Development of Advanced Stabilized Superconductor (Part 1)

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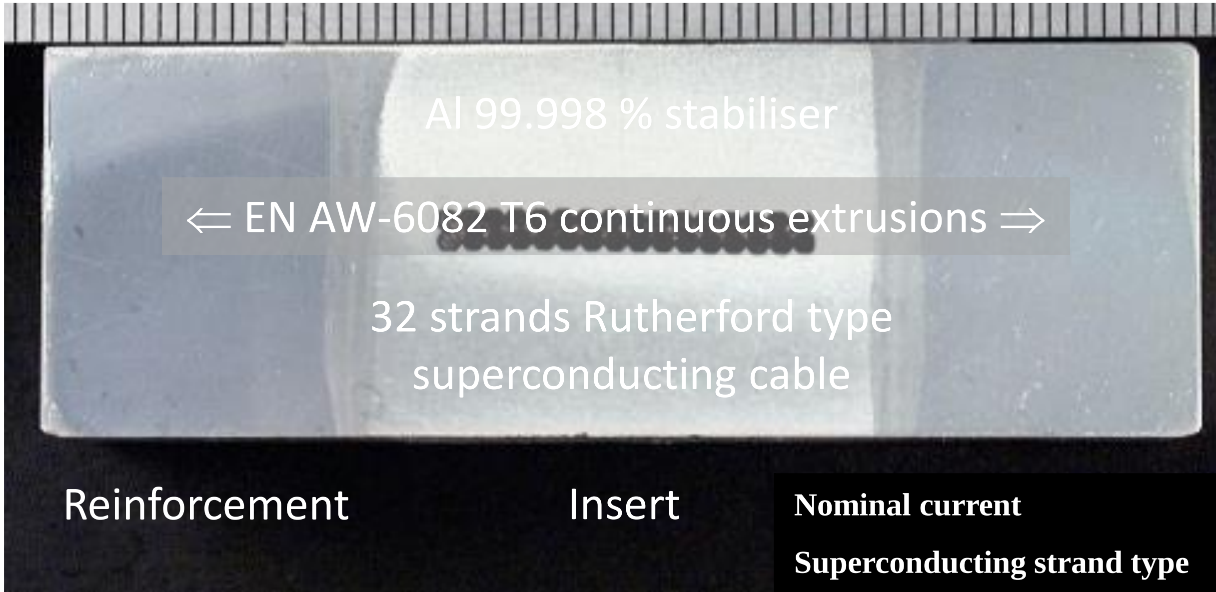
Outline

- **The present CMS conductor:**
  - **materials and developments**
  - **state of stress, safety factors**
- **Toward an improved conductor**
  - **replacement of the reinforcement alloy by EN AW-7020**
  - **replacement of pure Al stabiliser by cold drawn Al-0.1wt%Ni**
  - **weldability**
- **Comparison of mechanical properties and equivalent RRR of the improved conductor**
  - **with the actual CMS conductor**
  - **and conductors of other geometry (⇒ see Part 2 by B. Curé)**

See: S. Sgobba, D. Campi, B. Cure, P. El-Kallassi, P. Riboni and A. Yamamoto, "*Toward an Improved High Strength, High RRR CMS Conductor*," in IEEE Transactions on Applied Superconductivity, vol. 16, no. 2, pp. 521-524, June 2006, doi: 10.1109/TASC.2005.869687.

The present CMS conductor, materials and geometry



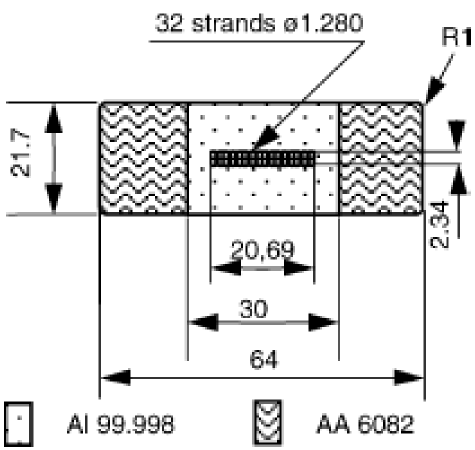
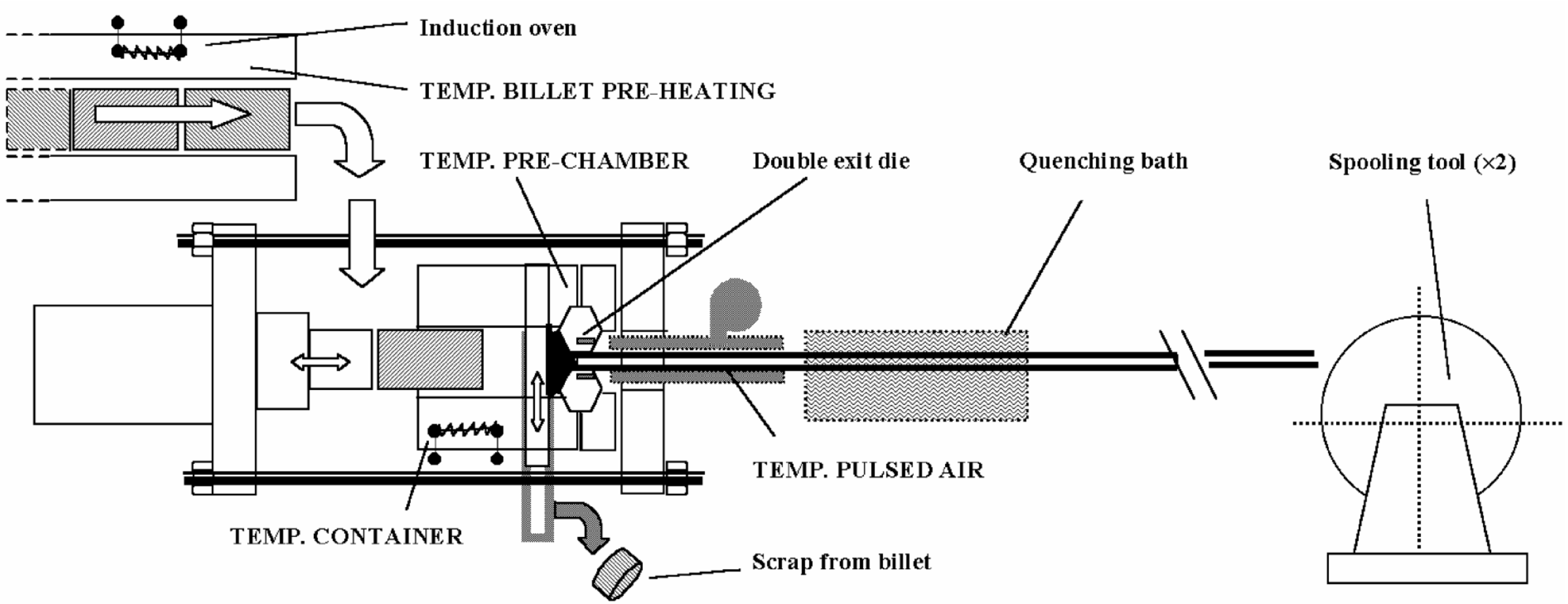


Fig. 1. Cross-section of the conductor.

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 stabiliser	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

The present CMS conductor, billet on billet extrusion of the reinforcement



Schematic representation of the extrusion line (S. Sequeira Tavares, S. Sgobba, *An improved billet on billet extrusion process of continuous aluminium alloy shapes for cryogenic applications in the Compact Muon Solenoid experiment*, J. of Mat. Proc. Technology 143–144 (2003) 584–590)

The present CMS conductor, curing cycle

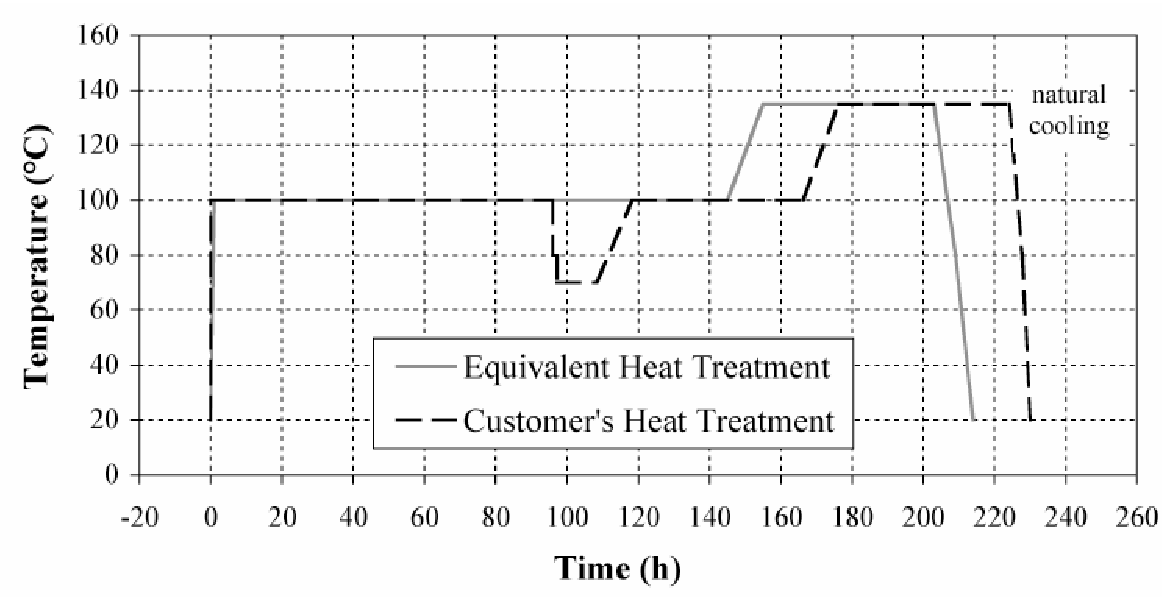
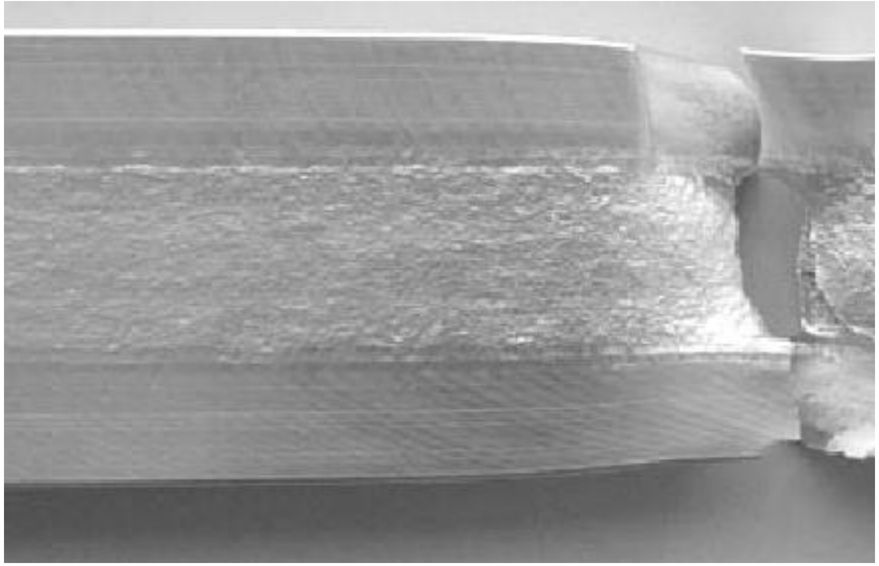
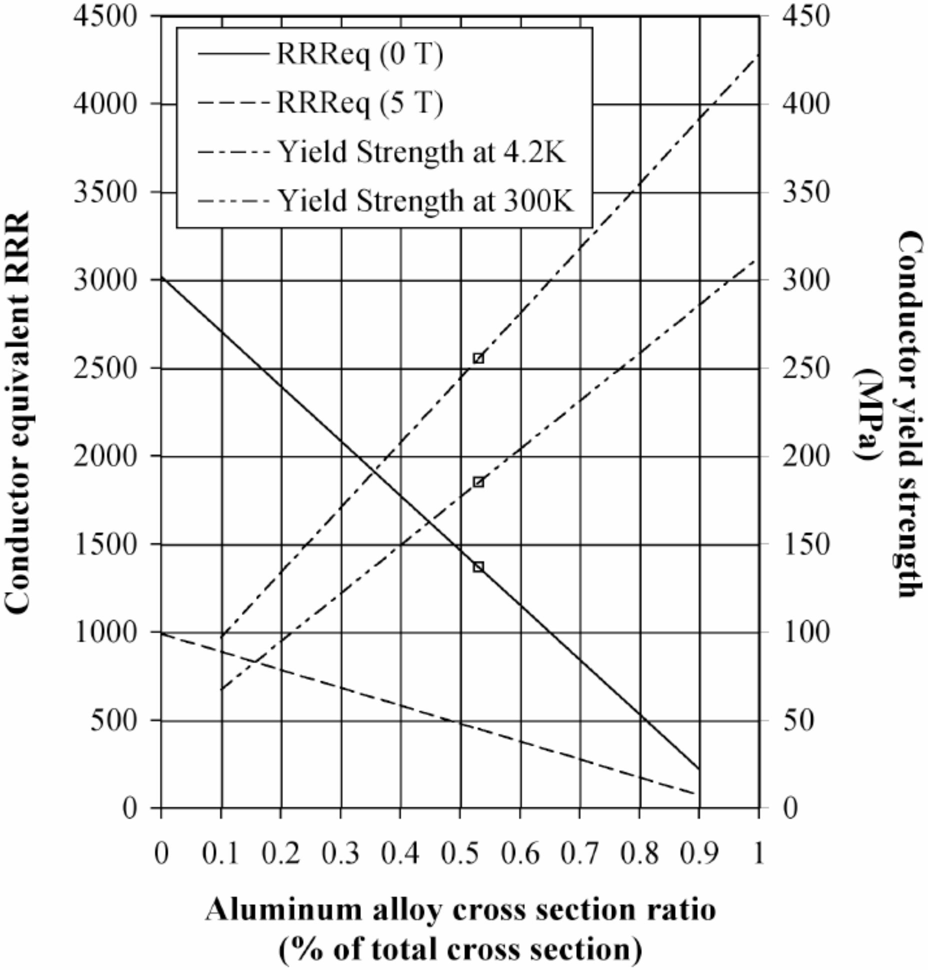


TABLE II
SUMMARY OF THE MEASURED (SPECIFIED/EXPECTED) TENSILE PROPERTIES DURING THE PRE-PRODUCTION PHASE

Property	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
As-received state, RT	295 (250)	171 (150)	20 (15)
After customer's heat treatment, RT	370 (280)	281 (175)	18 (15)
After customer's heat treatment, 4.2 K	684 (550)	428 (225)	16 (15)

The present CMS conductor, tensile and electrical properties





B. Curé et al., "*Mechanical Properties of the CMS Conductor*", IEEE Trans. Appl. Superconduc., vol. 14, no. 2, pp. 530-533, June 2004

The present CMS conductor, state of stress, safety factors

At the nominal field of 4 T and at 4.5 K :

- maximal tensile stress on the total conductor ⇒ 94 MPa
- maximal shear stress at the interface reinforcement - pure Al ⇒ 8 MPa
- maximum Von Mises stress on pure Al ⇒ 22 MPa
- idem on the reinforcement ⇒ 145 MPa

- for a design strength of ⇒ 225 MPa

- including a 1.5 safety factor

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A. Desirelli et al., “ FE Stress analysis of the CMS Magnet Coil”, IEEE Trans. Appl. Superconduc., vol. 10, pp. 419-423, March 2000

Toward an improved conductor, material selection

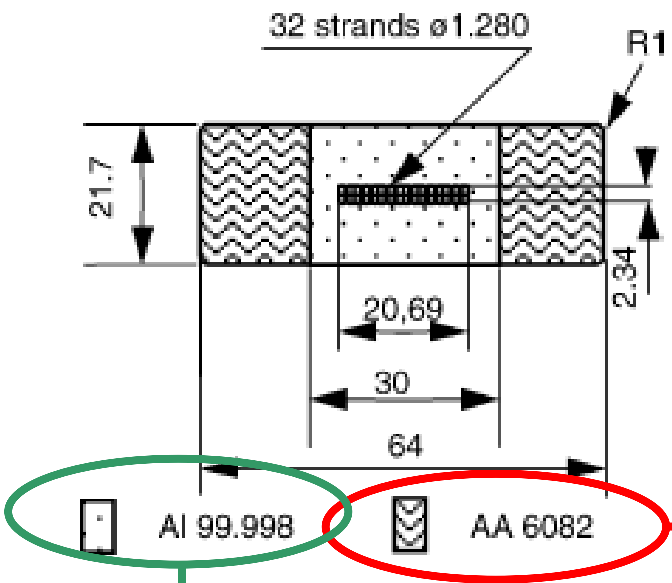


Fig. 1. Cross-section of the conductor.

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
- developed for the ATLAS thin solenoid superconductor (A. Yamamoto et al., *Development towards Ultra-thin Superconducting Solenoid Magnet for High Energy Particle Detectors*, Nuclear Physics B (Proc. Suppl.) 78 (1999), pp.565-570)
- enhanced mechanical strength
- without excessive degradation in RRR compared to pure Al

Toward an improved conductor, reinforcement

Extrudable, weldable

Table 11.14 Tensile properties of aluminum alloys at room temperatu

		n- n	Tempera- ture (K)	Tensile Strength, TS (MPa)	Yield Strength, YS (MPa)	Elongati in 4D (%)				
5083-O	25	L	RT	322	141	19.5				
			77	434	158	32				
			4	557	178	32				
5083-H321	25	L	RT	335	235	15				
			77	455	274	31.5				
			4	591	279	29				
6061-T651	25	L	RT	309	291	16.5				
			77	402	[illegible]	23				
			4	483	379	25.5				
		T	RT	309	[illegible]	[illegible]				
			77	405	[illegible]	20.5				
			4	485	[illegible]	23				
2219-T851	25	L	RT	466	[illegible]	11				
			77	568	[illegible]	13.8				
			4	659	[illegible]	15				
		T	RT	457	[illegible]	10.2				
			77	575	[illegible]	14	28	630	1.09	1.37
			4	674	[illegible]	15	23	690	1.03	1.37
7005-T5351	38ᵃ	L	RT	427	[illegible]	15	43	594	1.39	1.59
			77	578	[illegible]	17	27	683	1.18	[illegible]
			4	672	521	17	22	737	1.09	1.41
A356-T61	19	Casting	RT	[illegible]	[illegible]	8.3	10	354	1.23	1.70
			77	356	262	7.1	9	495	1.09	1.50
			4	356	262	4	4	412	1.15	1.57

ᵃExtrusion.

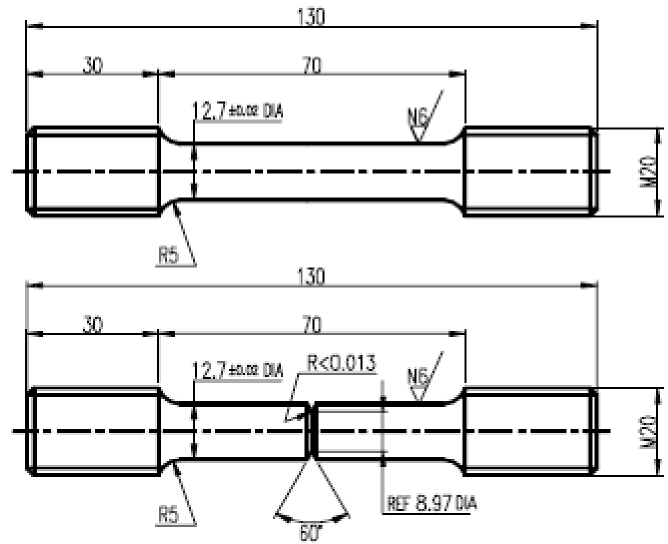


Fig. 3. Tensile and notch tensile design of the specimens. The design of the notch tensile specimens was done according to ASTM E 602-91.

Toward an improved conductor, reinforcement

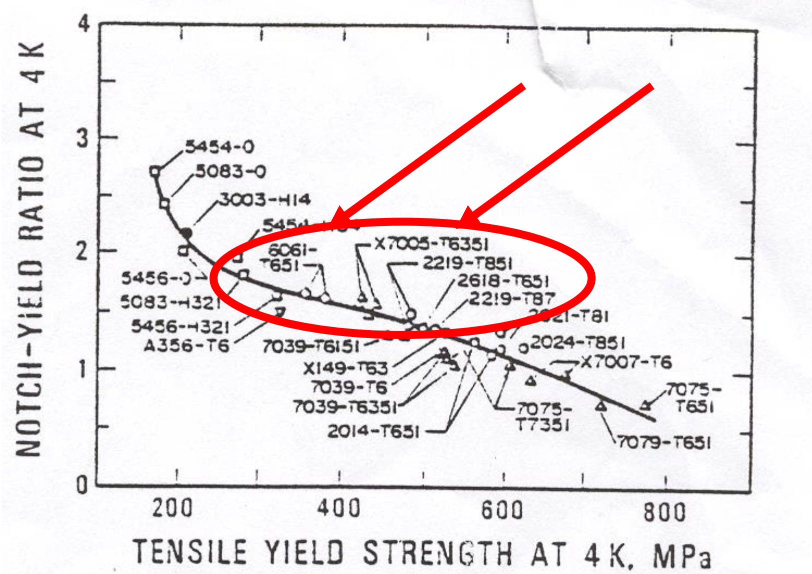


Figure 11.37 Notch-yield ratio vs. tensile yield strength for aluminum alloys at 4 K (Kaufman and Wanderer, 1971). ○ — 2xxx alloys; ● — 3xxx alloys; □ — 5xxx alloys; ◇ — 6xxx alloys; △ — 7xxx alloys; ▽ — casting alloys.

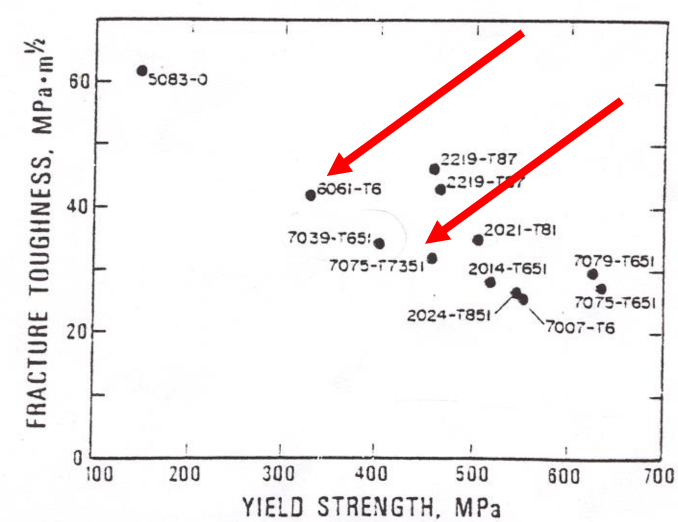


Figure 11.38 Fracture toughness of aluminum alloys at 77 K (McHenry, 1977).

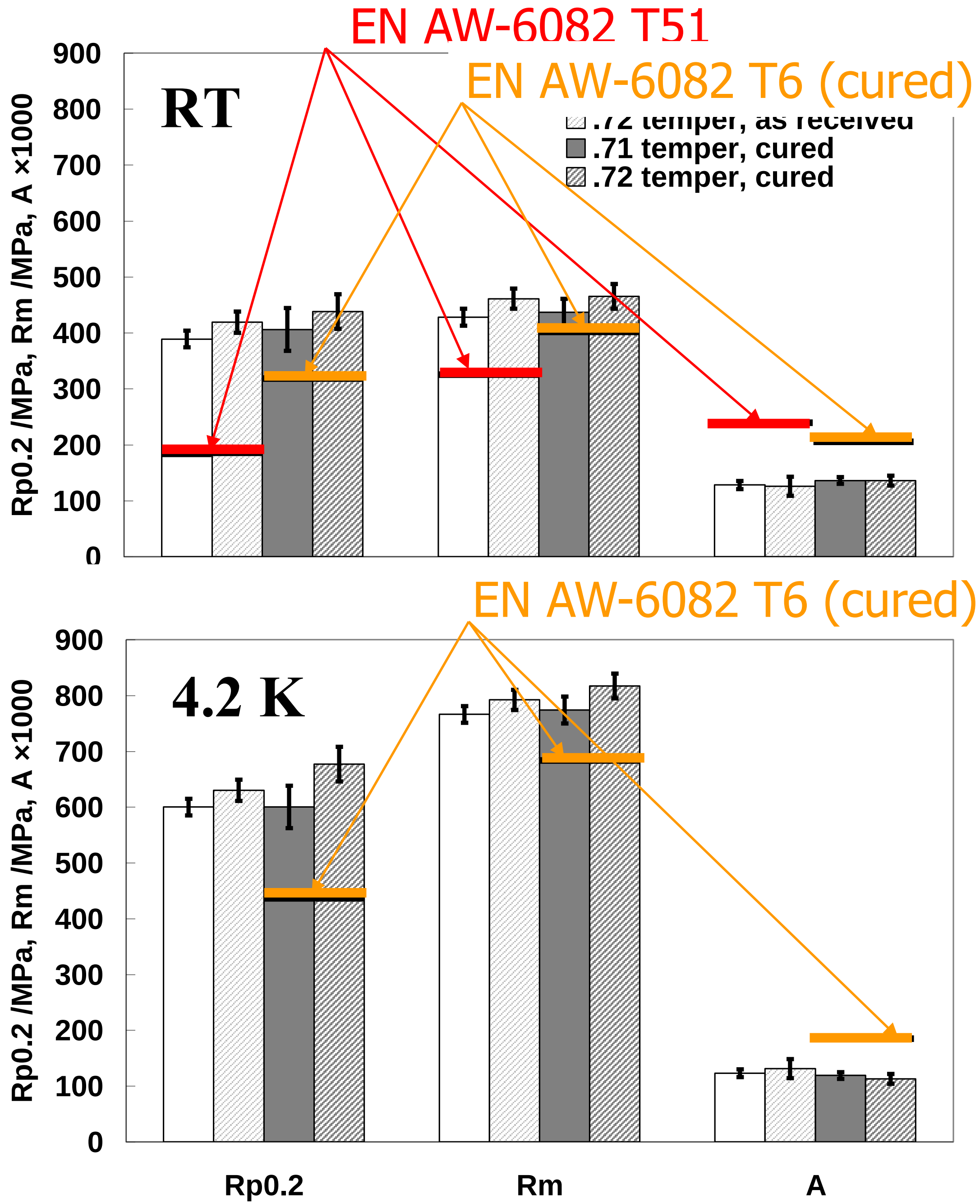
Toward an improved conductor, reinforcement

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
.72 temper, as received
.71 temper, cured
.72 temper, cured
Rp0.2 /MPa, Rm /MPa, A ×1000
900
800
700
600
500
400
300
200
100
0
EN AW-6082 T6 (cured)
4.2 K
Rp0.2 /MPa, Rm /MPa, A ×1000
900
800
700
600
500
400
300
200
100
0
Rp0.2
Rm
A

Toward an improved conductor, safety factors

EN AW-7020.72, cured, at RT

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

EN AW-7020.72, cured, at 4.2 K

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

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

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

Safety factors:

EN AW-7020.72 $\Rightarrow$ 3 (677 MPa/225 MPa)
EN AW-6082 T61 $\Rightarrow$ 1.9 (428 MPa/225 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:

225 MPa ⇒ 350 MPa

EN AW-7020.72 ⇒ **1.92** (6

EN AW-6082 T61 ⇒ **1.22**

with respect to a design st

"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"

A. Hervé et al., *Experience Gained from the Construction, Test and Operation of the Large 4-T CMS Coil*, paper presented at MT20 (2007)

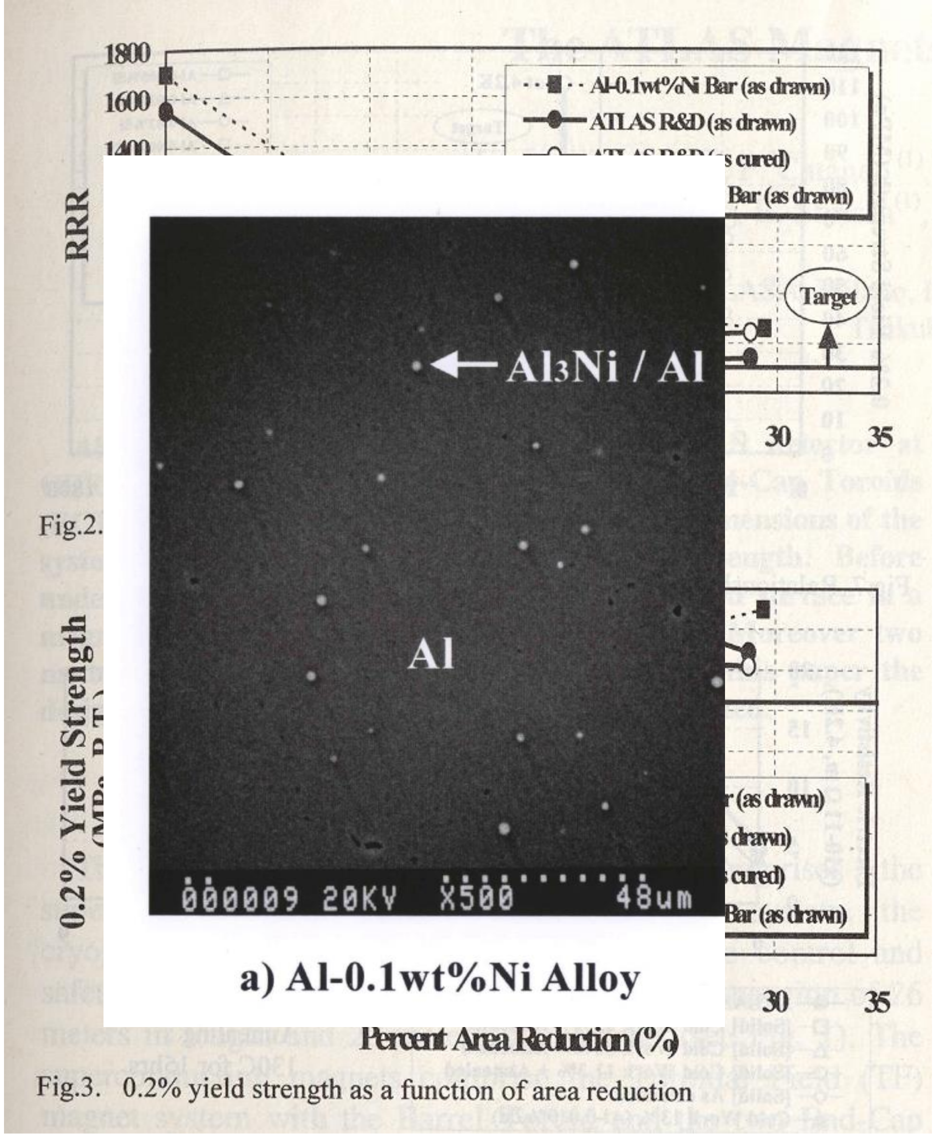
Toward an improved conductor, stabiliser

Candidate alloy:

- Al99.998 ⇒ Al-0.1wt%Ni
- developed for the ATLAS thin Solenoid superconductor
- aiming an Rp0.2 = 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

K. Wada et al., IEEE Trans. Appl. Superconduc., vol. 10, pp. 373-376, March 2000



Toward an improved conductor, stabiliser

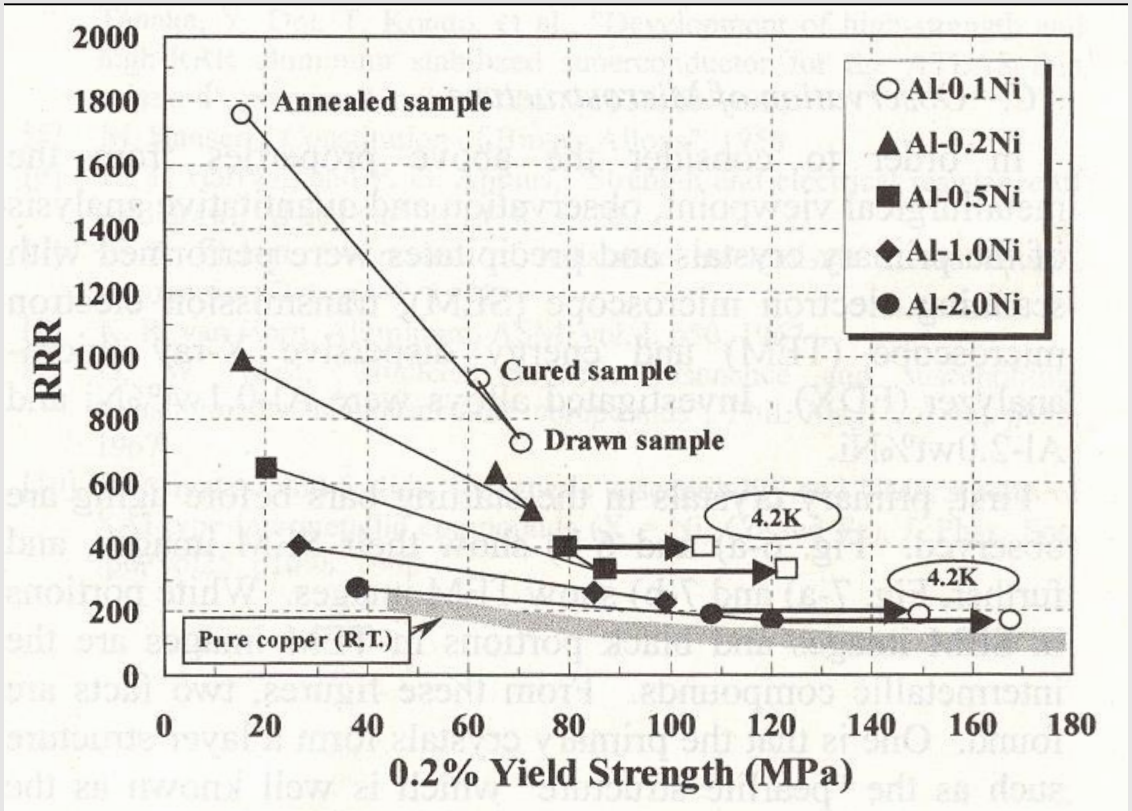


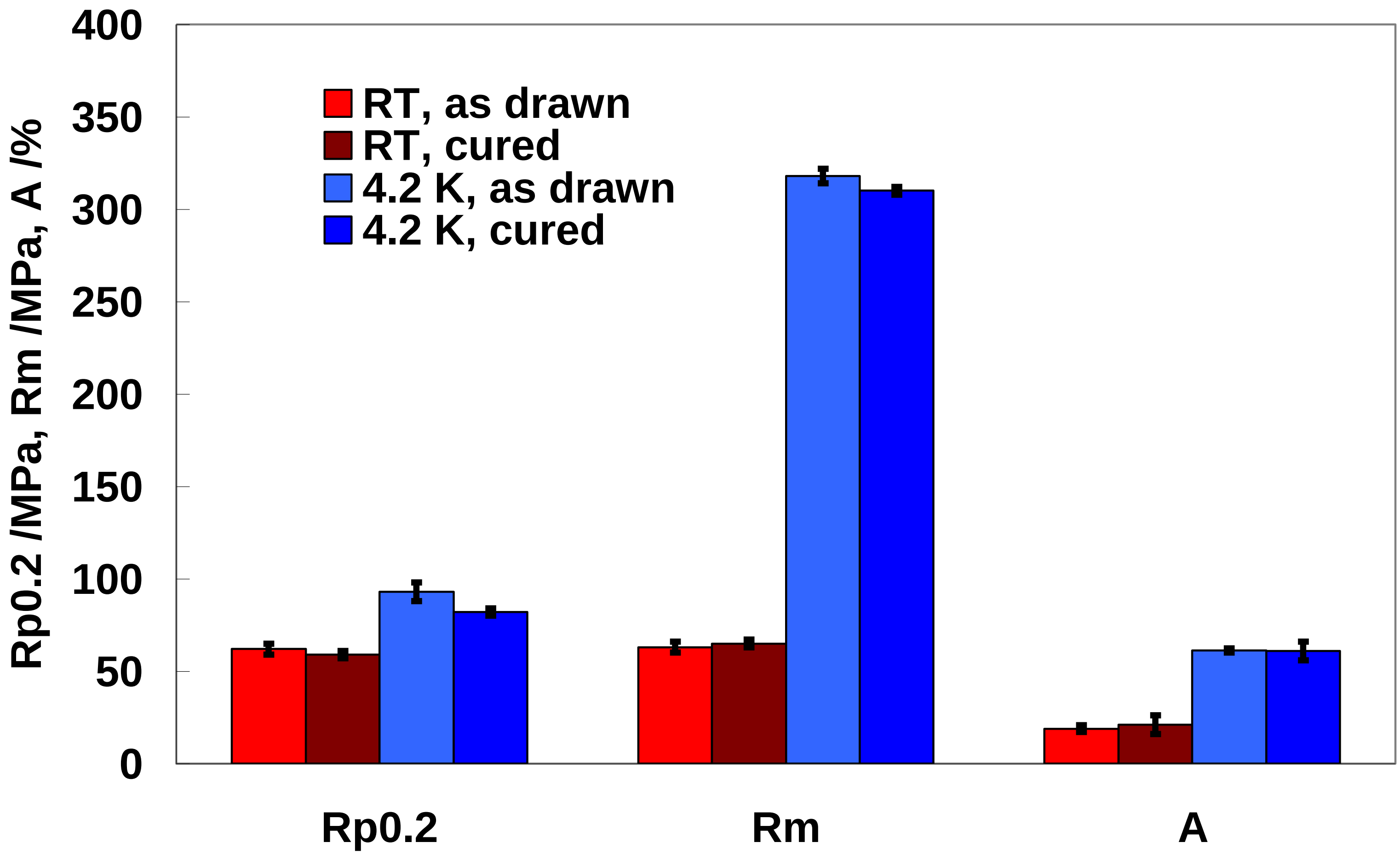
Fig. 3. Relationship between 0.2% yield strength and RRR

ATLAS coil curing:
130 °C-15 h

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

Al-0.1wt%Ni, from K. Wada et al., IEEE Trans. Appl. Superconduc., vol. 10, pp. 1012-1015, March 2000

Toward an improved conductor, stabiliser



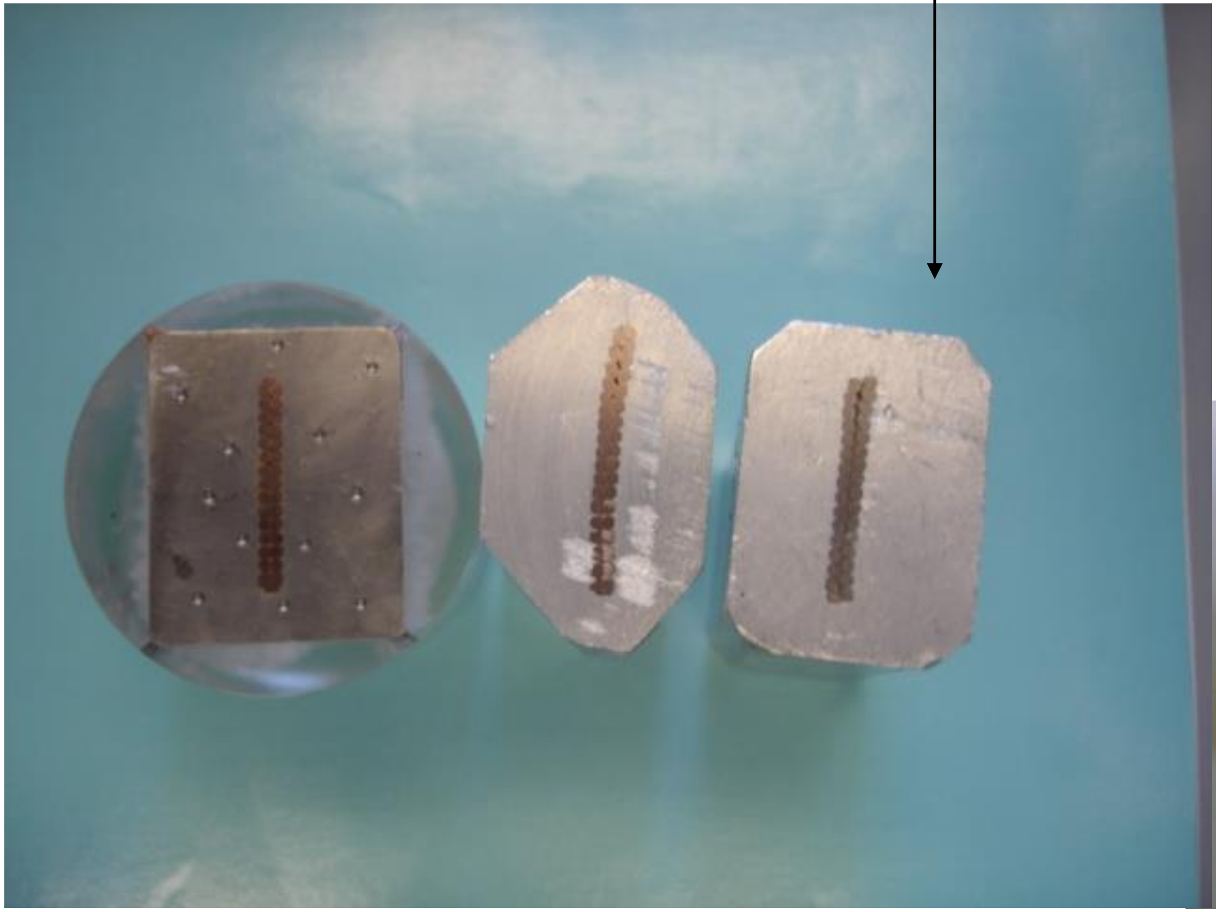
Al-0.1wt%Ni, CMS-type curing, at 4.2 K: Rp0.2 = 82±7 MPa

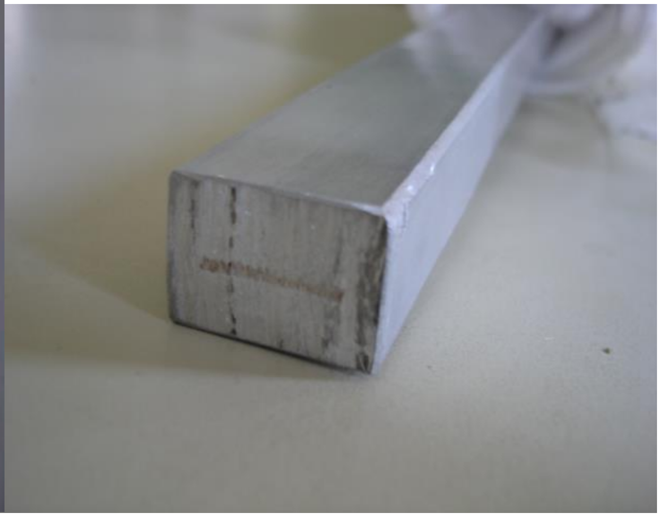
Toward an improved conductor, stabiliser

Four roll shaping process (courtesy of Outokumpu /IT)

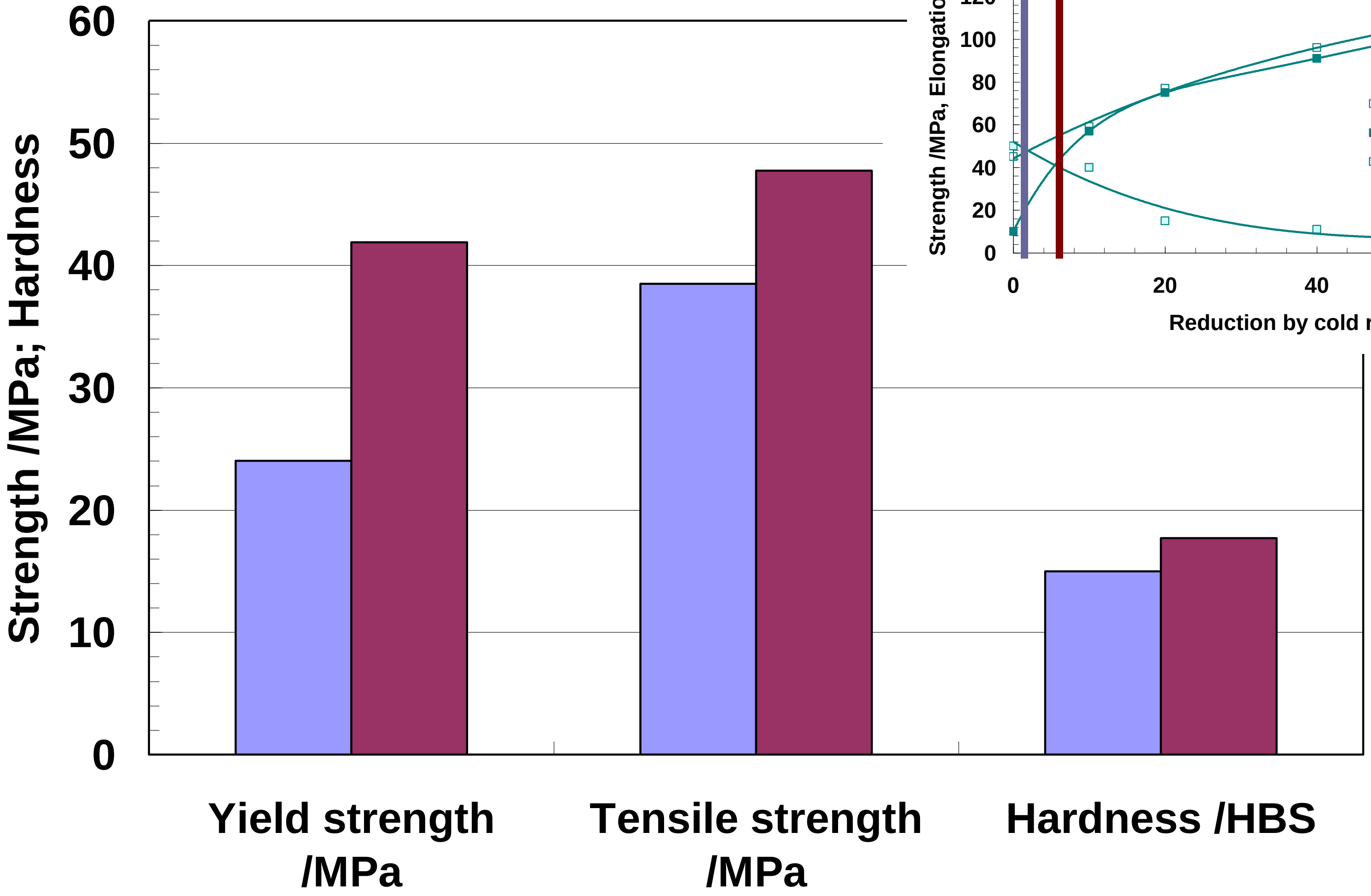
Toward an improved conductor, stabiliser

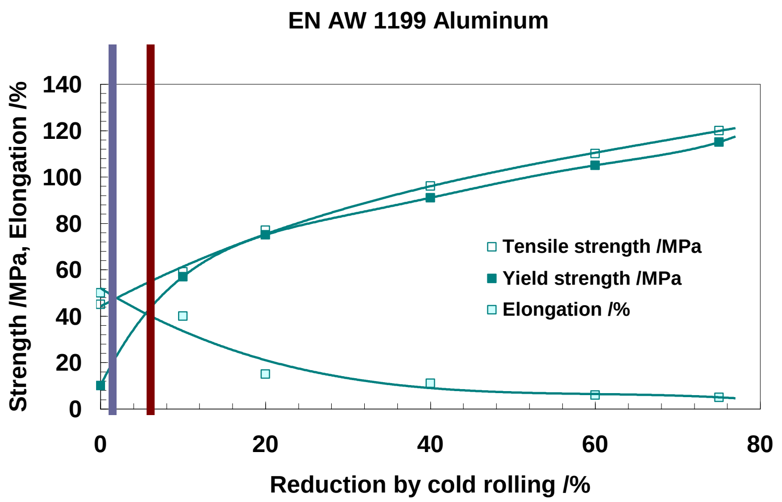
allowed 11.3 % reduction in area



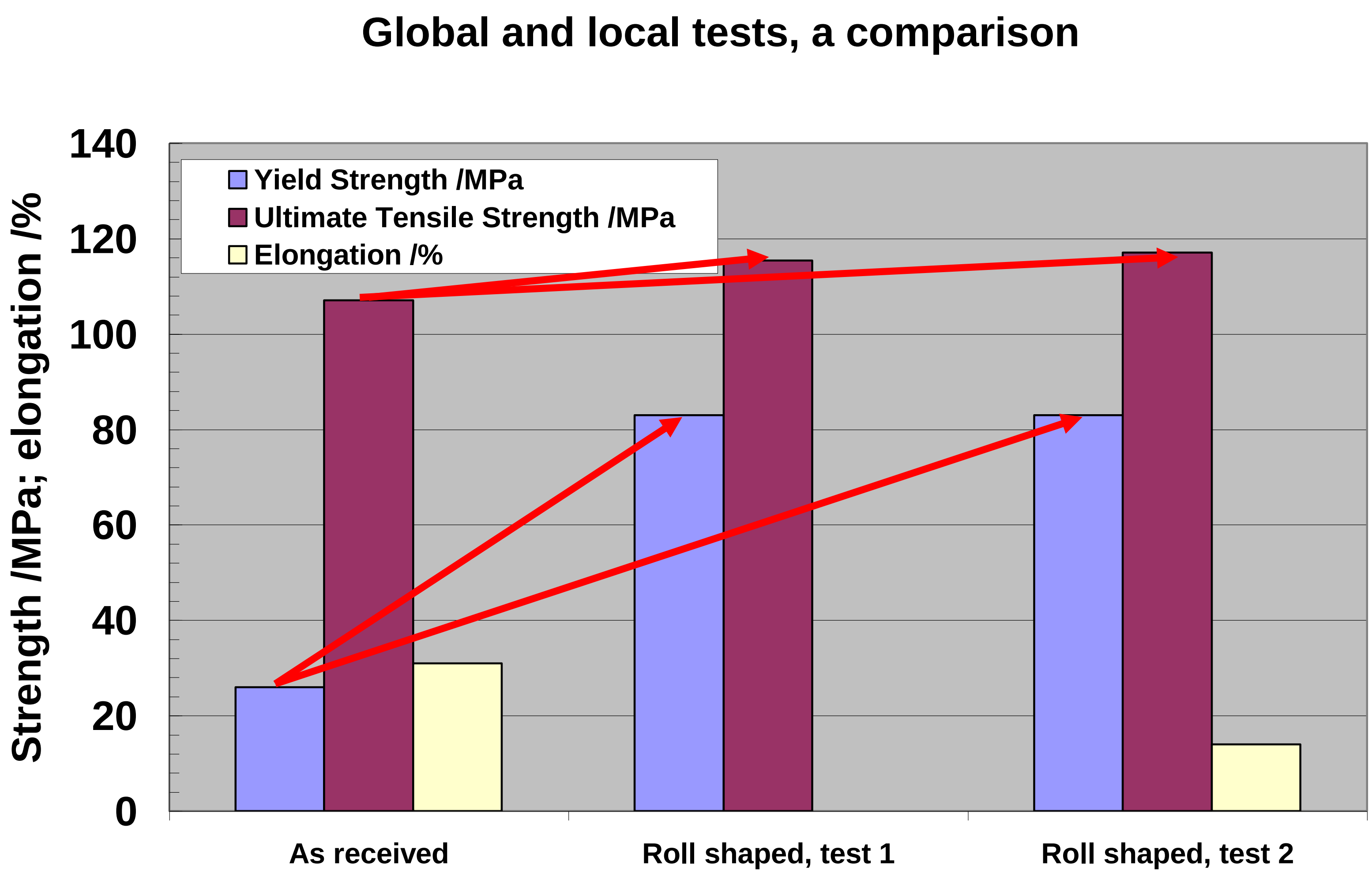


Toward an improved conductor, stabiliser

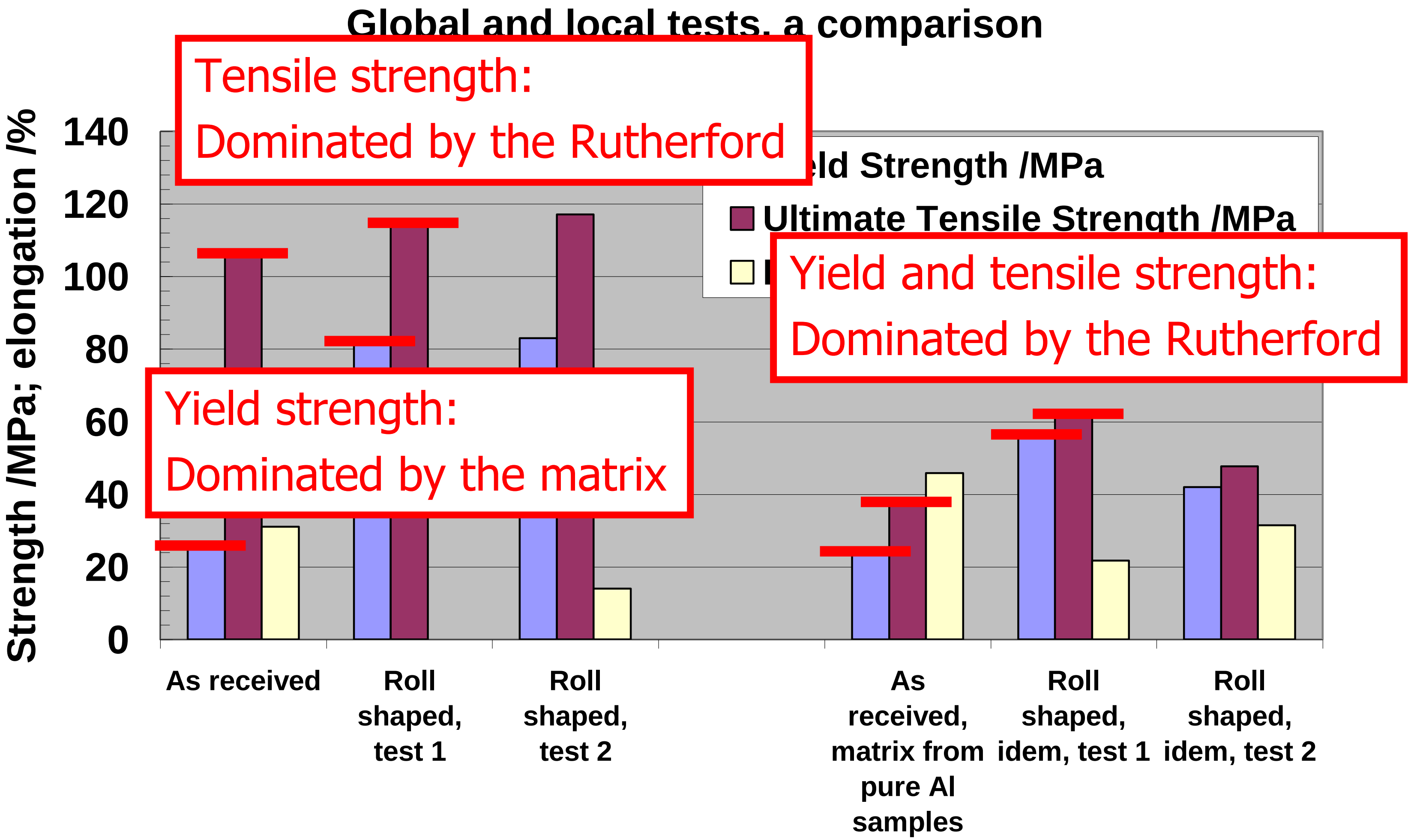




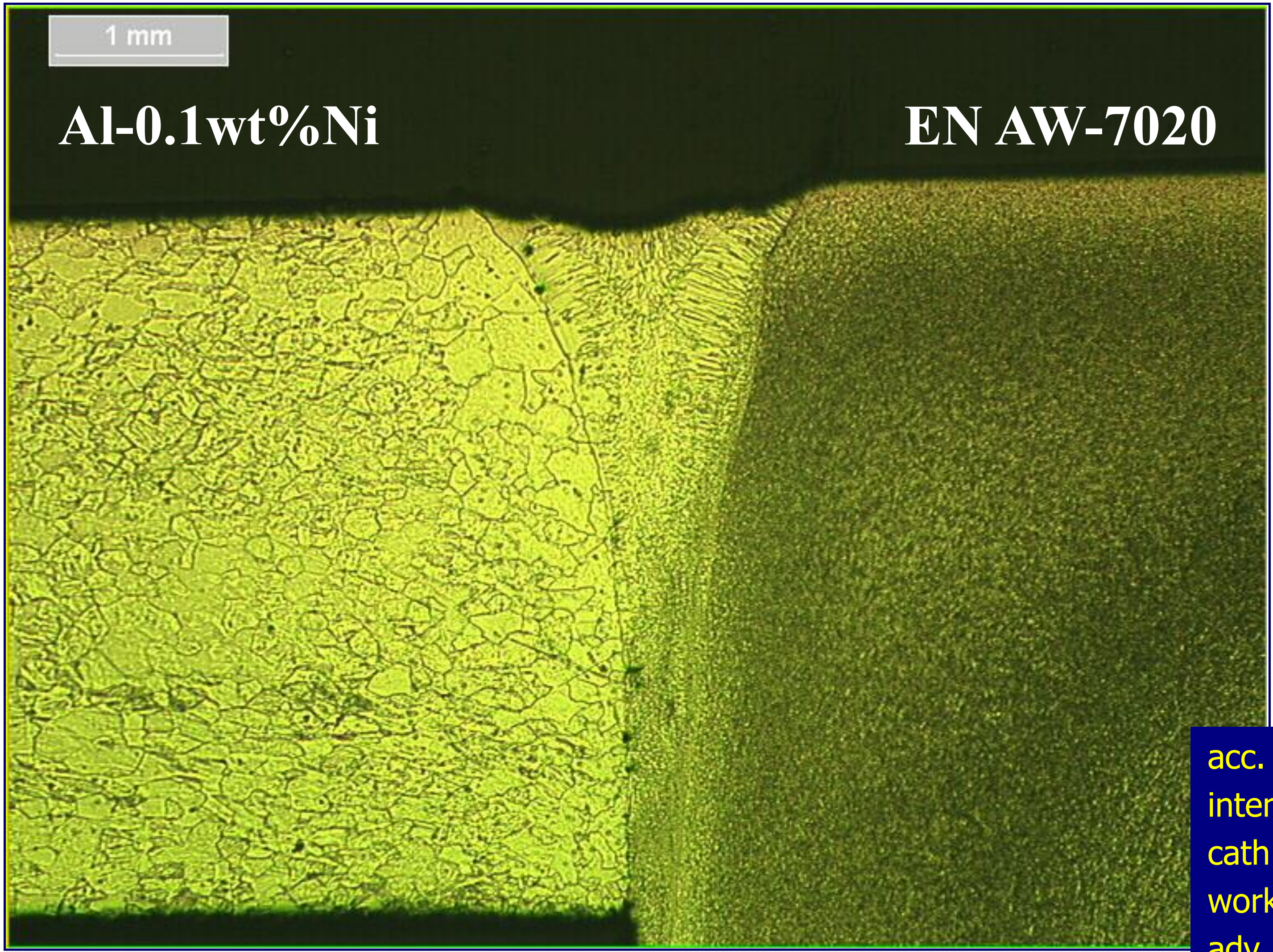
Toward an improved conductor, global tensile properties of a roll-shaped insert



Toward an improved conductor, global tensile properties of a roll-shaped insert



Toward an improved conductor, weldability



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

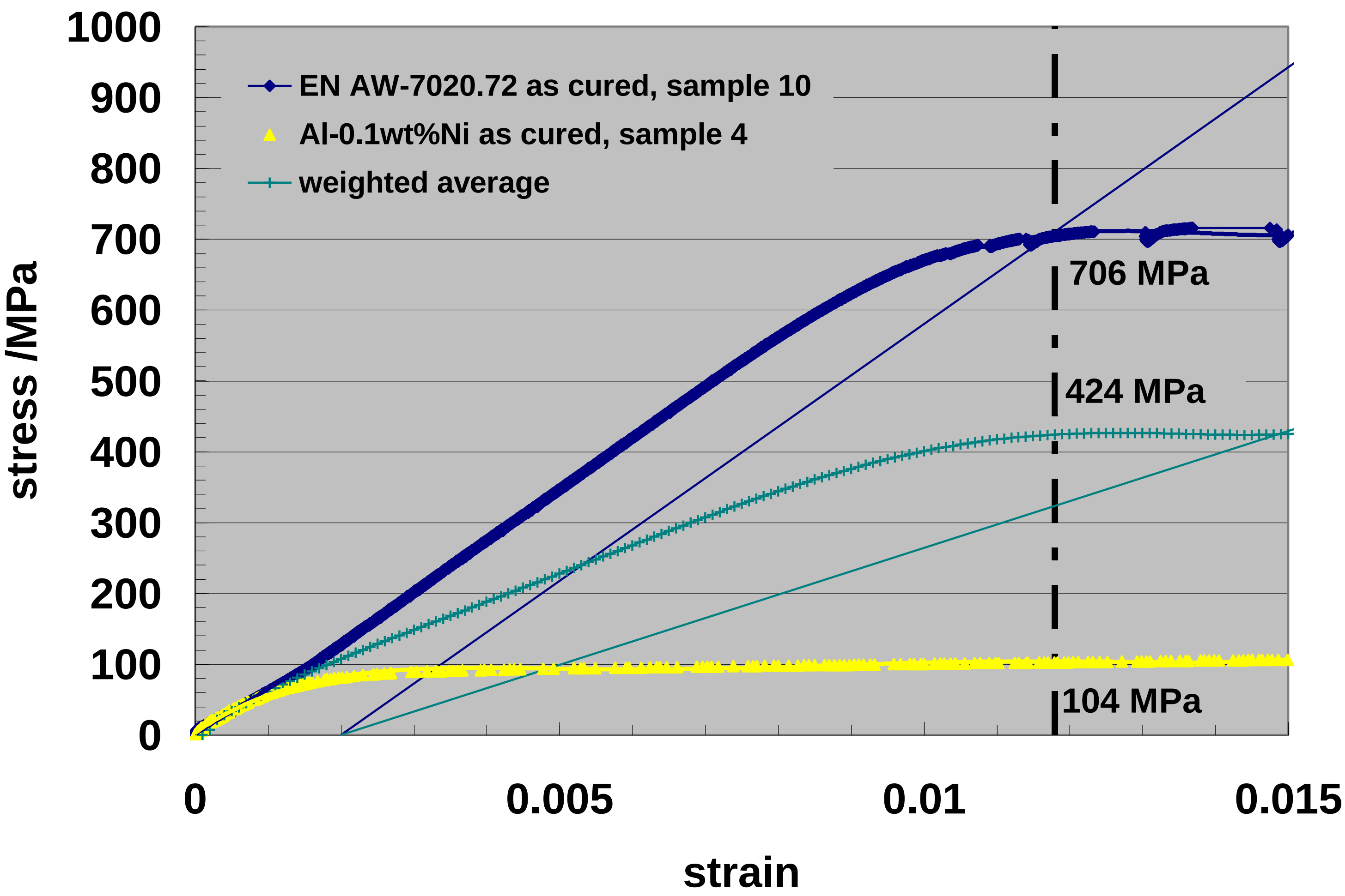
Equivalent stress σ_c acting on the improved full conductor:

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

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



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

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])

[1] B. Curé et al., "Mechanical Properties of the CMS Conductor", *IEEE Trans. Appl. Superconduc.*, vol. 14, no. 2, pp. 530-533, June 2004

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

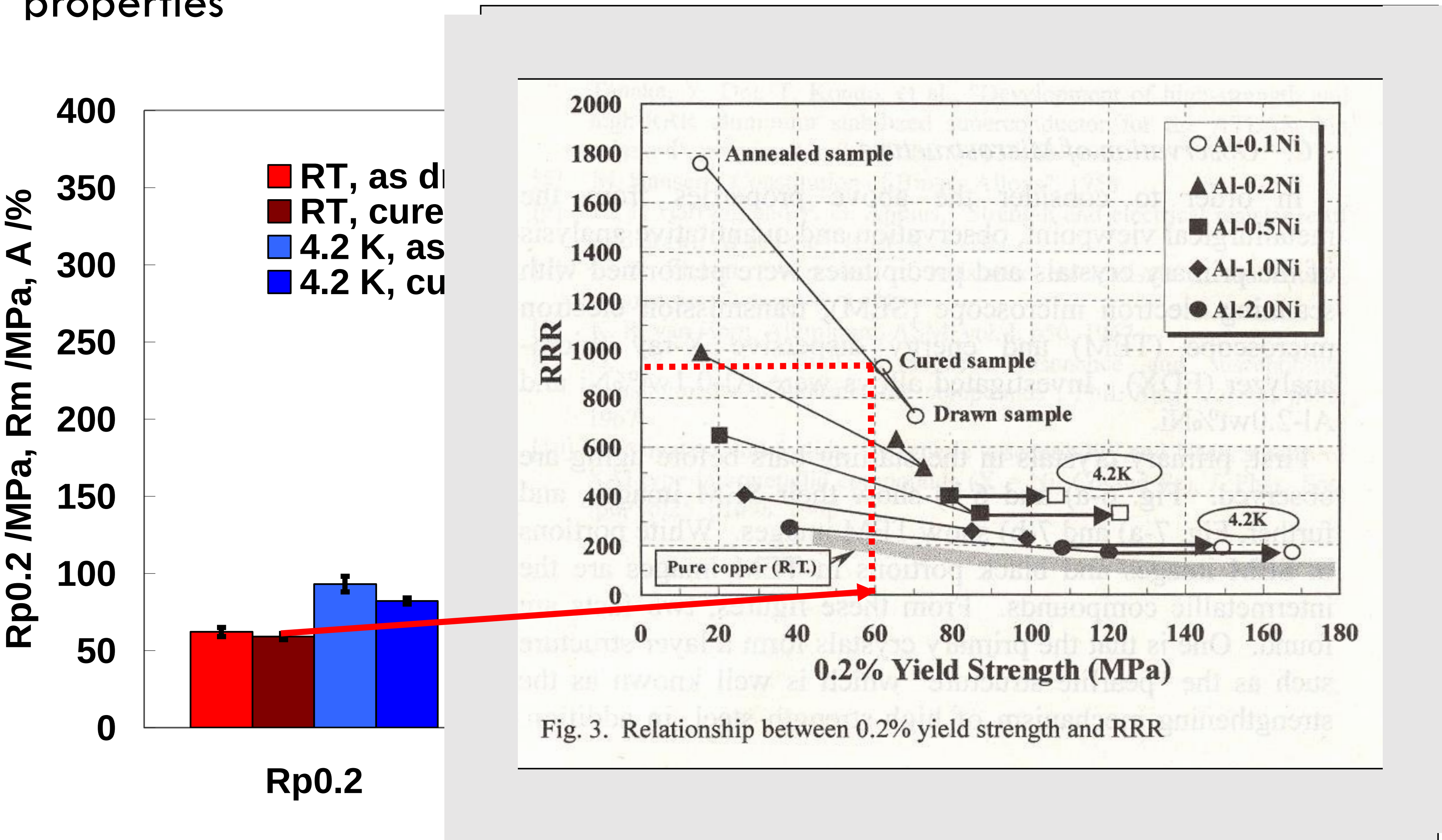
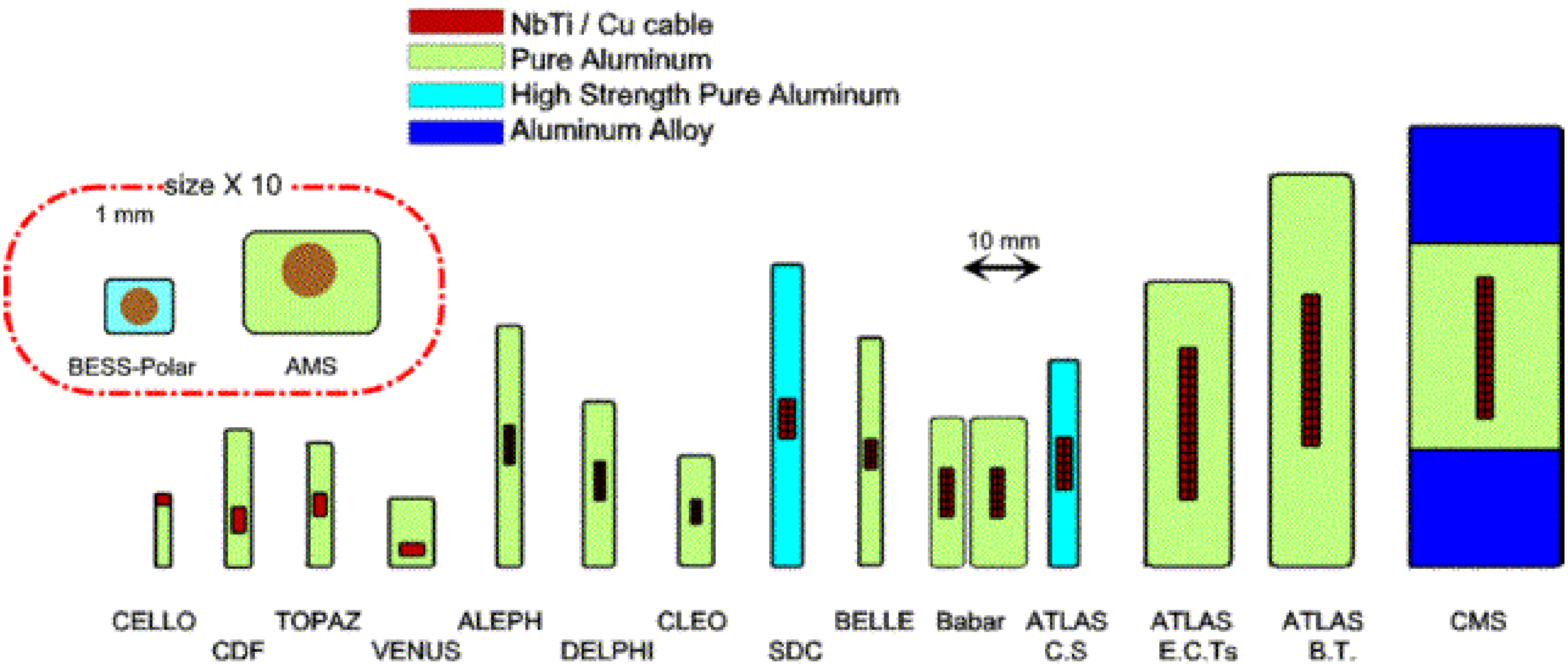


Fig. 3. Relationship between 0.2% yield strength and RRR

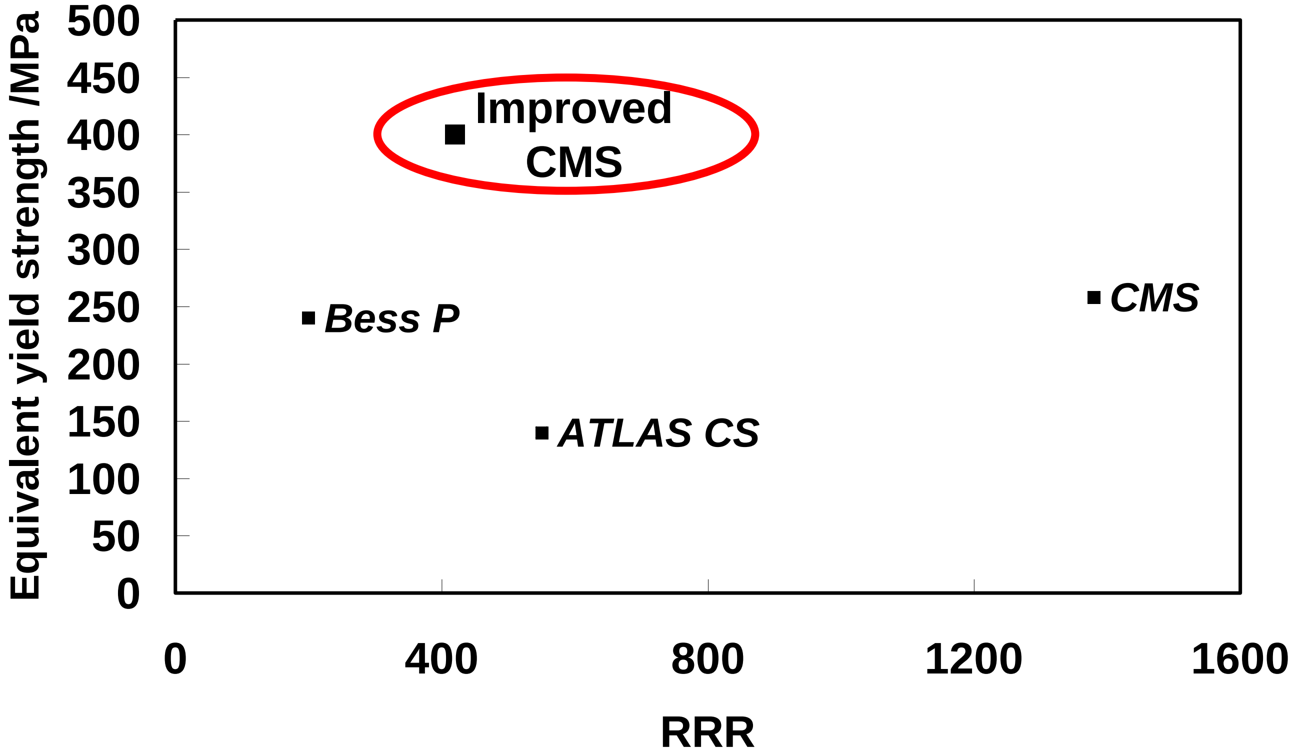
Al-0.1wt%Ni, CMS-type curing, at RT: Rp0.2 = 59±2 Mpa ⇒ RRR ≈ 900

Progress of Al-stabilized SC



A. Yamamoto, "Advances in Superconducting Magnets for Particle Physics", *IEEE Trans. Appl. Superconduc.*, vol. 14, no. 2, pp. 477-484, June 2004.

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



Conclusions

Toward a High Strength, High RRR CMS Conductor:

$\Rightarrow$ Selection of high performance, extrudable reinforcement and insert alloys

$\Rightarrow$ Potential suitability of the alloys demonstrated, compatible with curing

$\Rightarrow$ Good aptitude of the CMS insert to be cold reduced by roll shaping

$\Rightarrow$ Intrinsic and heterogeneous weldability of the alloys demonstrated