CAS course "Vacuum for Particle Accelerators", Lund, 6-16 June, 2017

Materials & Properties I: Introduction

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Outline

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 innovative and/or less common materials/processes
   ⇒ Discussion of:
      • Examples of application
      • Aspects related to manufacturing and joining
      • Failure analyses, including corrosion issues
3. Advanced manufacturing and material examination technologies
4. Conclusions
1. 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

(especially)

1. Sufficient mechanical strength
2. Corrosion resistance
3. High gas tightness (leak rates < 10^{-9} \text{ mbar} \cdot \text{l} \cdot \text{s}^{-1})
4. Low intrinsic vapor pressure
5. Low foreign gas content
6. Favorable degassing properties
7. High melting and boiling points
8. Clean surfaces
9. Adapted thermal expansion behaviour
10. High thermal fatigue resistance
11. Stainless steel is the dominant material

1. General rules

CAS course "Vacuum for Particle Accelerators"

Materials I: Introduction + cooling capillars
1. General rules

**FCC-hh prototype**

**Beam screen**

**IT-4203/TE/HL-LHC**

3.1.1 *Special austenitic grade stainless steel strip (CERN supply)*

The chemical composition of the CERN supplied stainless steel strip is given in table 2.

<table>
<thead>
<tr>
<th>%</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Mn</th>
<th>Si</th>
<th>Cu</th>
<th>S</th>
<th>P</th>
<th>B</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>19.0</td>
<td>0.8</td>
<td>10.7</td>
<td>11.8</td>
<td></td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>0.03</td>
<td>19.5</td>
<td>1.0</td>
<td>11.3</td>
<td>12.4</td>
<td>0.5</td>
<td>0.33</td>
<td>0.15</td>
<td>0.002</td>
<td>0.02</td>
<td>0.002</td>
</tr>
</tbody>
</table>

**FCC-hh prototype**

Being ordered:
- 3.1 km of finished strip;
- 4600 m of seamless cold-drawn cooling tubes in lengths of up to 14 m
- Same stainless steel as for the LHC

**Fine-blanked collars**

- More than 450 tonnes of austenitic stainless steel strips
- Same stainless steel specification as for the LHC

**MS-4294**
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, ferritic

- 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

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

C added to increase the "austenitic loop"
2.a Stainless steels, austenitic

AISI 304, the "18-8" or "18-10" stainless (18%Cr, 8-10%Ni)

- formed by an addition of an fcc element (Ni, Mn) to the FeCr system
- γ-phase loop expanded
- γ-phase enhanced and enlarged
- formation of ferrite can be suppressed (austenite former elements)
- transformation to martensite can be reduced or suppressed (increasing alloying elements)
vacuum applications: 304L, 316L, 316LN

2.a Stainless steels

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

D. Peckner, I.M. Bernstein, 1977

A.K. Jha et al., Engineering Failure Analysis
Metallographic observations of 316LN leaking bellow
2.a Stainless steels, inclusions

- Oversized (1,2,3) and thick (4) B type inclusions up to class 2
2.a Stainless steels, inclusions

RD ↔
2.a Stainless steels, inclusions

- For any wrought product (plate, tube, bar), an unfavourable inclusions alignment will be anyway present in the rolling or drawing direction.
Standard Test Methods for Determining the Inclusion Content of Steel\(^1\)

This standard is issued under the fixed designation E45; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (\(\varepsilon\)) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

### TABLE 1 Minimum Values for Severity Level Numbers (Methods A, D, and E)\(^{A,B}\)

<table>
<thead>
<tr>
<th>Severity</th>
<th>A (mm (in.) at 100×, or count)</th>
<th>B</th>
<th>C</th>
<th>D(^C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>3.7(0.15)</td>
<td>1.7(0.07)</td>
<td>1.8(0.07)</td>
<td>1</td>
</tr>
<tr>
<td>1.0</td>
<td>12.7(0.50)</td>
<td>7.7(0.30)</td>
<td>7.6(0.30)</td>
<td>4</td>
</tr>
<tr>
<td>1.5</td>
<td>26.1(1.03)</td>
<td>18.4(0.72)</td>
<td>17.6(0.69)</td>
<td>9</td>
</tr>
<tr>
<td>2.0</td>
<td>43.6(1.72)</td>
<td>34.3(1.35)</td>
<td>32.0(1.26)</td>
<td>16</td>
</tr>
<tr>
<td>2.5</td>
<td>64.9(2.56)</td>
<td>55.5(2.19)</td>
<td>51.0(2.01)</td>
<td>25</td>
</tr>
<tr>
<td>3.0</td>
<td>89.8(3.54)</td>
<td>82.2(3.24)</td>
<td>74.6(2.94)</td>
<td>36</td>
</tr>
<tr>
<td>3.5</td>
<td>118.4(4.65)</td>
<td>114.7(4.52)</td>
<td>102.9(4.05)</td>
<td>49</td>
</tr>
<tr>
<td>4.0</td>
<td>149.8(5.90)</td>
<td>153.0(6.02)</td>
<td>135.9(5.35)</td>
<td>64</td>
</tr>
<tr>
<td>4.5</td>
<td>188.7(7.47)</td>
<td>197.3(7.77)</td>
<td>173.7(6.84)</td>
<td>81</td>
</tr>
<tr>
<td>5.0</td>
<td>223.0(8.78)</td>
<td>247.6(9.75)</td>
<td>216.3(8.52)</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Severity</th>
<th>A (um (in.) at 1×, or count)</th>
<th>B</th>
<th>C</th>
<th>D(^C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>37.0(0.002)</td>
<td>17.2(0.007)</td>
<td>17.8(0.007)</td>
<td>1</td>
</tr>
<tr>
<td>1.0</td>
<td>127.0(0.005)</td>
<td>76.8(0.003)</td>
<td>75.6(0.003)</td>
<td>4</td>
</tr>
<tr>
<td>1.5</td>
<td>261.0(0.010)</td>
<td>184.2(0.007)</td>
<td>176.0(0.007)</td>
<td>9</td>
</tr>
<tr>
<td>2.0</td>
<td>436.1(0.017)</td>
<td>342.7(0.014)</td>
<td>320.5(0.019)</td>
<td>16</td>
</tr>
<tr>
<td>2.5</td>
<td>649.0(0.026)</td>
<td>554.7(0.022)</td>
<td>510.3(0.020)</td>
<td>25</td>
</tr>
<tr>
<td>3.0</td>
<td>898.0(0.035)</td>
<td>822.2(0.032)</td>
<td>746.1(0.029)</td>
<td>36</td>
</tr>
<tr>
<td>3.5</td>
<td>1181.0(0.047)</td>
<td>1147.0(0.045)</td>
<td>1029.0</td>
<td>49</td>
</tr>
<tr>
<td>4.0</td>
<td>1498.0(0.059)</td>
<td>1530.0(0.060)</td>
<td>1359.0</td>
<td>64</td>
</tr>
<tr>
<td>4.5</td>
<td>1898.0(0.075)</td>
<td>1973.0(0.078)</td>
<td>1737.0</td>
<td>81</td>
</tr>
<tr>
<td>5.0</td>
<td>2230.0(0.088)</td>
<td>2476.0(0.098)</td>
<td>2163.0</td>
<td>100</td>
</tr>
</tbody>
</table>
2.4. INCLUSIONS CONTENT

Amount and definition shall meet standard ASTM E45.

1. Micro-inclusions (indigenous inclusions detectable by microscopical test methods): method D is applicable. Severity level number 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. The table showing field counts shall be attached to the certificate.

2. Macro-inclusions (exogenous inclusions from entrapped slag or refractories): they are strictly forbidden and are cause for rejection.

X2CrNiMoN17-13-3

AISI 316LN

Spec. N°1001_1.4429_316LN_blanks

This document specifies the CERN technical requirements for 1.4429 (X2CrNiMoN17-13-3, AISI 316LN) stainless steel blanks for ultra-high vacuum applications (UHV) at CERN requiring vacuum firing at 950°C.
Materials I: Introduction

CAS course "Vacuum for Particle Accelerators"
2.a Stainless steels, macro-inclusions

Materials I: Introduction
Multidirectional forging alone, even if including upsetting is not enough to avoid the risk of leaks due to macroinclusions.
Materials I: Introduction

2.a Stainless steels, inclusions

10^{-5} \text{ torr l/s}

courtesy of A. Poncet
A. Choudhury: Vacuum Metallurgy, ASM Int., USA, (1990)

Fig. 23 Layout of a compact ladle furnace
2.a Stainless steels, steelmaking

- Stainless steels
- Steelmaking

- 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

- Diagram details:
  - EAF, LF1, LF2, VD, VOB, ingot casting, tap slag wagon, continuation

- Notes:
  - C \downarrow
  - P \downarrow
  - (to a limited extent) tapped as free as possible of slag into the ladle

- Metallurgical inclusions (NMI)
2.a Stainless steels, steelmaking: ESR
The additional cost of ESR ingots is in the order of 1 EUR/kg (Minutes of the visit to Company A on 27 January 2015, ITER CS Lower Keyblock Material Progress Meeting)

Courtesy of Breitenfeld Edelstahl /AT.
Electrodes of diam. 500 mm, 750 mm, 1000 mm, 1200 mm, respectively, up to a length of 4 m and a weight of 35 t. Annual capacity is 250 000 t.

Courtesy of Forgiatura Vienna /IT
Max. ingot weight/capacity: 250 t
Two furnace heads, electrode exchange, protective gas hood, fully coaxial design; biggest ESR plant worldwide in operation
Austenitic stainless steels to be furnished and preferentially used in their **solution annealed condition**

All standards (except for specific applications) impose furnishing in the **solution annealed condition**

Max. hardness also limited by relevant standards and

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**5.2 Heat Treatment:**

5.2.1 All pipe shall be furnished in the heat—treated condition in accordance with the requirements of Table 2. The

<table>
<thead>
<tr>
<th>Grade or UNS Designation</th>
<th>Heat Treating Temperature</th>
<th>Cooling/Testing Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>All grades not individually listed below:</td>
<td>1900 °F [1040 °C]</td>
<td>C</td>
</tr>
<tr>
<td>TP304H, TP316H</td>
<td>Cold finished 2000 °F [1100 °C]</td>
<td>D</td>
</tr>
<tr>
<td>Hot finished 1925 °F [1050 °C]</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>TP309H, TP321H, TP310H</td>
<td>Cold finished 1900 °F [1040 °C]</td>
<td>D</td>
</tr>
<tr>
<td>Hot finished 1900 °F [1040 °C]</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>TP321H, TP347H, TP348H</td>
<td>Cold finished</td>
<td>D</td>
</tr>
<tr>
<td>Hot finished</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

- Quenched in water or rapidly cooled by other means.

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**2.3. STRUCTURE**

The structure after **solution annealing**

**2.5. MECHANICAL PROPERTIES**

At room temperature, after solution annealing:

- Tensile strength \( R_m \) min. 600 N/mm²
- Yield stress \( R_{p0.2\%} \) min. 300 N/mm²
- Elongation at break \( A_5 \) min. 35%
- Brinell hardness \( HB \) 150-190

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Stainless steels, vacuum firing, stress relieving, possible sensitization

This document specifies the CERN technical requirements for 1.4429 (X2CrNiMoN17-13-3, AISI 316LN) stainless steel blanks for ultra-high vacuum applications (UHV) at CERN requiring vacuum firing at 950°C.

This document specifies the CERN technical requirements for 1.4435 (X2CrNiMo18-14-3, AISI 316L) stainless steel round bars for vacuum applications not requiring vacuum firing at 950°C.

This document specifies the CERN technical requirements for 1.4306 (X2CrNi19-11, AISI 304L) stainless steel round bars for vacuum applications not requiring vacuum firing at 950°C.

Vacuum firing of components and subassemblies to effectively remove the dissolved gas load in cleaned and degreased parts

- Outgassing
- Restriction due to B content in 316LN
  ⇒ see P. Chiggiato, Materials & Properties IV, 8/06
Stainless steels, vacuum firing, stress relieving, possible sensitization

Stress relieving:
- Select temperature-time combinations outside the sensitization range
- It can be made coincident with 950 °C vacuum firing treatment whenever possible
- Avoid ranges of σ-phase precipitation specially for welded structures

Stainless steels, vacuum firing, stress relieving, possible sensitization

Sample Young's modulus Yield Strength Ultimate Tensile Strength Uniform Elongation Total Elongation
EN48CA-4 198.2 1209 1494 10.4 11.0
TFb-4 197.9 1096 1601 37.1 43.1

316LN ITER grade, TF jackets, extra low C (<0.015%) grade, aged 200 h at 650 °C, tensile tested at 7 K
Stainless steels, vacuum firing, stress relieving, possible sensitization

Sensitization:
- Loss of corrosion resistance (Cr depletion at GB)
- Loss of ductility (specially at cryogenic temperatures), ductile-to-brittle transition onset
- Check the effects of your treatment against ASTM A262

⇒ Assembly techniques, brazeability and weldability, see S. Mathot, 15/06

Sensitization: oxalic acid etching, ASTM A262, practice A (⇒E)
2.a Stainless steels, alternative joining techniques, **HIP diffusion bonding**

**Courtesy of Fraunhofer IFAM Dresden /DE:**
- SS casing (1.4301)
- 950°C - 3h – 100 MPa Hot Isostatic Pressing (HIP)ing cycle
Figure 1 – UV light observation on the three samples after 30 minutes exposure to PT revelatory Androx developer 9D1B.

Figure 1 – SOI location and SEM (SE2) images of the SOI were some discontinuities.

Figure 1 – OM observation of the three samples after mechanical polishing and detail of crossing grains on OF-Cu sample, showing crossing grains (red cycles).

Figure 1 – Penetrant testing.
2.a/3 Advanced investigation techniques: X-ray microtomography

ITER magnet system, correction coils
He inlets and outlets of the NbTi cable-in-conduit conductor (CICC)

courtesy of ASIPP /CN
2.a/3 Advanced investigation techniques: X-ray microtomography

- Most stringent quality of welds imposed (EN ISO 5817 - level B) or equivalent
- Volumetric NDT inspections indispensable
- Application of X-ray laminography (planar X-ray micro-tomography)
2.a/3 Advanced investigation techniques: X-ray microtomography

- Laminography
2.a/3 Advanced investigation techniques: X-ray microtomography

Cracks (ref: 401) unacceptable to ISO 5817 level B

Excessive penetration and melt through (ref: 504) acceptable to ISO 5817 level B (h ≤ 1 mm + 0.1 b, where b is a width of weld reinforcement)

Wrap welded with the jacket and possibly with the superconductor
2.a/3 Advanced investigation techniques: X-ray microtomography

Tungsten inclusion (ref: 6021) according to ISO 5817 level B acceptance depends on application

Shrinkage grooves (ref: 5013) not acceptable to ISO 5817 level B

Excessive penetration (ref: 504) acceptable to ISO 5817 level B 
(h ≤ 1 mm + 0.1 b, where b is the width of weld reinforcement)
X-ray laminography: impressive correspondence between XR tomography and microoptical observations

## 2.b Aluminium and alloys

### CAS course "Vacuum for Particle Accelerators"

### Materials I: Introduction

#### Wrought Alloy Designations

<table>
<thead>
<tr>
<th>Alloy Group</th>
<th>Designation AA</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure aluminium</td>
<td>1xxx series</td>
<td>EN AW-6082 (6061), EN AW-5083</td>
</tr>
<tr>
<td>Al-Cu</td>
<td>2xxx series</td>
<td>EN AW-2219</td>
</tr>
<tr>
<td>Al-Mn</td>
<td>3xxx series</td>
<td>EN AW-3003</td>
</tr>
<tr>
<td>Al-Si</td>
<td>4xxx series</td>
<td>EN AW-2218</td>
</tr>
<tr>
<td>Al-Mg</td>
<td>5xxx series</td>
<td>EN AW-5083</td>
</tr>
<tr>
<td>Al-Mg-Si</td>
<td>6xxx series</td>
<td>EN AW-6082 (6061)</td>
</tr>
<tr>
<td>Al-Zn</td>
<td>7xxx series</td>
<td>EN AW-6082 (6061)</td>
</tr>
<tr>
<td>Al+other elements</td>
<td>8xxx series</td>
<td>EN AW-6082 (6061)</td>
</tr>
</tbody>
</table>

#### Weldability of Aluminium Alloys

<table>
<thead>
<tr>
<th>Weldability</th>
<th>Wrought alloys</th>
<th>Casting alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Readily Weldable</td>
<td>1060, 1100, 1350</td>
<td>3003, 3004, 3105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5005, 5050, 5052, 5056, 5083, 5086, 5154, 5202, 5254, 5454, 5456, 5457, 5552, 5567</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6061, 6063, 6070, 6101, 6201, 6262, 6463, 7005</td>
</tr>
<tr>
<td>Weldable in Most Applications(a)</td>
<td>2014, 4032, 6066</td>
<td>208.0, 308.0, 319.0, 332.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>413.0, 712.0</td>
</tr>
<tr>
<td>Limited Weldability(b)</td>
<td>2024, 2218, 2618</td>
<td>213.0, 222.0, 295.0, 296.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>333.0, 336.0, 354.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>512.0, 513.0, 514.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Die casting alloys</td>
</tr>
<tr>
<td>Welding Not Recommended</td>
<td>2011, 7075, 7178</td>
<td>242.0, 520.0, 535.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>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.
2.b Aluminium and alloys

### Filler Alloys

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°C (150°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 2.1: Filler Alloys

<table>
<thead>
<tr>
<th>Base Alloys</th>
<th>6061</th>
<th>6063</th>
<th>2024</th>
<th>2219</th>
<th>4043</th>
<th>5083</th>
<th>5183</th>
<th>5356</th>
<th>5554</th>
<th>5454</th>
<th>6005</th>
<th>6082</th>
<th>6101</th>
<th>6151</th>
<th>6201</th>
</tr>
</thead>
<tbody>
<tr>
<td>310.0, 332.0, 354.0, 355.0, C355.0, 360.0</td>
<td>2219</td>
<td>4043</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>412.0, 443.0, 444.0, 358.0, A356.0, A357.0, 359.0</td>
<td>4043</td>
<td>4145</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005, 7021, 7039, 7046, 7146, A712.0, C712.0</td>
<td>4043</td>
<td>4145</td>
<td>5183</td>
<td>5356</td>
<td>5554</td>
<td>5554</td>
<td>5454</td>
<td>5454</td>
<td>5356</td>
<td>5554</td>
<td>5554</td>
<td>5454</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6005</td>
<td>6061</td>
<td>6063</td>
<td>2024</td>
<td>2219</td>
<td>4043</td>
<td>5083</td>
<td>5183</td>
<td>5356</td>
<td>5554</td>
<td>5454</td>
<td>5454</td>
<td>5356</td>
<td>5554</td>
<td>5454</td>
<td>5454</td>
</tr>
</tbody>
</table>

Legend

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.
2.b Aluminium and alloys

EN AW 6061, typical US Al-alloy extrusion

EN AW 6082, 90% of the European production of Al-alloy extrusion

Table 1: Simplified summary of wrought aluminium alloys

<table>
<thead>
<tr>
<th>Legierungstyp</th>
<th>Werkstoff-Beispiel</th>
<th>Eignung für EB-Schweißen</th>
</tr>
</thead>
<tbody>
<tr>
<td>nicht aushärbar</td>
<td>Al, Al-Mn(-Mg)</td>
<td>Al99,5, sehr gut</td>
</tr>
<tr>
<td>aushärbar</td>
<td>Al-Mg-Si</td>
<td>AlMgSi1, sehr gut bei einem kritischen Mg,-Si-Anteil (Mg unter etwa 1%, Si unter etwa 0,6%); Neigung zur Heißrissigkeit</td>
</tr>
<tr>
<td></td>
<td>Al-Cu-Mg</td>
<td>AlCuMg2, gut bei niedrigen Cu-Gehalt (unter etwa 4%); Neigung zu Heißrissigkeit</td>
</tr>
<tr>
<td></td>
<td>Al-Zn-Mg(-Cu)</td>
<td>AlZnMgCu1,5, gut; geringfügiges Ausdampfen von Zn und Mg; Neigung zu Heißrissigkeit</td>
</tr>
</tbody>
</table>
2.b Aluminium and alloys

2.b Aluminium and alloys

EDMS 573069, Micro-optical characterisation of TIG welds between two EN AW 6060 tubes

Porosity:
• Gas entrapment from poor shielding, shielding gas, air
• Hydrogen from moisture, unclean wire surface, base metal
• Excessive cooling rate (outgassing)
### Aluminium and Alloys

#### Alloy Group vs Designation AA

<table>
<thead>
<tr>
<th>Alloy Group</th>
<th>Designation AA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure aluminium</td>
<td>1xxx series</td>
</tr>
<tr>
<td>Al-Cu</td>
<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>

**Legend:**
- Heat treatable
- Non heat treatable

()
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 /%
- time at T /h

domain of cumulative activation of NEG
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
2.b Aluminium and alloys: failure analysis of thin walled Al-alloy bellows for the LHCb experiment
3. Aluminium and alloys: failure analysis of thin-walled Al-alloy bellows for the LHCb experiment

Materials I: Introduction
2.b Aluminium and alloys

EN AW-2219-T6 forged blanks for ultra-high-vacuum applications
2.b Aluminium and alloys

Melt spinning is a rapid quenching process, cooling rates possible, up to $10^{+6} \, ^{\circ}C/s$

Very fine microstructure
High mechanical properties

<table>
<thead>
<tr>
<th>Alloy</th>
<th>E-Modulus (GPa)</th>
<th>Hardness (HB)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSA 501</td>
<td>70</td>
<td>159</td>
<td>550</td>
<td>510</td>
<td>16</td>
</tr>
<tr>
<td>RSA 905</td>
<td>90</td>
<td>180</td>
<td>600</td>
<td>475</td>
<td>7</td>
</tr>
<tr>
<td>RSA 8009</td>
<td>91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Recently, Al has been made by the Swiss ALUMINIUM-INDUSTRIE A.G. from pressed Al powder (so-called Al flake, about 1 $\mu \times 100 \, \mu$ with an O$_2$ content). The process is carried out at room temperature at pressures between 20 and 50 kg/mm$^2$; then follows sintering in air at 550—600 °C; then hot pressing at 500—600 °C, with a pressure of 50 kg/mm$^2$, and finally hot extrusion at 500 to 600 °C through a die, to produce a material of density 2.75 g/ml; this can be rolled or drawn, hot or cold and is known in the trade as “SAP”.

T. Mast, diploma work, 2014

Espe, 1966
2.d Other grades, innovative materials and manufacturing techniques

Ti6Al4V additive manufactured "spiral load" prototypes (power attenuation at the output of RF cavities)

⇒ Additional details about the process, see S. Mathot, 15/06

Selective Laser Melting Machine
SLM 280 HL available at CERN

Diaphragm for UHV leak tightness tests, different models

Tensile test specimens for a study of the influence of orientation and location

Ti6Al4V additive manufactured “spiral load” prototypes (power attenuation at the output of RF cavities)
2.d Other grades, innovative materials and manufacturing techniques

Porosity percent as measured by image analysis

⇒ Outgassing properties, see P. Chiggiato, 8/06
2.d Other grades, innovative materials and manufacturing techniques

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile Strength, min</th>
<th>Yield Strength (0.2 % Offset), min or Range</th>
<th>Elongation in 4D, min, %</th>
<th>Reduction of Area, min, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rm (MPa)</td>
<td>Rp0,2 (MPa)</td>
<td>A (%)</td>
<td></td>
</tr>
<tr>
<td>NO HIP</td>
<td>Reference</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1</td>
<td>B05412 M X</td>
<td>967,4 ± 3,1</td>
<td>10,7 ± 0,1</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>B05412 M Z</td>
<td>960,3 ± 7,2</td>
<td>14,0 ± 1,0</td>
<td></td>
</tr>
<tr>
<td>HIP treated</td>
<td>B05414 M X</td>
<td>989,6 ± 4,5</td>
<td>10,2 ± 0,7</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>B05414 M Z</td>
<td>959,9 ± 2,7</td>
<td>13,3 ± 0,8</td>
<td></td>
</tr>
<tr>
<td>NO HIP</td>
<td>#5 B05648 M X</td>
<td>990,3 ± 0,3</td>
<td>10,0 ± 0,9</td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td>B05713 M Z</td>
<td>985,7 ± 3,6</td>
<td>11,7 ± 1,0</td>
<td></td>
</tr>
<tr>
<td>HIP treated</td>
<td>#7 B05713 M X</td>
<td>942,3 ± 12,3</td>
<td>5,1 ± 1,3</td>
<td></td>
</tr>
<tr>
<td>#8</td>
<td>B05648 M Z</td>
<td>895,4 ± 12,8</td>
<td>5,5 ± 0,4</td>
<td></td>
</tr>
</tbody>
</table>

- Good isotropy achieved
- High strength
- Limited ductility, toughness? (might prevent cryogenic applications)
- Annealing and/or HIPping treatments should be foreseen
### Stainless steels

- **304L, general purpose**  \( \Rightarrow 3-3.5 \text{ EUR/kg} \)
- **304L, vacuum/cryogenic application**  \( \Rightarrow 6 \text{ EUR/kg} \)
- **316LN, as above**  \( \Rightarrow 11 \text{ EUR/kg (bars) to 32 EUR/kg (plates)} \)
- **316LN, blanks**  \( \Rightarrow 50 \text{ (and up to above 100) EUR/kg} \)
- **P506, 316L convolutions for bellows**  \( \Rightarrow 50-80 \text{ EUR/kg} \)
- **Additive manufactured 316L**  \( \Rightarrow 65 \text{ EUR/kg (powder)} \)

### Aluminium and Alloys

- **Al and alloys, general purpose**  \( \Rightarrow 5 \text{ EUR/kg} \)
- **EN AW 2219 forged blanks**  \( \Rightarrow 80 \text{ EUR/kg} \)
- **Special forgings, EN AW 6061, velo windows**  \( \Rightarrow 15 \text{ EUR/kg} \)

### Coppers

- **OFE Cu**  \( \Rightarrow 25-40 \text{ EUR/kg (3D forged)} \)
- **OF Cu**  \( \Rightarrow 10 \text{ EUR/kg (basis)} \)
- **CuBe, high (low) Be**  \( \Rightarrow 40-90 \text{ EUR/kg (strips)} \)
- **Glidcop**  \( \Rightarrow 55 \text{ EUR/kg} \)
- **Additive manufactured 99.9 % Cu**  \( \Rightarrow 100 \text{ EUR/kg (powder)} \)

### Titanium

- **Grade 2**  \( \Rightarrow 50 \text{ EUR/kg (plates)} \)
- **Ti6Al4V (ELI)**  \( \Rightarrow (50-140) \text{ EUR/kg (rods/plates)} \)
- **Additive manufactured Ti6Al4V**  \( \Rightarrow 320-360 \text{ EUR/kg (powder)} \)
CAS course "Vacuum for Particle Accelerators"

Materials I: Introduction

* belts, braces