Non – ferrous metals for particle accelerators

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CERN

ENGINEERING DEPARTMENT

MECHANICAL & MATERIALS ENGINEERING FOR PARTICLE ACCELERATORS AND DETECTORS

The most important slide of this presentation

- Materials are your friends.

"Close friends are truly life's treasures. Sometimes they know us better than we know ourselves." Vincent Van Gogh

- Get to know them as good as you can.

- Do not ask them for things they cannot do.

Outline

- Environmental conditions of particle accelerators
- General rules for selection of materials in particle accelerators
- Families of non – ferrous materials:
  - Aluminum
  - Copper
  - Titanium
  - Niobium
- Conclusions

Environmental conditions of particle accelerators

- Cryogenic temperatures.
- Ultra – high and extreme vacuum.
- Electro – magnetic fields.
- Radiation.
- High temperatures and high strain rate.

Environmental conditions of particle accelerators

- Cryogenic temperatures → down to 1.9 K (superfluid helium).

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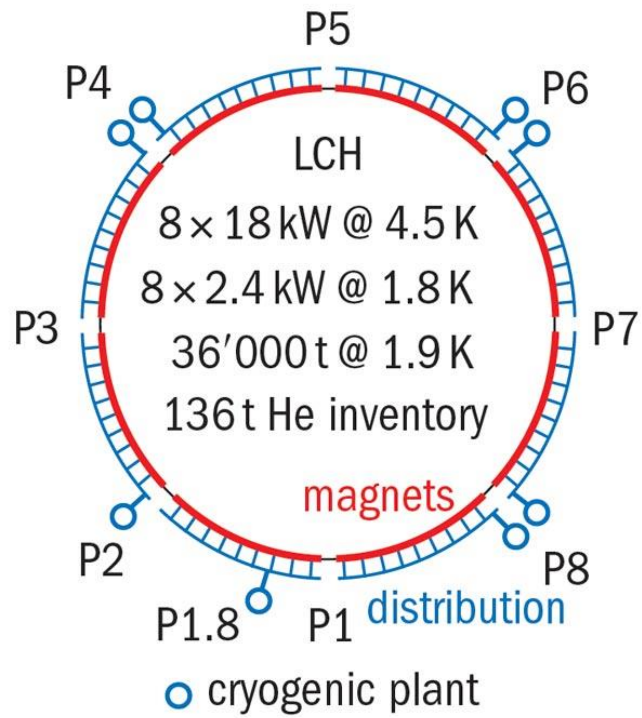

- High temperatures and high stra intercepting devices (dumps, collimators, targets).

Environmental conditions of particle accelerators

- Cryogenic temperatures → down to 1.9 K (superfluid helium).

- Ultra – high and extreme vacuum → down to 10^{-11} mbar.

Classification	Vacuum Level [a], [b], [c], [d]	
	Pa	Torr
Low or "Rough" Vacuum	133.3 to 1.33×10^{-1}	1 to 1×10^{-3}
Intermediate or "Soft" Vacuum	$<1.33 \times 10^{-1}$ to 1.33×10^{-3}	$< 1 \times 10^{-3}$ to 10^{-5}
High or "HV" Vacuum	$<1.33 \times 10^{-3}$ to 1.33×10^{-6}	$< 1 \times 10^{-5}$ to 10^{-8}
Ultrahigh or "UHV" Vacuum	$<1 \times 10^{-7}$ to 1×10^{-8}	7.5×10^{-10} to 7.5×10^{-11}
Extreme Ultrahigh Vacuum	$< 1 \times 10^{-10}$	$< 7.5 \times 10^{-13}$
Interstellar Space	10^{-17}	7.5×10^{-20}

From: Herring, Daniel H., Vacuum Heat Treatment, BNP Custom Media Group, 2012.

Environmental conditions of particle accelerators

- Cryogenic temperatures →
  helium).
- Ultra – high and extreme v
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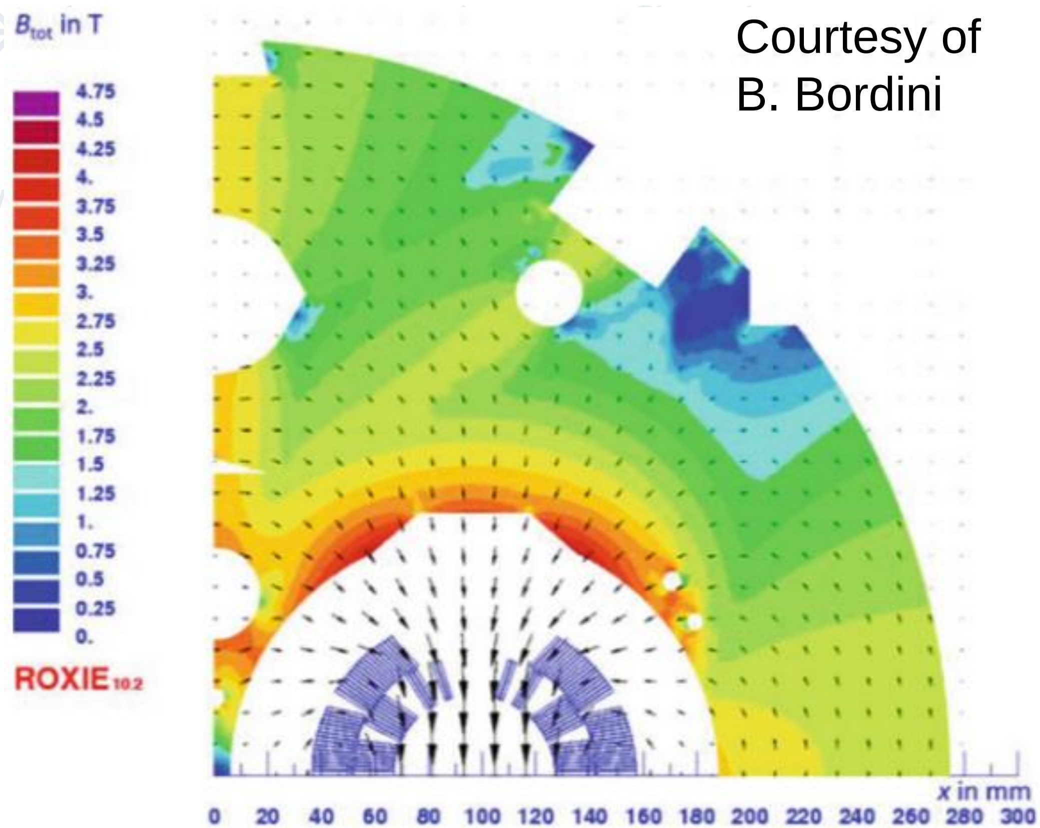
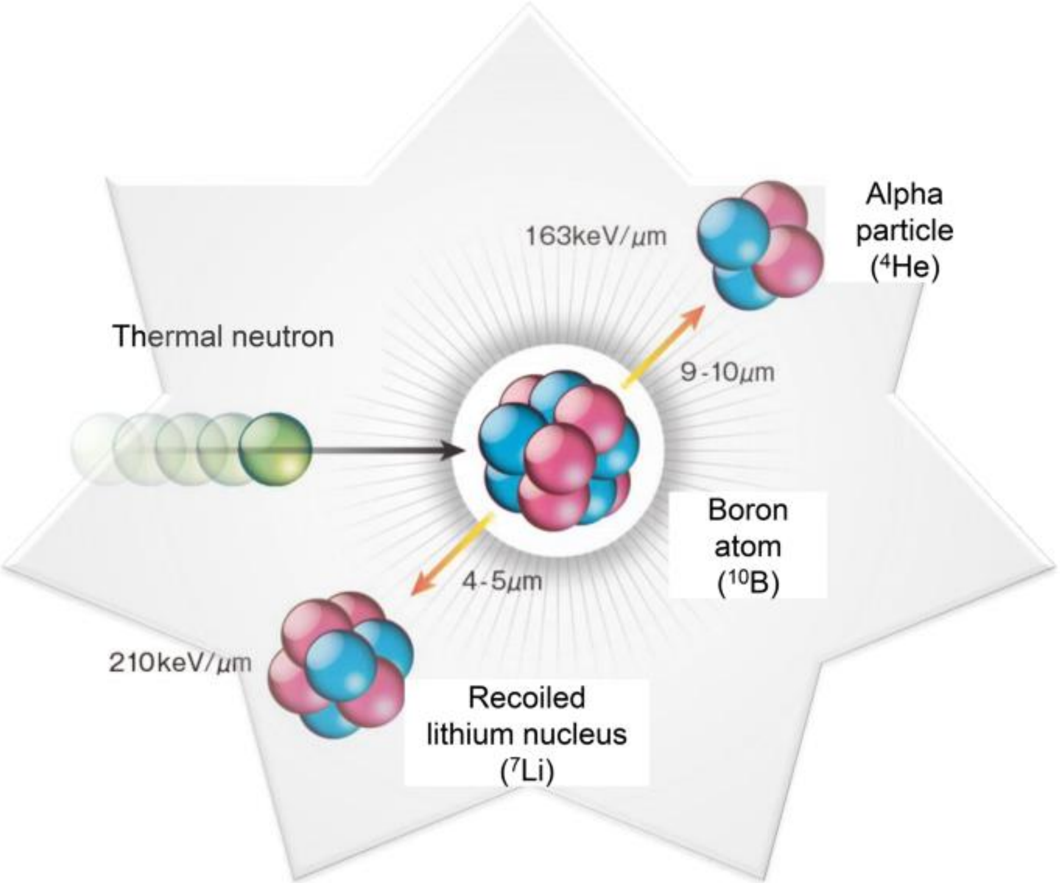
- Radiation.
- High temperatures and high strain rate → beam intercepting devices (dumps, collimators, targets).



Courtesy of B. Bordini

Environmental conditions of particle accelerators

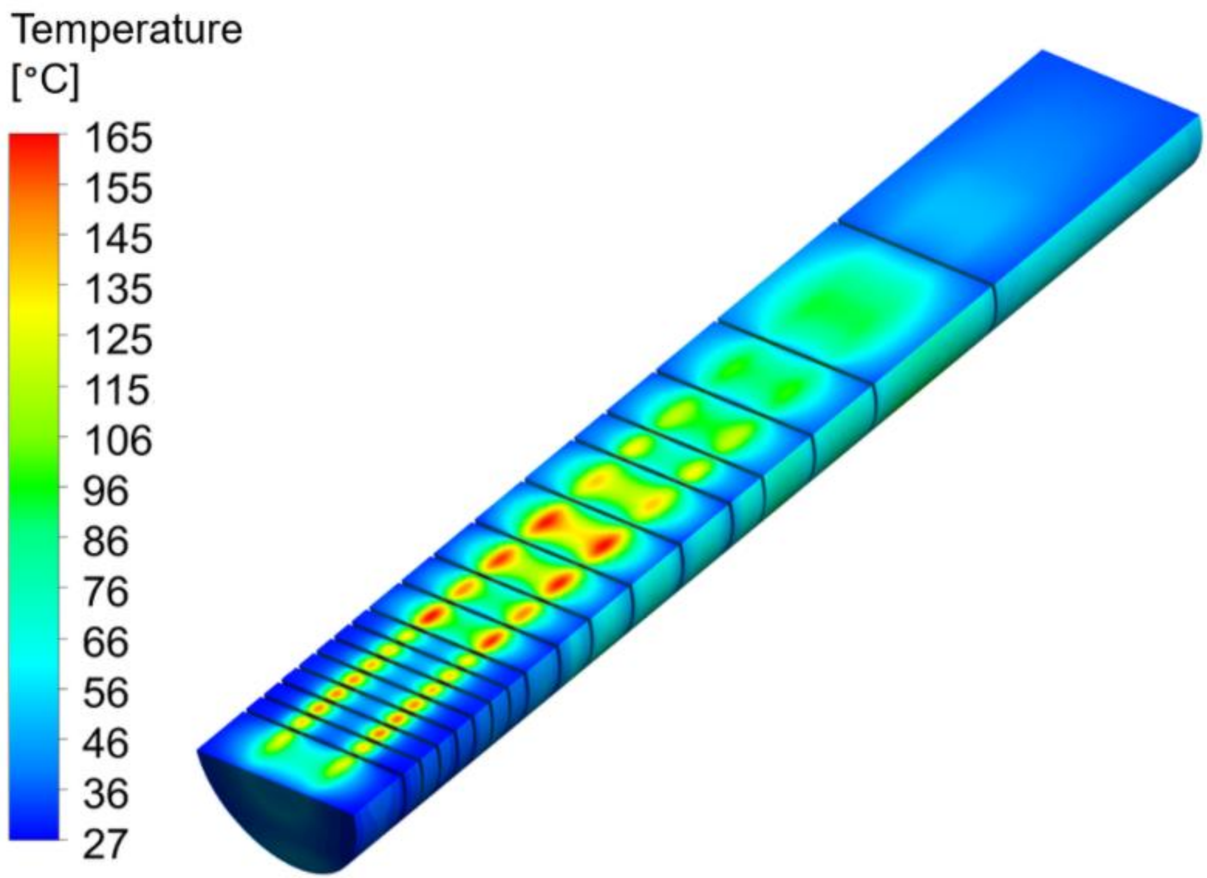
- Cryogenic temperatures helium).
- Ultra – high and extreme
- Electro – magnetic fields.
- Radiation.



- High temperatures and high strain rate → beam intercepting devices (dumps, collimators, targets).

Environmental conditions of particle accelerators

- Cryoger … id helium).
- Ultra – h … mbar.
- Electro …
- Radiatic …

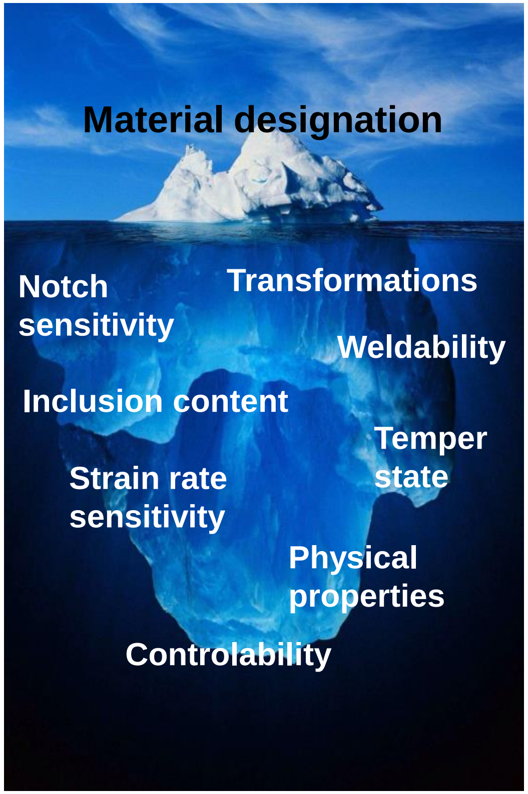


Courtesy of E. Lopez Sola

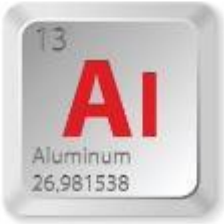
- High temperatures and high strain rate → beam intercepting devices (dumps, collimators, targets).

General rules for materials' selection in particle accelerators

- The golden rule to be remembered (from S. Sgobba in stainless steel, can be extended to any material):
  - "A material for an accelerator part is not a mere chemical composition or designation"
  - Low / high temperature, magnetism, ultrahigh vacuum, radiation, require special care.



Non – ferrous materials



- Aluminium
  - Second-most abundant metallic element in Earth's crust after silicon.
  - The name comes from its compound form, a mineral rock called ‘alumen’ (meaning binding) used as dyeing fixative.
  - Silver from clay

The legend sais that Tiberius beheaded a goldsmith who first crafted aluminium since it could devaluate the price of gold.

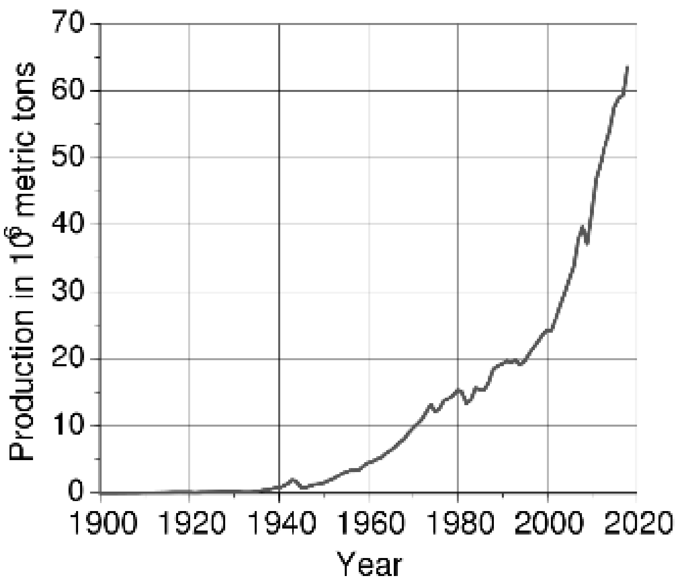
Non – ferrous materials

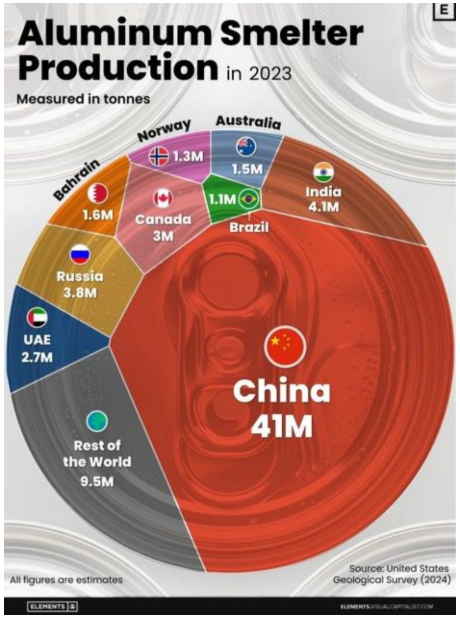
- Aluminium
  - Two millennia after, the extraction of Al from bauxite was very scarce. Al was more precious than gold (as Tiberius feared).

Napoleon III had, for his most distinguished guests, Al cutlery. The rest had to settle for gold.

Non – ferrous materials

- Aluminium
  - Electrolysis (Hall – Héroult process) of alumina (Bayer process).
  - Victim of its own success: it is produced in similar quantities than all other non-ferrous metals combined

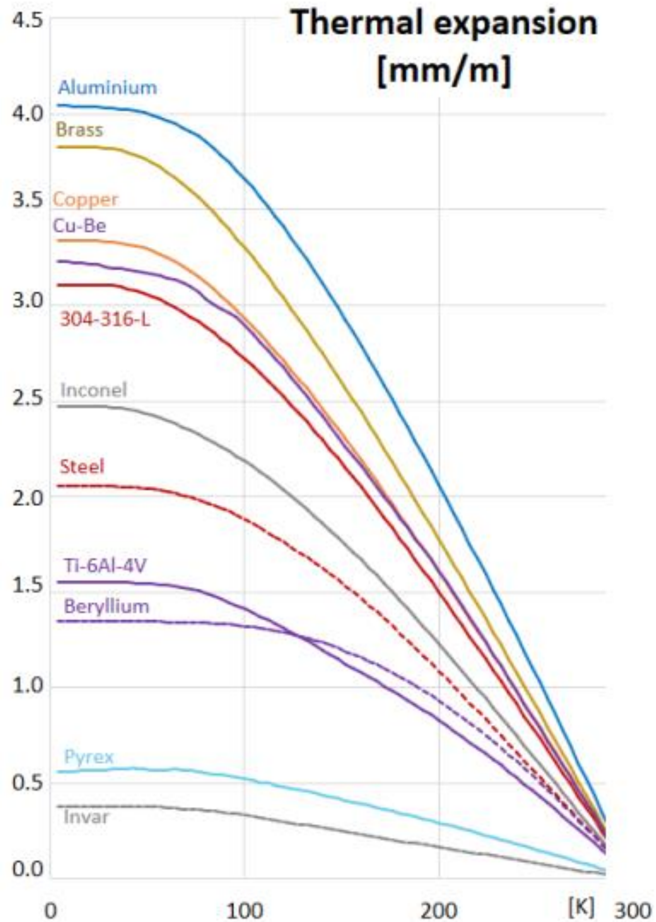


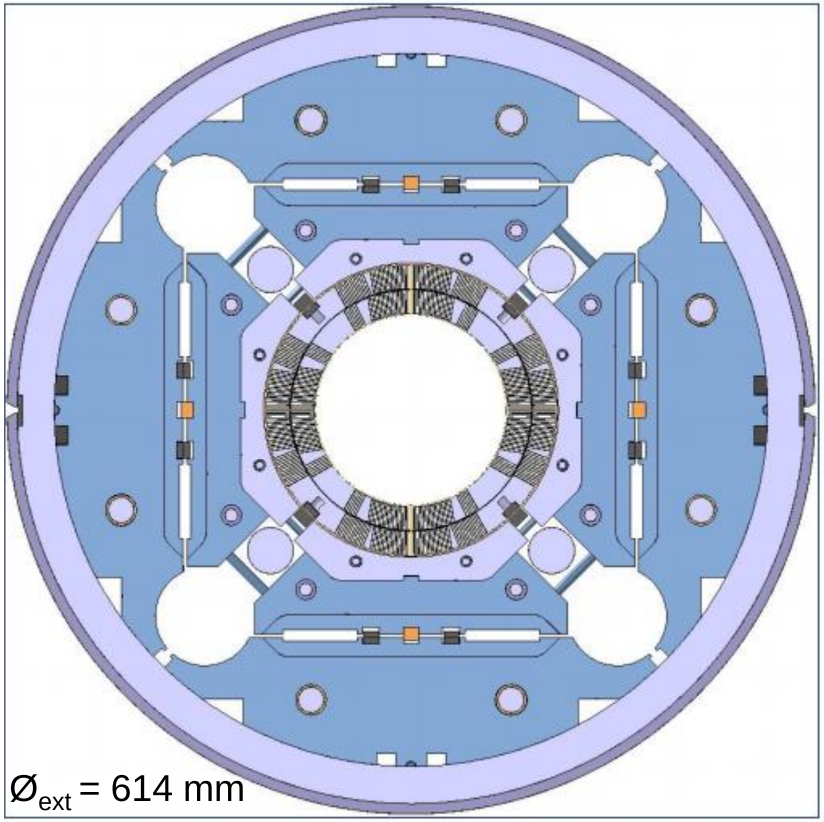


~ 70M tons in 2023

Aluminium for particle accelerators

- Low modulus of elasticity
- High thermal contraction coefficient
- Paramagnetic





Al shrinking cylinders for MQXF quadrupoles

Source: DUTHIL, Patxi. Material properties at low temperature. arXiv preprint arXiv:1501.07100, 2015.

Aluminium for particle accelerators

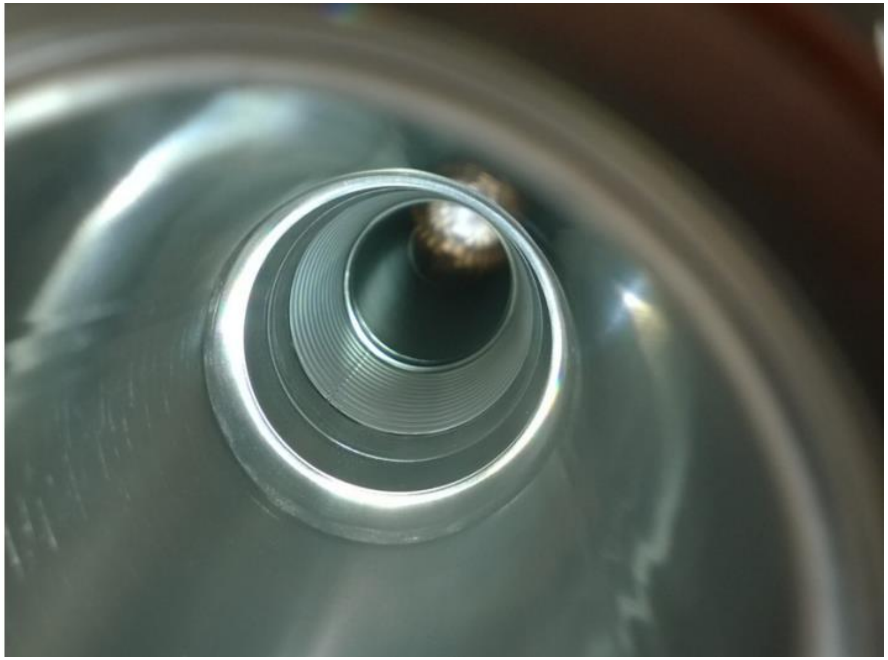
- Very low thermal emissivity
- High thermal and electrical conductivity

MLI (Al coated Mylar) HL – LHC's cold box

Al coil for CERN's first particle accelerator: The Synchrocyclotron

Aluminium for particle accelerators

- Feeble interaction with particle beams
  - Low density
  - Low atomic number



Developments of Al vacuum chambers and bellows

Wrought aluminum alloys

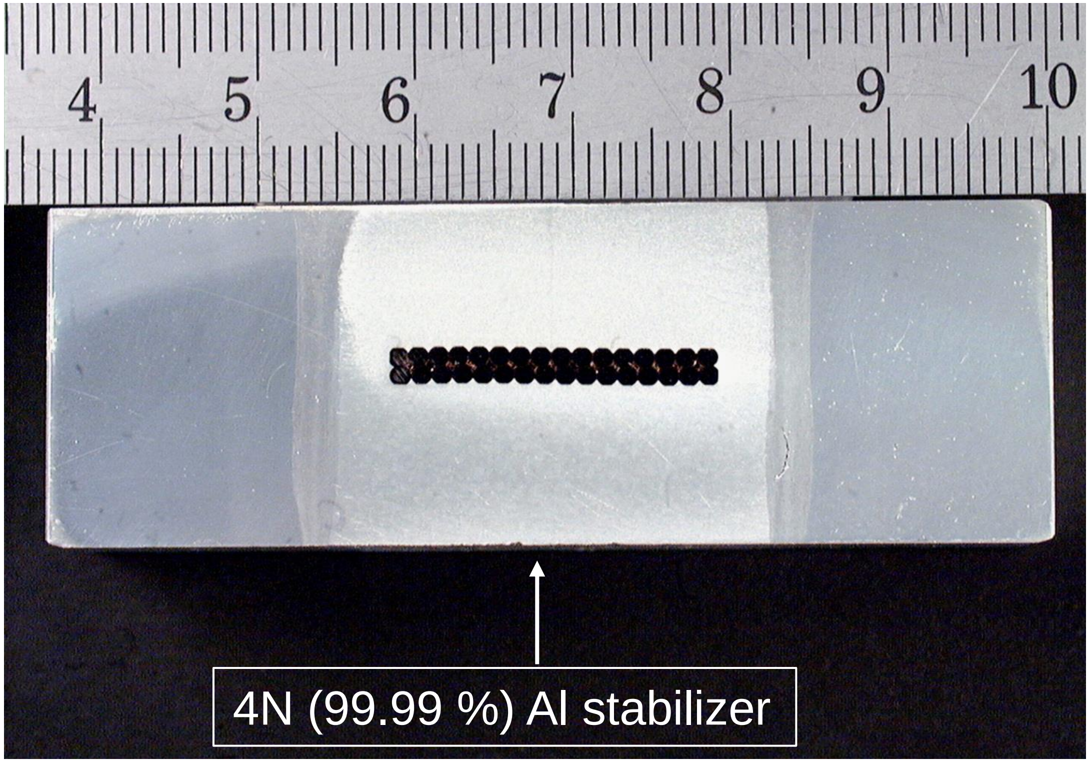
Designation AA	Major alloying elements	Alloy group	Heat treatable ?	Examples
1xxx	**-**	Pure Al	No	
2xxx	**Cu**	Al – Cu	Yes	2219
3xxx	**Mn**	Al – Mn	No	3003
4xxx	**Si**	Al – Si	No	Filler
5xxx	**Mg**	Al – Mg	No	5061
6xxx	**Mg, Si**	Al – Mg - Si	Yes	6082
7xxx	**Zn, Mg**	Al – Zn	Yes	7050
8xxx	**any**		(yes)	8090

(blue) → Can be strengthened by a suitable thermal treatment (heat treatable)

(grey) → Can only be strengthened by hot or cold working (non – heat treatable)

Wrought aluminum alloys designations

- 1xxx series (pure Al) ⟶ Excellent workability & ↑ conductivity

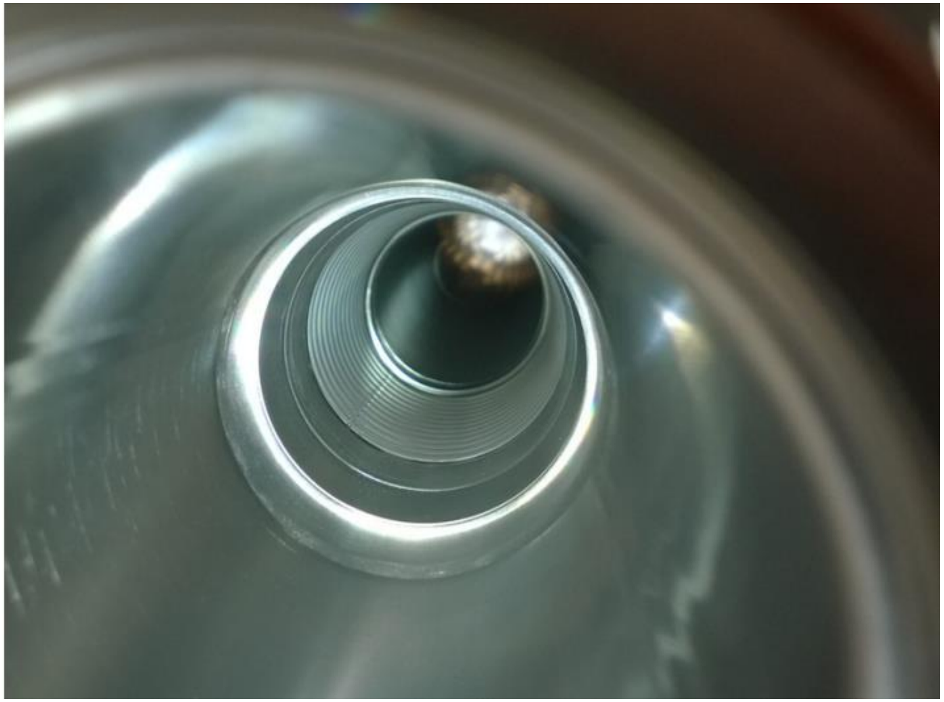


Example: CMS conductor

Wrought aluminum alloys designations

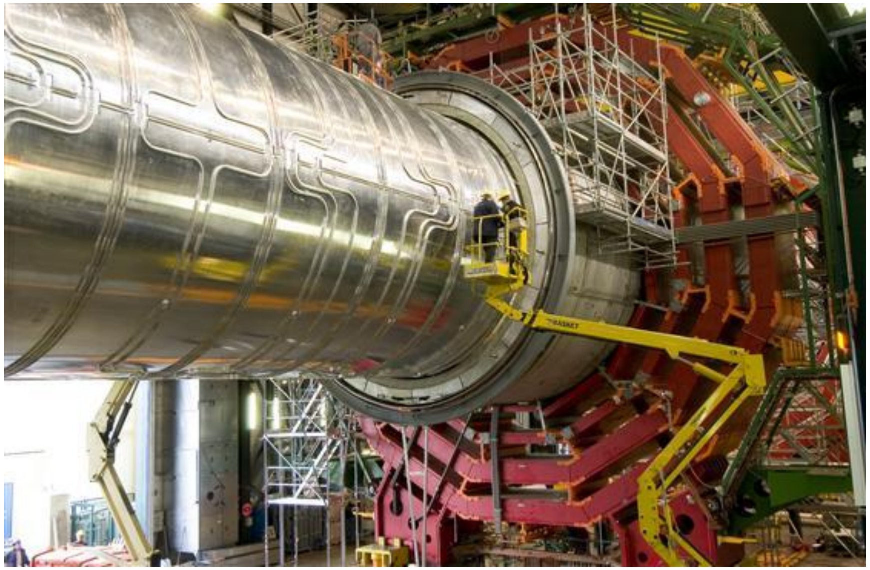
- 2xxx series (Al – Cu) ⟶ ↑ Mechanical properties ↓ corrosion resistance
  - Example: EN AW 2219 T6

Example: vacuum chamber bodies. (NEG coated).



Wrought aluminum alloys designations

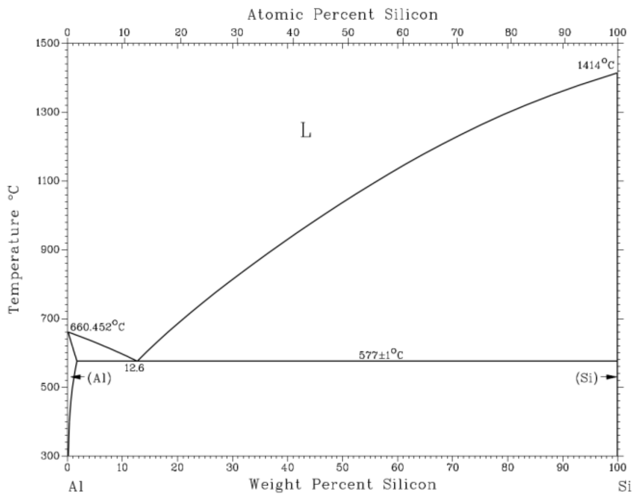
- 3xxx series (Al – Mn) → Moderate mechanical properties, workability, Corrosion resistance and th. conductivity
  - Example: EN AW 3003 H22



Example: CMS Solenoid thermal shield

Wrought aluminum alloys designations

- 4xxx series (Al – Si)
  - Major alloying element of this group is silicon, added in sufficient quantities (around 12%), cause substantial lowering of the melting point without producing brittleness (eutectic point).
  - Al - Si alloys are used in welding wire and as brazing alloys.



Wrought aluminum alloys designations

- 5xxx series (Al – Mg) ⟶ moderately ↑ mechanical properties ↑ ductility, weldability
  - EN AW 5083 H321, H116 and H111

Example: Mandrels for CMS coil

Example: hydroformed bellows

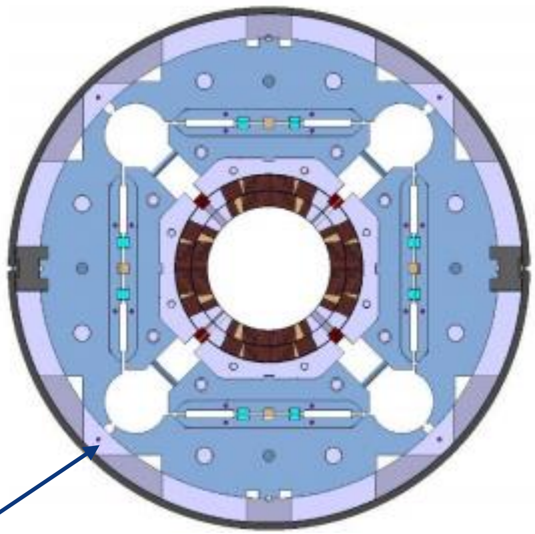
Wrought aluminum alloys designations

- 6xxx series (Al – Mg – Si) → Combination of formability, mechanical strength, weldability and weight
  - Example: EN AW 6082 T6

Example: ICARUS neutrino detector

Wrought aluminum alloys designations

- 7xxx series (Al – Zn – Mg) ⟶ ↑ Mechanical properties
  - Example: EN AW 7075 T6



Al shell

Example: Al shells MQXFBP1 magnet

Wrought aluminum alloys designations

- 8xxx series
  - Reserved for miscellaneous compositions. Alloying elements include: iron, lithium, copper, zinc, magnesium, silicon, manganese, vanadium, zirconium, titanium, chromium & bismuth.
  - Al – Li alloys, for weight reduction. Al - Li alloys possess increased Modulus of Elasticity, high specific stiffness, increased fatigue strength and cryogenic strength.

Wrought aluminum alloys: temper states

Alphanumeric designations that contain information about the thermomechanical history of the material to achieve the desired properties.

AA 7075	Min.	Max.	Approx
Plates, sheets; Annealed (O); 0.20 <= t <= 0.36 mm; Nominal thickness			
Yield stress, $R_{p0,2}$ (MPa)	-	145	-
Tensile stress, R_m (MPa)	-	276	-
Elongation, A (%)	9	-	-
	L_o = 50.8 mm or 4D		

AA 7075	Min.	Max.	Approx
Plates; Solution heat treated and artificially aged (T651); 0.20 < t <= 0.28 mm; Nominal thickness			
Yield stress, $R_{p0,2}$ (MPa)	434	-	-
Tensile stress, R_m (MPa)	510	-	-
Elongation, A (%)	5	-	-
	L_o = 50.8 mm		

Wrought aluminum alloys: temper states

"Men are like ~~steel:~~ materials if they loose their temper, they loose their worth"

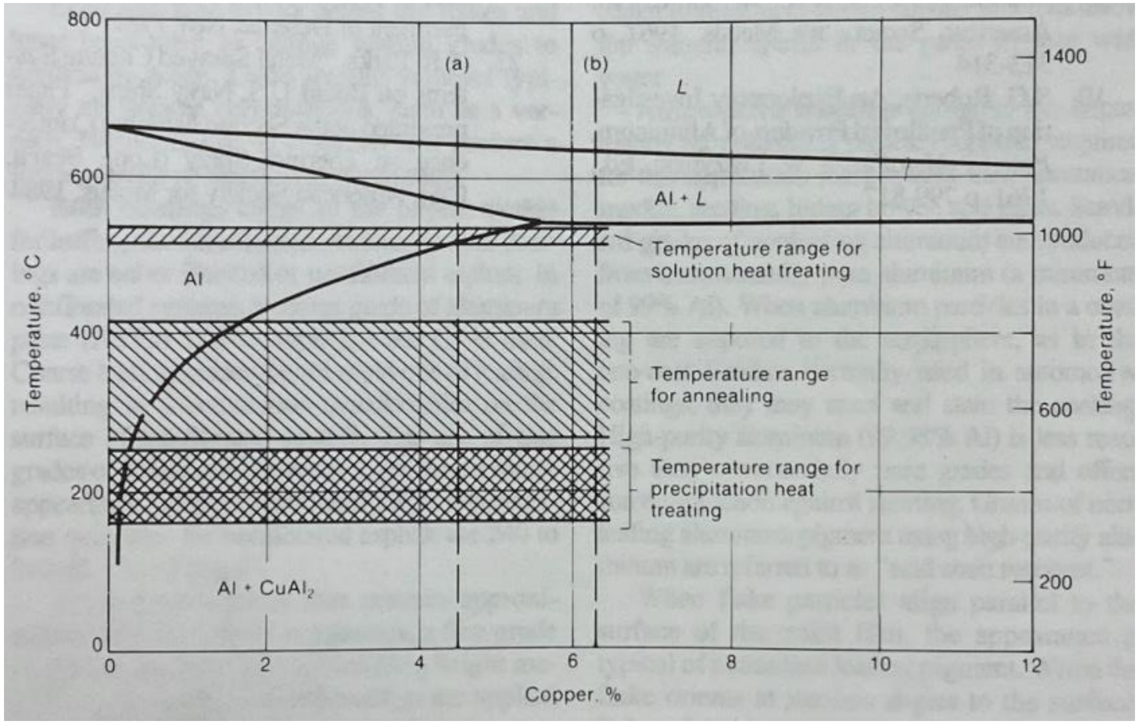
Wrought aluminum alloys: temper states

A capital letter indicating the major class of fabrication treatment(s) used + one (or more) numbers providing more specific information about how the processing was carried out.

Wrought aluminum alloys: temper states

- O, annealed: given a high – temperature treatment, sufficient to remove the effects of prior working, usually resulting in complete recrystallization of the material. Lowest strength and maximum ductility and toughness.

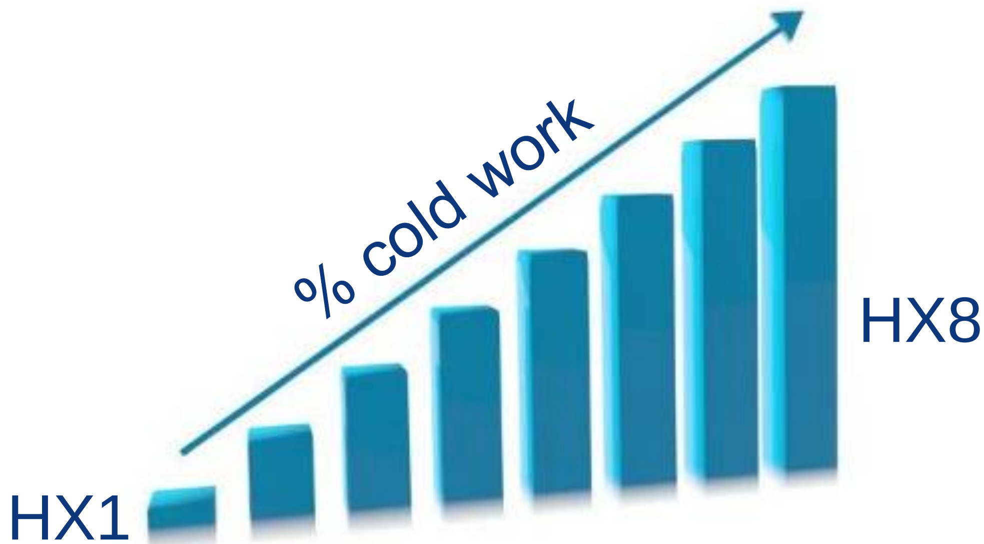
Source: ASM aluminium and aluminium alloys handbook



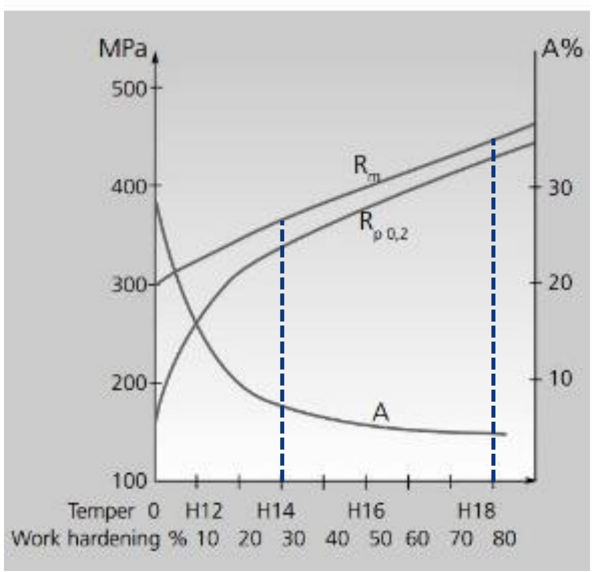
Portion of Al – Cu phase diagram

Wrought aluminum alloys: temper states

- H, strain hardened: non-heat-treatable wrought alloys that have had their strength increased by strain hardening. H is always followed by two or more digits:
  - The first number after the H tells whether the strain-hardened alloy has been thermally treated
  - The second number indicates the approximate amount of cold work



WORK HARDENING CURVE OF ALLOY 5083



Source: Aluminium in Commercial Vehicle – European Aluminium Association – 2011

Wrought aluminum alloys: temper states

- **H, strain hardened:** non-heat-treatable wrought alloys that have had their strength increased by strain hardening. H is always followed by two or more digits:
  - The first number after the H tells whether the strain-hardened alloy has been thermally treated
  - The second number indicates the approximate amount of cold work
  - Any subsequent numbers define special practices, variations of the normal indicated by the first two numbers.

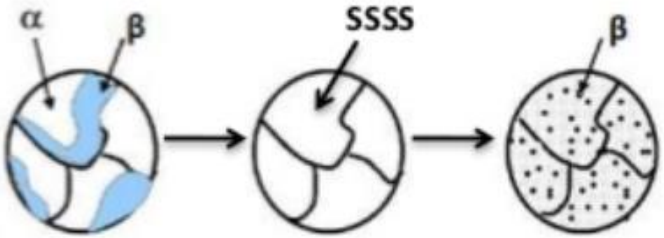
Example:
AA 5083 H116 (marine grade)

Wrought aluminum alloys: temper states

- T, thermally treated to produce stable tempers: heat-treatable wrought alloys that have followed a solution heat treatment followed by a quench and either natural or artificial aging.

Heat treatment to increase the strength of Al alloys is a three step process:

1. Solution heat treatment: dissolution of soluble phases
2. Quenching: development of supersaturation
3. Age hardening: precipitation of finely dispersed precipitates



Wrought aluminum alloys: temper states

- T, thermally treated to produce stable tempers: heat-treatable wrought alloys that have followed a solution heat treatment followed by a quench and either natural or artificial aging. T is always followed by one or more digits:
  - The first digit after the T can be any from 1 to 10. It is a combination of:
    - Cooled from elevated temperature or solution heat treatment
    - Cold worked or not cold worked
    - Naturally aging or artificial ageing

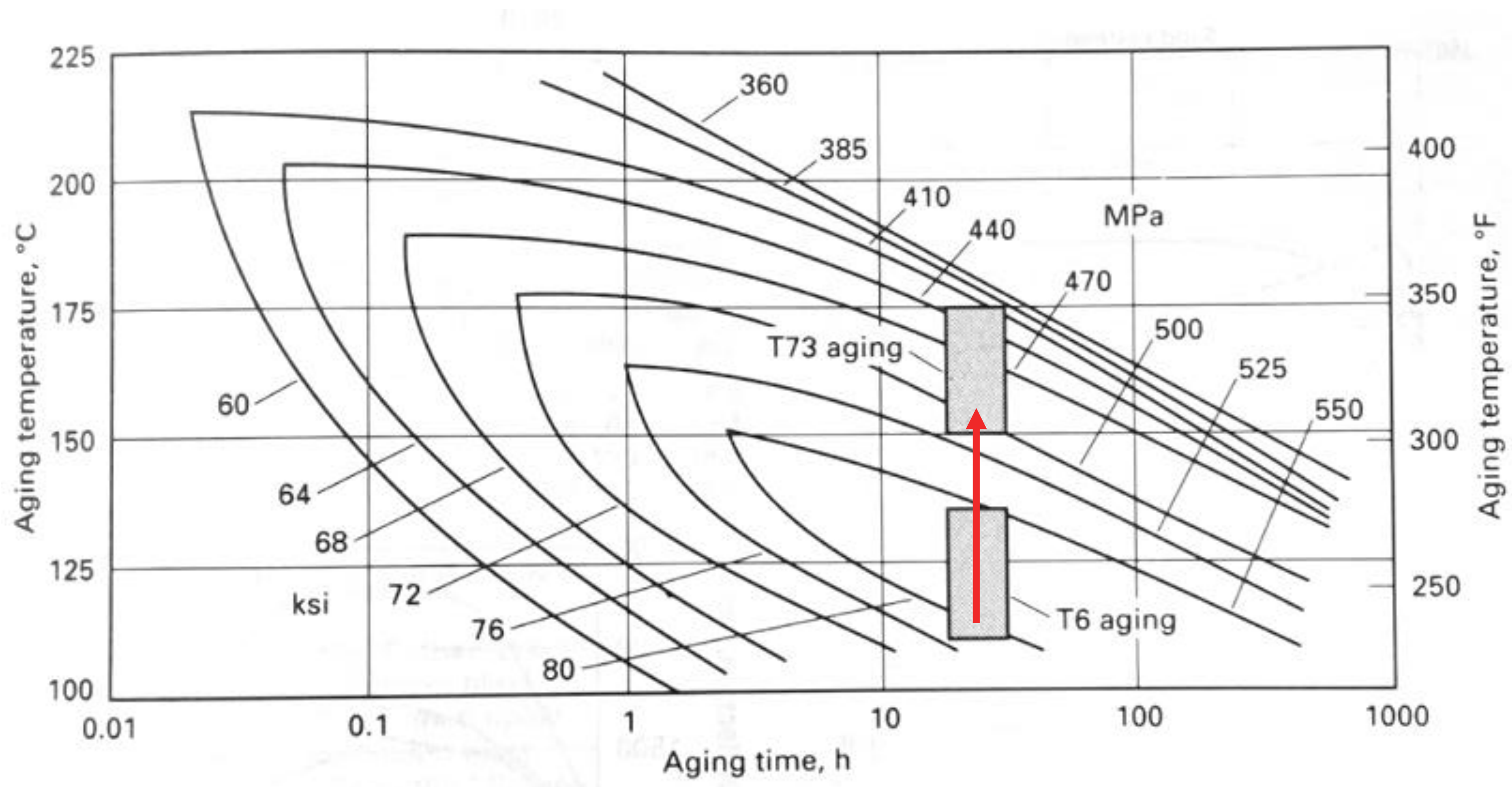
Table 2 — Summary of processing for achieving T tempers

Ageing	Cold worked	Cooled from shaping process	Furnace solution heat-treated[a]
Natural	No	T1	T4
	Yes	T2	T3
artificial	No	T5	T6, T7
	Yes - before ageing	T10	T8
	Yes - after ageing	-	T9

[a] See footnote 4 to text in 8.1

From EN 515:
Al and Al alloys
- Wrought products -
Temper designations

Wrought aluminum alloys: temper states



Source: ASM aluminium and aluminium alloys handbook

Iso – yield – strength curves for EN AW 7075

Wrought aluminum alloys: temper states

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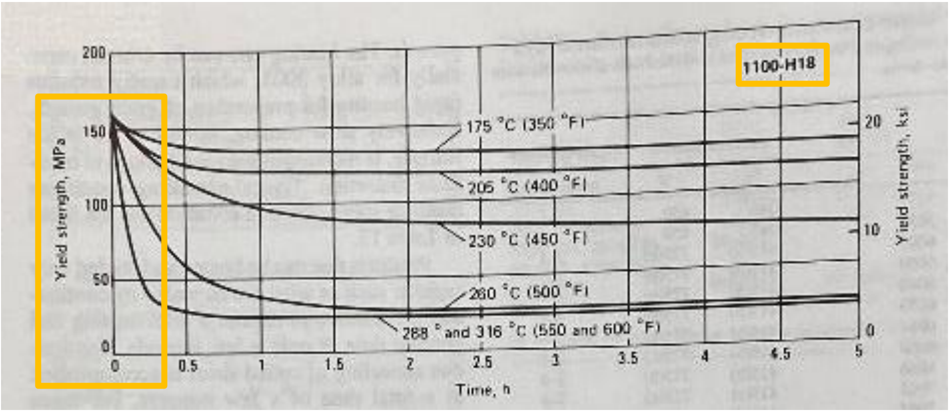
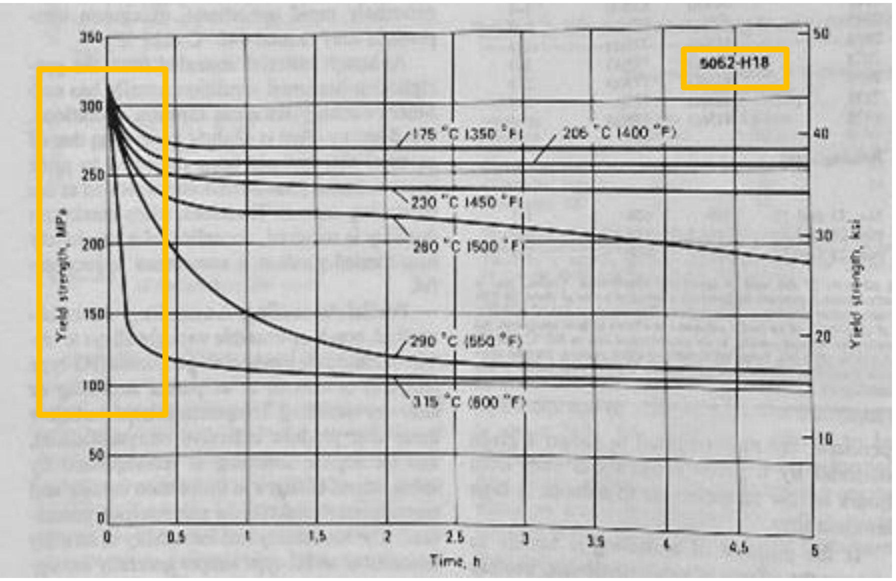
  - The first digit after the T can be any from 1 to 10. It is a combination of:
    - Cooled from elevated temperature or solution heat treatment
    - Cold worked or not cold worked
    - Naturally aging or artificial ageing
  - Additional numbers indicate a variation in treatment that significantly alters the product characteristics that are or would be obtained using the basic treatment. There is not a full list of all such possible variations.

Wrought aluminum alloys: weldability

- Most non – heat treatable alloys plus series 6xxx can be fusion welded, and precaution should be taken with heat treatable high strength alloys.
  - When non – heat treatable alloys are welded, they loose the effect of an eventual work hardening → softening of HAZ.

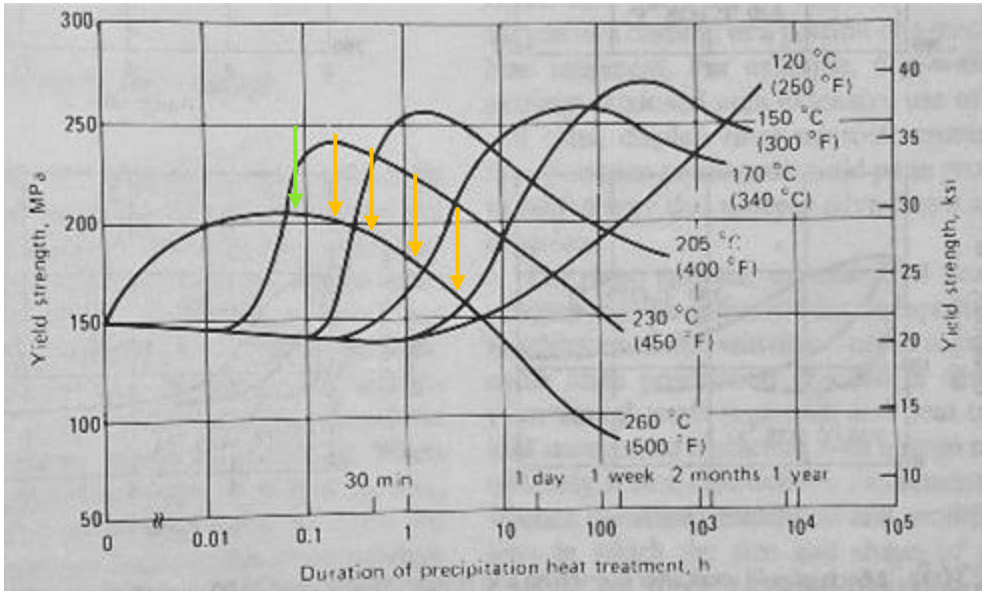




Source: ASM aluminium and aluminium alloys handbook

Wrought aluminum alloys: weldability

- Most non – heat treatable alloys plus series 6xxx can be fusion welded, and precaution should be taken with heat treatable high strength alloys.
  - When welding heat – treatable alloys → redistribution of hardening constituents → softening of HAZ. Attention to liquation cracking.

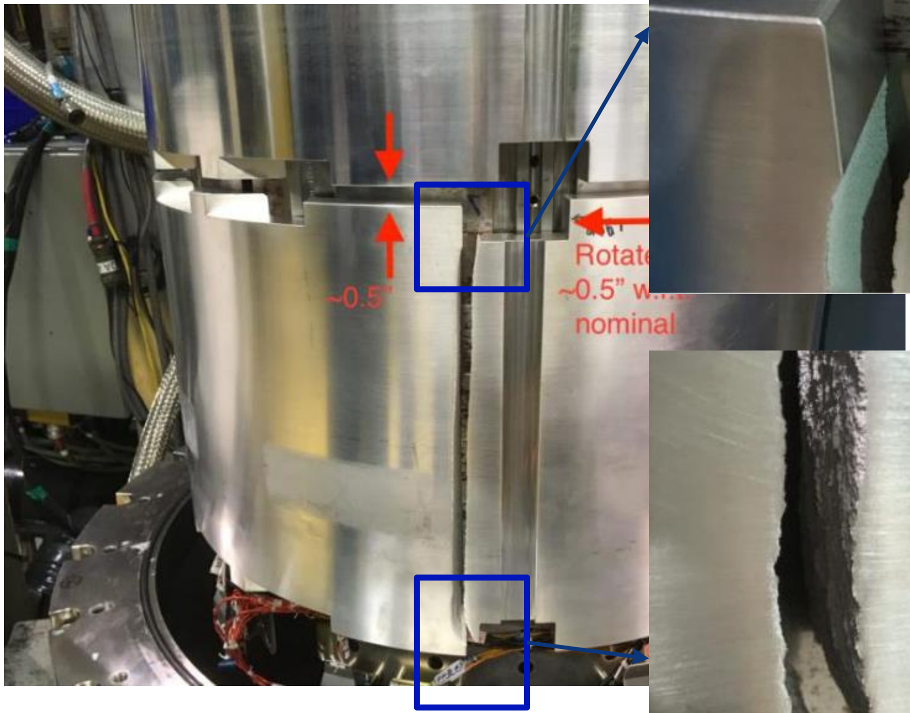


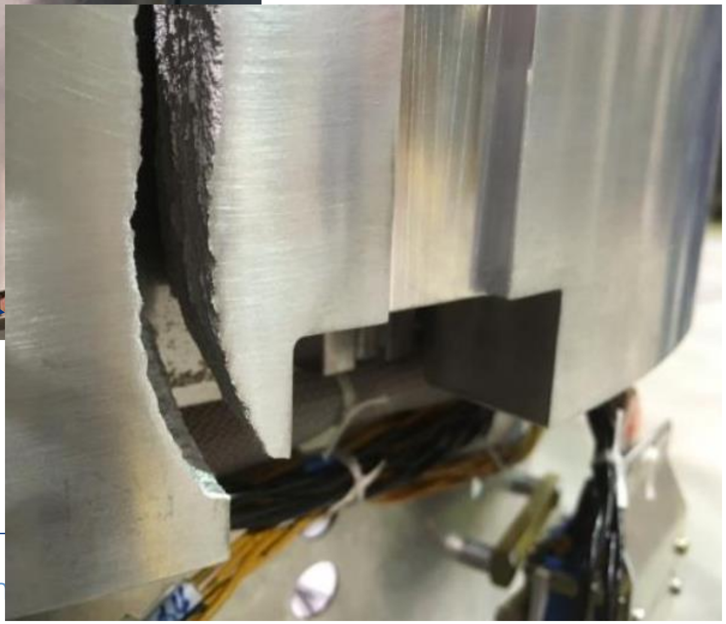
Source: ASM aluminium and aluminium alloys handbook

EN AW 6061

Wrought aluminum alloys: failure analysis

Catastrophic failure of MQXFAP2 Al shell. Failure analysis: EDMS 2088319





Wrought aluminum alloys: failure analysis

Mechanical testing at cryogenic temperature shows the material choice is correct

Material	Direction	E [GPa]	$Rp_{0.2}$ [MPa]	R_m [MPa]	A [%]	Z [%]
AA 7075 T652	Circumferential	84.0 ± 1.4	634.1 ± 11.5	750.6 ± 9.8	4.1 ± 0.2	12.2 ± 1.1
AA 7075 T652	Axial	85.2 ± 1.3	539.6 ± 5.2	659.7 ± 5.8	4.5 ± 0.1	12.0 ± 0.2

Material	Direction	K_Q [MPa√m]
AA 7075 T652	R - C	15.8 – 16.5
AA 7075 T652	C - R	24.0 – 27.2
AA 7075 T6	R - C	13.6 – 16.3

MÉTROLOGIE EN-MME-MM

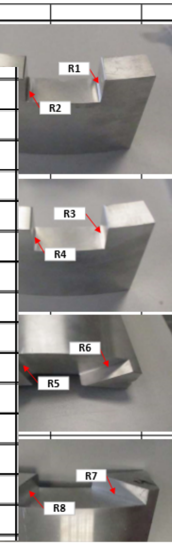
CERTIFICAT DE CONTRÔLE

CONCLUSION CONTRÔLE		VISA MME	ACCEPTATION CLIENT
	OK	Nom :	Nom :
X	Non Conforme	Date :	Date :

NUMERO DE PLAN: LHCMQXFB0040 / 0041 ind. A — REQUERANT: MOYRET P. FERRACIN P.
DESIGNATION: half aluminium shell / aluminium shell
NOMBRE DE PIECES: ...
Nº EDMS: 2058433 — CONTROLEUR: RIGAUD J.Ph.
Job.: J3053222

page 1/1

spécification	Résultat de mesure / troisième série
échantillons USA	
EN AW-7075 T652	
+0.5 +0.2 ISO 13715	R1: R1.4
	R2: R1.5
	R3: R<0.02
	R4: R<0.02
	R5: R<0.02
	R6: R<0.02
	R7: R<0.02
	R8: R<0.02



DATE 19.12.2018
APPROUVE PAR A.CHERIF
Température : 20 °C — Moyens utilisés (incertitude de mesure estimée) : — Unités de mesure : mm
Projecteur de profil (± 0.005mm) ; Plastiform ;

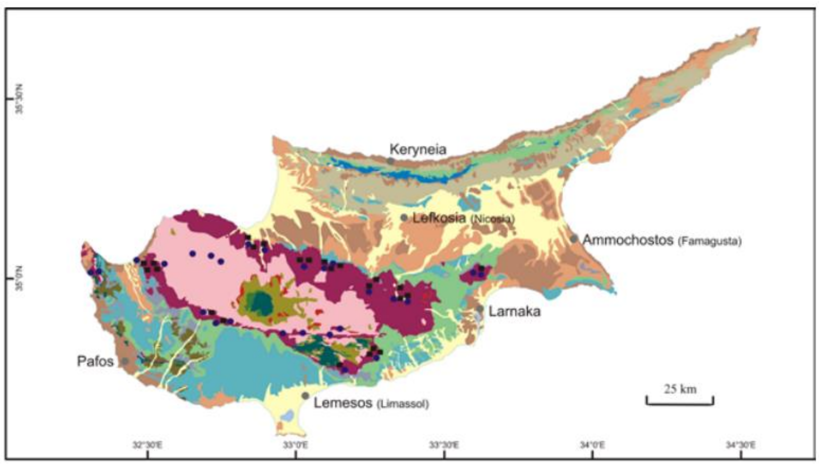
However, EN AW 7075 T651 is sensitive to the presence of sharp notches at 4 K.

Aluminium alloy shell:
failure analysis and material properties at cryogenic temperature.
EDMS 2088319

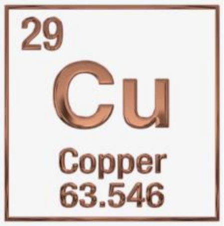
Non – ferrous materials

29
Cu
Copper
63.546

- Copper
  - Its name comes from ‘cuprum’, meaning “from the island of Cyprus”.

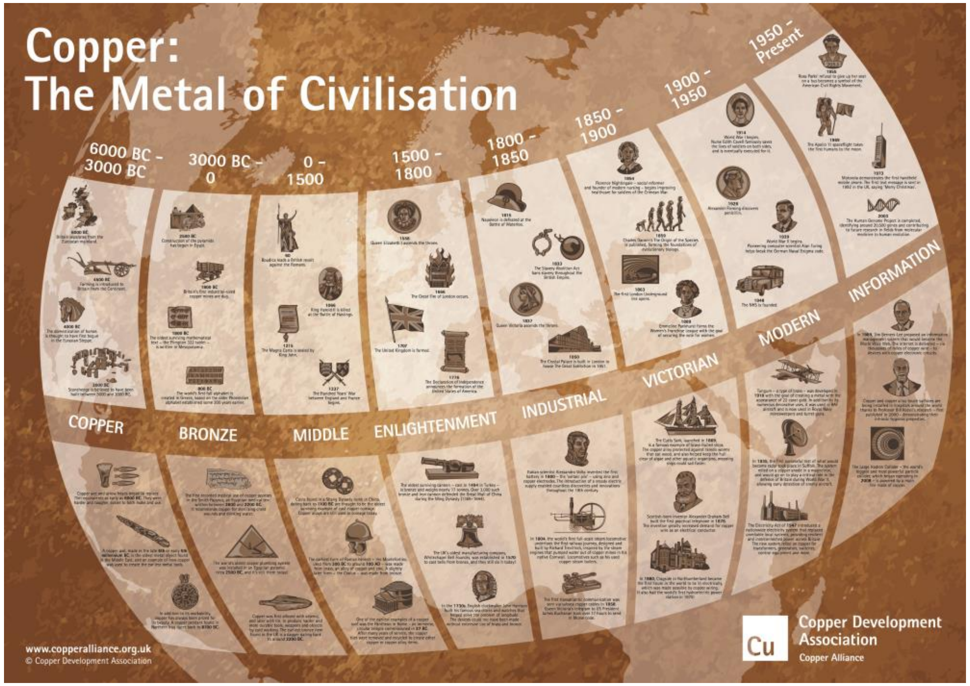


Non – ferrous materials



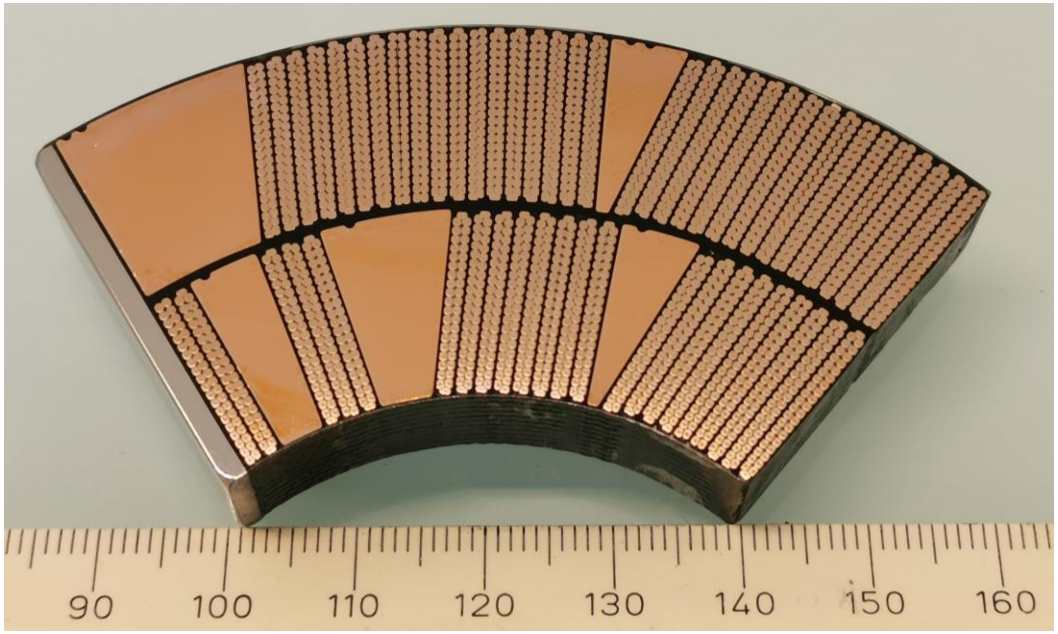
- Copper
  - One of the oldest materials known, and one of the most produced.

~ 21.5M tons in 2023



Copper for particle accelerators

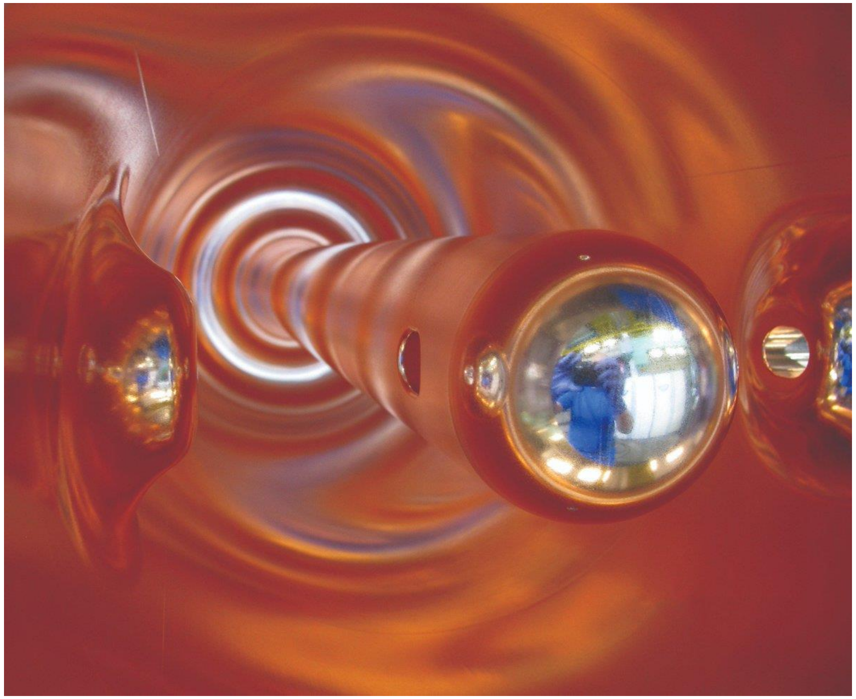
- Elastic modulus close to Nb_3Sn
- Diamagnetic



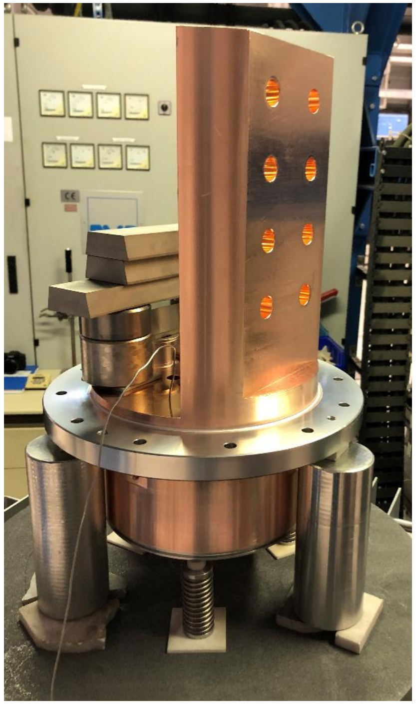
Courtesy: M. Crouvizier

Copper for particle accelerators

- Extremely high thermal and electrical conductivity



HIE ISOLDE quarter wave resonator substrate

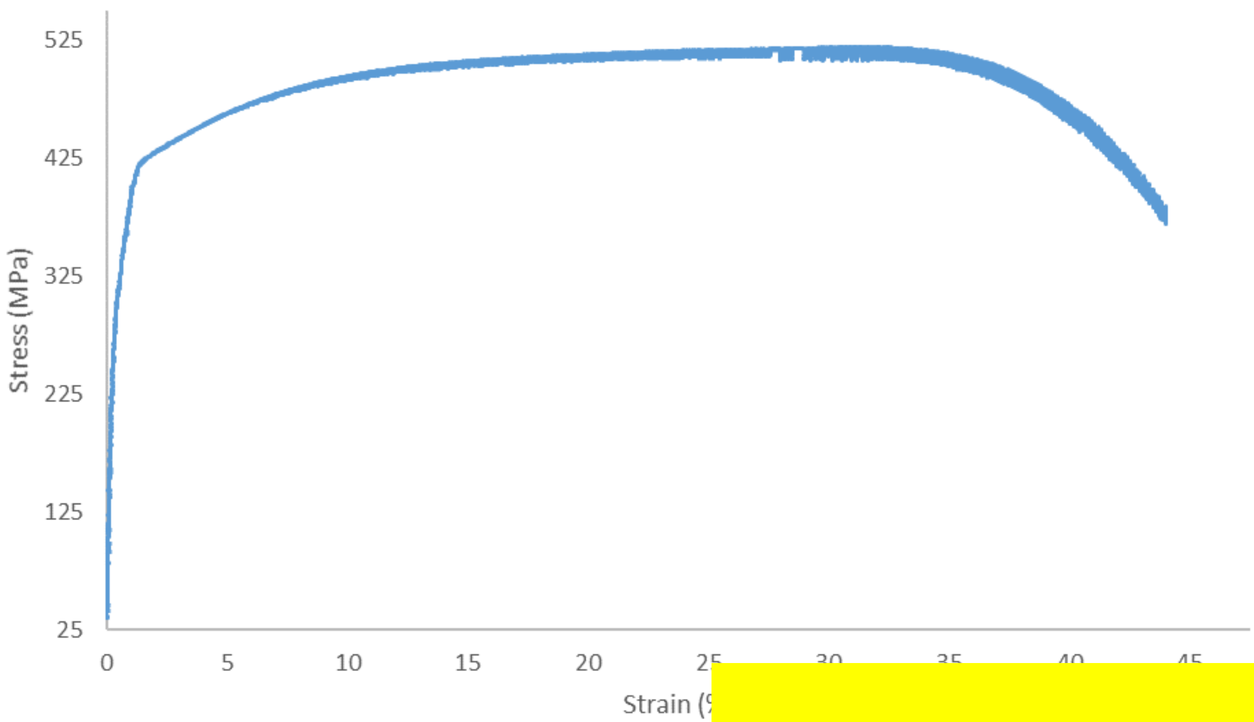


Courtesy: P. Moyret

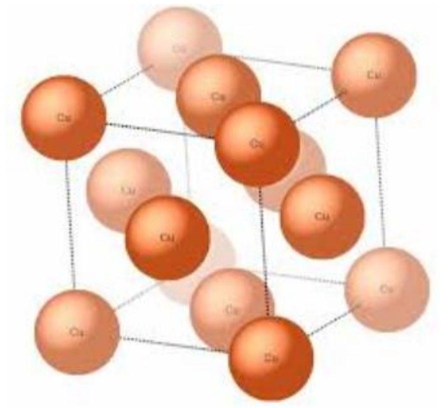
18 kA HL-LHC current leads

Copper for particle accelerators

- Ductile and tough down to 4 K



Stress vs strain curve OFE – co
state.



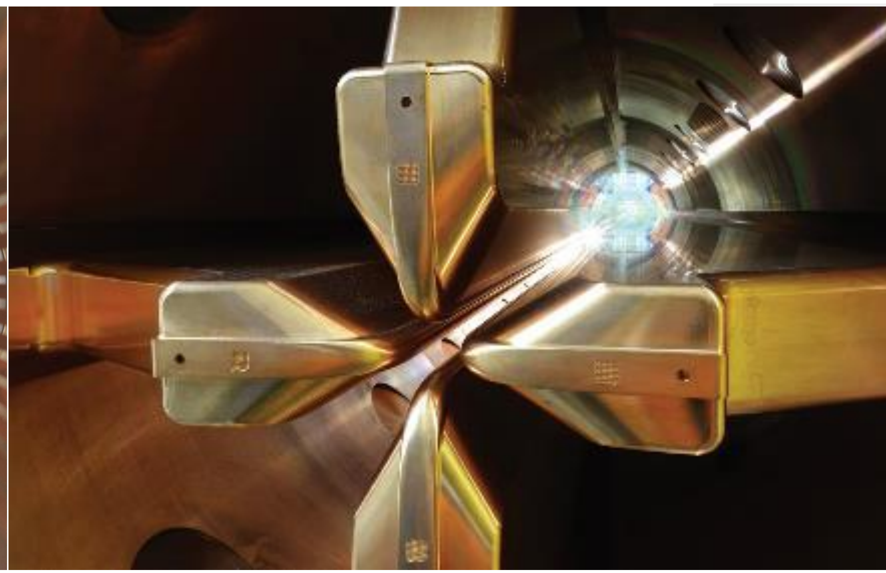
Face centered cubic (FCC) crystal structure

See also →
CAS course on "Mechanical & Materials engineering", K-P. Weiss, Mechanical testing

Copper for particle accelerators

- High availability, moderate price, formability, machinability.

RF fingers of a collimator



RFQ

Cu gasket Conflat flange UHV

Wrought copper alloys: temper states

Annealed tempers

Temper Codes	Temper Names
O10	Cast and Annealed (Homogenized)
O11	As Cast and Precipitation Heat Treated
O20	Hot Forged and Annealed
O25	Hot Rolled and Annealed
O26	Hot Rolled and Temper Annealed
O30	Hot Extruded and Annealed
O31	Hot Extruded and Precipitation Heat Treated
O32	Hot Extruded and Temper Annealed
O40	Hot Pierced and Annealed
O50	Light Anneal
O60	Soft Anneal
O61	Annealed
O65	Drawing Anneal
O68	Deep Drawing Anneal
O70	Dead Soft Anneal

Cold worked tempers

Temper Codes	Temper Names
H00	⅛ Hard
H01	¼ Hard
H02	½ Hard
H03	¾ Hard
H04	Hard
H06	Extra Hard
H08	Spring
H10	Extra Spring
H12	Special Spring
H13	Ultra Spring
H14	Super Spring

Temper Codes	Temper Names
H50	Hot Extruded and Drawn
H52	Hot Pierced and Drawn
H55	Light Drawn, Light Cold-Worked
H58	Drawn General Purpose
H60	Cold Heading, Forming
H63	Rivet
H64	Screw
H66	Bolt
H70	Bending
H80	Hard Drawn

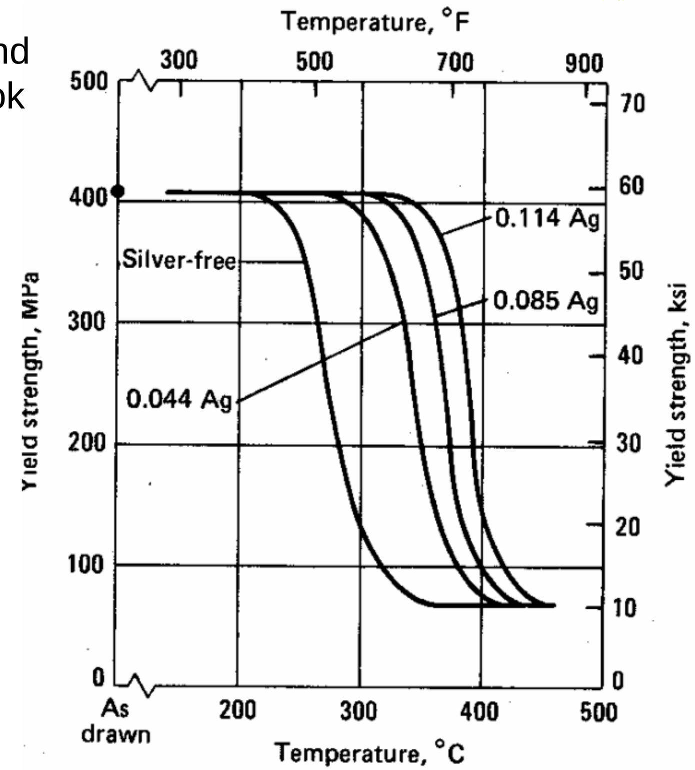
Copper and copper alloys

Generic name	UNS No.	Composition
Wrought alloys		
Coppers(a)	C10100–C15815	>99% Cu
High-copper alloys(b)	C16200–C19900	>96% Cu
Brasses		
Leaded brasses		
Tin brasses		

Source: ASM copper and copper alloys handbook

"electrical coppers"
Cu OFE, C10100
Cu OF, C10200
Cu OFS, C10700

99.8Cu-0.15Al_2O_3, C15715



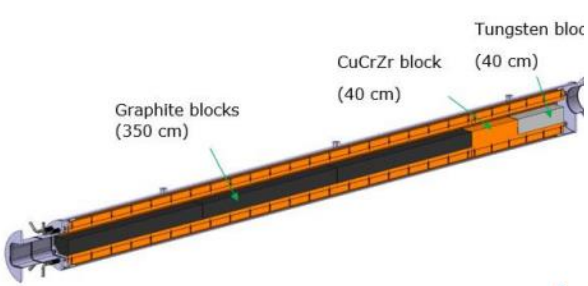
CERN Phase II collimator.
Glidcop© sectorized jaw

Copper and copper alloys

Generic name	UNS No.	Composition
Wrought alloys		
Coppers(a)	C10100–C15815	>99% Cu
High-copper alloys(b)	C16200–C19900	>96% Cu
Brasses	C20100–C28000	Cu-Zn
Leaded brasses	C31200–C38500	Cu-Zn-Pb
		Cu-Zn-Sn-Pb
		Cu-Sn-P
		Cu-Sn-Pb-P

High strength copper alloys
Cu-2%Be, C17200
Cu-0.3%Be-0.5%Co, C17410

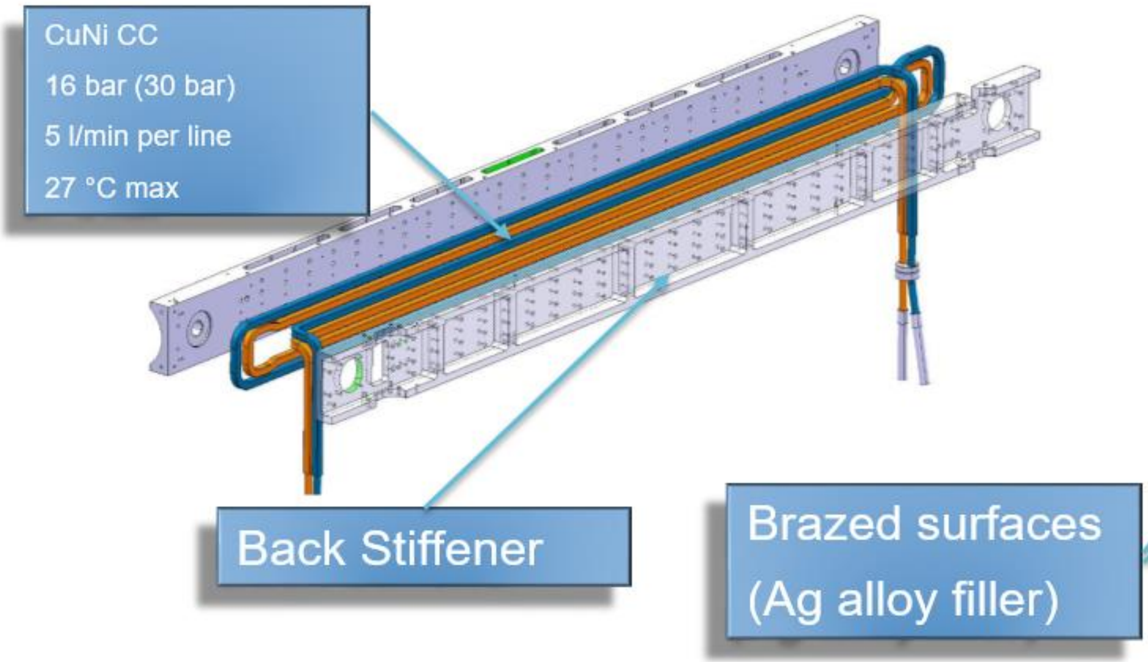
Cu-1%Cr-0.15%Zr,C18150

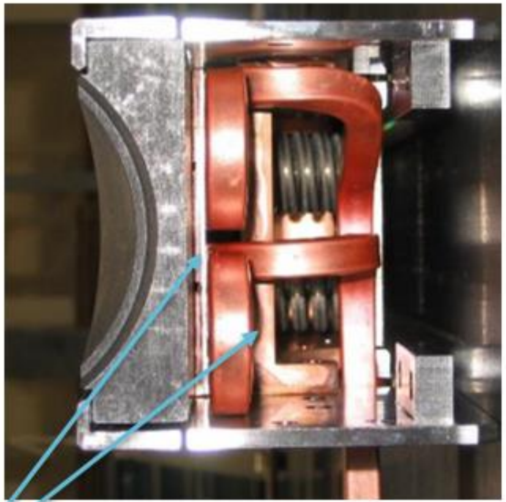


C18150 for TIDVG dump's core & cooling plates

Copper and copper alloys

Generic name	UNS No.	Composition
Wrougl		
Coppers		
High-co		
Brasses		
Leaded		
Tin bras		
Phosphc		
Leaded		
Copper-		
Aluminu		
Silicon		
Other cc		
Copper		
Nickel s		





70Cu-30Ni, C71500
90Cu-10Ni, C70600

C70600 for the cooling circuit of phase II collimators

OFE Copper

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Materials Technical Specification
GS-IS & EN-MME

26.02.2015

Technical Specification

N° 2001 - Ed. 8
EDMS No: 790779

Oxygen-Free Electronic copper
Bars/blanks/ingots

Cu-OFE

This document specifies the CERN technical requirements for Cu-OFE bars/blanks/ingots, equivalent to UNS C10100 Grade 1, according to ASTM B224 with a maximum oxygen content of 5 ppm.

Original : English

2.2. CHEMICAL COMPOSITION

The composition shall conform to the requirements of the UNS C10100 Grade 1 according to the standard ASTM B170.

O_2	0.0005% in mass max.

2.3. HYDROGEN EMBRITTLEMENT

According to ASTM B170 and F68, the material shall be free from hydrogen embrittlement.

Weldability / brazeability

2.6. MECHANICAL PROPERTIES

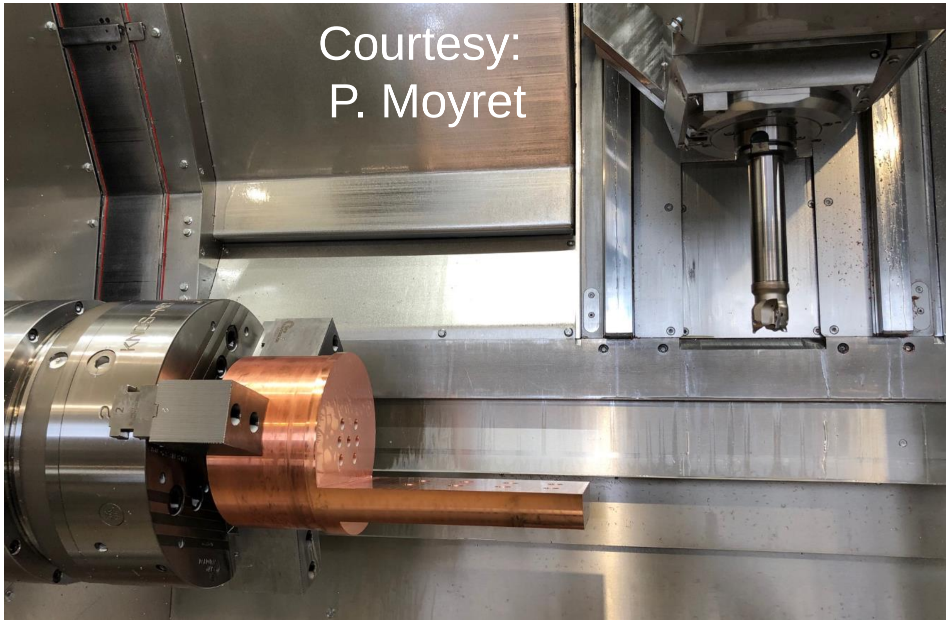
In accordance with the size, the products shall be given the necessary treatment to allow delivery as close as possible to the quarter-hard state, according to ASTM B152 and the required mechanical properties given in the following table.
Tensile testing shall be carried in accordance with ISO 6892-1. Tensile testing must be performed both longitudinal and transverse direction.
At room temperature:

Tensile strength	R_m		240-280* N/mm²
Yield stress	$R_{p0.2\%}$		200-240* N/mm²
Elongation at break	A_5	min.	25*%
Brinell hardness 20 kgf (2 mm ball)	HBS	min.	60*

*Any value out of these ranges shall be agreed between CERN and manufacturer prior to delivery.

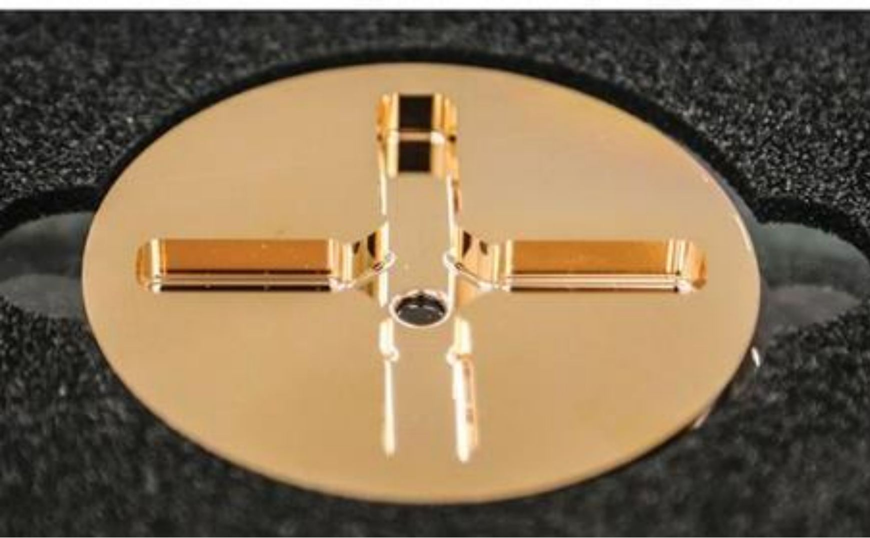
Ease of machining

OFE Copper

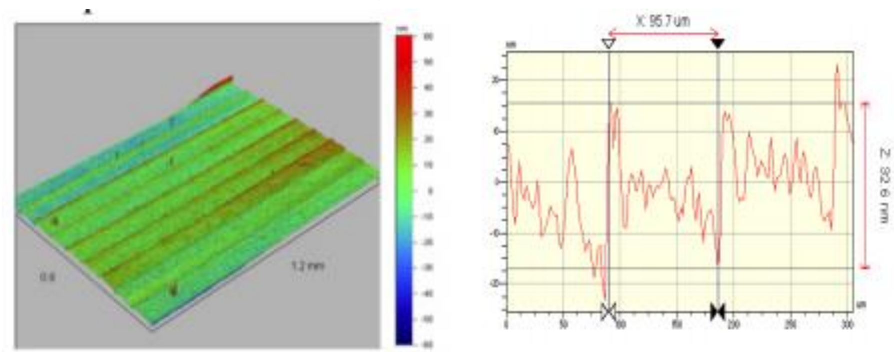


18 kA HL-LHC current lead during machining.

CLIC accelerating structure.
Diamond turning / milling



R_a = 5 nm



Courtesy: S. Atieh

See also →
CAS course on "Mechanical & Materials engineering", J. Tschoepel, Machining

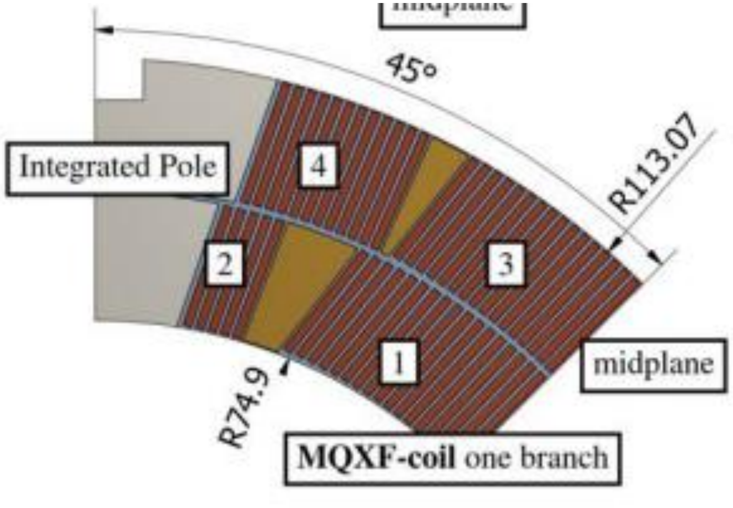
Non – ferrous materials

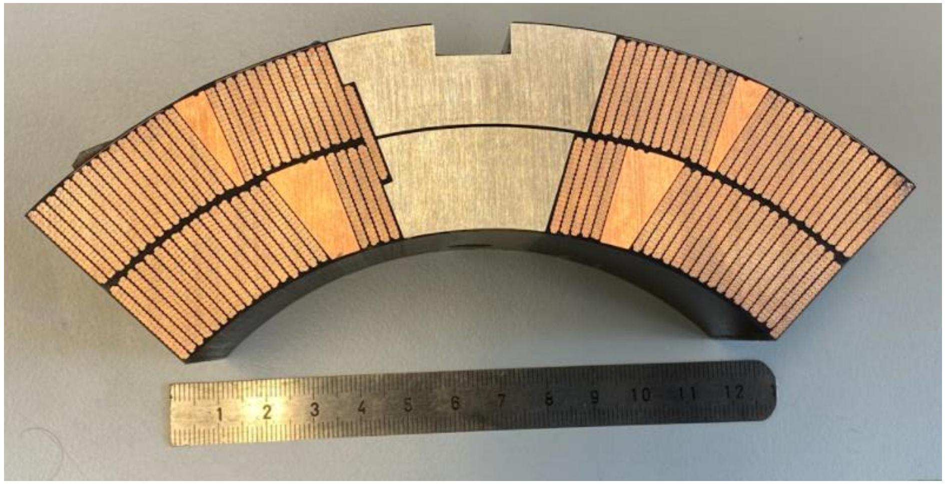
- Titanium
  - The name comes from Titan, son of Gaea.
  - Everyone knows it from the song of David Guetta
  - High corrosion resistance, low density, high mechanical resistance.

If price is not a problem, Ti overwhelms Al in many aspects

Titanium in particle accelerators

- High specific strength.
- Paramagnetic
- Lower thermal expansion / contraction than stainless steel



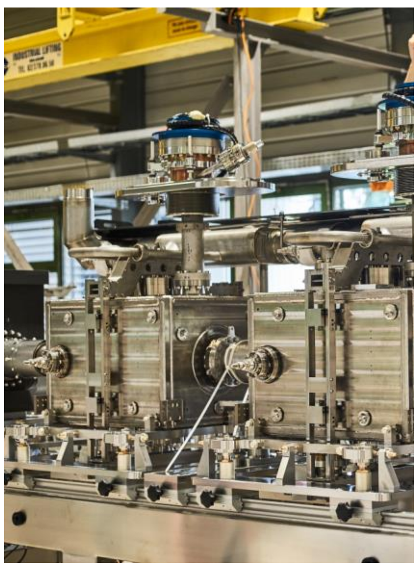


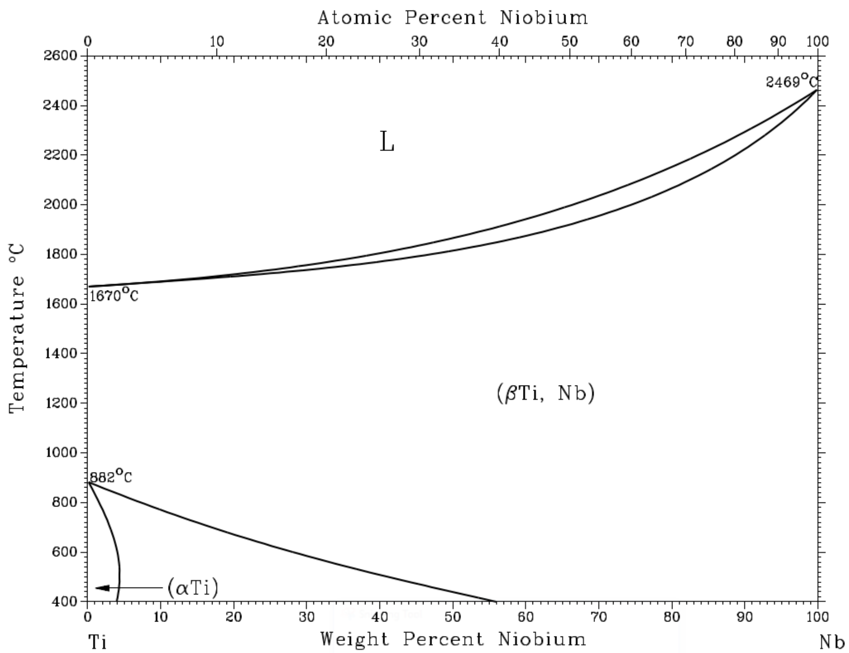
Cross section MQXF. Ti pole

Courtesy: C. Loffler

Titanium in particle accelerators

- Certain grades are ductile and moderately tough at cryogenic temperature.
- Thermal contraction closer to Nb than stainless steel.
- Weldable with Nb (total solubility)

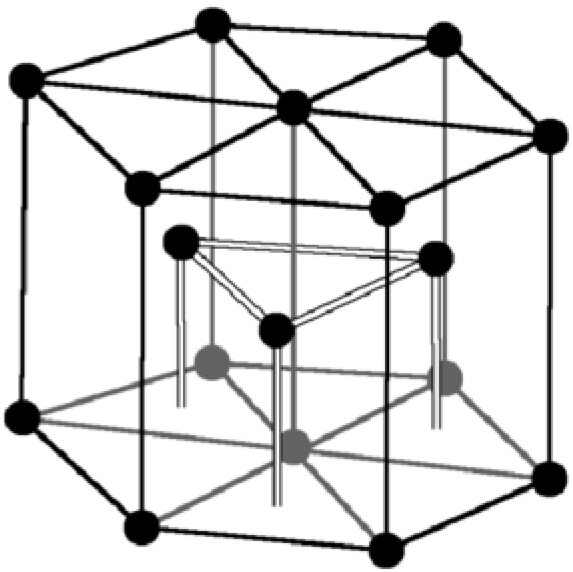




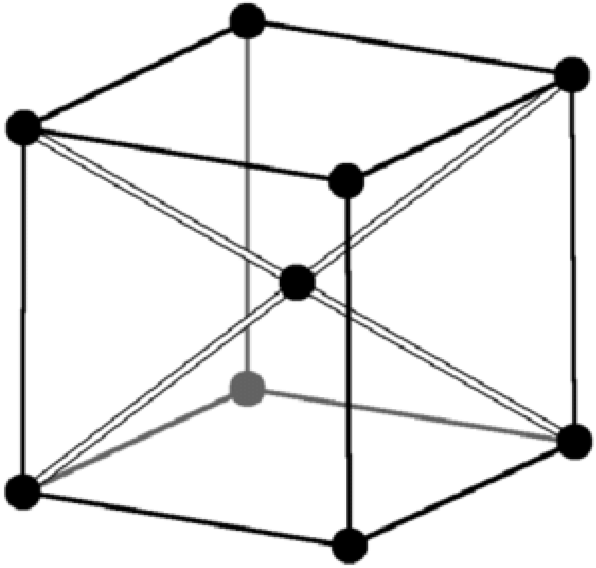
Titanium (II) He tanks of the crab cavities for HL - LHC

Titanium grades

- Microstructures of Ti



α Ti – hexagonal closed packed (HCP)



β Ti – body centred cubic (BCC)

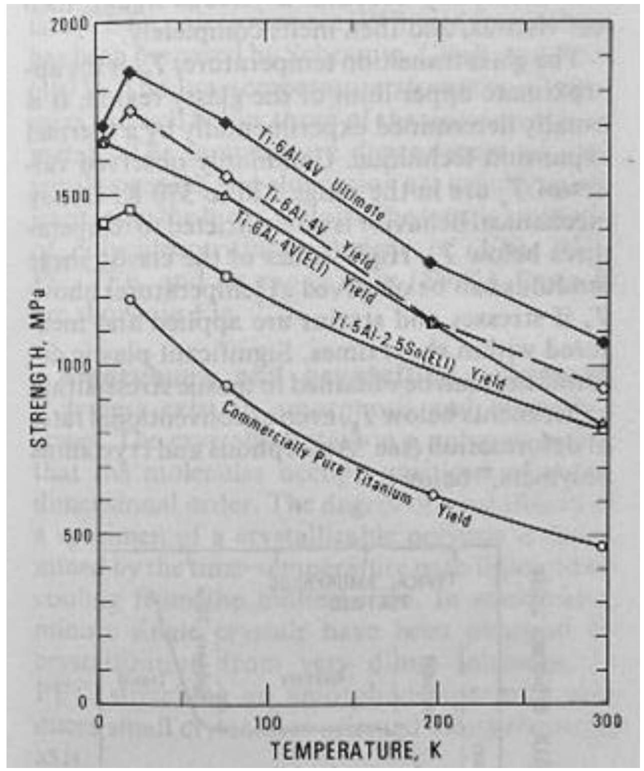
We privilege compact structures (**α – Ti**) for cryogenic application

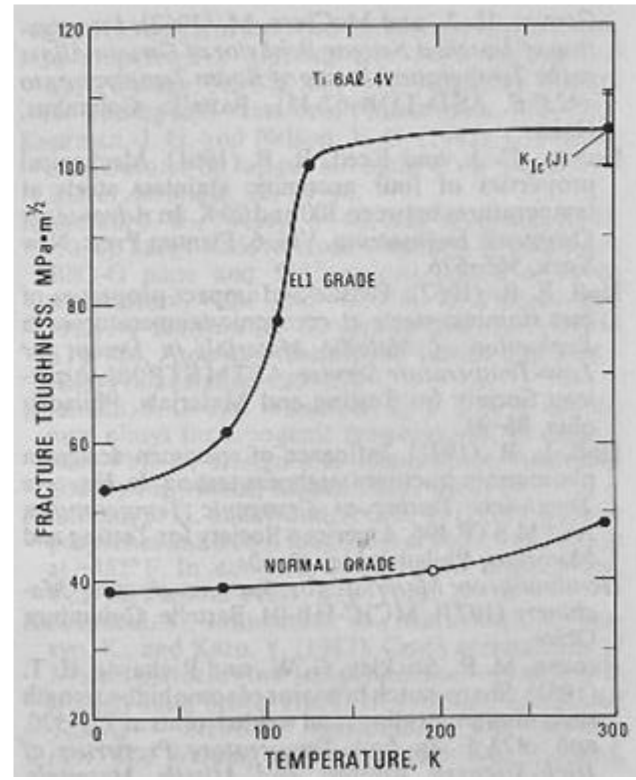
Titanium grades

- Extra – low interstitials (ELI)

At any rate pure titanium was finally produced. But it was only by stretching the point considerably that this metal could be accepted as pure, for it still contained several tenths of a per cent of impurities. Only several tenths, but they were like a fly in the ointment. The impurities made titanium fragile and brittle and unsuitable for machining. It earned a bad fame for being a useless, good-for-nothing metal.

In 1925, the Dutch scientists van Arkel and de Boer decomposed titanium tetrachloride on a heated tungsten wire and obtained high-purity titanium. And then it became clear that Hunter's assertion concerning the brittleness of titanium could not stand up to criticism: the metal produced by van Arkel and de Boer was highly plastic, could be forged like iron and rolled into sheets, strip, wire and even the thinnest foil.





We privilege ELI grades for cryogenic application

Titanium grades

Designation	Tensile strength (min) MPa	Tensile strength (min) ksi	0.2% yield strength (min) MPa	0.2% yield strength (min) ksi	Impurity limits, wt% (max) N	C	H	Fe	O	Nominal composition, wt% Al	Sn	Zr	Mo	Others
Unalloyed grades														
ASTM grade 1														
ASTM grade 2														
ASTM grade 3														
ASTM grade 4														
ASTM grade 7														
ASTM grade 11														
α and near-α alloys														
Ti-0.3Mo-0.8Ni														
Ti-5Al-2.5Sn														
Ti-5Al-2.5Sn-ELI														
Ti-8Al-1Mo-1V														
Ti-6Al-2Sn-4Zr-2Mo														
Ti-6Al-2Nb-1Ta-0.8Mo														
Ti-2.25Al-11Sn-5Zr-1Mo														
Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si														
α-β alloys														
Ti-6Al-4V(a)														
Ti-6Al-4V-ELI(a)														
Ti-6Al-6V-2Sn(a)														
Ti-8Mn(a)														
Ti-7Al-4Mo(a)														
Ti-6Al-2Sn-4Zr-6Mo(b)														
Ti-5Al-2Sn-2Zr-4Mo-4Cr(b)(c)														
Ti-6Al-2Sn-2Zr-2Mo-2Cr(c)														
Ti-3Al-2.5V(d)														
Ti-4Al-4Mo-2Sn-0.5Si														
β alloys														
Ti-10V-2Fe-3Al(a)(c)														
Ti-13V-11Cr-3Al(b)														
Ti-8Mo-8V-2Fe-3Al(b)(c)														
Ti-3Al-8V-6Cr-4Mo-4Zr(a)(c)														
Ti-11.5Mo-6Zr-4.5Sn(a)														
Ti-15V-3Cr-3Al-3Sn														
Ti-15Mo-3Al-2.7Nb-0.2Si														

Pure Ti

He tanks surrounding Crab cavities. Ti grade 2

(a) Mechanical properties given for the annealed condition; may be solution treated and aged to increase strength. (b) Mechanical properties given for the solution-treated-and-aged condition; alloy not normally applied in annealed condition. (c) Semicommercial alloy; mechanical properties and composition limits subject to negotiation with suppliers. (d) Primarily a tubing alloy; may be cold drawn to increase strength. (e) Combined $O_2 + 2N_2 = 0.27\%$. (f) Also solution treated and aged using an alternative aging temperature (480 °C, or 900 °F)

Titanium grades

Designation	Tensile strength (min) MPa	Tensile strength (min) ksi	0.2% yield strength (min) MPa	0.2% yield strength (min) ksi	Impurity limits, wt% (max) N	C	H	Fe	O	Nominal composition, wt% Al	Sn	Zr	Mo	Others
Unalloyed grades														
ASTM grade 1														
ASTM grade 2														
ASTM grade 3														
ASTM grade 4														
ASTM grade 7														
ASTM grade 11														
α and near-α alloys														
Ti-0.3Mo-0.8Ni														
Ti-5Al-2.5Sn														
Ti-5Al-2.5Sn-ELI														
Ti-8Al-1Mo-1V														
Ti-6Al-2Sn-4Zr-2Mo														
Ti-6Al-2Nb-1Ta-0.8Mo														
Ti-2.25Al-11Sn-5Zr-1Mo														
Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si														
α-β alloys														
Ti-6Al-4V(a)														
Ti-6Al-4V-ELI(a)														
Ti-6Al-6V-2Sn(a)														
β alloys														
Ti-10V-2Fe-3Al(a)(c)														
Ti-13V-11Cr-3Al(b)														
Ti-8Mo-8V-2Fe-3Al(b)(c)														
Ti-3Al-8V-6Cr-4Mo-4Zr(a)(c)														
Ti-11.5Mo-6Zr-4.5Sn(a)														
Ti-15V-3Cr-3Al-3Sn														
Ti-15Mo-3Al-2.7Nb-0.2Si														

Grade 5
& Grade 5 ELI
(grade 23)

RF feedthrough flanges of the crab cavities. Ti grade 23

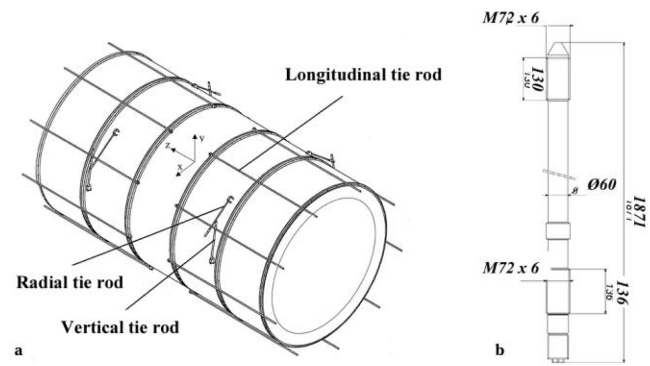
(a) Mechanical properties given for the annealed condition; may be solution treated and aged to increase strength. (b) Mechanical properties given for the solution-treated-and-aged condition; alloy not normally applied in annealed condition. (c) Semicommercial alloy; mechanical properties and composition limits subject to negotiation with suppliers. (d) Primarily a tubing alloy; may be cold drawn to increase strength. (e) Combined $O_2 + 2N_2 = 0.27\%$. (f) Also solution treated and aged using an alternative aging temperature (480 °C, or 900 °F)

Titanium grades

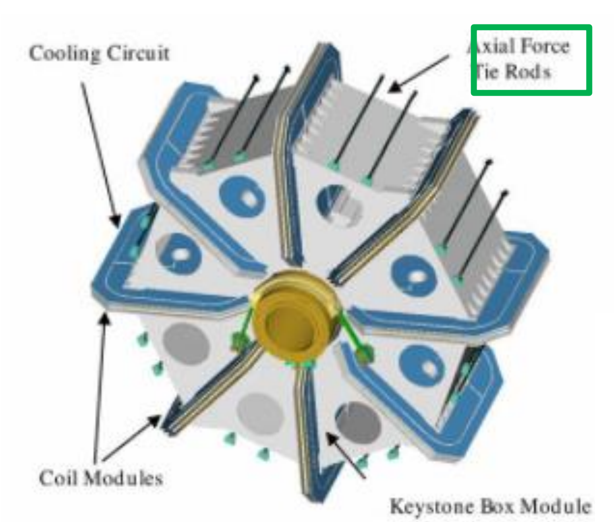
Designation	Tensile strength (min) MPa	Tensile strength (min) ksi	0.2% yield strength (min) MPa	0.2% yield strength (min) ksi
Unalloyed grades				
ASTM grade 1				
ASTM grade 2				
ASTM grade 3				
ASTM grade 4				
ASTM grade 7				
ASTM grade 11				
α and near-α alloys				
Ti-5Al-2.5Sn				
Ti-5Al-2.5Sn-ELI				
α-β alloys				
Ti-6Al-4V(a)				

Grade 6
& Grade 6 ELI

Source: S. Sgobba *et al*. (2003, July). Manufacturing, quality control and assessment of the cryogenic properties of a titanium alloy for application to the coil suspension system of the Compact Muon Solenoid (CMS). In *Proc. 10th World Conference on Titanium* (pp. 13-18).



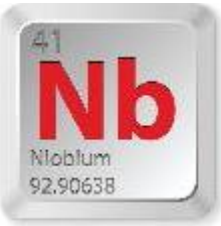
CMS longitudinal tie rods



Axial force tie rods of the ATLAS barrel toroid magnet

Source: P. Jenni (CERN), ATLAS overview, status and plans. Workshop on cooperation in HEP between CERN and China. Beijing, 14 – 15 May 2005.

Non – ferrous materials



- Niobium
  - Element of the periodic system with the highest critical temperature.
  - The name comes from Niobe, the daughter of Tantalus:

Non – ferrous materials

- Niobium
  - Element of the periodic system with the highest critical temperature.
  - The name comes from Niobe, the daughter of Tantalus:
    - Nb is found in combination with Ta (Coltan)
    - You can still find it in old texts by Cb (columbium)

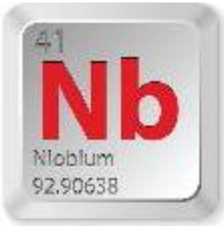
Mineral Coltan, a combination of columbite

3 Teledyne Wah Chang, Albany, Oregon, 97321 P.O.Box 460
"Columbium, Properties, Processes and Products"

9 F.T. Sisco, E. Epremian
"Columbium and Tantalum"
John Wiley and Sons Inc., (New York, London) 1963

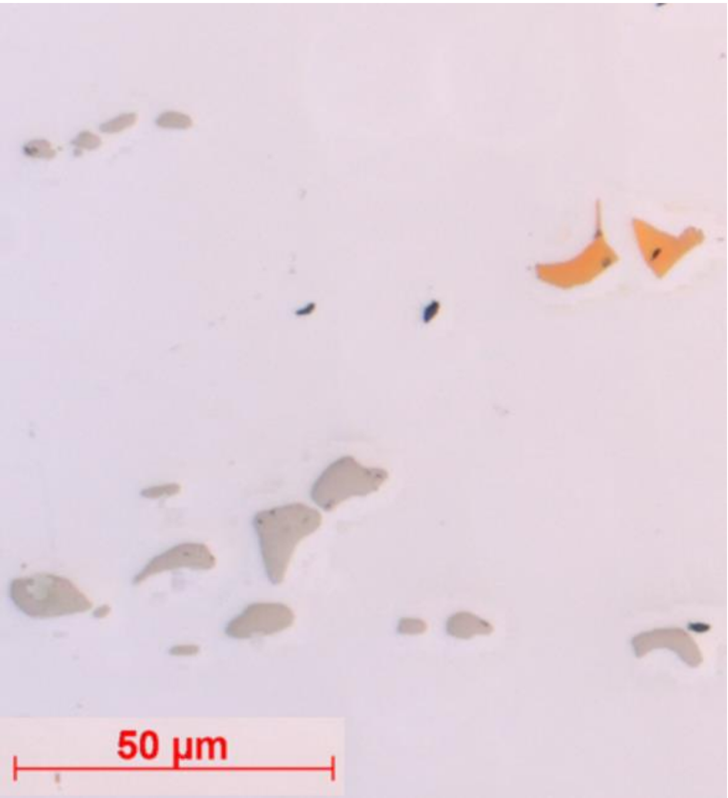
Source: Bauer, W. (1980). Fabrication of niobium cavities. In *Proc. 1st Workshop RF Supercond., M. Kuntze, ed., Karlsruhe* (p. 271).

Families of non – ferrous materials



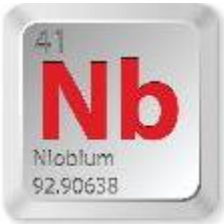
- Niobium
  - 90 % of its production is used to alloy stabilized steel grades or high temperature superalloys.

Inconel 718 for ITER magnet supports.

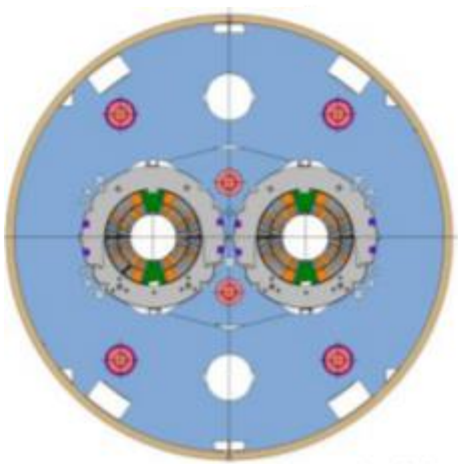


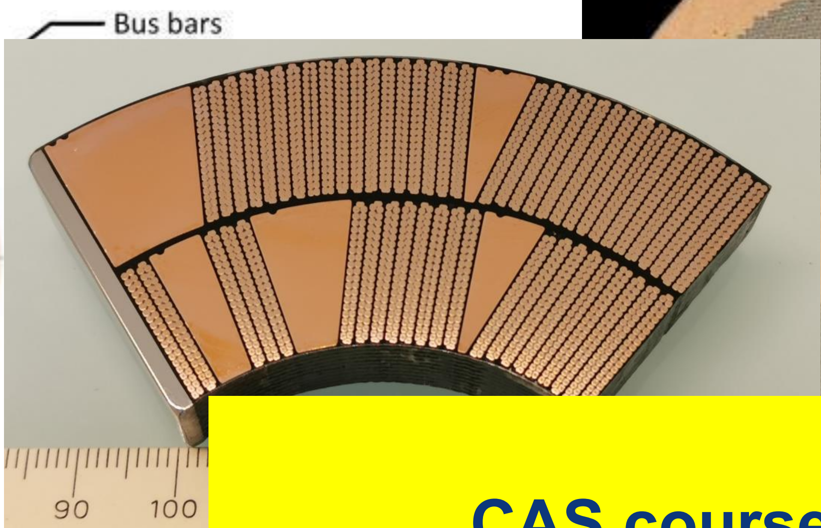
Nb, Ti carbides and nitrides in dark grey and yellow respectively. Inconel 718 for ITER magnet supports.

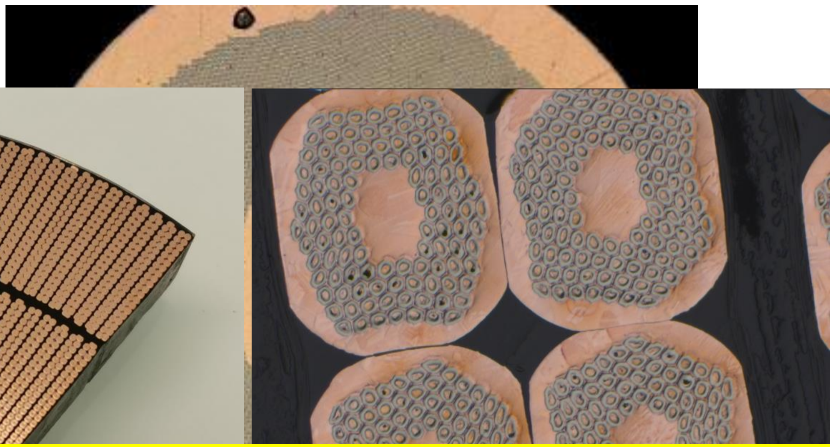
Non – ferrous materials



- Niobium
  - 90 % of its production is used to alloy stabilized steel grades or high temperature superalloys.
  - Superconducting wires for high field magnets (NbTi, Nb_3Sn).







11T dipole

LHC dipole

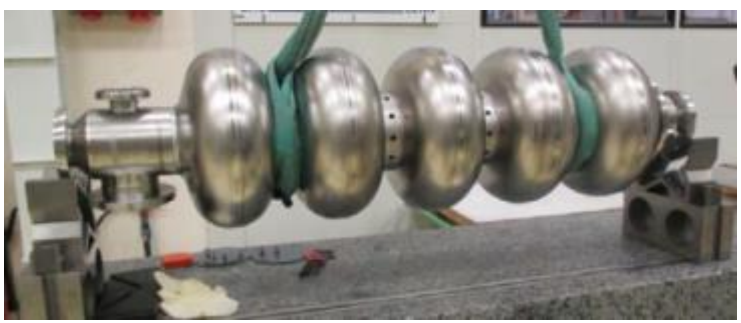
11

See also →
CAS course on "Mechanical & Materials engineering", S. Sanfilippo, Superconducting Magnets

Non – ferrous materials

- Niobium
  - 90 % of its production is used to alloy stabilized steel grades or high temperature superalloys.
  - Superconducting wires for high field magnets (NbTi, Nb_3Sn)
  - Ultrahigh purity Nb

DQW crab cavity



5 cell elliptical cavity

RFD crab cavity

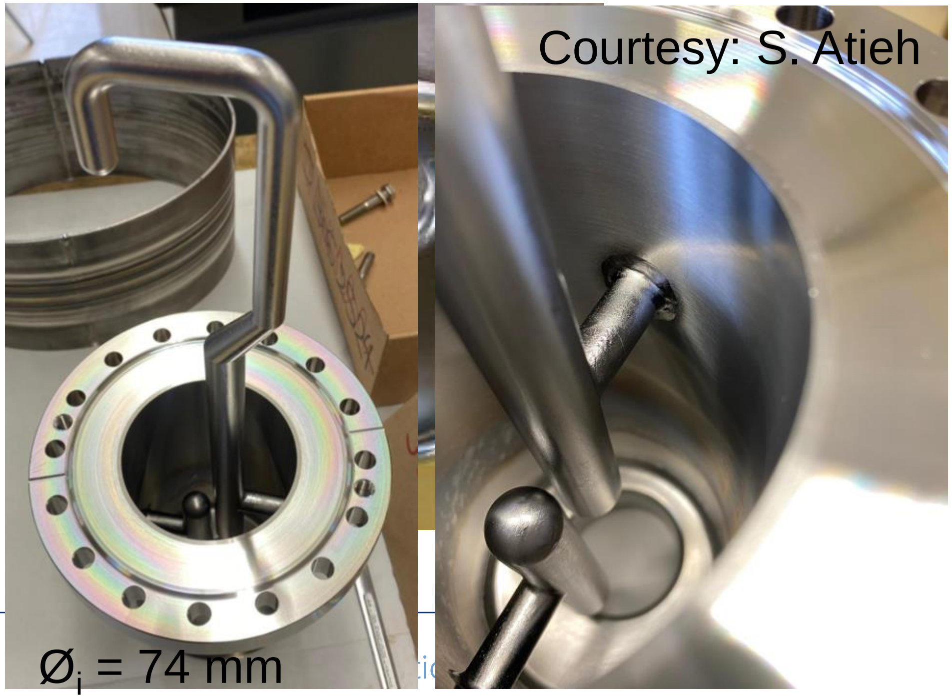
Niobium for SCRF cavities

- High critical temperature (9.2 K)
- High critical magnetic field
- High formability, 'easy' to machine and weldable.
- Available in practically any size

Spoke cavity

Source: Shepard, K. W et al, (1999). Prototype 350 MHz niobium spoke-loaded cavities.

High order mode (HOM) antenna



Niobium grades

- ASTM B392 & B393

Designation: B393 – 18

Standard Specification for
Niobium and Niobium Alloy Strip, Sheet, and Plate[1]

Designation: B392 – 18

Standard Specification for
Niobium and Niobium Alloy Bar, Rod, and Wire[1]

1. Scope

1.1 This specification covers five grades of wrought niobium and niobium alloy strip, sheet, and plate as follows:

1.1.1 *R04200-Type 1*—Reactor grade unalloyed niobium,

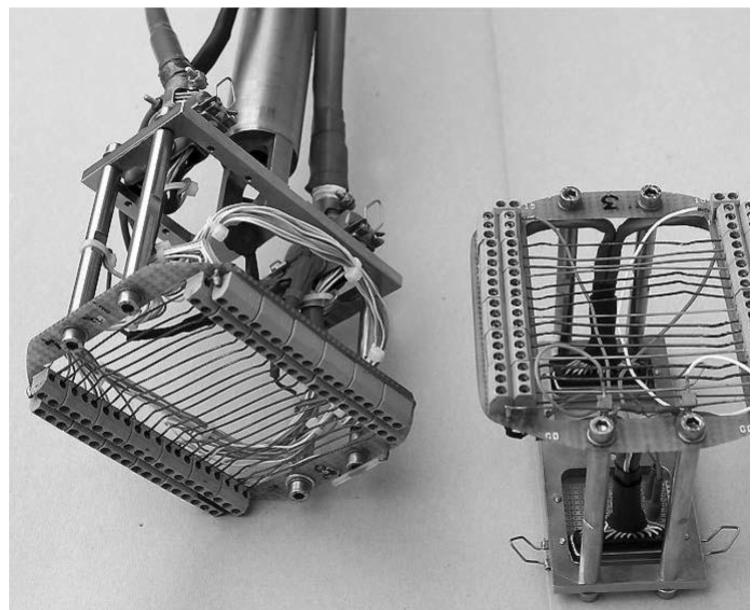
1.1.2 *R04210-Type 2*—Commercial grade unalloyed niobium,

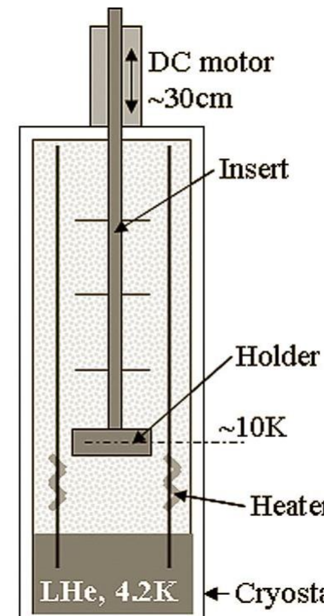
1.1.3 *R04251-Type 3*—Reactor grade niobium alloy containing 1 % zirconium,

1.1.4 *R04261-Type 4*—Commercial grade niobium alloy containing 1 % zirconium, and.

1.1.5 *R04220-Type 5*—RRR grade pure niobium.

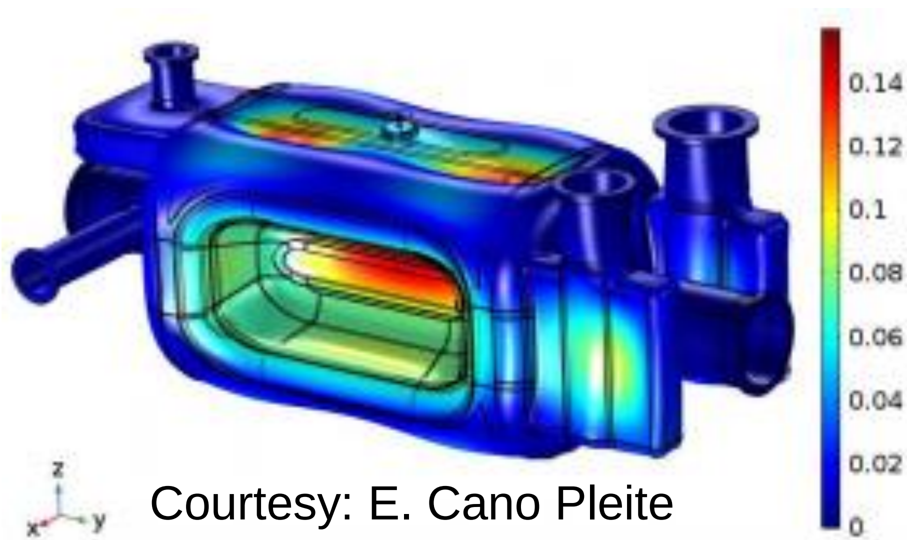
RRR = residual resistivity ratio
An accurate measurement of the purity above 99.999%





Niobium grades & SCRF

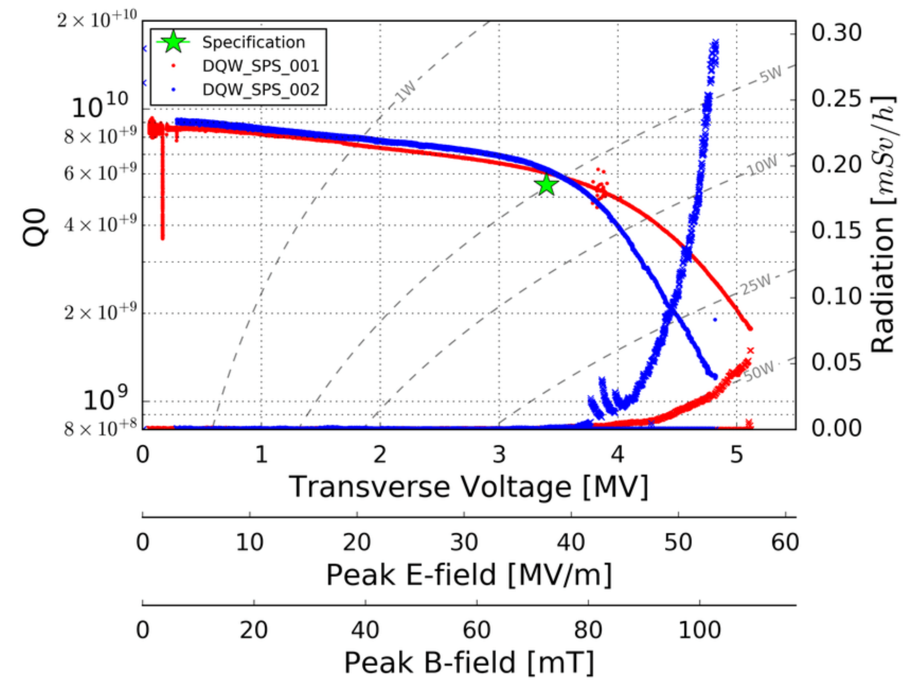
- CERN technical specification
  - Equilibrium between:
    - RF performance
    - Mechanical robustness
    - Material soundness



Courtesy: E. Cano Pleite

Displacements (in mm) of RFD cavity.
1 bar external pressure

RF performance DQW cavities



NDT of Nb technical specification

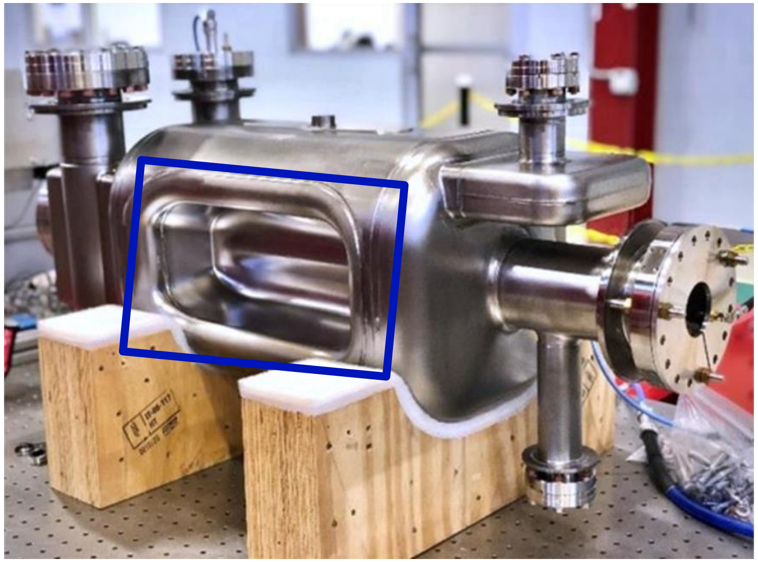
Visual inspection	EN 13018	On final product after all metallurgical processing for every item, 100%
Dye penetrant (optional)	Written procedure, based on EN 10228-2, following approval by CERN	Upon demand by CERN; on final product after all metallurgical processing for every item, 100%
Macro-/ micro-optical	Specimen preparation: ASTM E3 Macro-etching: ASTM E340 Micro-etching: ASTM E407	Upon demand by CERN; on witness sample of final product after all metallurgical processing for every item.
Ultrasonic	Written procedure based on: -EN 10228-4 for the method -EN 4050-4 for acceptance criteria Following approval by CERN	On final product after all metallurgical processing for every item, 100%

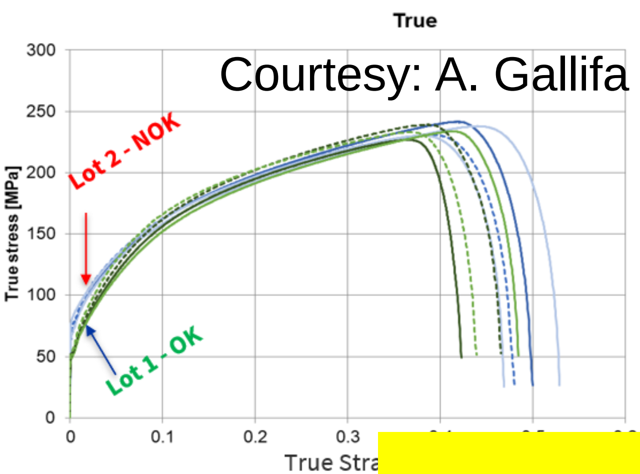
CAS cours
engineeri

SCRF Nb: failure analysis

RFD Pole forming trials held at CERN Main Workshop (May 2022).

- Same material specification
- Same material supplier
- **2 different material lots**
- Same tooling
- Same operators
- Same forming procedure
- Same press machine





Material	$n_{0.02-0.20}$	$R_{p0.2}/R_m$
Lot OK	0.35 – 0.38	0.31 – 0.33
Lot NOK	0.28 – 0.30	0.42 – 0.50

[A. Gallifa Terricabras, et al Optimizing the Manufacture of High-Purity Niobium SRF Cavities Using the Forming Limit Diagram: A Case Study of the HL-LHC Crab Cavities RFD Pole.]

Material that shows bad formability complies with CERN Nb spec. & DESY

Strain hardening co

See also →

CAS course on "Mechanical & Materials engineering", F. Carra, Computational tools

Conclusions

- Key takeaways:
    - Materials are your friends, **get to know them as good as you can.**
    - "A material for an accelerator part is not a mere chemical composition or designation":
        - Specification. Fabrication route. Temper state
        - Controls
        - Price
    - Attention to "the hidden iceberg properties" (e.g. notch sensitivity, strain hardening) and to the butterfly effect.

- The very particular environment of particle accelerators limits the choice.

- Time (and problems) are saved if material selection is integrated from the beginning of the conceptions.
    - Advanced non conventional materials require extensive prior R&D

Thank you for your attention.
Questions?

CERN

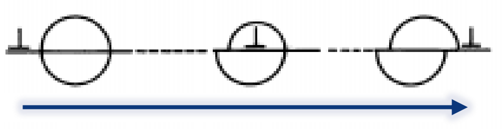
Engineering Department

MECHANICAL & MATERIALS ENGINEERING FOR PARTICLE ACCELERATORS AND DETECTORS

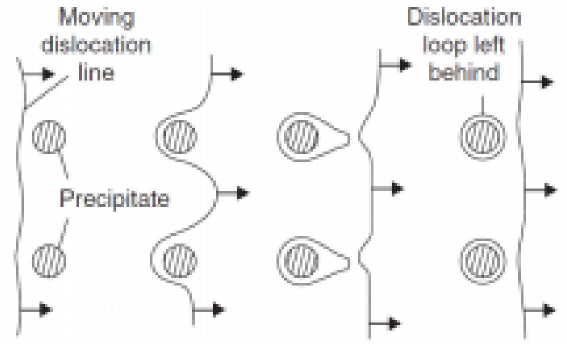
Additional slides

Precipitation strengthening

- Dislocations are the carriers of plastic deformation
- Precipitates hinder dislocation motion. There are 2 types: coherent and incoherent



A dislocation cuts through a coherent particle, i.e. it passes through the precipitate on the same slip plane as in the matrix



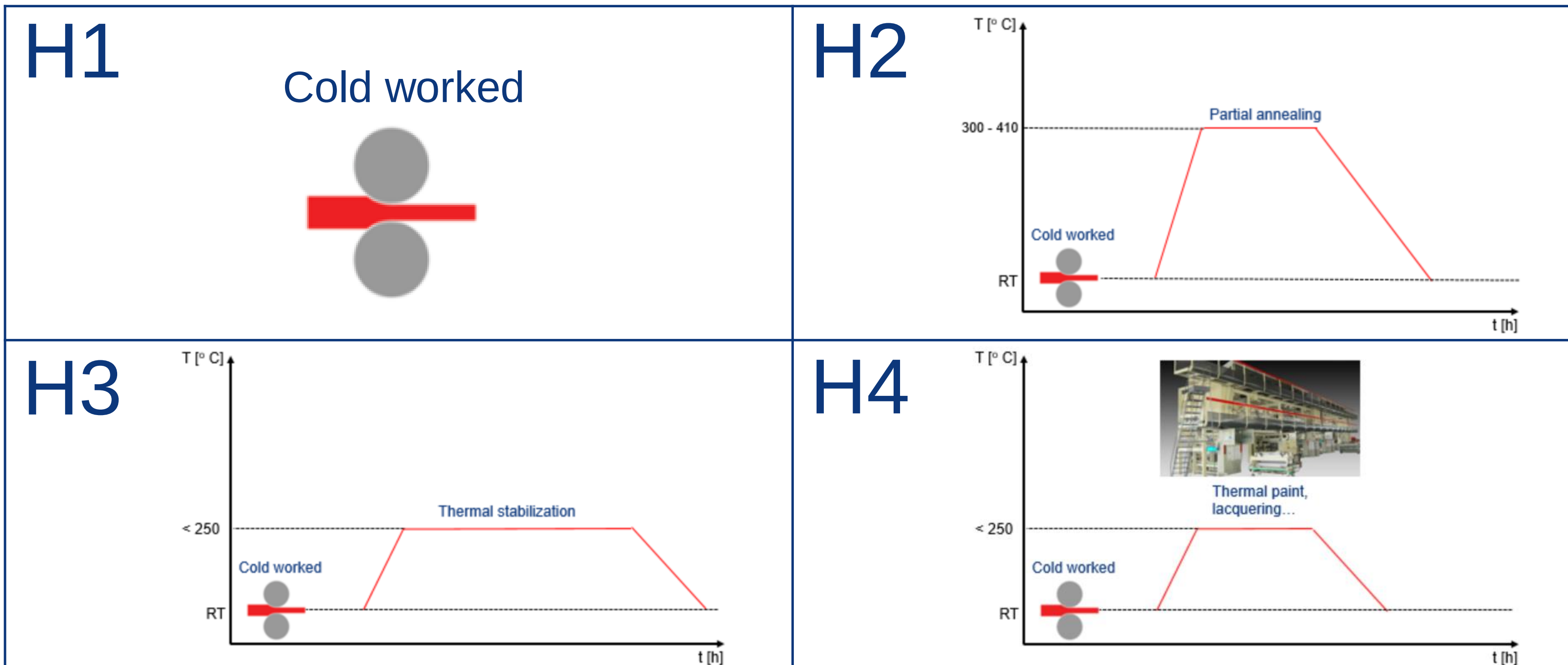
Dislocation bows out between incoherent precipitates

A loop is left around each particle

From R. E. Smallman and A. H. W. Ngan. Physical Metallurgy and Advanced Materials. Elsevier, 2007

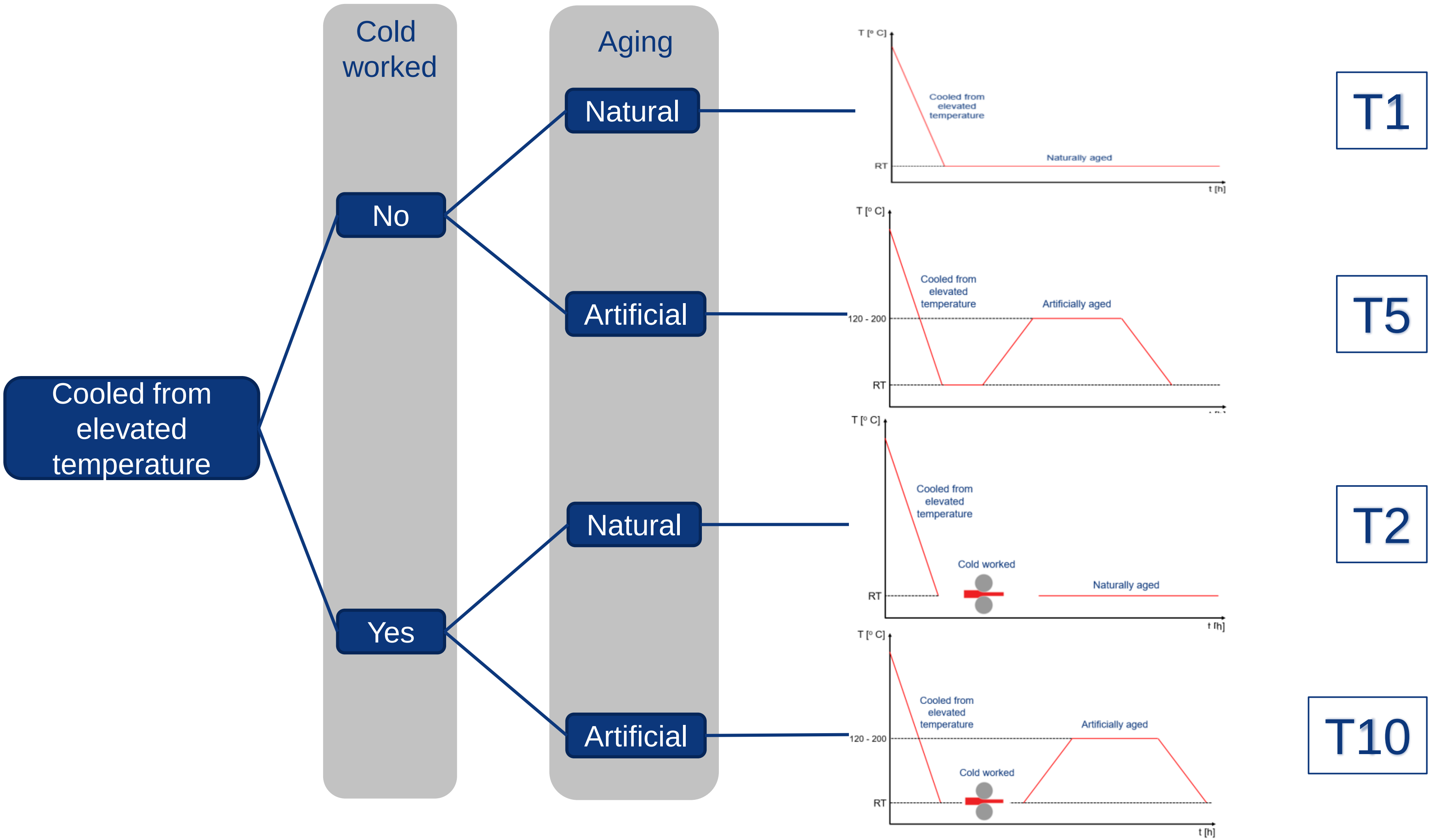
Wrought aluminum alloys: temper states

- **H, strain hardened:** non-heat-treatable wrought alloys that have had their strength increased by strain hardening. H is always followed by two or more digits:
  - The first number after the H tells whether the strain-hardened alloy has been thermally treated:



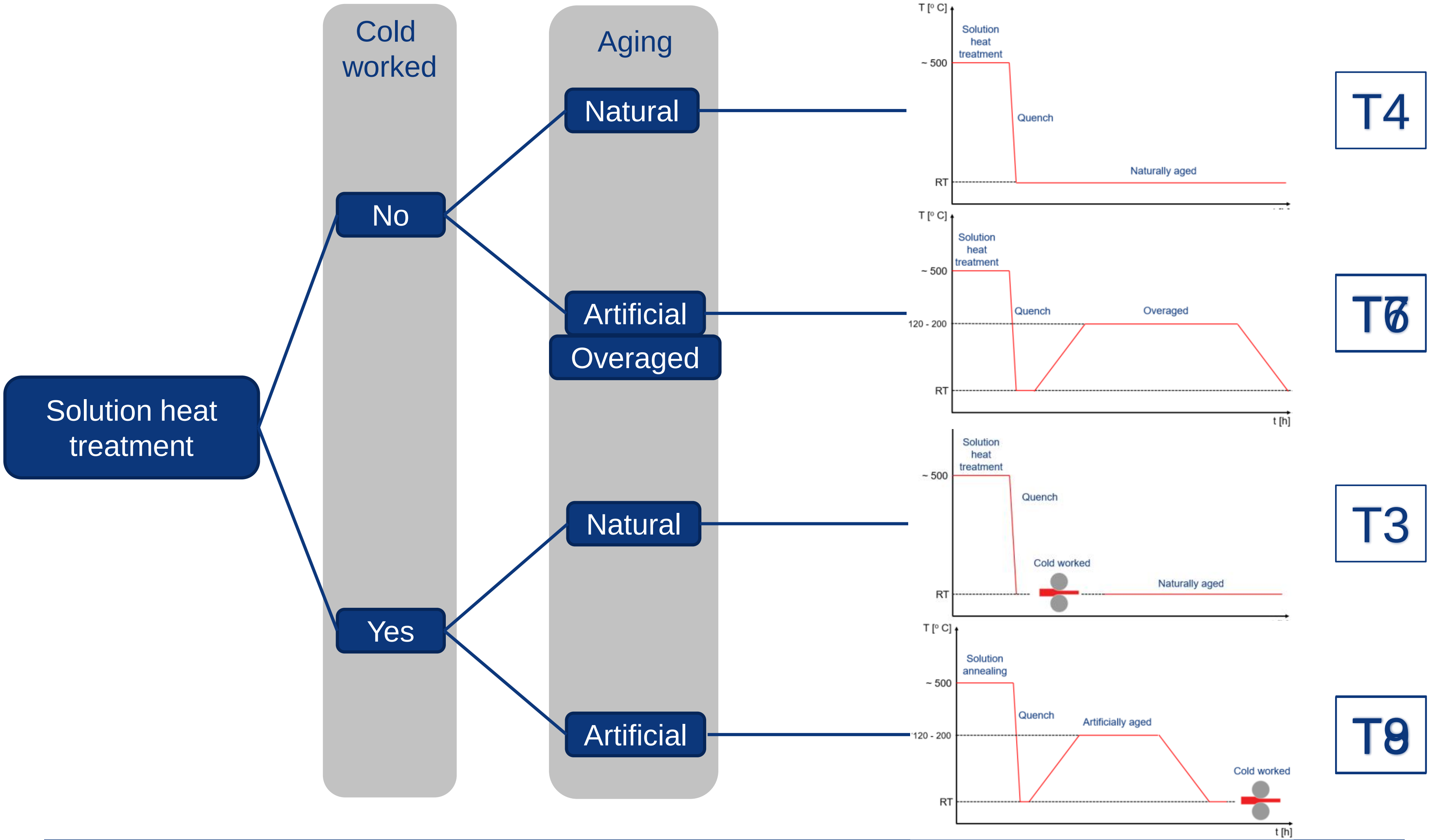
Wrought aluminum alloys: temper states

- T, thermally treated to produce stable tempers:



Wrought aluminum alloys: temper states

- T, thermally treated to produce stable tempers:



Prices

Aluminium and alloys

- Al and Al alloys general purpose → 5 EUR / Kg
- EN AW 2219 forged blanks → 80 EUR / Kg
- Special forgings, EN AW 6061 → 15 EUR / Kg

Coppers

- OFE Cu → 25 - 40 EUR / Kg (3D forged)
- OF Cu→ 10 EUR / Kg (basis)
- CuBe, high (low) Be → 40 - 90 EUR / Kg (strips)
- Glidcop → 55 EUR / Kg

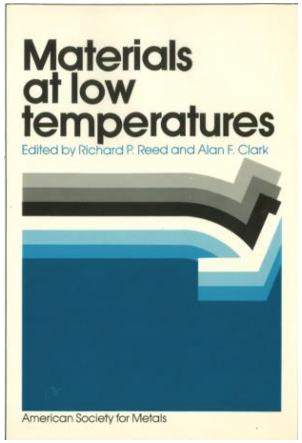
Titanium

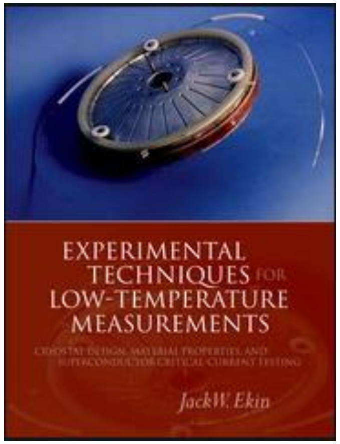
- Grade 2→ 50 EUR / Kg (plates)
- Ti6Al4V (ELI) → 50 (140) EUR / Kg

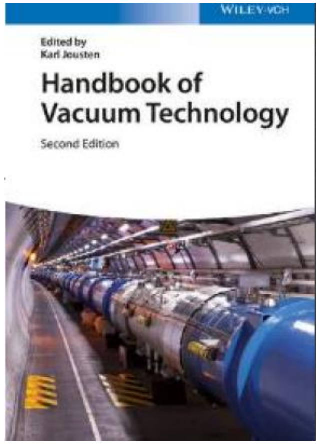
Niobium

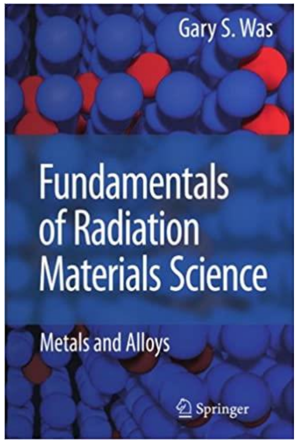
- Nb (RRR 300) → 600 EUR / Kg

Books


Materials at low temperatures
Edited by Richard P. Reed and Alan F. Clark
American Society for Metals


EXPERIMENTAL TECHNIQUES FOR LOW-TEMPERATURE MEASUREMENTS
Jack W. Ekin


WILEY-VCH
Edited by
Karl Jousten
Handbook of Vacuum Technology
Second Edition


Gary S. Was
Fundamentals of Radiation Materials Science
Metals and Alloys
Springer