Options for yield strength enhancement of Al-stabilised superconductors

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Outline of the talk

• The present CMS conductor:
  □ materials and developments
  □ state of stress, safety factors

• Toward an improved conductor
  □ reinforcement alloy EN AW-6082 or EN AW-7020?
  □ replacement of pure Al stabilizer by cold drawn Al-0.1wt%Ni
  □ weldability

• Comparison of mechanical properties and equivalent RRR of the improved conductor

• Limits and perspective of alternative solutions for yield strength enhancement
The present CMS conductor consists of a superconducting cable made of 32 strands of Rutherford type. The strands are NbTi-Cu stabilized with a Cu/SC ratio of 1.1. The stabilizer material is Al 99.998%. The reinforcement material is EN AW-6082 T6 continuous extrusions.

### Specifications:

- **Nominal Current:** 20 kA
- **Superconducting Strand Type:** NbTi-Cu stabilized
- **Strand Cu/SC Ratio:** 1.1
- **Number of Strands:** 32
- **Strand Diameter:** 1.28 mm
- **Rutherford Cable Cross Section:** 20.68 mm x 2.34 mm
- **Insert Cross Section:** 30 mm x 21.6 mm
- **High Purity Aluminum Stabilizer:** Al 99.998%
- **RRR Aluminum at 0 T, Annealed:** > 1500
- **Reinforcement Material:** EN AW-6082
- **Conductor Cross Section:** 64 mm x 21.6 mm
- **Quantity Produced:** 21 lengths x 2600 m

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**Fig. 1. Cross-section of the conductor.**
The present CMS conductor, billet on billet extrusion of the reinforcement

Fig. 2. Yield strength results from the pre-production phase around the die mark region.

Scrap from billet

A dedicated production line has been designed and implemented by Tornado Machinery GmbH to perform the automated EB welding of the beam conductors. Each beam conductor exceeds 2.4 meters.

The three growths of components are (from right to left) downstream and central SRFQ sections fitting into the CMS withstand rig.
The present CMS conductor, curing cycle

![Graph showing temperature vs. time with different heat treatments]

**Table II**

Summary of the measured (specified/expected) tensile properties during the pre-production phase

<table>
<thead>
<tr>
<th>Property</th>
<th>Tensile strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received state, RT</td>
<td>295 (250)</td>
<td>171 (150)</td>
<td>20 (15)</td>
</tr>
<tr>
<td>After customer's heat treatment, RT</td>
<td>370 (280)</td>
<td>201 (175)</td>
<td>18 (15)</td>
</tr>
<tr>
<td>After customer's heat treatment, 4.2 K</td>
<td>684 (550)</td>
<td>428 (225)</td>
<td>16 (15)</td>
</tr>
</tbody>
</table>
Toward an improved conductor, material selection

Replace by:
- a higher strength Al-alloy
- extrudable
- weldable
- compatible with a cryogenic application
- maintaining high ductility and strength at 4.2 K
- even after a curing cycle

Replace by:
- cold drawn Al-0.1wt%Ni alloy
- enhanced mechanical strength
- without excessive degradation in RRR compared to pure Al
Toward an improved conductor, reinforcement

Extrudable, weldable
Toward an improved conductor, reinforcement

Candidate alloy:

- EN AW-7020 (Al-Zn4.5Mg1 alloy), equivalent of EN AW-7005
- Extrudable and weldable

- High ductility and strength at 4.2 K even after curing?

- Sections of 18±0.4 mm x 24±0.4 mm supplied by Otto Fuchs /DE
- Lengths of 3 m to 6 m
- Two different T6-type tempers (designation .71 and .72 according to DIN 17007)
EN AW-6082 T51

EN AW-6082 T6 (cured)

RT

EN AW-6082 T6 (cured)

4.2 K

EN AW-7020.72, cured, at 4.2 K

\[ Rp0.2 = 677 \text{ MPa} \]

\[ Rm = 817 \text{ MPa} \]
Toward an improved conductor, safety factors

EN AW-7020.72, cured, at RT

\[ \frac{R_{p0.2}(\text{EN AW } 7020.72 \text{ as - cured})}{R_{p0.2}(\text{EN AW } 6082 \text{ T61 as - cured})} = 1.3 \]

EN AW-7020.72, cured, at 4.2 K

\[ \frac{R_{p0.2}(\text{EN AW } 7020.72 \text{ as - cured})}{R_{p0.2}(\text{EN AW } 6082 \text{ T61 as - cured})} = 1.6 \]

EN AW-7020.72, cured, at RT and 4.2 K

\[ \frac{R_{m}(\text{EN AW } 7020.72 \text{ as - cured})}{R_{m}(\text{EN AW } 6082 \text{ T61 as - cured})} = 1.2 \]

Safety factors:

EN AW-7020.72 \Rightarrow 3 \ (677 \text{ MPa}/225 \text{ MPa})
EN AW-6082 T61 \Rightarrow 1.9 \ (428 \text{ MPa}/225 \text{ MPa})

with respect to the actual 4 T design strength at 4.2 K
Toward an improved conductor, safety factors

From 4 T to 5 T:

“It seems difficult, respecting construction codes, to exceed a hoop strain of 0.15%. In the case of CMS, this corresponds to a maximum Von Mises stress of 140 MPa, requiring alloys with Rp0.2 > 210 MPa and Rm > 420 MPa at 4.2 K.

Thus one can tentatively conclude that the selected alloys EN AW-6082-T51 for the reinforcement and EN AW-5083-H321 for the mandrels are perfectly suitable for a 5-T coil”

Toward an improved conductor, stabilizer

Candidate alloy:

- Al99.998 $\Rightarrow$ Al-0.1wt%Ni
- developed for the ATLAS thin solenoid superconductor
- aiming an $R_{p0.2} = 85$ MPa at 4.2 K after curing

- Al-0.1wt%Ni is a work-hardenable alloy
- softens only partially with curing cycles
- compromise strength/RRR

A. Yamamoto et al., Nuclear Physics B 78 (1999), pp. 565-570;
Toward an improved conductor, stabilizer

ATLAS coil curing: 130 °C-15 h

Effect of CMS coil curing (including a 135 °C-50 h plateau)?

Fig. 3. Relationship between 0.2% yield strength and RRR

Toward an improved conductor, stabilizer

20% to 23% typical reduction in area

Al-0.1wt%Ni, CMS-type curing, at 4.2 K: Rp0.2 = 82±7 MPa
Four roll shaping process (courtesy of Outokumpu /IT)
Toward an improved conductor, stabilizer

allowed 11.3 % reduction in area
Toward an improved conductor, stabilizer

EN AW 1199 Aluminum

Graph showing:
- Reduction by cold rolling (%)
- Tensile strength (MPa)
- Yield strength (MPa)
- Elongation (%)

Bar charts for:
- Yield strength (MPa)
- Tensile strength (MPa)
- Hardness (HBS)
Toward an improved conductor, global tensile properties of a roll-shaped insert

<table>
<thead>
<tr>
<th></th>
<th>As received</th>
<th>Roll shaped, test 1</th>
<th>Roll shaped, test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength /MPa</td>
<td>20</td>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>Ultimate Tensile Strength /MPa</td>
<td>40</td>
<td>100</td>
<td>140</td>
</tr>
<tr>
<td>Elongation /%</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
</tbody>
</table>
Toward an improved conductor, weldability

Al-0.1wt%Ni EN AW-7020

acc. /kV = 120
intensity /mA = 9.26
cath. curr /A = 1.35
working distance /mm = 150
adv. speed /mm·s⁻¹ = 16.7
X,Y scanning
Comparison of properties, basis for a comparison of 4.2 K properties

Equivalent stress $\sigma_c$ acting on the improved full conductor:

$$\sigma_c S_c = \sum_i \sigma_i S_i = \sigma_{AlNiinsert} S_{AlNiinsert} + \sigma_{7020} S_{7020}$$

- $\sigma_{AlNiinsert} = \text{stress in the insert}$
- $\sigma_{7020} = \text{stress in the reinforcement}$
- $S_{AlNiinsert} = \text{cross sectional area of the insert}$
- $S_{7020} = \text{cross sectional area of the reinforcement}$

Contribution of the Rutherford to the yield neglected (conservative in the case of roll shaped inserts)
Comparison of properties, basis for a comparison of 4.2 K properties

![Graph showing stress-strain curves for different samples.]

- EN AW-7020.72 as cured, sample 10
- Al-0.1wt%Ni as cured, sample 4
- Weighted average

Stress /MPa:
- 706 MPa
- 424 MPa
- 104 MPa

Strain: 0 to 0.015
At 4.2 K, as CMS-cured state:

Minimum yield strength of the full conductor, evaluated at the 0.2% yield point of the reinforcement,

• for EN AW-7020.72 + Al-0.1wt%Ni = 400 MPa
• for EN AW-6082 (T6) + Al99.998 = 258 MPa [1]

Equivalent RRR = 420 (RRR of the as-cured Al 0.1wt%Ni = 900 x cross sectional ratio of the insert [1])

Comparison of properties, basis for a comparison of 4.2 K properties

Al-0.1wt%Ni, CMS-type curing, at RT: Rp0.2 = 59±2 MPa
⇒ RRR ≈ 900
Progress of Al-stabilized SC

Comparison of properties, basis for a comparison of 4.2 K properties

![Graph](image)
Composite Al-based pure metal conductors

- High purity aluminum composite conductors with Al-alloy matrix developed in the 90ies

- Typical properties at 20 K:
  - YS ≥ 165 MPa
  - UTS ≥ 276 MPa
  - 1.5 % ≤ A ≤ 8 %

**Table 2. Measured wire RRR, calculated filament RRR, and filament diameters**

<table>
<thead>
<tr>
<th>Sample</th>
<th>RRR</th>
<th>D, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>30, 19, 8-4 Annealed</td>
<td>544</td>
<td>124</td>
</tr>
<tr>
<td>30, 4, 8-4</td>
<td>764</td>
<td>269</td>
</tr>
<tr>
<td>30, 19, 4-2</td>
<td>558</td>
<td>124</td>
</tr>
<tr>
<td>50, 19, 8-4</td>
<td>683</td>
<td>206</td>
</tr>
<tr>
<td>30, 19, 8-4 As-extruded</td>
<td>428</td>
<td>124</td>
</tr>
<tr>
<td>30, 4, 8-4</td>
<td>364</td>
<td>269</td>
</tr>
<tr>
<td>30, 19, 4-2</td>
<td>413</td>
<td>124</td>
</tr>
<tr>
<td>50, 19, 8-4</td>
<td>398</td>
<td>206</td>
</tr>
</tbody>
</table>
Composite Al-based pure metal conductors

Limiting mechanical strain of 0.1 % to 0.2 %

350 MPa, RRR 400 to 500 in magnetic fields up to 10 T

Current densities not cited: "could carry much higher current densities than the practical $2 \times 10^8$ A/m$^2$ of lightweight SC"
Al-stabilised NbTi multifilament SC

- M. Young, E. Gregory, E. Adam and W. Marancik, *Fabrication and Properties of an aluminum-stabilized NbTi Multifilament Superconductor*


![Embedding in EN AW-6061 (EN AW-5052 reported)](image)

High purity Al "tube"

**RRR = 320**

Critical current density at 5 T = 1630 A/mm²

Fig. 2. Cross section of an Al-stabilized superconductor containing 121 NbTi filaments in an 1100 Al matrix sheathed in high-purity aluminum.
Al-stabilised Nb$_3$Sn multifilament SC


- **High purity Al (RRR = 2500 to 5000)**
- **Reacted "monolith" (80000 filaments in a CuSn matrix)**
- **Duratherm reinforcement (Co-Ni-Cr alloy)**

**Fig. 3** Stabilized monolith NS 80000 (dimensions 6.6 x 3.6 mm$^2$) produced by coextrusion with Al and strengthening Duratherm.

**Fig. 2** Four types of Al stabilized Nb$_3$Sn composites (dimensions 16 x 5.24 mm$^2$) produced by coextrusion.

- Al added after the reaction treatment
- Simultaneous extrusion with reacted Nb$_3$Sn
- Length up to 100 m (limited by length of reacted Nb$_3$Sn)
- $R = 580$ for the "80000" version
- $\sigma = 186$ MPa at RT, idem
Aluminium alloy DS-Al-550

High temperature compression strength
(according to Hellum and Luton, proc. ESA Symp. 1990)

Mechanical properties at 4.2 K
after a 10 h thermal treatment

Particle size, 2 nm to 10 nm
Particle spacing, 80 nm
Expected RRR, less than 10
Conclusions

Toward a High Strength, High RRR Conductor:

⇒ Selection of high performance, extrudable reinforcement and insert alloys

⇒ Potential suitability of the alloys demonstrated, compatible with curing

⇒ Good aptitude of the CMS insert to be cold reduced by roll shaping

⇒ Intrinsic and heterogeneous weldability of the alloys demonstrated

Alternative solutions:

⇒ Not fully industrially confirmed

⇒ Dispersion strengthened or composite Al-based alloys alternative to Al-0.1wt%Ni should be the object of a careful design
Toward an improved conductor, reinforcement


Fig. 3. Tensile and notch tensile design of the specimens. The design of the notch tensile specimens was done according to ASTM E 602-91.

Fig. 5. Notch tensile strength over yield strength.