Materials of high vacuum technology, an overview

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CERN
1. General rules for the selection and specification of quality materials for vacuum technology; an historical perspective

2. The main families of metals and alloys used in vacuum technology: from production processes to the final inspections
   - a) Stainless steels
   - b) Aluminium and alloys
   - c) Copper and alloys
   - d) Other and less common materials (and processes)

⇒ Discussion of

   Examples of application
   Aspects related to manufacturing, joining, near net shaping techniques
   Failure analyses, including corrosion issues...

3. Conclusions
General rules

1. Ease of degassing
2. Adequate strength at high as well as low T
3. Thermal expansion coefficients
4. The purity of the material
5. Exact knowledge of the material properties, critical selection, careful control
6. Very constant properties of the raw materials, to be specially prepared
7. Ease of fabrication and cost of vacuum materials are often of secondary importance (sic!)

(From Materials of High Vacuum technology, Pergamon Press, 1966)

General rules

1. Ease of machinability and joining
2. Sealing glasses, ceramics and other insulators
3. Materials to yield low outgassing rates
4. Bakeability
5. Interdependence of cleaning, joining, construction and application
6. Stainless steel is the dominant material

A look into the historical developments of materials for vacuum devices


K. Diels, Werkstoffe und Werkstoffverbindungen in der Vakuum-Technik, Essen, Classen, 1968


2.a Stainless steels

Stainless steel: iron alloys containing a minimum of approx. 11% Cr

Fig. 2 The iron-chromium phase diagram. (From “Metals Handbook,” vol. 8, p. 291, 8th ed., American Society for Metals, Metals Park, Ohio.)
2.a Stainless steels, introduction and ferritic grades

- Ferritic grades, 14.5% to 27% Cr
- Resistant to corrosion
- Subject to grain growth during firing
- Ferromagnetic at RT and below
- Brittle at low T
2.a Stainless steels, martensitic grades

- martensitic grades, Cr between 11.5% and 18%, C up to 1.2%
- hardenable by HT
- high strength
- ferromagnetic at RT
- brittle at low T

C added to increase the "austenitic loop"

Stainless steels, austenitic grades formed by an addition of a fcc element (Ni, Mn) to the FeCr system can be suppressed by transformation to martensite can be reduced or suppressed (increasing alloying elements) Ni, Mn (C, N...). AISI 304, the "18-8" or "18-10" stainless (18% Cr, 8-10% Ni).
vacuum applications: 304L, 316L, 316LN

2.a Stainless steels, austenitic grades, low C

Why low C (304L, 316L, 316LN)?
"Sensitization" of base metal, HAZs and welds

M$_{23}$C$_6$ (Cr$_{23}$C$_6$)

Cr depleted zones

Fig. 55 Appearance of Type 304 stainless steel (0.065% carbon) sensitized for 6 days (144 h) at various temperatures. Specimens etched electrolytically in 10% oxalic acid. 128 (a) 550°C (1022°F). 750x. (b) 650°C (1202°F). 750x. (c) 750°C (1382°F). 750x. (d) 850°C (1562°F). 750x.

A.K. Jha et al., Engineering Failure Analysis, in press

D. Peckner, I.M. Bernstein, 1977
UNS 21904, Cr20Ni7Mn9N, C=0.03%

stabilized grades: 321, 347, 316Ti
Metallographic observations of 316LN leaking bellow
Oversized (1, 2, 3) and thick (4) B type inclusions up to class 2
Follow-up meeting of
EB Cooling Blocks MPR

Conclusions

Stainless steels, inclusions

RD ⇔
2.a Stainless steels, inclusion content

For any wrought product (plate, tube, bar), an unfavourable inclusions alignment will be anyway present in the rolling or drawing direction.

Multidirectional forging might not be applicable due to the diameter needed of the capable product.
Investigations of TS-MME-MM on the materials supplied to date

EDMS 673464:
27 mm outer Ø, 4 mm wall thickness
316L tubes
sample 1 delivered 14/10/05

Original magnification: 100 x
inclusion type B class 2½
3.2.2 Inclusions

Amount and definition shall meet standard ASTM E45-97e1, method D.

The class of inclusions shall be at most 1 for types A, B and C and at most 1.5 for type D.

The tolerance for acceptance may be a half-class above the set limit to the extent of 2% of the fields counted.

FORGED ROUND BAR
FOR VACUUM APPLICATIONS
STAINLESS STEEL
TYPE X2CrNiMoN17-13-3 (1.4429, AISI 316LN)
10^{-5} \text{ torr l/sec}

courtesy of A. Poncet
Electrical Arc Furnace: functions solely as a melt-down unit. Tapped as free as possible of slag into the ladle. Degassing, deoxidation (down to 8-15 ppm), dehydrogenisation (down to 0.8 ppm), desulfurization (from 240 ppm to 10 ppm), removal of Non-Metallic Inclusions (NMI). Pure gaseous oxygen blown onto the metal; for a pressure of 0.02 bar abs., C down to 0.015 % before Cr losses begin. Metallic Inclusions (NMI)
Variant:

PESR, at a working pressure of 42 bars, to allow nitrogen alloying
2.a Stainless steels, welding metallurgy

<table>
<thead>
<tr>
<th>Element</th>
<th>Content wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>16.00 - 18.50*</td>
</tr>
<tr>
<td>Ni</td>
<td>12.00 - 14.00*</td>
</tr>
<tr>
<td>C</td>
<td>0.030 max.</td>
</tr>
<tr>
<td>Si</td>
<td>1.00 max.</td>
</tr>
<tr>
<td>Mn</td>
<td>2.00 max.</td>
</tr>
<tr>
<td>Mo</td>
<td>2.00 - 3.00*</td>
</tr>
<tr>
<td>N</td>
<td>0.14 - 0.20*</td>
</tr>
<tr>
<td>P</td>
<td>0.045 max.</td>
</tr>
<tr>
<td>S</td>
<td>0.015 max.</td>
</tr>
<tr>
<td>Fe</td>
<td>Remainder</td>
</tr>
</tbody>
</table>

CERN 316LN

- γ-stabilizers: Ni + 30 x % C, 30 x % Mn, 0.5 x % Mn
- δ-stabilizers: Mn + 2.00 - 3.00* or Mo + 2.00 - 3.00*
Schaeffler equivalent formulae for $Cr_{eq}$ and $Ni_{eq}$

\[
Cr_{eq} = Cr + 1.5Si + 1.37Mo
\]

\[
Ni_{eq} = Ni + 0.31Mn + 22C + 14.2N
\]
2.a Stainless steels, welding metallurgy
2.a Stainless steels, effect of delta-ferrite on magnetic susceptibility

S. SGOBBA, C. BOUDOT, Matériaux et Techniques 95, n°11-12, p. 23 (1997).
Other phase transformation and their influence on magnetic behaviour

Martensitic transformations

Antiferromagnetic transitions

see:


2) S. Sgobba, Magnetic Properties of Materials and Phase Transformations, CERN Technical training EMAG-2005, 4-14 April 2005,
2.a Stainless steels, brazeability to ceramics

- High T (> 500 °C) vacuum brazing
- Metal/ceramic matching expansion coefficient (Kovar), and/or
- Ductility of the "unmatched" metal
EB welding

SS
Kovar
Al$_2$O$_3$

for application to LEIR

- **Anisotropy of ceramics**

- **96% Al$_2$O$_3$**, UTS compression, RT = 2070 MPa
tensile, RT = 180 MPa
tensile, 1100 °C = 90 MPa
### Wrought Al Alloy Designations

#### Alloys

<table>
<thead>
<tr>
<th>Alloy Group</th>
<th>Designation AA</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure aluminium</td>
<td>1xxx series</td>
<td>EN AW-2219</td>
</tr>
<tr>
<td>Al-Cu</td>
<td>2xxx series</td>
<td>EN AW-3003</td>
</tr>
<tr>
<td>Al-Mn</td>
<td>3xxx series</td>
<td>weld fillers</td>
</tr>
<tr>
<td>Al-Si</td>
<td>4xxx series</td>
<td>EN AW-5083</td>
</tr>
<tr>
<td>Al-Mg</td>
<td>5xxx series</td>
<td>EN AW-6082</td>
</tr>
<tr>
<td>Al-Mg-Si</td>
<td>6xxx series</td>
<td>(6061)</td>
</tr>
<tr>
<td>Al-Zn</td>
<td>7xxx series</td>
<td>EN AW-2101</td>
</tr>
<tr>
<td>Al+other elements</td>
<td>8xxx series</td>
<td>6201, 6262, 6463</td>
</tr>
</tbody>
</table>

#### Table 2: Weldability of aluminum alloys by the gas metal-arc and gas tungsten-arc processes

<table>
<thead>
<tr>
<th>Weldability</th>
<th>Designations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readily Weldable</td>
<td>Wrought alloys: 1060, 1100, 1350, 2219, 3003, 3004, 3105, 5005, 5050, 5052, 5056, 5083, 5086, 5154, 5252, 5254, 5454, 5456, 5457, 5652, 5657, 6061, 6063, 6070, 6101, 6201, 6262, 6463, 7005</td>
</tr>
<tr>
<td>Weldable in Most Applications (a)</td>
<td>Wrought alloys: 2014, 4032, 6066, Casting alloys: 208.0, 308.0, 319.0, 332.0, 413.0, 712.0</td>
</tr>
<tr>
<td>Limited Weldability (b)</td>
<td>Wrought alloys: 2024, 2218, 2618, Casting alloys: 213.0, 222.0, 295.0, 296.0, 333.0, 336.0, 354.0, 512.0, 513.0, 514.0, Die casting alloys</td>
</tr>
<tr>
<td>Welding Not Recommended</td>
<td>Wrought alloys: 2011, 7075, 7178, Casting alloys: 242.0, 520.0, 535.0, 705.0, 707.0, 710.0, 711.0, 713.0, 771.0</td>
</tr>
</tbody>
</table>

(a) May require special techniques for some applications. (b) Require special techniques.
## Legend

Filler alloys are rated on the following characteristics:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>Ease of welding (relative freedom from weld cracking.)</td>
</tr>
<tr>
<td>S</td>
<td>Strength of welded joint (&quot;as welded&quot; condition.) (Rating applies particularly to fillet welds. All rods and electrodes rated will develop the specified minimum strengths for butt welds.)</td>
</tr>
<tr>
<td>D</td>
<td>Ductility. (Rating is based upon free bend elongation of the weld.)</td>
</tr>
<tr>
<td>C</td>
<td>Corrosion resistance in continuous or alternate immersion in fresh or salt water.</td>
</tr>
<tr>
<td>T</td>
<td>Recommended for service at sustained temperatures above $65.5^\circ\text{C}(150^\circ\text{F}).</td>
</tr>
<tr>
<td>M</td>
<td>Colour match after anodizing.</td>
</tr>
</tbody>
</table>

- A, B, C and D are relative ratings in decreasing order of merit. The ratings have relative meaning only within a given block.
- Combinations having no rating are not usually recommended.
- Ratings do not cover these alloys when heat-treated after welding.

### Table

<table>
<thead>
<tr>
<th>Base Alloys</th>
<th>Characteristics</th>
<th>1066 EC</th>
<th>1100</th>
<th>2014, 2026</th>
<th>2003, ACLAD 3003</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>WS DCT M</td>
<td>WS DCT M</td>
<td>WS DCT M</td>
<td>WS DCT M</td>
</tr>
<tr>
<td>319.0, 332.0,</td>
<td></td>
<td>B AAAAA</td>
<td>B AAAAA</td>
<td>B AAAAA</td>
<td>B AAAAA</td>
</tr>
<tr>
<td>354.0, 355.0,</td>
<td></td>
<td>A BAAAA</td>
<td>C C B C A</td>
<td>C C B C A</td>
<td>C C B C A</td>
</tr>
<tr>
<td>C355.0, 380.0</td>
<td></td>
<td>A A B A A</td>
<td>A A B A A</td>
<td>A A B A A</td>
<td>A A B A A</td>
</tr>
<tr>
<td>413.0, 443.0,</td>
<td></td>
<td>A A A A A</td>
<td>A A A A A</td>
<td>A A A A A</td>
<td>A A A A A</td>
</tr>
<tr>
<td>444.0, 356.0,</td>
<td></td>
<td>A A B A A</td>
<td>A A B A A</td>
<td>A A B A A</td>
<td>A A B A A</td>
</tr>
<tr>
<td>A356.0, A357.0,</td>
<td></td>
<td>A A B A A</td>
<td>A A B A A</td>
<td>A A B A A</td>
<td>A A B A A</td>
</tr>
<tr>
<td>359.0</td>
<td></td>
<td>S354</td>
<td>S354</td>
<td>S354</td>
<td>S354</td>
</tr>
<tr>
<td>4043, 4145, 5183, 5354, 5554, 5654</td>
<td>B A B A A</td>
<td>A B A A</td>
<td>A B A A</td>
<td>A B A A</td>
<td>A B A A</td>
</tr>
<tr>
<td>6005, 6063, 6101, 6151, 6201, 6351, 6391</td>
<td>A C A A</td>
<td>A C A A</td>
<td>A A B A</td>
<td>A A B A</td>
<td>A A B A</td>
</tr>
</tbody>
</table>

30/05/2006 Special CERN Accelerator School
Alloys, weldability

EN AW-6063

Al0.2-0.6Si0.46-0.9Mg

EN AW-3003

Al0.15Cu1.3Mn
### 2.b) Aluminium and alloys

#### Heat treatable Non heat treatable

<table>
<thead>
<tr>
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<th>Designation AA</th>
</tr>
</thead>
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<tr>
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<td>2xxx series</td>
</tr>
<tr>
<td>Al-Mn</td>
<td>3xxx series</td>
</tr>
<tr>
<td>Al-Si</td>
<td>4xxx series</td>
</tr>
<tr>
<td>Al-Mg</td>
<td>5xxx series</td>
</tr>
<tr>
<td>Al-Mg-Si</td>
<td>6xxx series</td>
</tr>
<tr>
<td>Al-Zn</td>
<td>7xxx series</td>
</tr>
<tr>
<td>Al+other element (Li)</td>
<td>8xxx series</td>
</tr>
</tbody>
</table>
2.b) Aluminium and alloys

Non heat treatable

- **H18** (work hardened to the hardest state)
- **O** (annealed) or **H111** (as-fabricated)

**Annealing T: 343 °C**

**Fabrication Characteristics**
- Annealing temperature: 343 °C (650 °F); holding at temperature not required
- Hot working temperature: 260 to 510 °C (500 to 950 °F)
2.b) Aluminium and alloys

EN-AW 6061

O (solution annealed)

Toward artificially aged states (T6x tempers) ⇒
2.b) Aluminium and alloys, EN AW 2219

Properties at RT, affect of aging at high T

UTS, YS /MPa El. in 50 mm /%

domain of cumulative activation of NEG

YS, aging at 100 °C
YS, aging at 150 °C
YS, aging at 205 °C
YS, aging at 230 °C
YS, aging at 260 °C
YS, aging at 315 °C
YS, aging at 370 °C

*domain of cumulative activation of NEG*
Failure of thin walled Al-alloy bellows for the LHCb experiment

- EN AW 2219 bellows
- machined from forged round blocks
- welded assembly (2 flanges + 2 bellows + 1 tube)
- for the LHCb experiment

- leaks detected on a significant fraction of bellows
Failure of thin walled Al-alloy bellows for the LHCb experiment
Failure of thin walled Al-alloy bellows for the LHCb experiment

Figure 2932 / E1
The microstructure of the block 5 near outer surface no. 1.
Average ASTM E112 grain size 10,5 ± 0,5.
Magnification 700 X.
Etchant : 200 g chromic acid, 20 g sodium sulfate, and 17 ml hydrochloric acid (35 %) in 1000 ml distilled water.

Figure 2932 / E2
The microstructure of the block 5 near outer surface no. 1.
Average ASTM E112 grain size 10,5 ± 0,5.
Magnification 700 X.
Etchant : 200 g chromic acid, 20 g sodium sulfate, and 17 ml hydrochloric acid (35 %) in 1000 ml distilled water.

Figure 2932 / E3
The microstructure of the block 5 at centerline.
Average ASTM E112 grain size 9,5 ± 0,5.
Magnification 700 X.
Etchant : 200 g chromic acid, 20 g sodium sulfate, and 17 ml hydrochloric acid (35 %) in 1000 ml distilled water.
## Alloys containing:
- Zn
- Pb
- Cd
- Se
- S...

### High strength copper alloys

- Cu-2%Be, C17200
- Cu-0.3%Be-0.5%Co, C17410
- Cu OF, C10100
- Cu OFE, C10200
- Cu OFS, C10700
- Cu-2%Be, C17200
- Cu-0.3%Be-0.5%Co, C17410

These alloys might result in unsuitable vapour pressures.

### 2.c) Copper and alloys

**TABLE 1 Chemical Composition**

<table>
<thead>
<tr>
<th>Element</th>
<th>Grade 1</th>
<th>Grade 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper, min %</td>
<td>99.99^a</td>
<td></td>
</tr>
<tr>
<td>Copper (including silver), min %</td>
<td>ppm, max</td>
<td>99.95 ppm, max</td>
</tr>
<tr>
<td>Antimony</td>
<td>4</td>
<td>...</td>
</tr>
<tr>
<td>Arsenic</td>
<td>5</td>
<td>...</td>
</tr>
<tr>
<td>Bismuth</td>
<td>1</td>
<td>...</td>
</tr>
<tr>
<td>Cadmium</td>
<td>1</td>
<td>...</td>
</tr>
<tr>
<td>Iron</td>
<td>10</td>
<td>...</td>
</tr>
<tr>
<td>Lead</td>
<td>5</td>
<td>...</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.5</td>
<td>...</td>
</tr>
<tr>
<td>Nickel</td>
<td>10</td>
<td>...</td>
</tr>
<tr>
<td>Oxygen</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Phosphorus^c</td>
<td>3</td>
<td>...</td>
</tr>
<tr>
<td>Selenium</td>
<td>3</td>
<td>...</td>
</tr>
<tr>
<td>Silver</td>
<td>25</td>
<td>...</td>
</tr>
<tr>
<td>Sulfur</td>
<td>15</td>
<td>...</td>
</tr>
<tr>
<td>Tellurium</td>
<td>2</td>
<td>...</td>
</tr>
<tr>
<td>Tin</td>
<td>2</td>
<td>...</td>
</tr>
<tr>
<td>Zinc</td>
<td>1</td>
<td>...</td>
</tr>
</tbody>
</table>

^a If the analytical uncertainty is not incorporated into the specified limits.
^b Copper is determined by the difference of impurity total from 100.
^c Refer to Section 13.

**brazeability, weldability**

OFE, OF Cu, respectively
4. **MANUFACTURING PROCESS**

In accordance with the diameter, the bars shall be given the necessary treatment to allow delivery in the **HALF-HARD** state.

5.2 **HOMOGENEITY**

The homogeneity of the bar shall be ultrasonically inspected solely to detect continuity faults.

Each copper bar shall be ultrasonically tested at frequencies $\geq 4$ MHz, depending on the thickness. If the attenuation is:

- $> 20\%$ Rejected.

The details of the ultrasonic inspection will be agreed upon between the manufacturer and CERN as a function of the product.
**data for:**

- Cu wire
- CW 90 %
- to 2 mm diam.

**then**

- annealed ½ h at various T

(source ASM Handbook)

**Fig. 3 Softening characteristics of oxygen-free copper containing various amounts of silver**

![Graph showing softening characteristics of copper with various silver contents](image-url)
2.c) Copper and alloys

- Copper base dispersion strengthened materials, referred as: Oxide Dispersion Strengthened (ODS)

- GlidCop®, trademark of SCM Metal Products, Inc., manufacturer of metal powders and pastes for powder metallurgy. Based on a Cu-Al$_2$O$_3$ system.

- Oxides immiscible in liquid Cu

  - Internal oxidation
    - Mechanical mixing
    - Coprecipitation from salt solutions
    - Selective internal oxidation


Figure 1: Softening resistance of GlidCop AL-15 versus OF copper and Zirconium Copper. (Note: Properties measured at room temperature, after exposure to elevated temperatures for one hour.)

Nadkarni, Mechanical Properties of Metallic Components, 1993, p.297
• **GlidCop® AL-25**
  - based on a thermally stable reinforcement (Al$_2$O$_3$)
  - acts as barrier to dislocation movement and to recrystallisation

• Cu-2% Be, aged 360 °C, 6h
  - based on the usual GP ⇒ (γ’’) ⇒ γ’ ⇒ γ precipitation (Rioja and Laughlin, 1980)
  - thermally unstable system (diffusion controlled)

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S. Sgobba, thèse EPFL n° 1215 (1994)
Bending Magnet Radiation

Courtesy of R. Kersevan
After capsule removal by pickling and heat treatment, before machining

HIPed AISI 316LN end covers for CERN LHC project (courtesy of Metso)
**Powder production**

**Melting and gas atomizing**
Melted and refined steel is fed through special nozzles into a high-speed inert gas flow, which atomizes the molten steel into fine, spherical solidified powder particles.

**Sieving and storage**
The atomized powder is sieved according to its particle size into separate fractions for a variety of applications. The powder will be carefully stored to guarantee its cleanliness.

**Capsule making**

**Capsule making and compaction**
The production capsule for each component will be made out of thin plate by shaping and welding. This capsule will then be filled with gas atomized powder by vibrating the capsule. The capsule is oversized, to allow for the shrinkage which occurs during the powder compaction.

If the end product is designed to comprise of different materials, the powders will be encapsulated separately into different sections of the capsule. The other material can also be a solid product, such as a casting to be coated with special material.

**Evacuation and closing**
After the capsule has been filled with powder, the air will be evacuated and the capsule closed tightly.

**Hot Isostatic Pressing (HIP)**

The temperature/pressure cycle of the hot isostatic pressing:

The sealed capsules are moved to a pressure vessel used in the HIP-process. With the aid of high-pressure Ar-gas the capsule is subjected, in the pressure vessel, to an isostatic pressure, which by means of high temperature (about 70% of the melting point of the material being used) turns the powder into a 100% compact material.

The homogeneity of the end product is the same as that of the powder. The properties are even and do not depend on the orientation.
PM 316 LN, Microstructure:
Grain size according to ASTM E112: N° 6 to 7

100 μm

Inclusions

Mainly globular-type
99.85Cu-0.15Zr, UNS C15000

99.97+ % Mo
Bimetallic structures

HIP diffusion bonding, CuZr/Mo

Coextrusion, Cu/Ni/Mo

10 mm
## Stainless steels

- 304L, general purpose ⇒ 5 sFr/ kg
- 304L, vacuum applications ⇒ 8.50 sFr/ kg
- 316LN, vacuum applications ⇒ 16-18 sFr/ kg
- 316LN, blanks ⇒ 50 (up to 135) sFr/ kg
- P506, 316L convolutions ⇒ 40-80 sFr/ kg

## Coppers

### Special materials or bimetals

- Mo, 99.97% (CLIC) ⇒ 1800 sFr/ kg
- Mo/ CuZr bimetal (CLIC) ⇒ 40000 sFr/ m, Ø 85 mm
- Ti grade 2, CNGS end windows ⇒ 54 sFr/ kg
- Nb (ILC cavities) ⇒ 270 sFr/ kg

### Glidcop

⇒ 42 $/ kg

(pelow convolutions vs. end trianges)

## Al alloys

- plates EN AW 1050 ⇒ 5 sFr/ kg
- plates EN AW 5754 ⇒ 7 sFr/ kg
- plates EN AW 6082 ⇒ 6.50-8 sFr/ kg
- special forgings, EN AW 6061, velo windows ⇒ 18 sFr/ kg
3) Conclusions

- **Proper selection should keep into account:**
  - (a) availability *(Ti grade 2 plates for the CNGS end windows, EN AW 2219...)*
  - (b) ease of fabrication into a given form *(EN AW 6082...)*

- **Selection as a function of properties and further operations**
  - (a) strength, ductility as a function of *T* *(cryogenic applications, NEG activation, baking...)*
  - (b) weldability *(Al-alloys...), machinability (pure Cu...)*

- **Corrosion issues**
  - (a) thin walled components *(LHCb velo windows, bellows, ATLAS Pixel cooling circuit...)*
  - (b) use of halogen-activated fluxes to be avoided in a *SS* environment
3) Conclusions

Consider the material aspects at the beginning of a project:

a) availability (more than 1 y delay for a special SS, P506 for the beam screen)

b) interest of considering alternative techniques, including near net shaping (PM for the end covers of LHC dipole magnets)

New projects will eventually force into less conservative solutions:

bimetals by HIP assisted diffusion bonding, explosion bonding (CLIC, ILC)