Non – ferrous materials for particle accelerators

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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).

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

• Electromagnetic fields.

• Radiation.

• High temperatures and high strain rate → beam intercepting devices (dumps, collimators, targets).
Environmental conditions of particle accelerators

- Cryogenic temperatures $\rightarrow$ down to 1.9 K (superfluid helium).
- Ultra – high and extreme vacuum $\rightarrow$ down to $10^{-11}$ mbar.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Vacuum Level [a], [b], [c], [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low or &quot;Rough&quot; Vacuum</td>
<td>133.3 to $1.33 \times 10^{-1}$</td>
</tr>
<tr>
<td>Intermediate or &quot;Soft&quot; Vacuum</td>
<td>$&lt;1.33 \times 10^{-1}$ to $1.33 \times 10^{-3}$</td>
</tr>
<tr>
<td>High or &quot;HV&quot; Vacuum</td>
<td>$&lt;1.33 \times 10^{-3}$ to $1.33 \times 10^{-6}$</td>
</tr>
<tr>
<td>Ultrahigh or &quot;UHV&quot; Vacuum</td>
<td>$&lt;1 \times 10^{-7}$ to $1 \times 10^{-8}$</td>
</tr>
<tr>
<td>Extreme Ultrahigh Vacuum</td>
<td>$&lt; 1 \times 10^{-10}$</td>
</tr>
<tr>
<td>Interstellar Space</td>
<td>$10^{-17}$</td>
</tr>
</tbody>
</table>

Environmental conditions of particle accelerators

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- Electro – magnetic fields.

- Radiation.

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Courtesy of B. Bordini
Environmental conditions of particle accelerators

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Courtesy of E. Lopez Sola
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”:
    
    • Specification. Fabrication route. Temper state
    • Controls
    • Price
  
  • 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 says 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 greater quantities than all other non-ferrous metals combined
Aluminium for particle accelerators

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

Aluminium for particle accelerators

- High thermal and electrical conductivity

MLI (Al coated polyimide) 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

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

- Can be strengthened by a suitable thermal treatment (heat treatable)
- Can only be strengthened by hot or cold working (non – heat treatable)
Wrought aluminum alloys designations

• 1xxx series (pure Al)

Example: CMS conductor
Wrought aluminum alloys designations

• 2xxx series (Al – Cu)
  • Example: EN AW 2219 T6

Example: vacuum chamber bodies. (NEG coated).
Wrought aluminum alloys designations

• 3xxx series (Al – Mn)
  • 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 (up to 12%), cause substantial lowering of the melting point without producing brittleness.
  • Al - Si alloys are used in welding wire and as brazing alloys.
Wrought aluminum alloys designations

• 5xxx series (Al – Mg)
  • EN AW 5083 H321 & H116

Example: Mandrels for CMS coil
Wrought aluminum alloys designations

• 6xxx series (Al – Mg – Si)
  • Example: EN AW 6082 T6

Example: ICARUS neutrino detector
Wrought aluminum alloys designations

• 7xxx series (Al – Zn – Mg)
  • Example: EN AW 7075 T6

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.

| 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 |

| 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: if they lose their temper, they lose 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.

BS EN 515:2017

Aluminium and aluminium alloys — Wrought products — Temper designations
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

Source: Aluminium in Commercial Vehicle – European Aluminium Association – 2011
Wrought aluminum alloys: temper states

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  - 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>
<thead>
<tr>
<th>Ageing</th>
<th>Cold worked</th>
<th>Cooled from shaping process</th>
<th>Furnace solution heat-treated&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>No</td>
<td>T1</td>
<td>T4</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>T2</td>
<td>T3</td>
</tr>
<tr>
<td>artificial</td>
<td>No</td>
<td>T5</td>
<td>T6, T7</td>
</tr>
<tr>
<td></td>
<td>Yes - before ageing</td>
<td>T10</td>
<td>T8</td>
</tr>
<tr>
<td></td>
<td>Yes - after ageing</td>
<td>-</td>
<td>T9</td>
</tr>
</tbody>
</table>

<sup>a</sup> 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

• **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
  - 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
Wrought aluminum alloys: weldability

• Porosity:
  • Gas entrapped from poor shielding
  • Hydrogen from moisture
  • Excessive cooling rate (outgassing)
  • Endogenous (elements such as Na)

Welding qualification EN AW – 6082 T6 (ICARUS project). EDMS 1564550
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 however, EN AW 7075 T651 is sensitive to the presence of sharp notches at 4 K.

<table>
<thead>
<tr>
<th>Material</th>
<th>Direction</th>
<th>E [GPa]</th>
<th>$R_{P0.2}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>A [%]</th>
<th>Z [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 7075 T652</td>
<td>Circumferential</td>
<td>84.0 ± 1.4</td>
<td>634.1 ± 11.5</td>
<td>750.6 ± 9.8</td>
<td>4.1 ± 0.2</td>
<td>12.2 ± 1.1</td>
</tr>
<tr>
<td>AA 7075 T652</td>
<td>Axial</td>
<td>85.2 ± 1.3</td>
<td>539.6 ± 5.2</td>
<td>659.7 ± 5.8</td>
<td>4.5 ± 0.1</td>
<td>12.0 ± 0.2</td>
</tr>
<tr>
<td>AA 7075 T6</td>
<td>R - C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA 7075 T652</td>
<td>C - R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Aluminium alloy shell: failure analysis and material properties at cryogenic temperature. EDMS 2088319
Non – ferrous materials

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

![Copper map and image of mining site](image-url)
Non – ferrous materials

• Copper

  • One of the oldest materials known.

Clay cuneiform tablet complaining about a wrong grade of Cu (1750 BC)
Copper for particle accelerators

- Elastic modulus close to Nb$_3$Sn
- Diamagnetic

Courtesy: M. Crouvizier
Copper for particle accelerators

- Extremely high thermal and electrical conductivity

HIE ISOLDE quarter wave resonator substrate

LHC 400 MHz accelerating cavity

$\varnothing_{\text{equator}} = 693\ \text{mm}$
Copper for particle accelerators

- Ductile and tough down to 4 K

Stress vs strain curve OFE – copper. ¼ hard (H01) temper state.

Face centered cubic (FCC) crystal structure
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

<table>
<thead>
<tr>
<th>Temper Codes</th>
<th>Temper Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>O10</td>
<td>Cast and Annealed (Homogenized)</td>
</tr>
<tr>
<td>O11</td>
<td>As Cast and Precipitation Heat Treated</td>
</tr>
<tr>
<td>O20</td>
<td>Hot Forged and Annealed</td>
</tr>
<tr>
<td>O25</td>
<td>Hot Rolled and Annealed</td>
</tr>
<tr>
<td>O26</td>
<td>Hot Rolled and Temper Annealed</td>
</tr>
<tr>
<td>O30</td>
<td>Hot Extruded and Annealed</td>
</tr>
<tr>
<td>O31</td>
<td>Hot Extruded and Precipitation Heat Treated</td>
</tr>
<tr>
<td>O32</td>
<td>Hot Extruded and Temper Annealed</td>
</tr>
<tr>
<td>O40</td>
<td>Hot Pierced and Annealed</td>
</tr>
<tr>
<td>O50</td>
<td>Light Anneal</td>
</tr>
<tr>
<td>O60</td>
<td>Soft Anneal</td>
</tr>
<tr>
<td>O61</td>
<td>Annealed</td>
</tr>
<tr>
<td>O65</td>
<td>Drawing Anneal</td>
</tr>
<tr>
<td>O68</td>
<td>Deep Drawing Anneal</td>
</tr>
<tr>
<td><strong>O70</strong></td>
<td>Dead Soft Anneal</td>
</tr>
</tbody>
</table>

Cold worked tempers

<table>
<thead>
<tr>
<th>Temper Codes</th>
<th>Temper Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>H00</td>
<td>1/8 Hard</td>
</tr>
<tr>
<td>H01</td>
<td>1/4 Hard</td>
</tr>
<tr>
<td>H02</td>
<td>1/2 Hard</td>
</tr>
<tr>
<td>H03</td>
<td>3/4 Hard</td>
</tr>
<tr>
<td>H04</td>
<td>Hard</td>
</tr>
<tr>
<td><strong>H06</strong></td>
<td>Extra Hard</td>
</tr>
<tr>
<td>H08</td>
<td>Spring</td>
</tr>
<tr>
<td>H10</td>
<td>Extra Spring</td>
</tr>
<tr>
<td>H12</td>
<td>Special Spring</td>
</tr>
<tr>
<td>H13</td>
<td>Ultra Spring</td>
</tr>
<tr>
<td>H14</td>
<td>Super Spring</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temper Codes</th>
<th>Temper Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>H50</td>
<td>Hot Extruded and Drawn</td>
</tr>
<tr>
<td>H52</td>
<td>Hot Pierced and Drawn</td>
</tr>
<tr>
<td>H55</td>
<td>Light Drawn, Light Cold-Worked</td>
</tr>
<tr>
<td>H58</td>
<td>Drawn General Purpose</td>
</tr>
<tr>
<td>H60</td>
<td>Cold Heading, Forming</td>
</tr>
<tr>
<td>H63</td>
<td>Rivet</td>
</tr>
<tr>
<td>H64</td>
<td>Screw</td>
</tr>
<tr>
<td>H66</td>
<td>Bolt</td>
</tr>
<tr>
<td>H70</td>
<td>Bending</td>
</tr>
<tr>
<td>H80</td>
<td>Hard Drawn</td>
</tr>
</tbody>
</table>
Copper and copper alloys

<table>
<thead>
<tr>
<th>Generic name</th>
<th>UNS No.</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wrought alloys</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coppers(a)</td>
<td>C10100–C15815</td>
<td>&gt;99% Cu</td>
</tr>
<tr>
<td>High-copper alloys(b)</td>
<td>C16200–C19900</td>
<td>&gt;96% Cu</td>
</tr>
<tr>
<td>Brasses</td>
<td>C20100–C28000</td>
<td>Cu-Zn</td>
</tr>
<tr>
<td>Leaded brasses</td>
<td>C31200–C38500</td>
<td>Cu-Zn-Pb</td>
</tr>
<tr>
<td>Tin brasses</td>
<td>C40400–C48600</td>
<td>Cu-Zn-Sn-Pb</td>
</tr>
<tr>
<td></td>
<td>C50100–C52480</td>
<td>Cu-Sn-P</td>
</tr>
<tr>
<td></td>
<td>C53400–C54400</td>
<td>Cu-Sn-Pb-P</td>
</tr>
</tbody>
</table>

“electrical coppers”
Cu OFE, C10100
Cu OF, C10200
Cu OFS, C10700

99.8Cu-0.15Al₂O₃, C15715

CERN Phase II collimator.
Glidcop® sectorized jaw
Copper and copper alloys

<table>
<thead>
<tr>
<th>Generic name</th>
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<th>Composition</th>
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<tbody>
<tr>
<td>Wrought alloys</td>
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</tr>
<tr>
<td>Brasses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Led brasses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten blocks</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

CuNi CC
16 bar (30 bar)
5 l/min per line
27 °C max

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

C70600 for the cooling circuit of phase II collimators
OFE Copper

Technical Specification

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

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

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:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>240-280* N/mm²</td>
</tr>
<tr>
<td>Yield stress</td>
<td>200-240* N/mm²</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>25%</td>
</tr>
<tr>
<td>Brinell hardness</td>
<td>60*</td>
</tr>
</tbody>
</table>

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

Ease of machining

Weldability / brazeability

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.
OFE Copper

S. Mathot with a compact RFQ

CLIC accelerating structure. Diamond turning / milling

Courtesy: S. Atieh

$R_a = 5 \text{ nm}$
Non – ferrous materials

• Titanium
  • The name comes from Titan, son of Gaea.
  • 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 close 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

\(\alpha\) Ti – hexagonal closed packed (HCP)  
\(\beta\) Ti – body centred cubic (BCC)

We privilege compact structures (\(\alpha\) – Ti) for cryogenic application
Titanium grades

- Extra – low interstitials (ELI)

We privilege ELI grades for cryogenic application
### Titanium grades

<table>
<thead>
<tr>
<th>Designation</th>
<th>Tensile strength (min)</th>
<th>0.2% yield strength (min)</th>
<th>Impurity limits, wt% (max)</th>
<th>Nominal composition, wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>ksi</td>
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<tr>
<td>Unalloyed grades</td>
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<tr>
<td>ASTM grade 2</td>
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</table>

- **Pure Ti**
- **He tanks surrounding Crab cavities. Ti grade 2**

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

<table>
<thead>
<tr>
<th>Designation</th>
<th>Tensile strength (min)</th>
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<tbody>
<tr>
<td></td>
<td>MPa  ksi</td>
<td>MPa  ksi</td>
<td>N   C   H   Fe   O</td>
<td>Al  Sn  Zr  Mo  Others</td>
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<tr>
<td>Unalloyed grades</td>
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<td>ASTM grade 1</td>
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<td>ASTM grade 2</td>
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<td>ASTM grade 11</td>
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<tr>
<td>α and near-α alloys</td>
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<tr>
<td>Ti-0.3Mo-0.8Ni</td>
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<tr>
<td>Ti-5Al-2.5Sn</td>
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<tr>
<td>Ti-5Al-2.5Sn-ELI</td>
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<td>Ti-8Al-1Mo-1V</td>
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<td>Ti-6Al-2Sn-4Zr-2Mo</td>
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<td>Ti-6Al-2Nb-1Ta-0.8Mo</td>
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<td>Ti-2.25Al-11Sn-5Zr-1Mo</td>
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<td>Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si</td>
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<td>α-β alloys</td>
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<td>Ti-6Al-4V(a)</td>
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<td>Ti-6Al-4V-ELI(a)</td>
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<tr>
<td>Ti-6Al-6V-2Sn(a)</td>
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</tbody>
</table>

Grade 5 & Grade 5 ELI (grade 23)

RF feedthrough flanges of the crab cavities.
Ti grade 23
Titanium grades

<table>
<thead>
<tr>
<th>Designation</th>
<th>Tensile strength (min) MPa</th>
<th>0.2% yield strength (min) MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unalloyed grades</td>
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<tr>
<td>ASTM grade 1</td>
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<td>ASTM grade 2</td>
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<td>ASTM grade 3</td>
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<td>ASTM grade 10</td>
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<tr>
<td>Ti-6Al-2.5Sn</td>
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<tr>
<td>Ti-6Al-2.5Sn-ELI</td>
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<tr>
<td>Ti-6Al-4V</td>
<td>780</td>
<td>600</td>
</tr>
</tbody>
</table>

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).

Axial force tie rods of the ATLAS barrel toroid magnet


CMS longitudinal tie rods

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).
Non – ferrous materials

• Niobium

• Element of the periodic system with the highest critical temperature.

• The name comes from Niobe, the daughter of Tantalus:

But the Greek queen

Not the one in the movie ‘The Matrix’
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

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.
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, Nb₃Sn).

LHC dipole
11T dipole
11T dipole’s coil section
NbTi wire
Nb₃Sn wires
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, Nb₃Sn)
  • Ultrahigh purity Nb

DQW crab cavity

5 cell elliptical cavity

RFD crab cavity

11-06-2021
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


High order mode (HOM) antenna

Courtesy: S. Atieh

$\Omega_o = 440 \text{ mm}$

$\Omega_i = 74 \text{ mm}$
Niobium grades

- ASTM B392 & B393

**RRR = residual resistivity ratio**
An accurate measurement of the purity above 99.999%
Niobium grades & SCRF

- CERN technical specification
  (based on DESY’s technical specification)
  - Equilibrium between:
    - RF performance
    - Mechanical robustness
    - Material soundness

RF performance DQW cavities

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

NDT of Nb technical specification

Courtesy: E. Cano Pleite
Conclusions

• The golden rule to be remembered:
  • “A material for an accelerator part is not a mere chemical composition or designation”:
    • Specification. Fabrication route. Temper state
    • Controls
    • Price
  • Attention to less known properties (e.g. notch sensitivity)

• 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 imply extensive prior R&D
Thank you for your attention
Questions?