - ADI

- **Multi-step heat treatment of GJS**
- **Ausferritic structure**
  - Acicular ferrite and carbon-enriched austenite (without carbide precipitation!)
  - R_m up to 1500-1600 MPa
  - 'Steely' characteristics
- **Very good wear resistance**
  - Even greater with added hard carbides (CADI)
- **Lower specific weight than steel (~10%)**
  - Comparable mechanical properties



ADI 800/ EN GJS-800-8

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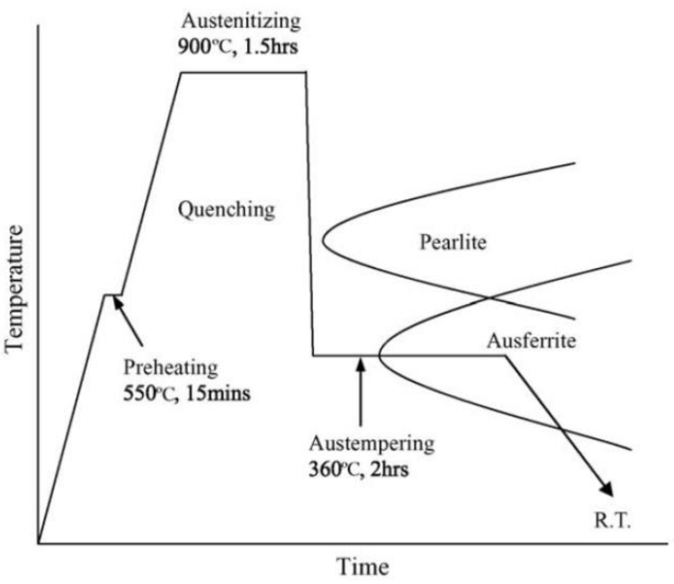
http://schonlau-werke.de/en/manufacturing-products/materials/austempered-ductile-iron
http://www.claasguss.de/html_e/html/produkt_02_05.html

Multi-step heat treatment - ADI

- **Austenizing**
  - Heating above AC1 temperature (840 – 950 ° C)
  - Completely austenitic microstructure
- **Quenching**
  - Avoiding formation of perlite
- **Austempering**
  - Salt / oil bath or furnace (250 – 450° C)
  - Isothermal transformation
  - Ferrite needles and austenite (Ausferrite)
  - Too short holding time
    - *Metastable residual austenite*
  - Too long holding time
    - *Bainite formation (ferrite with carbide precipitation)*



http://www.claasguss.de/html_e/pdf/THBl8_engl.pdf

Austempered ductile iron ADI

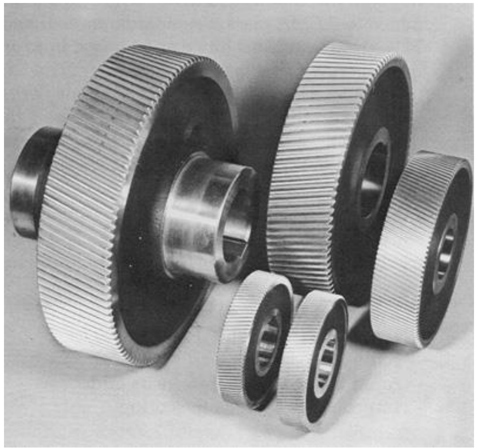
ADI crankshaft

- TVR sportscars

304.8 mm (12 in)

ADI gears

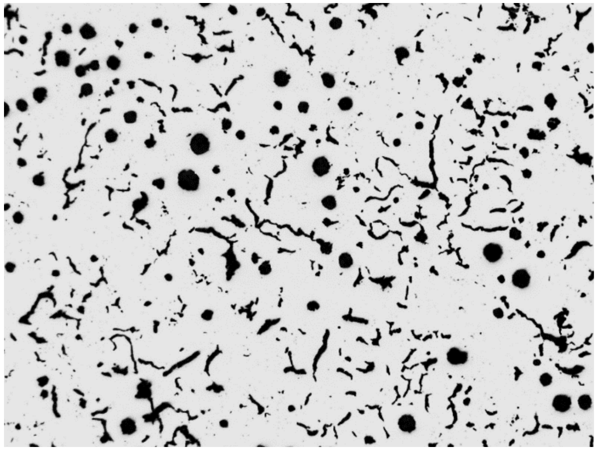
- Kymi Kymmene Engineering, Finland



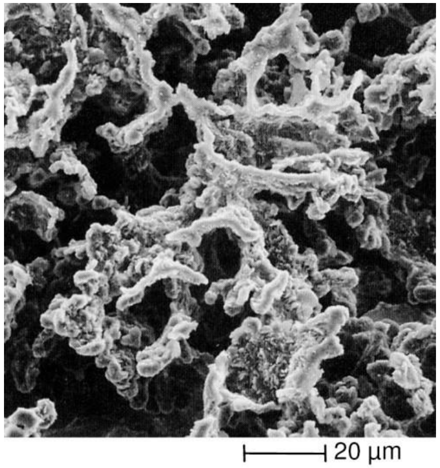
http://www.htw-aalen.de/gta/de/eisenguss/eisenguss.htm
http://www.ductile.org/didata/section4/4intro.htm

Vermicular graphite iron GJV

- **Deliberately insufficent treatment to spheroidize graphite**
  - Three-dimensional "worms"
- **Properties between GJL and GJS**
- **Ferritic-pearlitic structure**
  - $R_m \leq 600$ MPa
- **Especially suitable for thermally and mechanically stressed parts**



EN GJV-400



http://www.claasguss.de/html_e/pdf/THBl12_engl.pdf

Vermicular graphite iron - GJV

- **Advantages vs. GJL**
  - Better tensile strength and elongation at fracture
  - Higher fracture toughness
  - Properties are less dependent on wall thickness

- **Advantages vs. GJS**
  - Lower coefficient of thermal expansion
  - Higher thermal conductivity
  - Lower modulus of elasticity
  - Better thermal shock resistance and lower tendency of distortion
  - Better damping capacity
  - Better fluidity

http://www.claasguss.de/html_e/pdf/THBl12_engl.pdf

Vermicular graphite iron GJV

Audi V12 TDI crankcase

- EN GJV-450
- 500PS / 1‘000 Nm
- More rigid and fatigue-resistant
  - Thinner walls and less weigh

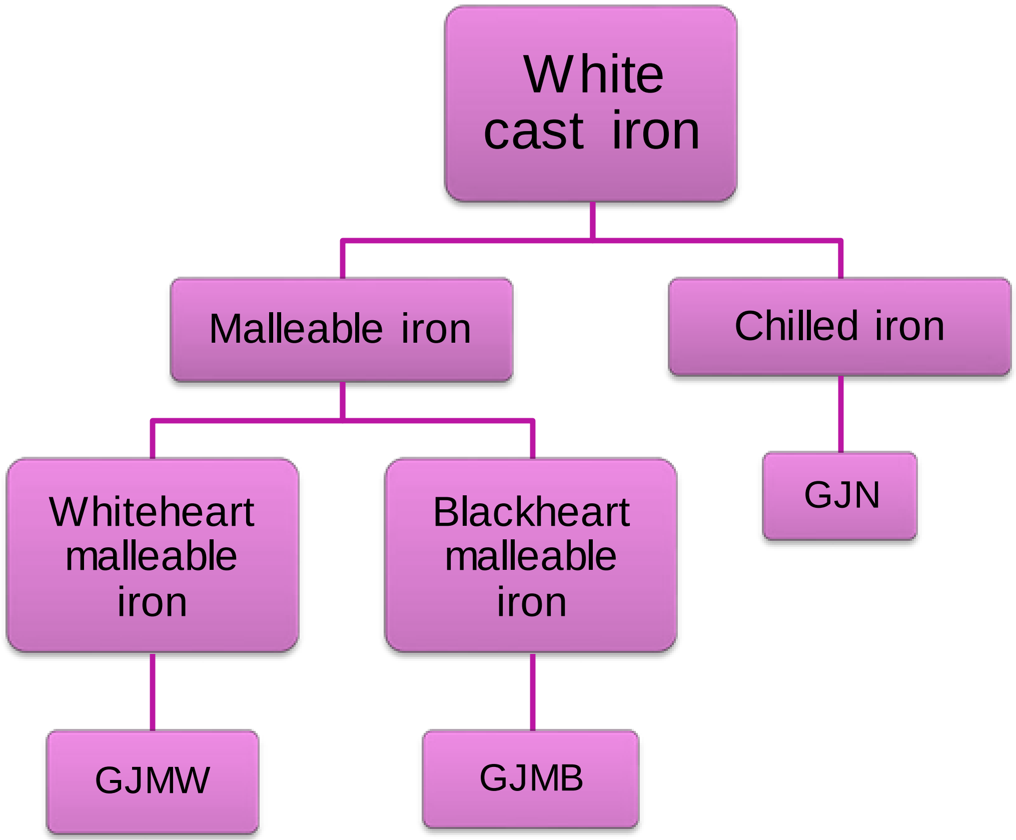
MAN TG-A cylinder block

- EN GJV-450
- 430 PS

http://www.claasguss.de/html_e/pdf/THBl12_engl.pdf
http://trucks.autoreview.ru/new_site/trucks/archives/2004/n03/4_man/1.htm

Google Books: Gefüge Der Gusseisenlegierungen

White cast iron



White cast iron

x

- **Carbide stabilizing elements (Mn, S)**
  - Graphite-free solidification
    - Fe_3C
  - Pearlite and ledeburite (hypoeutectic)
  - White color at the fracture surface
  - Hard and brittle
    - Less applications, but great wear resistance
- **Intermediate product in steel production**
  - Heat treatment of malleable iron
    - Cementite decomposition - tempered carbon (equiaxed nodular graphite)
    - Tempered carbon has less interfaces with microstructure
      - Better mechanical properties

Google Books: Gefüge Der Gusseisenlegierungen

Cast steel - GS

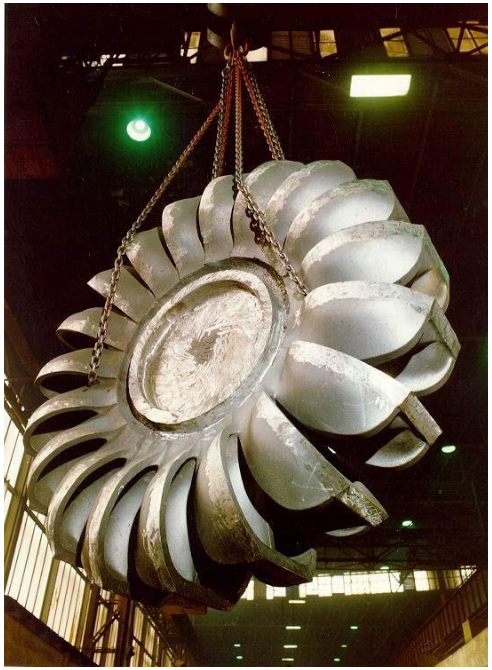
- **Advantages**
  - Better mechanical properties available through various heat treatments
  - Malleable
  - Weldable
  - Corrosion resistance
  - Wide range of materials
  - Adjustable strength properties
- **Disadvantages**
  - Higher melting point > 1400° C
    - *High demands on technology*
  - Bad mould-filling capacity
    - *More viscous than cast iron*
      - **hypoeutectic**
  - High shrinkage factor ~2%
  - Castings without heat treatment wholly unusable
    - *Brittle in as-cast form*
    - *Coarse grain structure*
    - *Dendritic*

http://www.maschinenbau-wissen.de/skript/werkstofftechnik/stahl-eisen/31-stahlguss

Cast steel - GS

Pelton wheel

– High strength

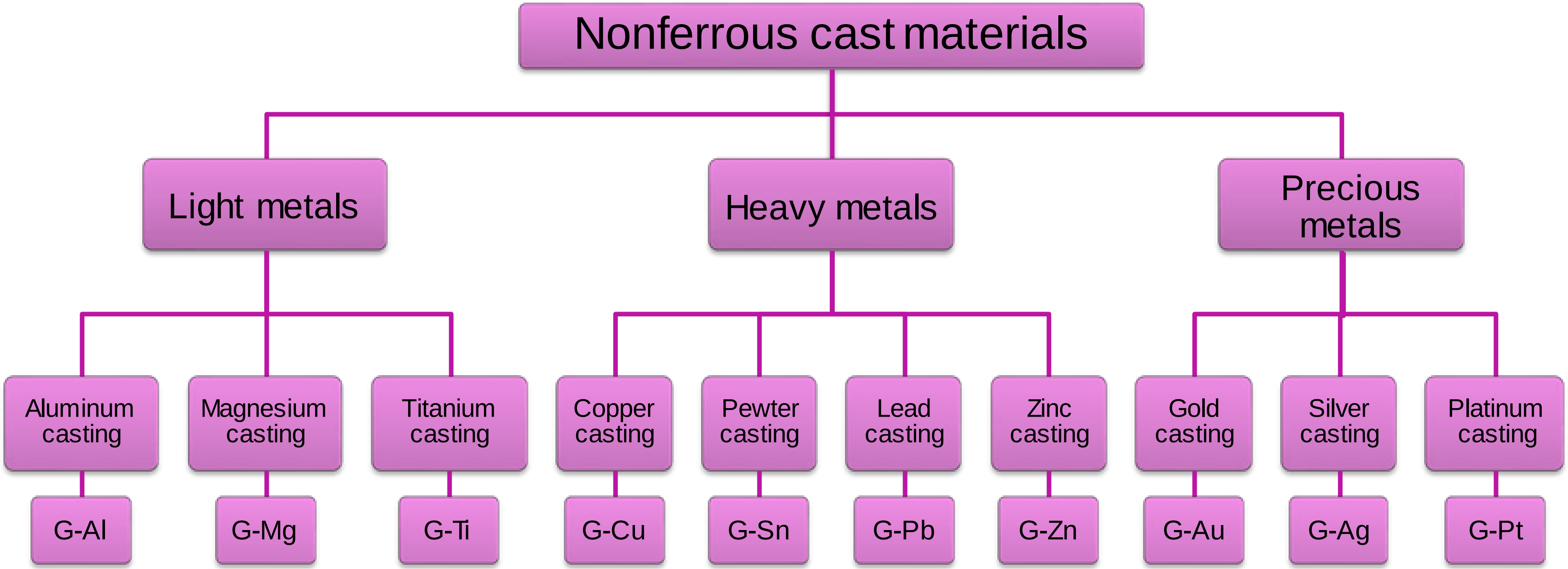


Shunting switch

– G-X120Mn12

http://www.voestalpine.com/giesserei_traisen/de/products/foundry_products.html

Classification of nonferrous cast materials



http://www.hoffmann-group.com/download/de/zhb_2006_2007/teil/web_pdf/053-093.pdf

Aluminium alloys

- **Suitable for complex thin-walled parts**
- **High dimensional accuracy**
- **Low weight with high rigidity**
  - Good strength-weight ratio
- **Smooth surfaces and edges**
- **Good machinability**
- **High thermal conductivity**
- **Good electrical conductivity**
- **Corrosion and weathering resistance**
- **Several surface treatments possible**

http://www.openpr.de/news/278394/Aluminiumguss-verdraengt-herkoemmlichen-Grau-und-Stahlguss.html

Aluminium alloys – designation system

Aluminium Alloy Designation System (CEN)

		Major alloying element	Atoms in solution	Work hardening	Precipitation hardening	
WROUGHT ALLOYS*) EN AW-	1XXX	None (min. 99.00% Al)		X		Non-heat treatable alloys
	3XXX	Mn	X	X		
	4XXX	Si	X	X		
	5XXX	Mg	X	X		
	2XXX	Cu	X	(X)	X	Heat treatable alloys
	6XXX	Mg + Si	X	(X)	X	
	7XXX	Zn	X	(X)	X	
	8XXX	Other	X	(X)	X	

CASTING ALLOYS*) EN AB- EN AC- EN AM-	1XXX0	None (min. 99.00% Al)
	2XXX0	Cu
	4XXX0	Si
	5XXX0	Mg
	7XXX0	Zn
	8XXX0	Sn
	9XXX0	Master Alloys

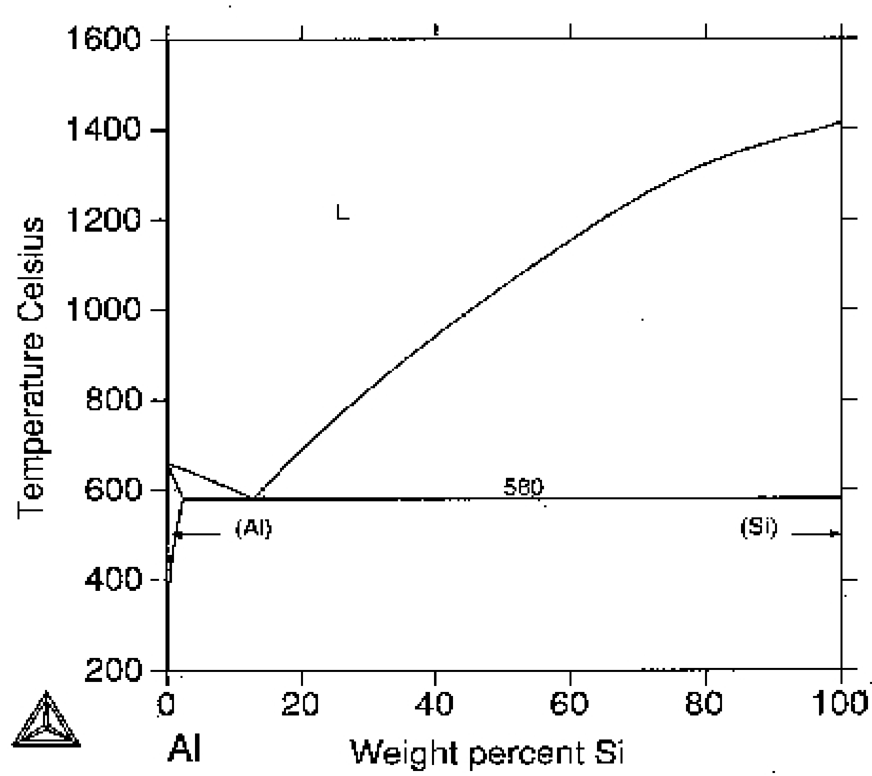
*) letters preceding the alloy numbers have the following meaning

EN = European Standard
A = Aluminium
B = Ingot
C = Cast Alloy
M = Master Alloy
W = Wrought Alloy

http://www.eaa.net/eaa/education/TALAT/lectures/1501.pdf

Aluminium alloys

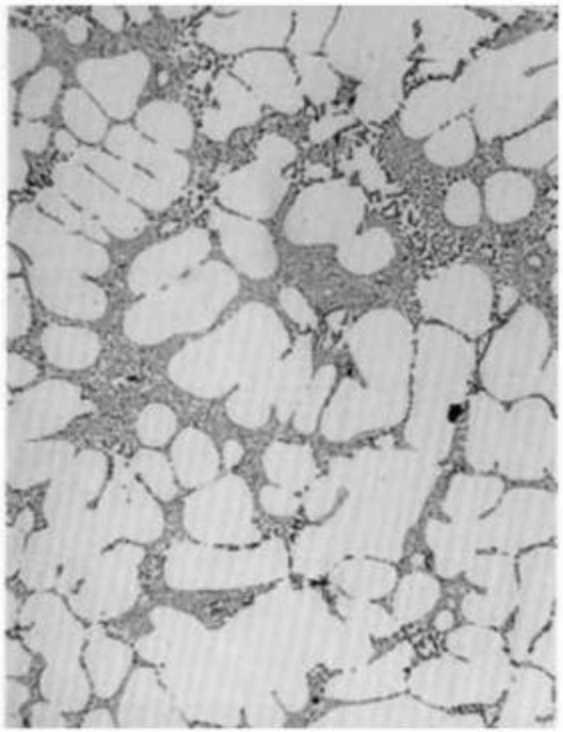
- **Al Si (4xxx)**
  - Near eutectic (12% Si)
    - *Low melting point (576° C)*
    - *Good fluidity*
    - *Less shrinkage*
    - *High strength*
  - Hypereutectoid (up to 25% Si)
    - *Used as piston alloys*
    - *Worse fluidity*
    - *Primary solidification of Si*
    - *Higher wear resistance due to precipitated Si crystals*
    - *Lower coefficient of expansion*

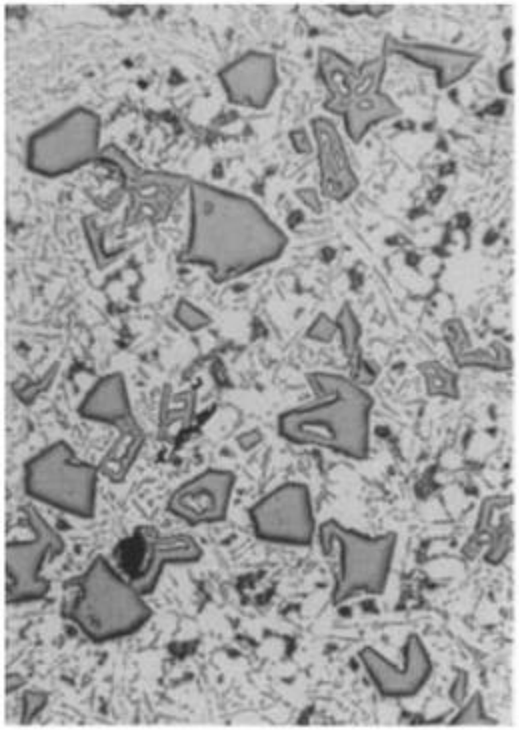


http://www.hoffmann-group.com/download/de/zhb_2006_2007/teil/web_pdf/053-093.pdf
http://www.msm.cam.ac.uk/phase-trans/abstracts/M7-8.html

Aluminium alloys

Hypoeutectic | Eutectic | Hypereutectic





http://mciron.mw.tu-dresden.de/lut/vorlesung/script_ft1/FT1%20VL%20%202%20Gu%C3%9Ftechnik.pdf

Aluminium alloys

Daimler valve body

- AlSi9Cu3
- Wall-thickness: 2-6mm
- Drafts: 1° (valve core 5°)

BMW integral cross member

- EN AC - AlMg5Si2Mn
- Weldable without pre-treatment

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http://www.alumag.de/downloads/Innovation%20durch%20Aluminiumguss,%20KSM.pdf http://www.dynacast.com/casting/magnesium/

Magnesium alloys

- **Lightest of all structural metals**
  - **~ 1800 kg/m³**
  - Excellent strength-weight ratio
- **Hexagonal lattice**
  - High strength
  - High electrical and thermal conductivity
  - Without Al and Zn
    - *Brittle*
    - *Notch-sensitive*
- **Excellent machinability**
- **Good damping coefficient**
  - Better vibration reduction than Al or GJx

Magnesium alloys

- **Al and Zn**
  - Avoid problems with brittleness and notch-sensitivity
- **Mg**
  - Increases corrosion resistance
- **Ce and Th**
  - Increases high temperature strength
- **Zr**
  - Grain refinement
  - Increases strength and formability

Roos, Maile: Werkstoffkunde für Ingenieure

Magnesium alloys – designation system

- Two letters for the major alloying elements
- Two digits for the approximate percentage of the elements
- Possible letter for the different alloy modifications
- Example: AZ91C
  - Approx. 9% Al; approx. 1% Zn; 3rd modification

Letter	Alloying Element
A	Aluminum
B	Bismuth
C	Copper
D	Cadmium
E	Rare earth
F	Iron
H	Thorium
K	Zirconium
L	Beryllium
M	Manganese
N	Nickel
P	Lead
Q	Silver
R	Chromium
S	Silicon
T	Tin
Z	Zinc

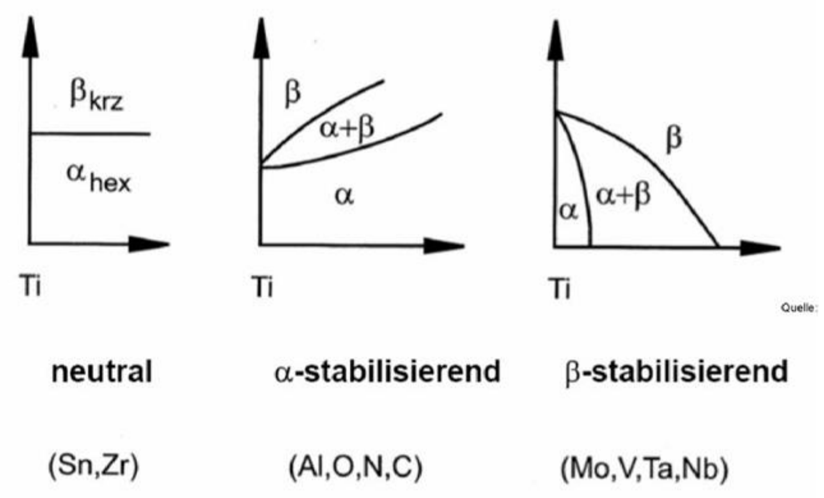
http://www.arcraftplasma.com/welding/weldingdata/metalstd.htm

Titanium alloys

- **Very high tensile strength and toughness**
  - even at extreme temperatures
- **Light weight**
- **Properties depending on phase**
  - α phase
  - α+β phase
  - β phase
- **Extreme corrosion resistance**
  - Very dense TiO_2 layer
  - Biocompatibility
- **Expensive**

Titanium alloys

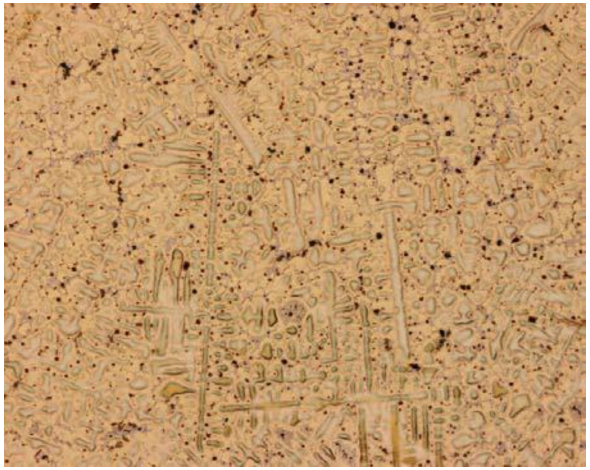
- **α phase**
  - Good fracture toughness
  - Good creep resistance
  - Not heat-treatable
- **α+β phase**
  - High mechanical strength
    - *Up to 1000 MPa*
  - Heat-treatable
  - Ti6Al4V (50% of world usage)
- **β phase**
  - Heat-treatable
  - Very high strength
    - *up to 1400 MPa*



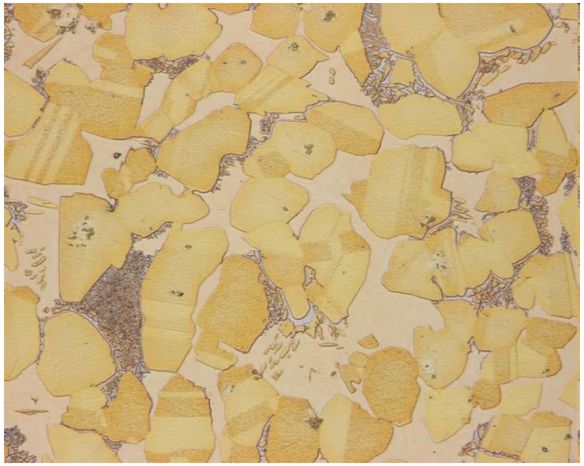
http://www.substech.com/dokuwiki/doku.php?id=classification_of_titanium_alloys

Copper alloys

- **Properties**
  - Corrosion resistance
  - Good bearing qualities
  - Attractive appearance
- **Bronze**
  - CuSn
- **Brass**
  - CuZn
- **Red brass (gunmetal)**
  - CuZnSn
- **Aluminium bronze**
  - CuAl



CuSn11 (50:1)



CuAl20 (500:1)

Bronze (CuSn)

- **Up to 20% Sn**
  - 9 – 12% for casting alloys
- **Nonmagnetic**
- **High thermal and electrical conductivity**
- **High corrosion resistance**
  - Seawater resistance
- **Good wear resistance**
- **Good damping coefficient**
- **Red brass (CuZnSn)**
  - Cheaper due to cheap Zn
  - Similar properties

http://www.kupfer-institut.de/front_frame/frameset.php3?client=1&lang=1&idcat=33&parent=14

Brass (CuZn)

- **5 to 45 % Zn**
- **Tensile strength up to 750 MPa**
- **No cryogenic embrittlement**
- **Good corrosion resistance**
  - Depends on alloying element
- **Antimicrobial**
  - Used at public places
- **Specialbrass**
  - CuZn + other element

Pump impeller
- CuZn37Mn3Al2PbSi

Multi Cone Synchro System
- Depends on the application

http://www.kupfer-institut.de/front_frame/pdf/i05_0307.pdf
http://www.otto-fuchs.com

Aluminium bronze (CuAl)

- **9 – 14% Al**
- **High corrosion resistance**
  - Seawater resistance
- **Good wear resistance**
- **Good cavitation resistance**
- **Applications**
  - Ship propeller
  - Sliding elements
  - Bearings
  - Chemical industries
  - Gear wheels

World largest ship propeller (MMG)

- CuAl9Ni6Fe5Ma
- Container ship with 120,000 PS
- 9,6 m; 131 t

http://www.kupfer-institut.de/front_frame/frameset.php3?client=1&lang=1&idcat=33&parent=14

Nickel-based alloys

- **Pure nickel**
  - Ductile and tough
    - *Face-centered cubic crystal structure up to its melting point*
- **High resistance against**
  - Corrosion environments
  - High temperatures (≤1100° C)
  - Mechanical stresses
- **Base for developing many special alloys**
- **Intermetallic phases**
  - very high strength alloys
  - low- and high-temperature