EN Engineering Department

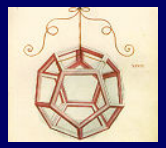
1st Linear Collider Detector (ILC/CLIC) Magnet Workshop

Options for yield strength enhancement of Al-stabilised superconductors

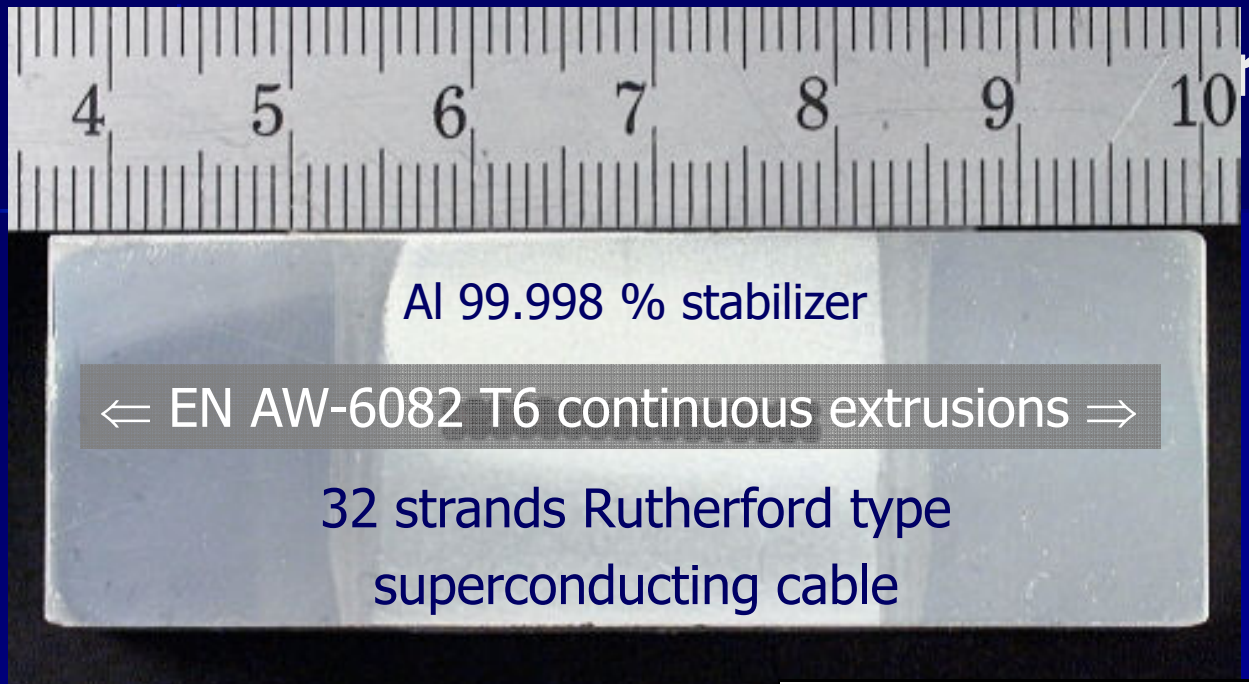
S. Sgobba

CERN, CH-1211 Geneva

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



Reinforcement Insert

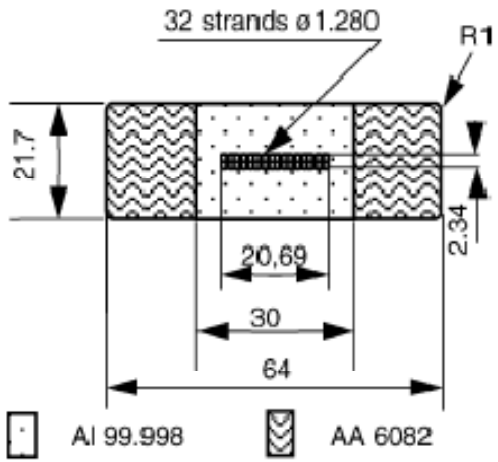


Fig. 1. Cross-section of the conductor.

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 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

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

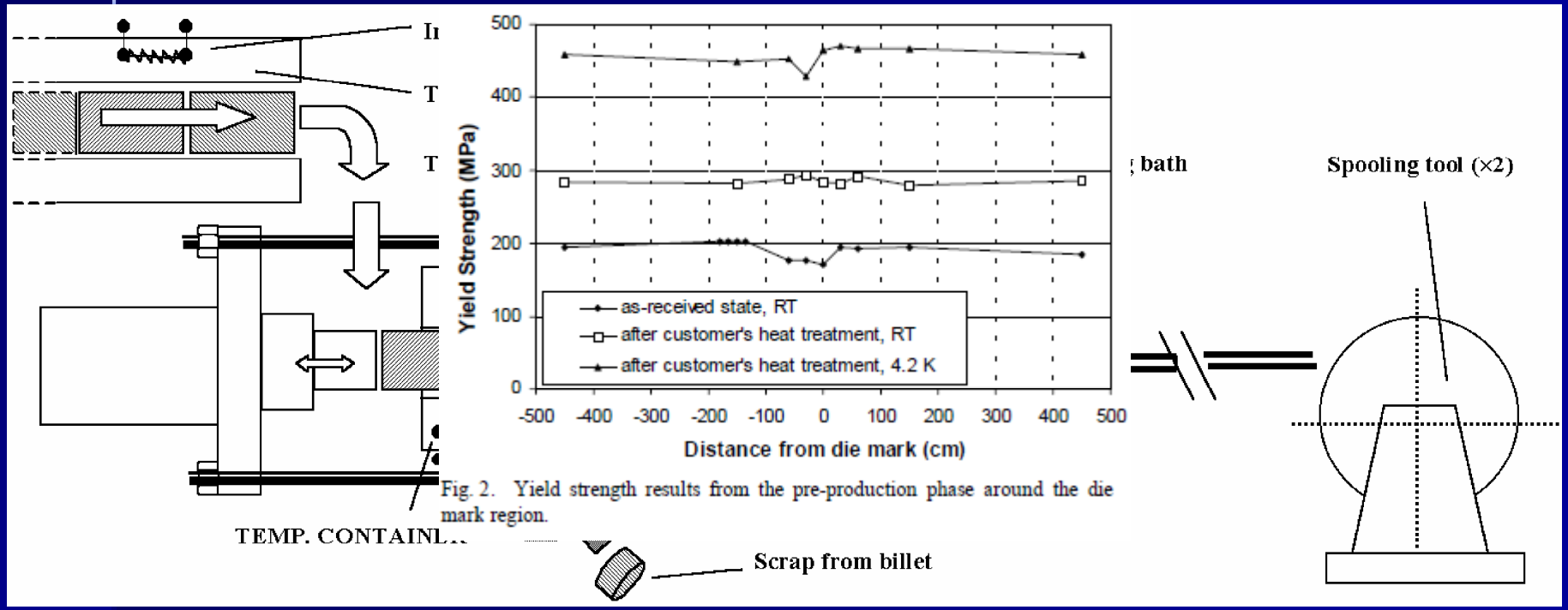
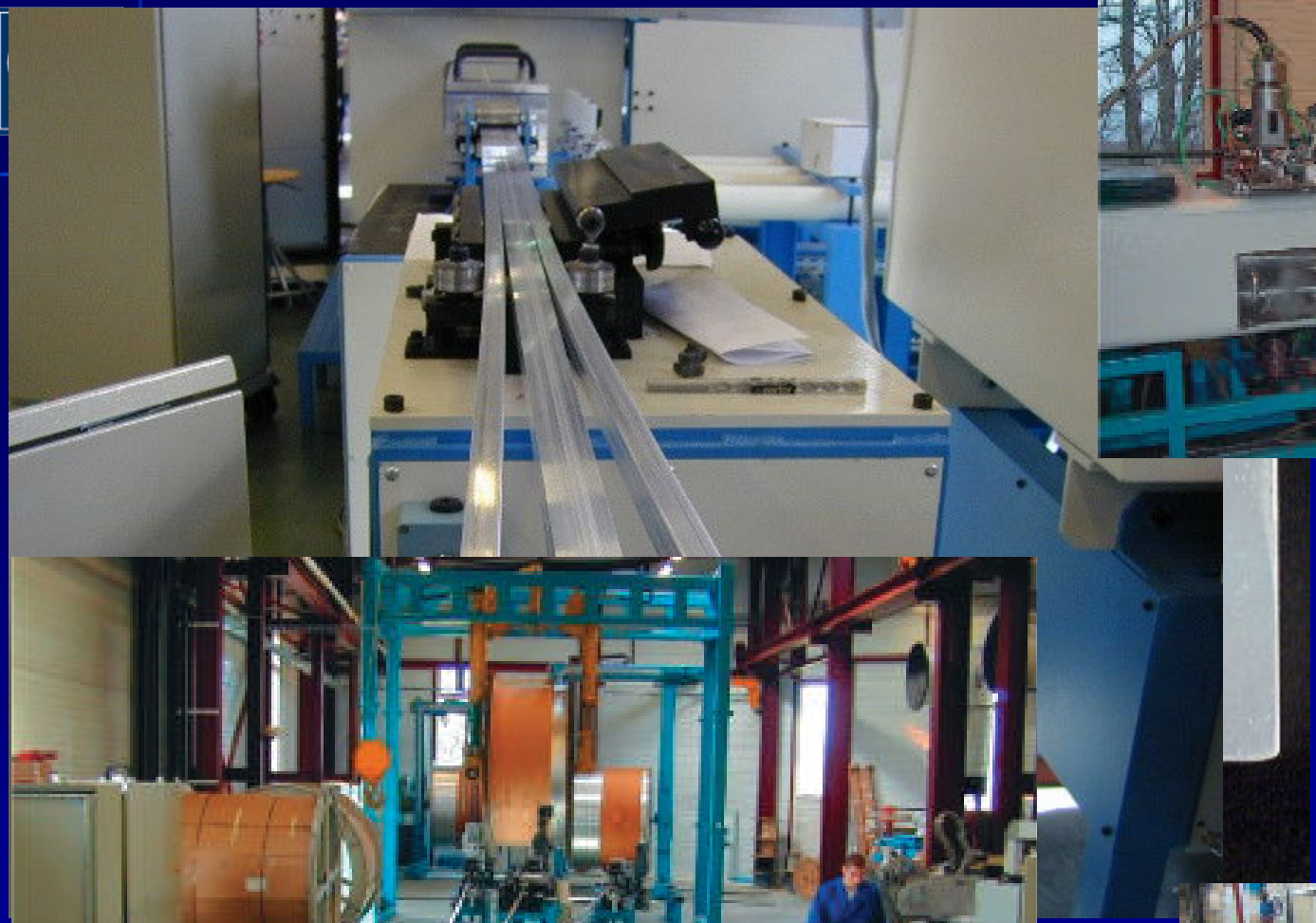


Fig. 2. Yield strength results from the pre-production phase around the die mark region.

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)



A dedicated production line has been designed and implemented by Technetics (Annecy, France) to perform the continuous EB welding of the two reinforcement sections around the so-called insert. The production line is 70 m long and its nominal EB welding speed is 2 m/min.
The three parts of components are deposited, straightened and cleaned before entering into the EB welding chamber.

The present CMS conductor, curing cycle

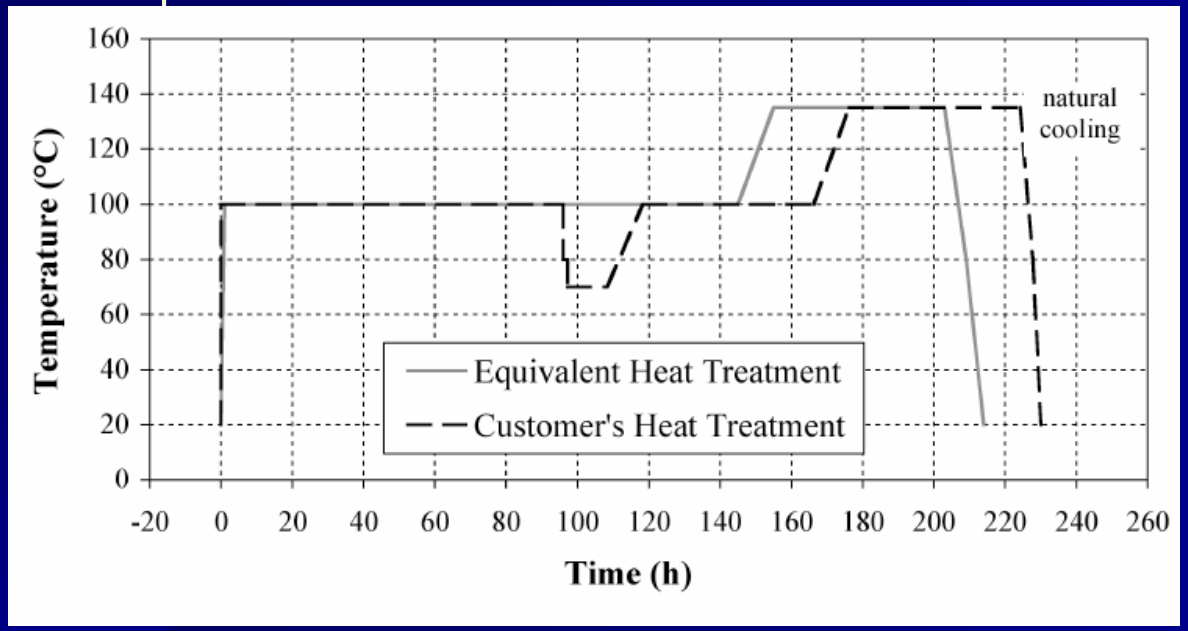
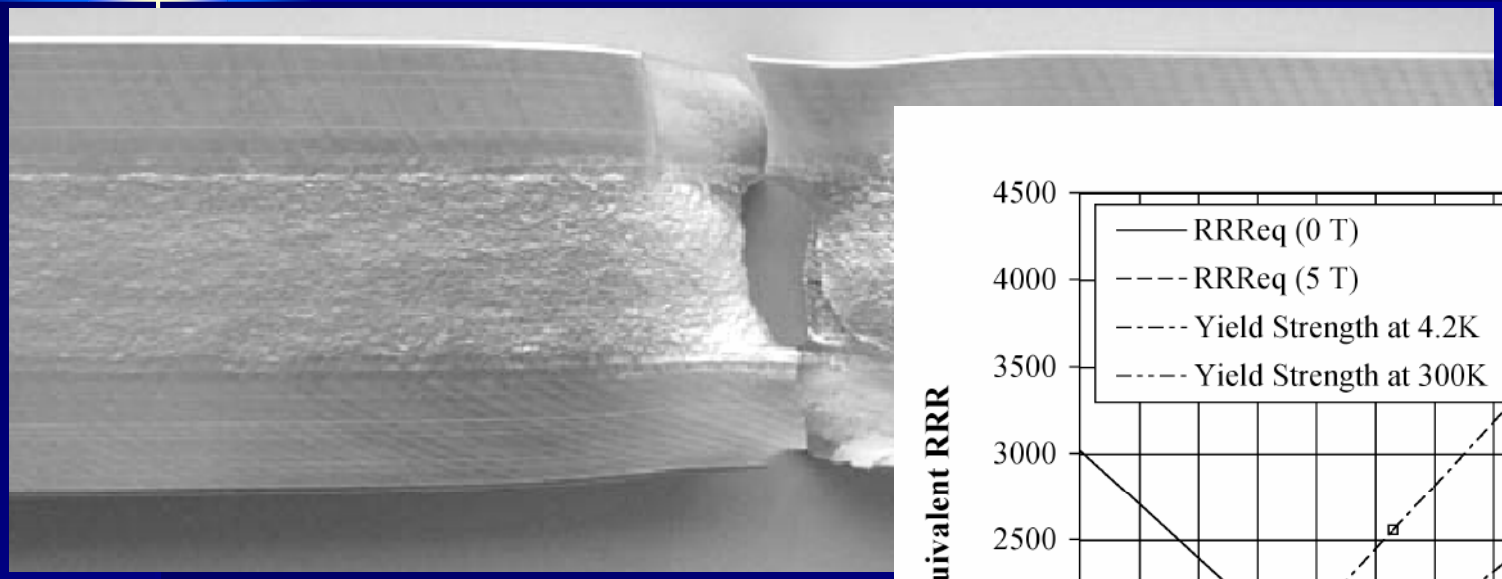
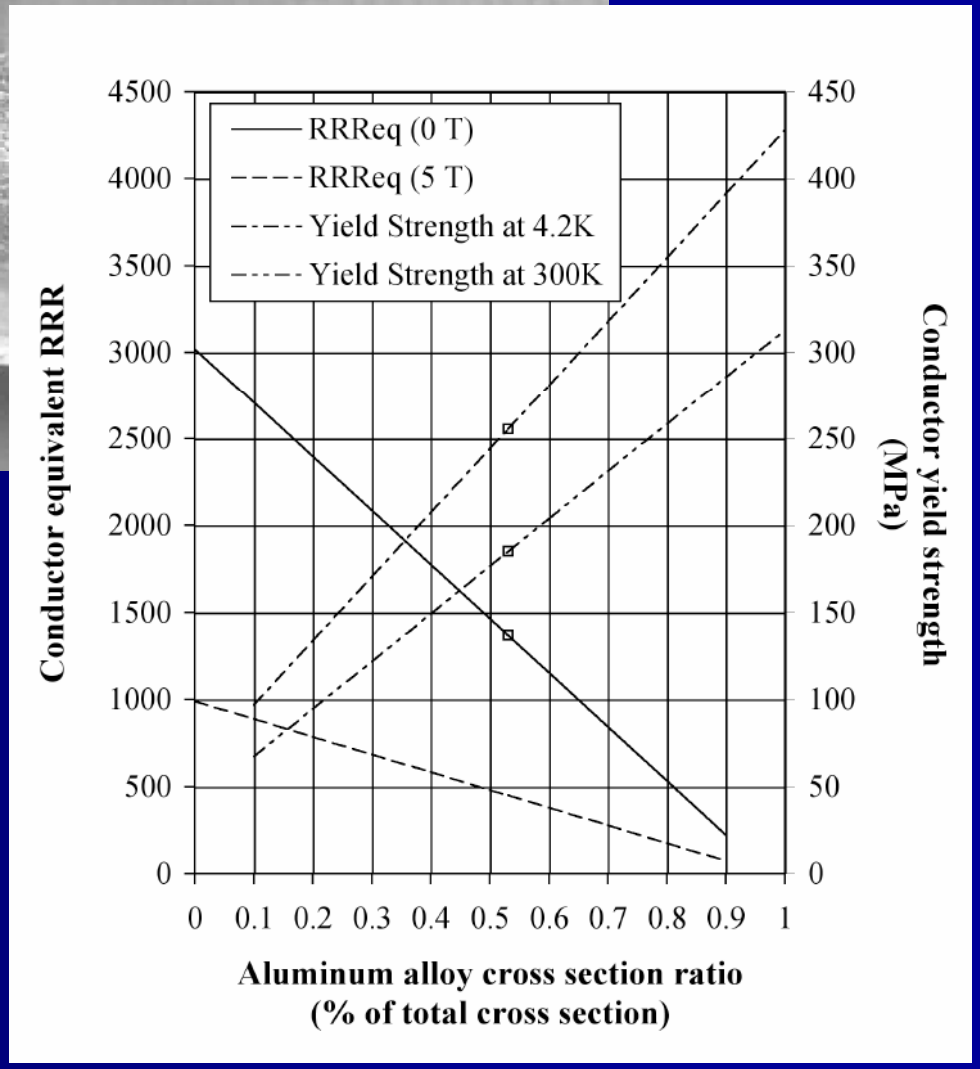


TABLE II
SUMMARY OF THE MEASURED (SPECIFIED/EXPECTED) TENSILE PROPERTIES DURING THE PRE-PRODUCTION PHASE

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

Toward an improved conductor, material selection

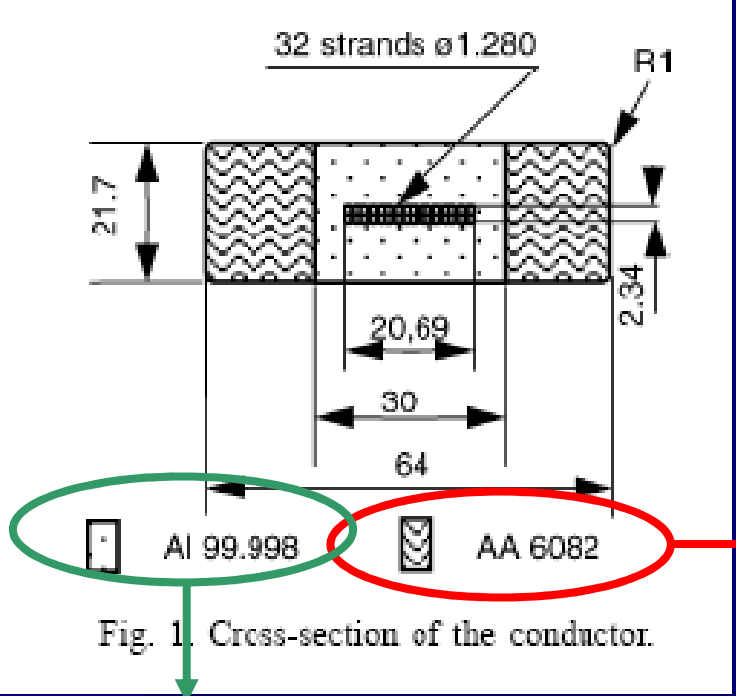


Fig. 1. Cross-section of the conductor.

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

Table 11.14 Tensile properties of aluminum alloys at room temperatu

Extrudable, weldable

		n-in	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]	15.2
			77	405	321	20.5
			4	485	393	23
2219-T851	25	L	RT	466	371	11
			77	568	440	13.8
			4	659	484	15
		T	RT	457	313	10.2
			77	575	402	14
			4	674	511	15
7005-T5351	38[a]	L	RT	427	319	15
			77	578	[illegible]	17
			4	672	521	17
A356-T61	19	Casting	RT	287	[illegible]	8.8
			77	356	262	7.1
			4	356	262	4

[a]Extrusion.

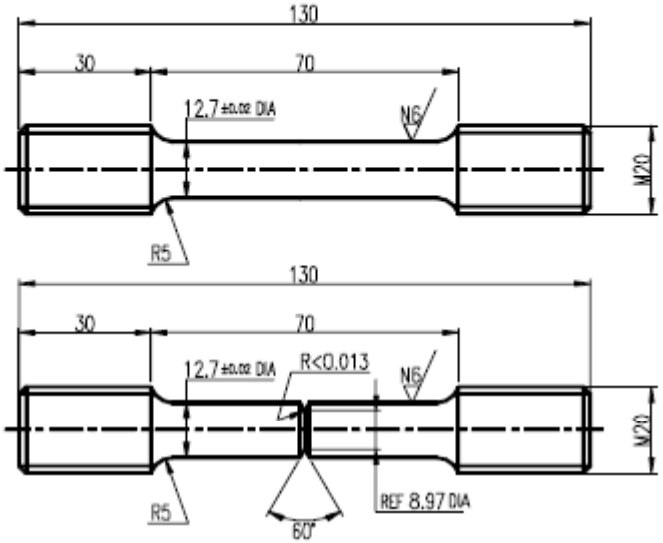


Fig. 3. Tensile and notch tensile design of the specimens. The design of the notch tensile specimens was done according to ASTM E 602-91.

28	630	1.09	1.37
23	690	1.03	1.37
43	594	1.39	1.59
27	683	1.18	1.47
22	737	1.09	1.41
10	354	1.23	1.70
9	495	1.09	1.50
4	412	1.15	1.57

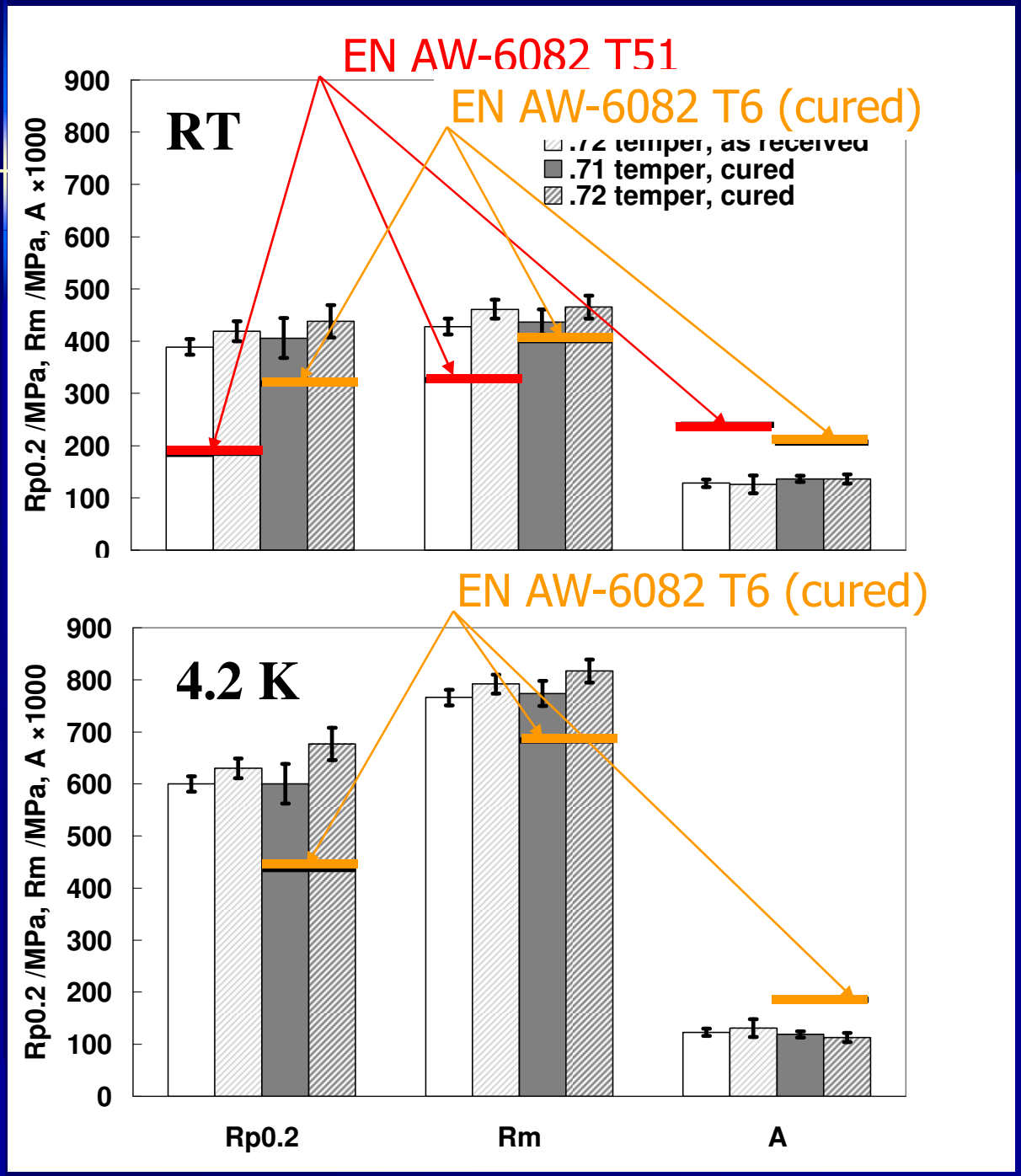
Toward an improved conductor, reinforcement

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-7020.72, cured, at 4.2 K

Rp0.2 = 677 MPa

Rm = 817 MPa

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 ⇒ 1.9

EN AW-6082 T61 ⇒ 1.

with respect to a desig

"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, stabilizer

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

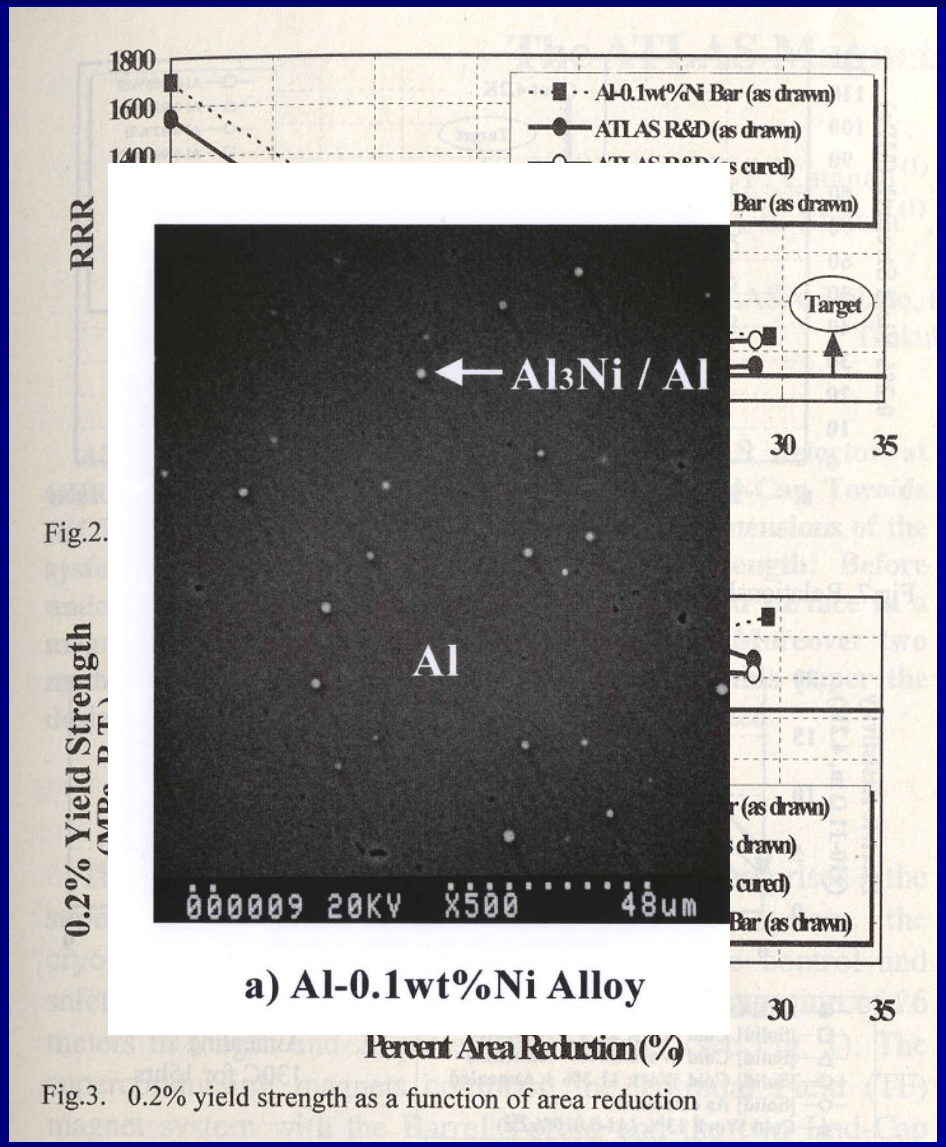


Fig.3. 0.2% yield strength as a function of area reduction

A. Yamamoto et al., Nuclear Physics B 78 (1999), pp. 565-570;

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

Toward an improved conductor, stabilizer

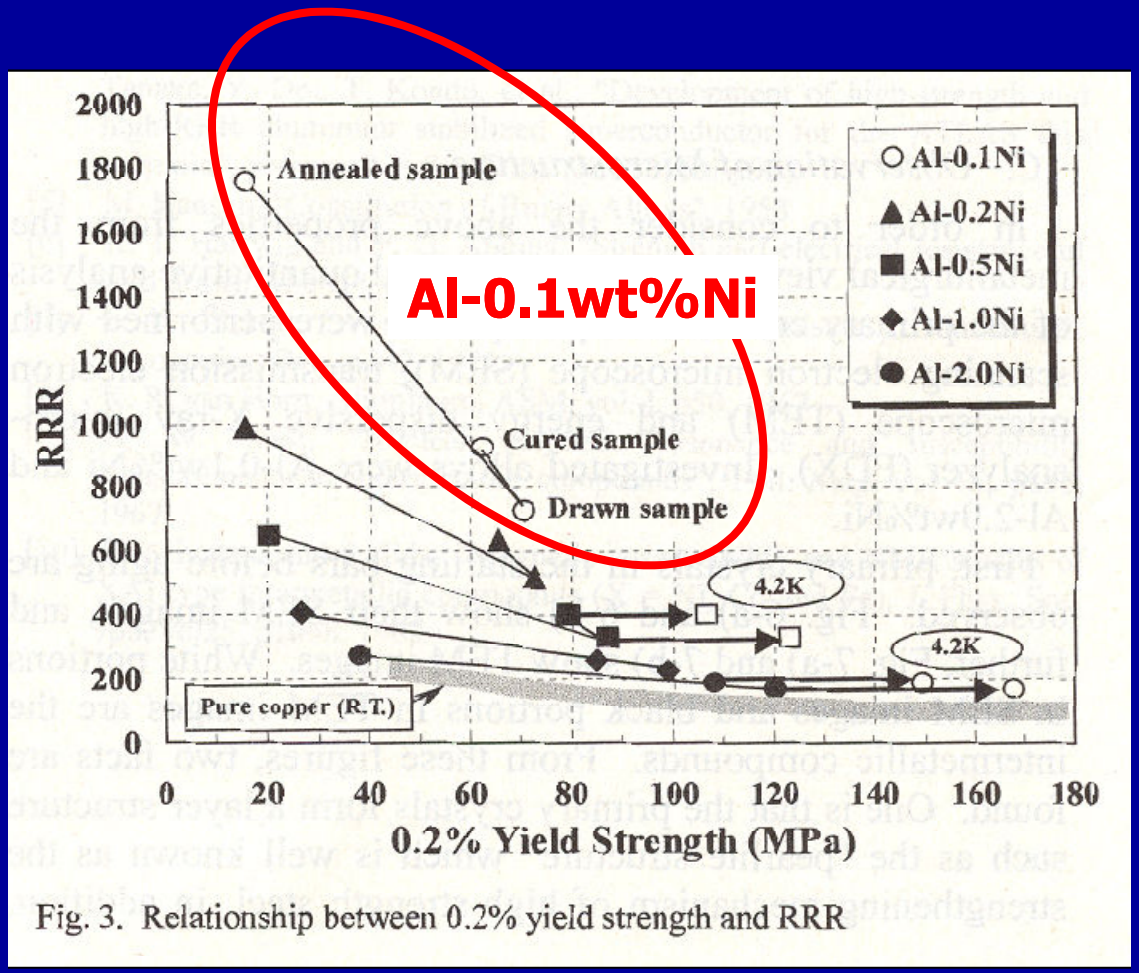


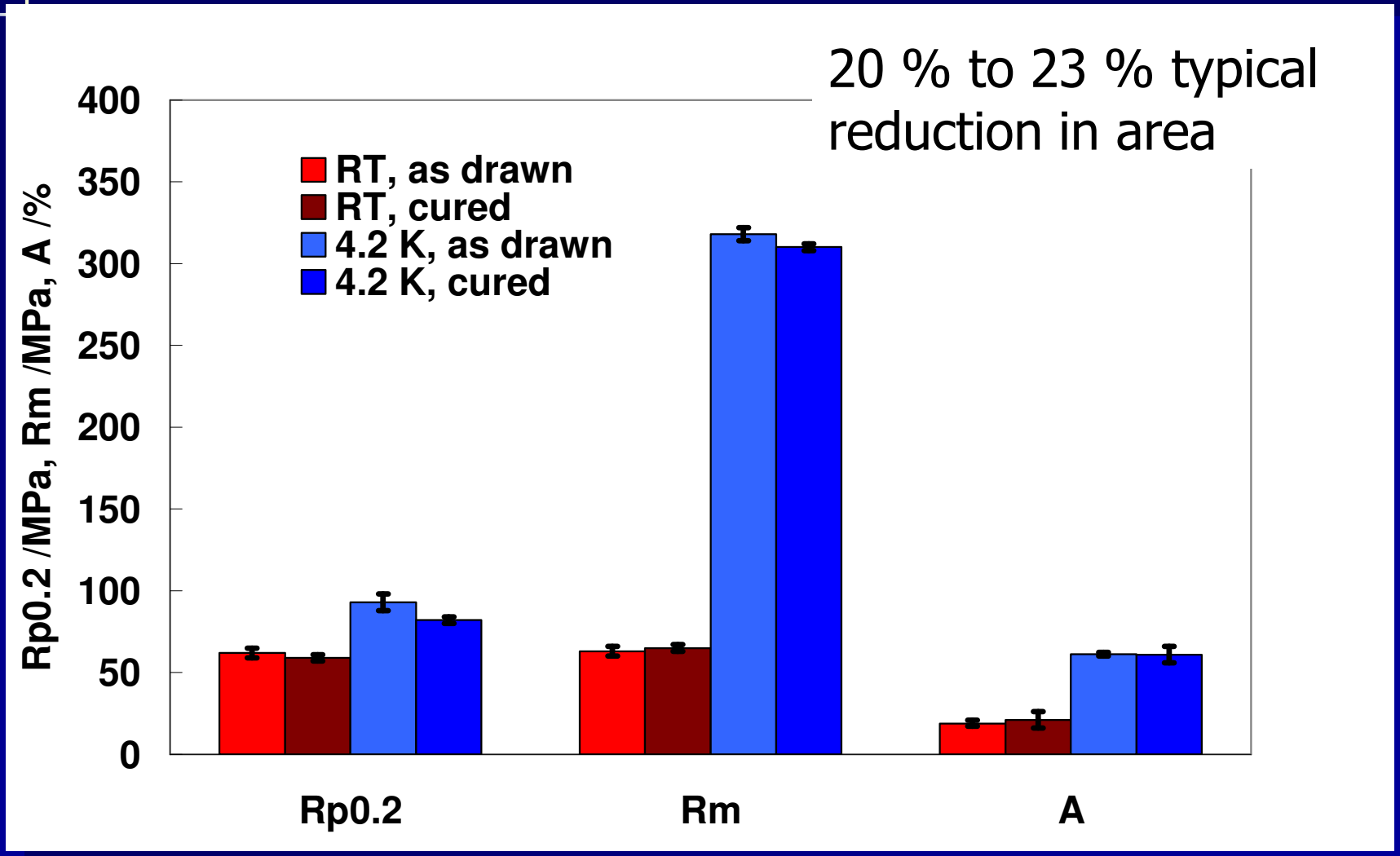
Fig. 3. Relationship between 0.2% yield strength and RRR

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, stabilizer

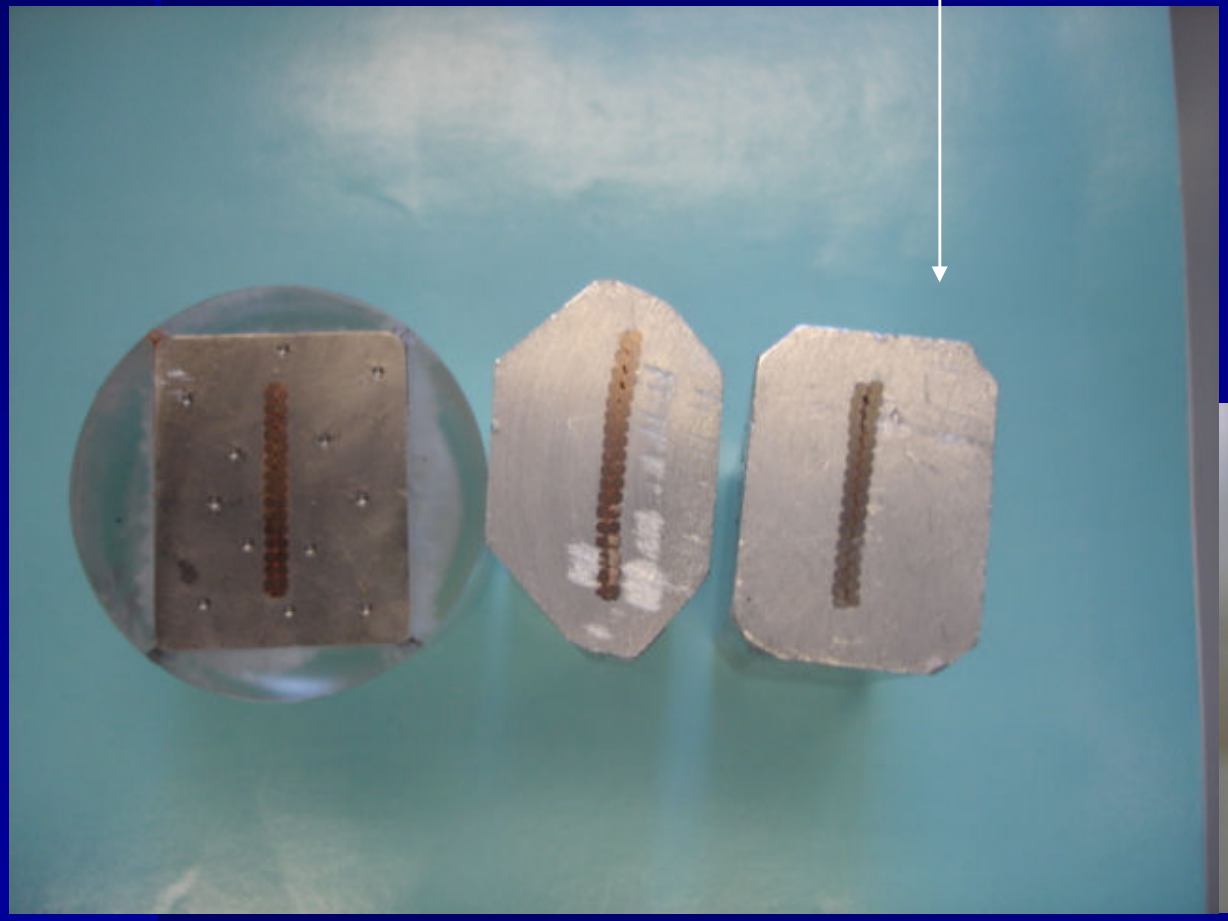


Al-0.1wt%Ni, CMS-type curing, at 4.2 K: Rp0.2 = 82±7 MPa

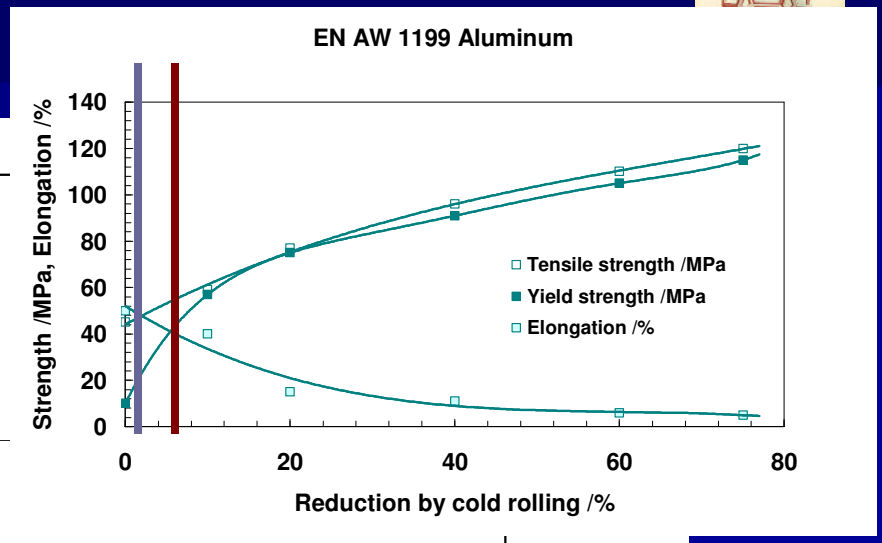
Four roll shaping process (courtesy of Outokumpu /IT)

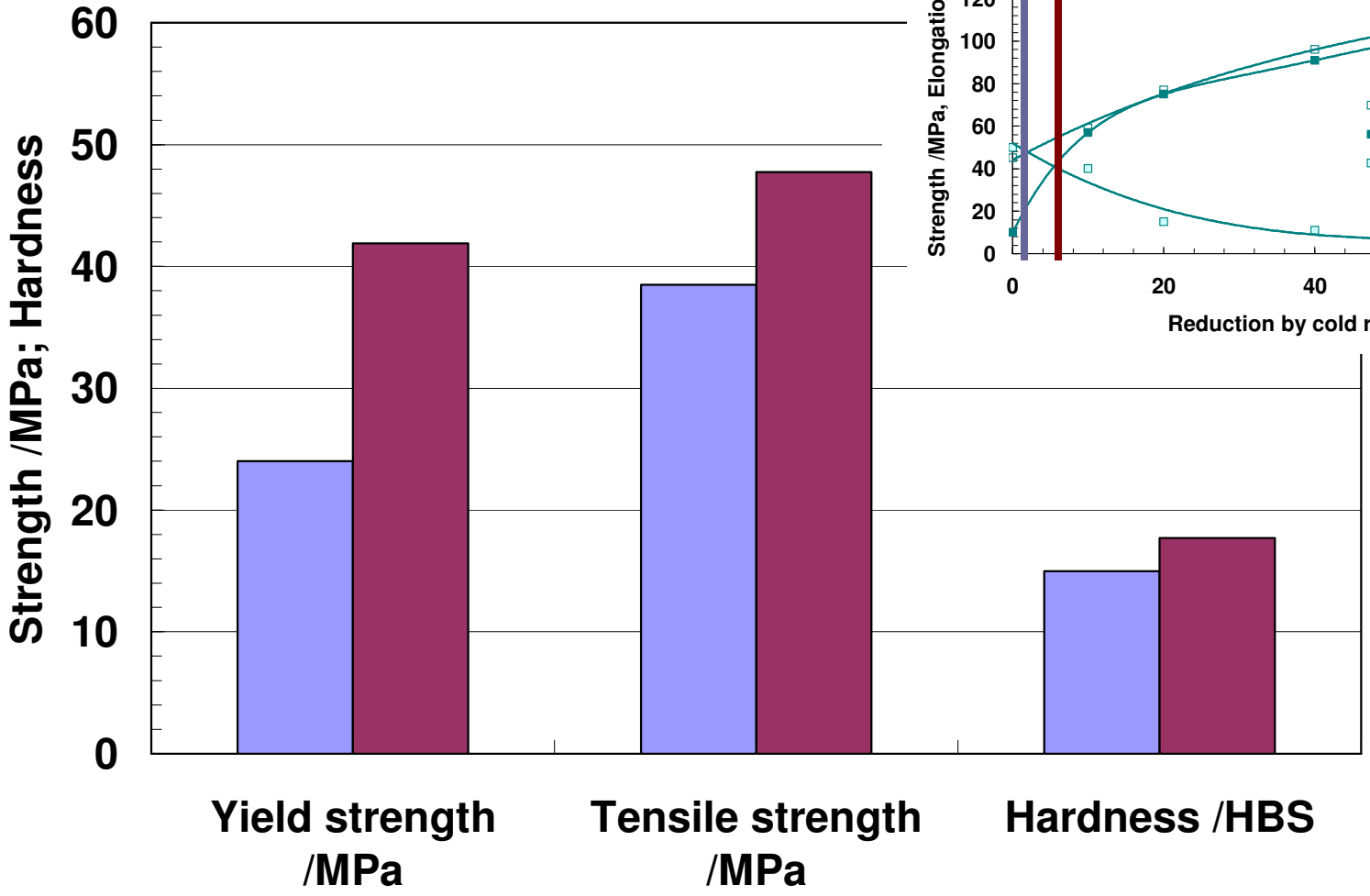
Toward an improved conductor, stabilizer

allowed 11.3 % reduction in area

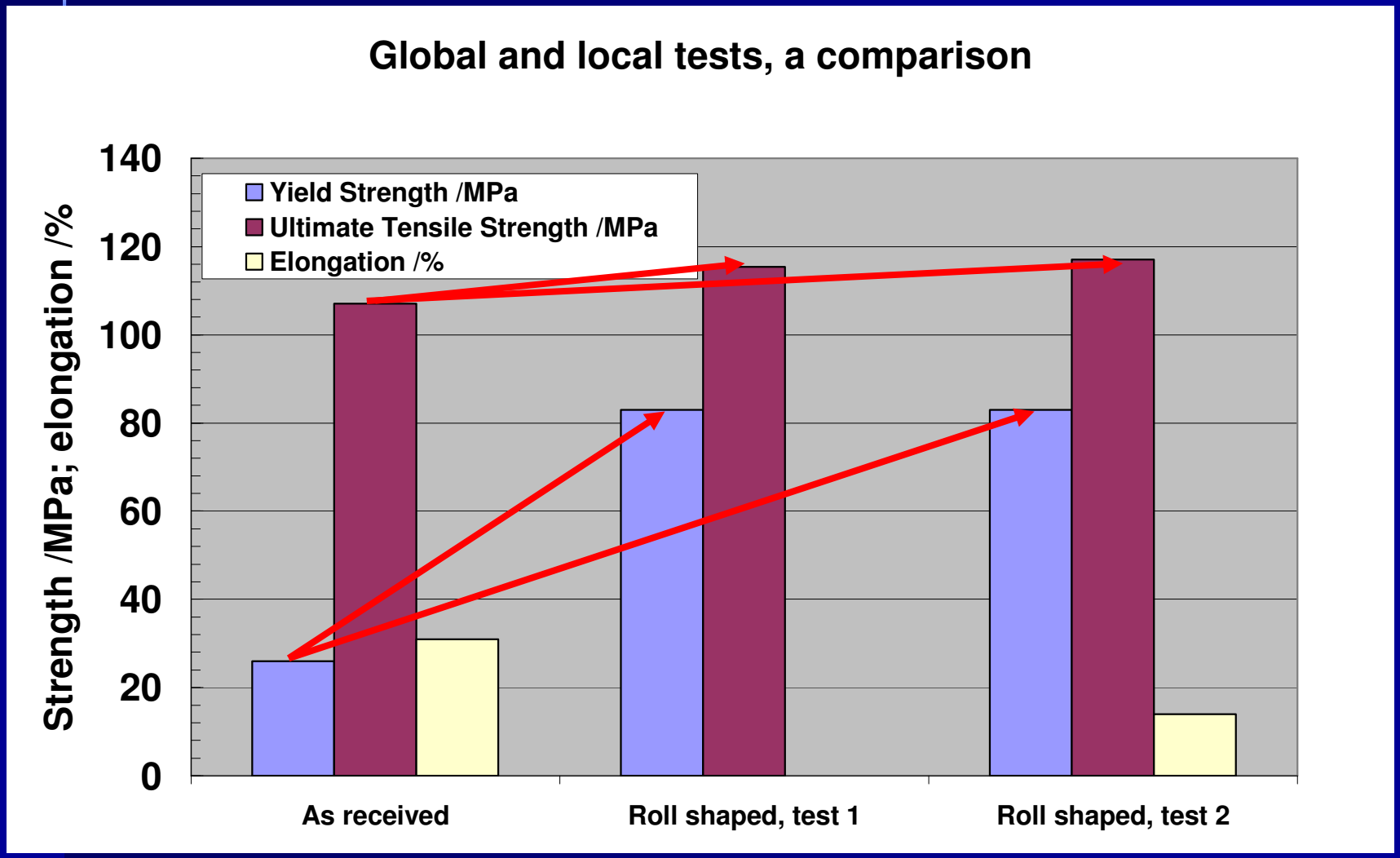


Toward an improved conductor, stabilizer

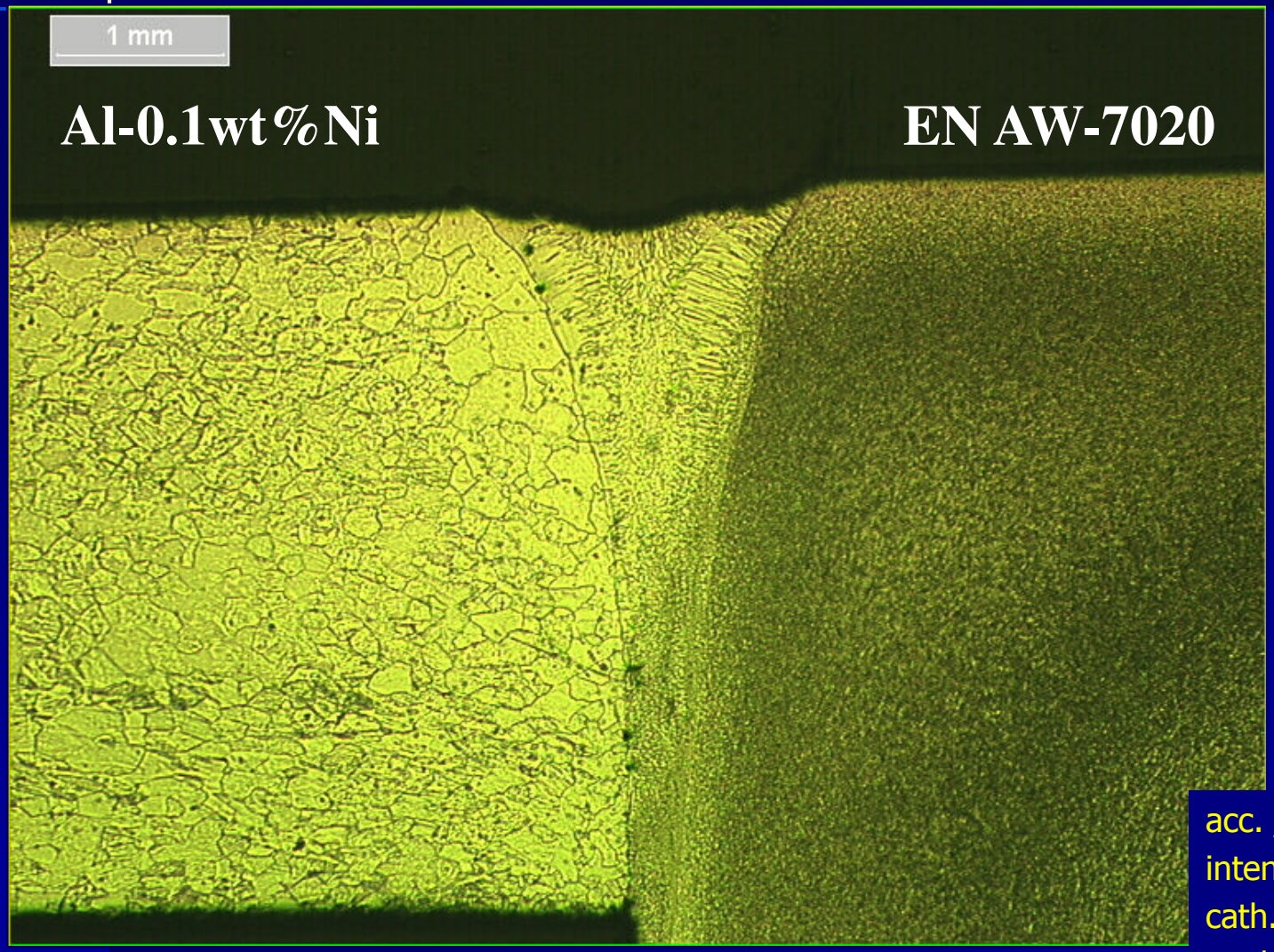




Toward an improved conductor,
global tensile properties of a roll-shaped insert



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:

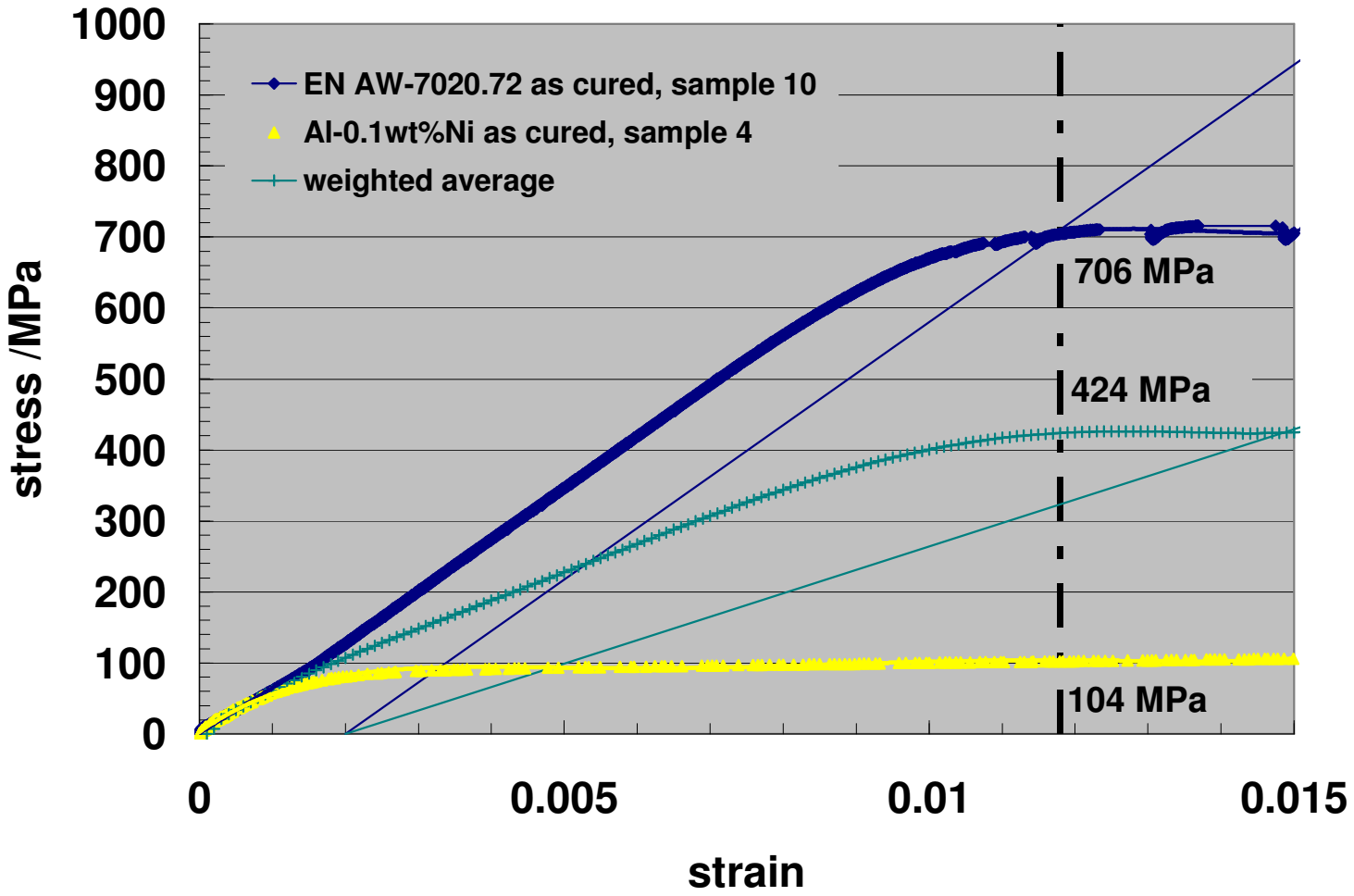
$$\sigma_c S_c = \sum_i \sigma_i S_i = \sigma_{AlNiinsert} S_{AlNiinsert} + \sigma_{7020} S_{7020}$$

$\sigma_{AlNiinsert}$ = 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,

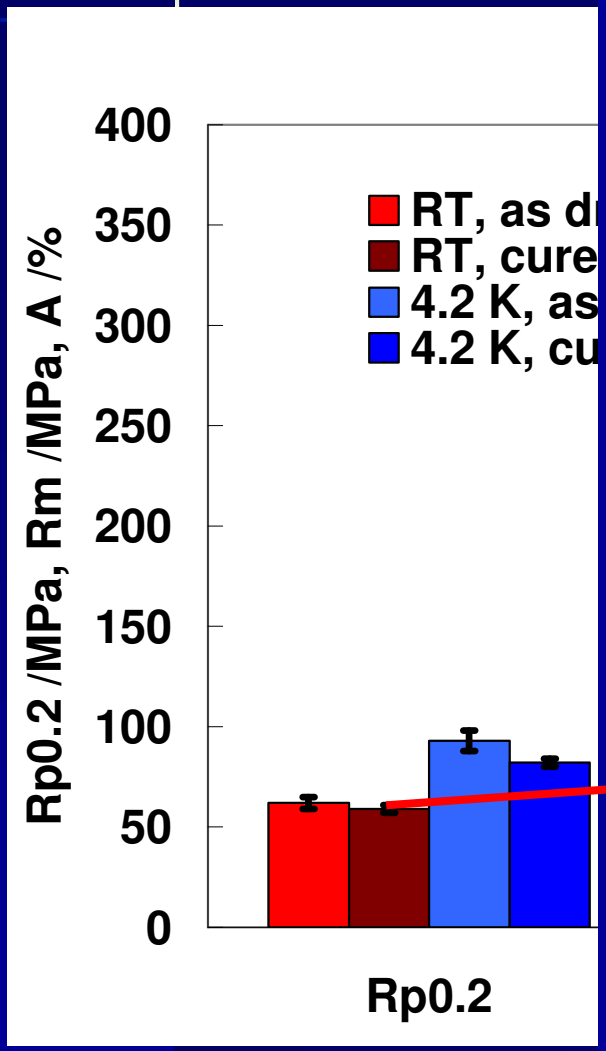
- for EN AW-7020.72 + Al-0.1wt%Ni = 400 MPa
- for EN AW-6082 (T6) + Al99.998 = 258 MPa [1]

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



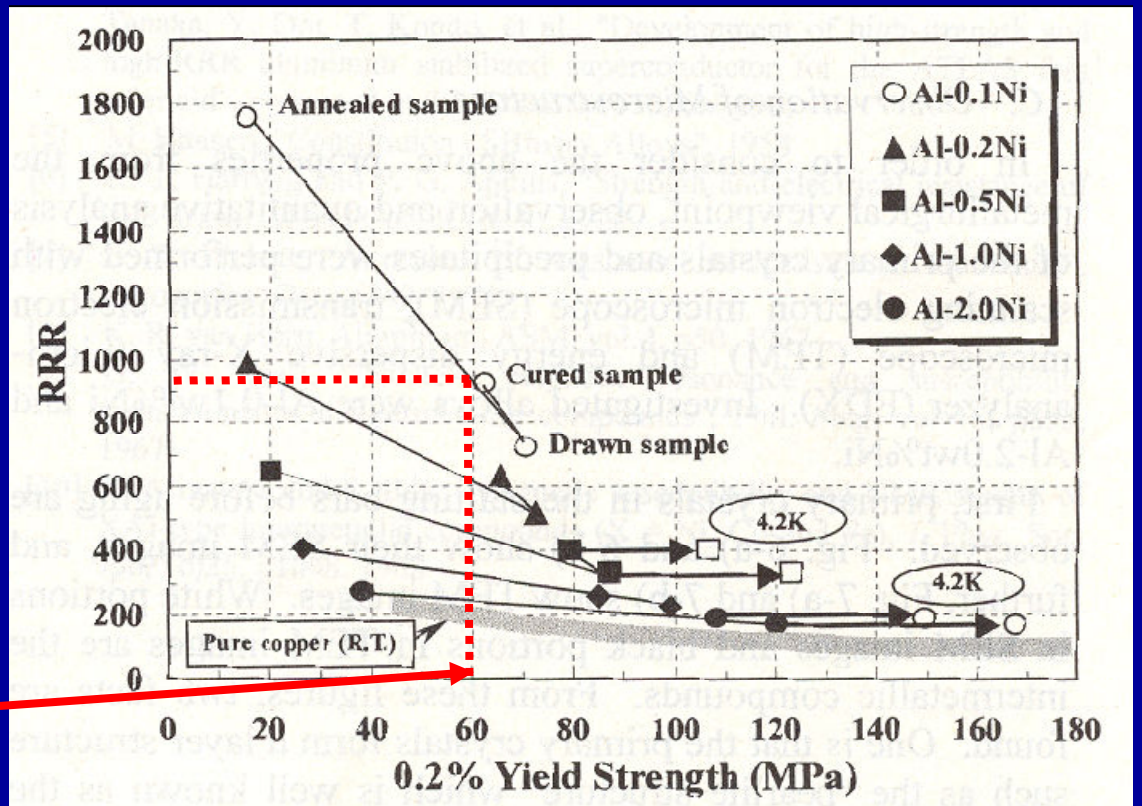
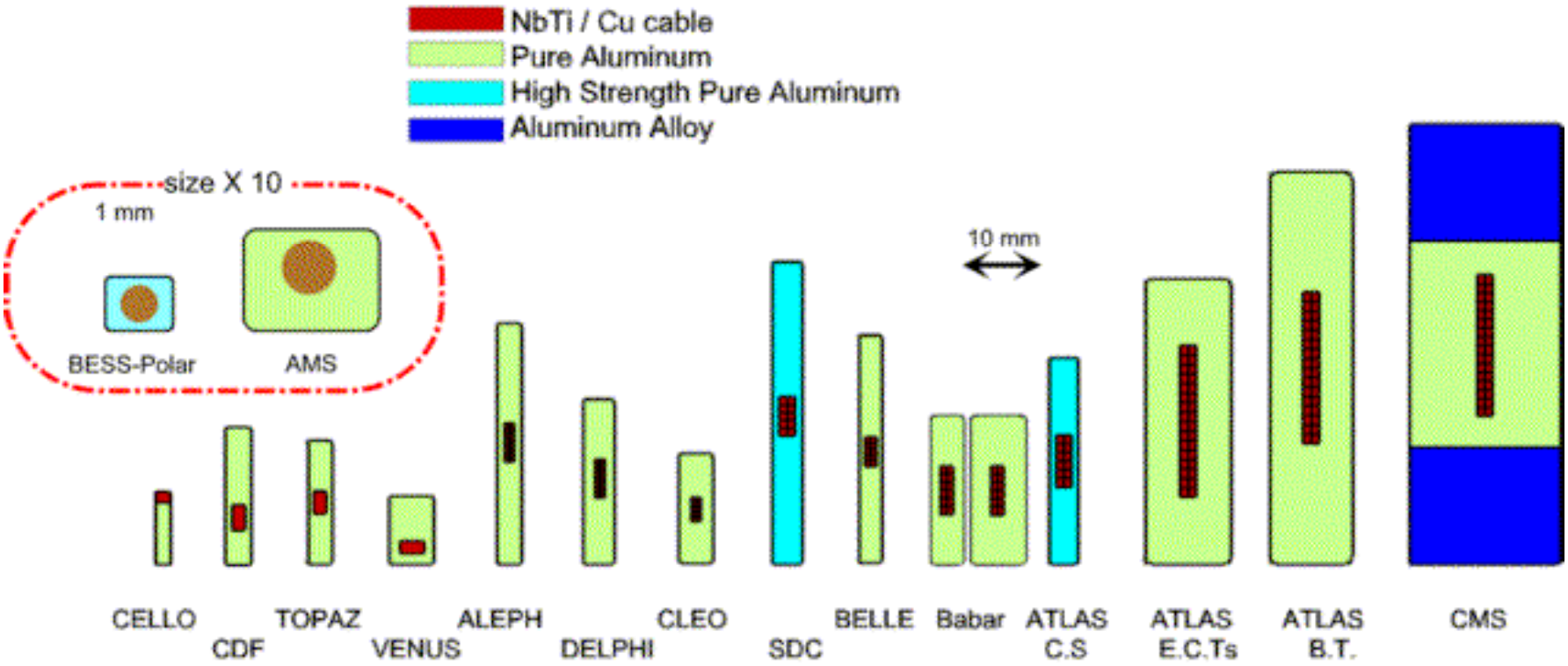


Fig. 3. Relationship between 0.2% yield strength and RRR

Al-0.1wt%Ni, CMS-type curing, at RT: Rp0.2 = 59±2 MPa

⇒ RRR ≈ 900

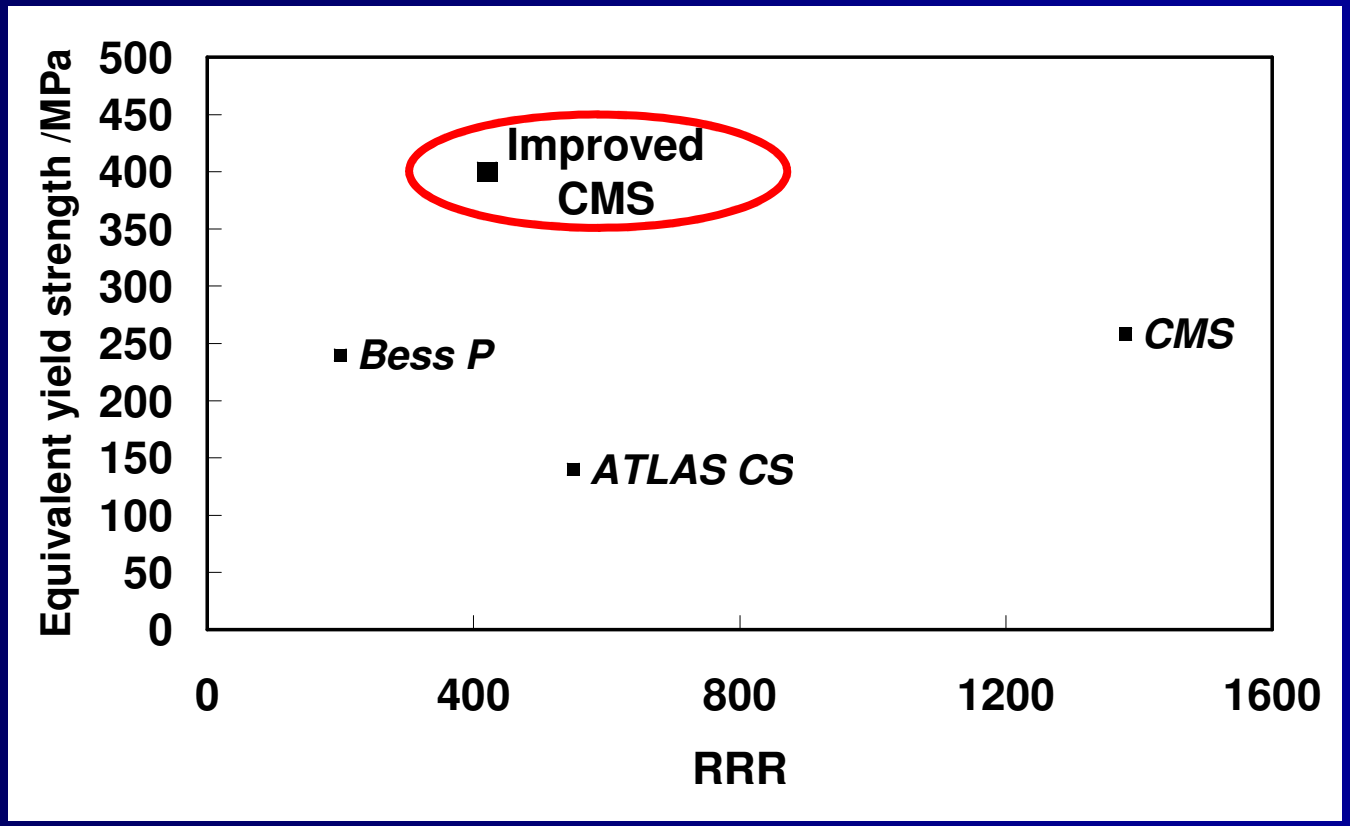
Progress of Al-stabilized SC



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



Composite Al-based pure metal conductors

5N Al, RRR=1500

Al-Fe-Ce from PM, VHP

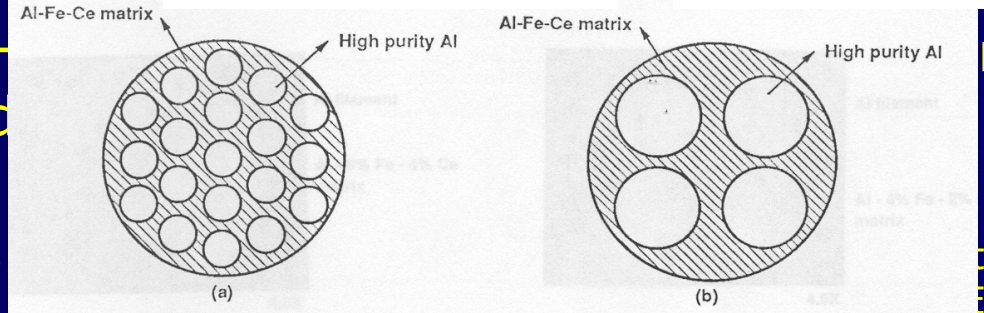


Fig. 1. Schematics illustrating the composite conductor design. (a) 19 filament configuration; (b) 4 filament configuration.

H rs with Al-alloy matrix

d

t-Patterson AFB, OH), *The origin and future of*

Typical properties at 20 K:

YS ≥ 165 MPa

UTS ≥ 276 MPa

1.5 % ≤ A ≤ 8 %

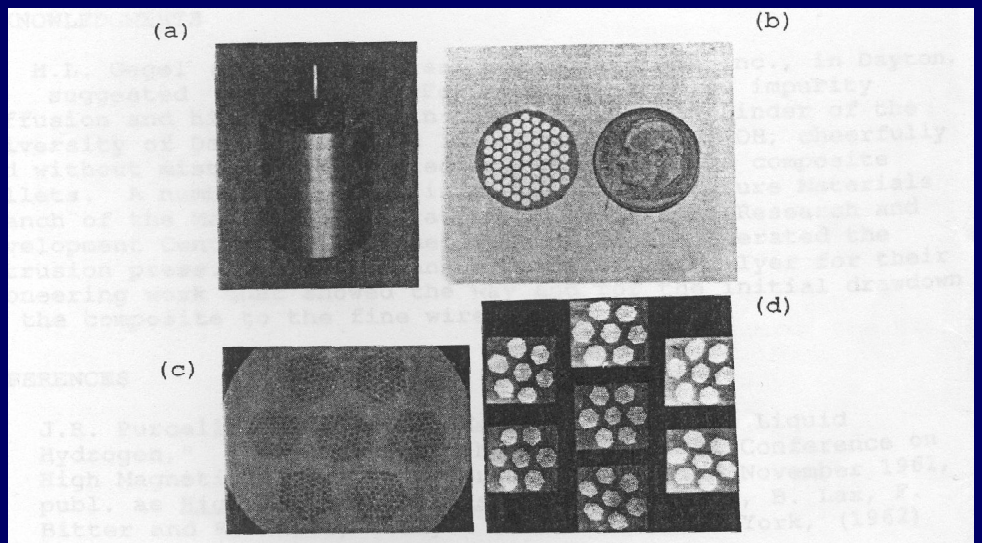


Fig. 1 Successive reductions and restacking of (a) pure aluminum rods in an Al-Fe-Ce billet with 61 filaments, (b) after reduction, (c) restacking and reduction with 427 filaments and (d) with 2989 filaments.

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

Sample	RRR	D, μm
30,19,8-4 Annealed	544	124
30, 4,8-4 "	764	269
30,19,4-2 "	558	124
50,19,8-4 "	683	206
30,19,8-4 As-extruded	428	124
30, 4,8-4 "	364	269
30,19,4-2 "	413	124
50,19,8-4 "	398	206

Composite Al-based pure metal conductors

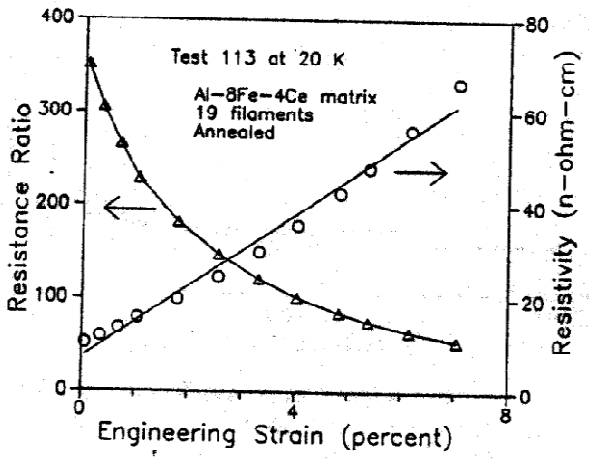


Fig. 4. Resistance ratio and resistivity at 20 K.

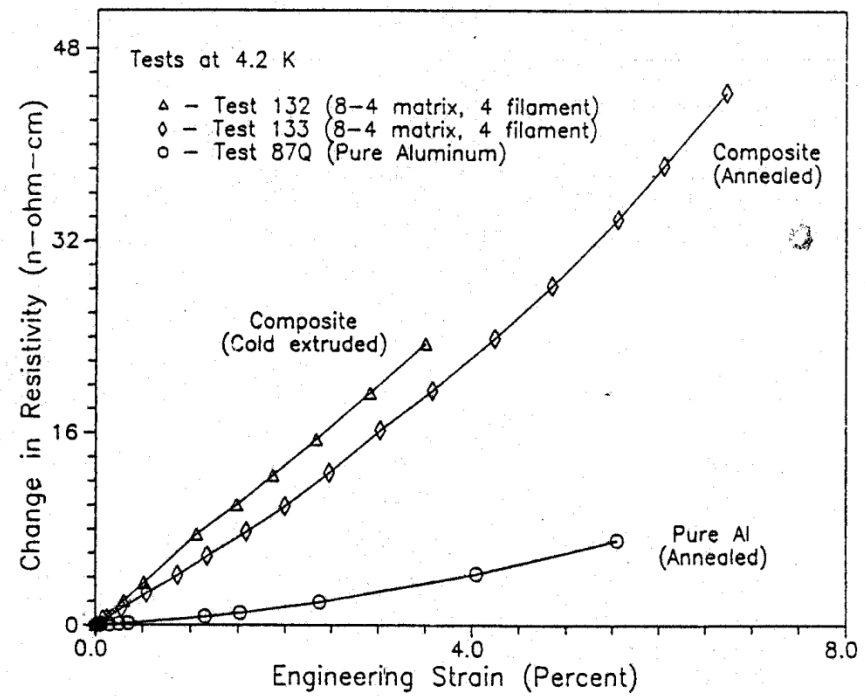


Fig. 6. Change in resistivity versus engineering strain at 4.2 K for pure aluminum (Test 87Q) and aluminum composite conductors (Tests 132 and 133). Composites have 8Fe-4Ce matrix and 4 filaments.

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 $2 \cdot 10^8$ 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*

- S. Murase, , Y. Koike, Y. Nakayama, T. Toyoda, E. Suzuki, K. Mendelssohn, *Aluminum stabilized Nb--Ti superconducting wires,* Proceedings of the fifth international cryogenic engineering conference, Kyoto, Japan, 7 May 1974, IPC Science and Technology Press Ltd., Guildford, Eng. (1974)

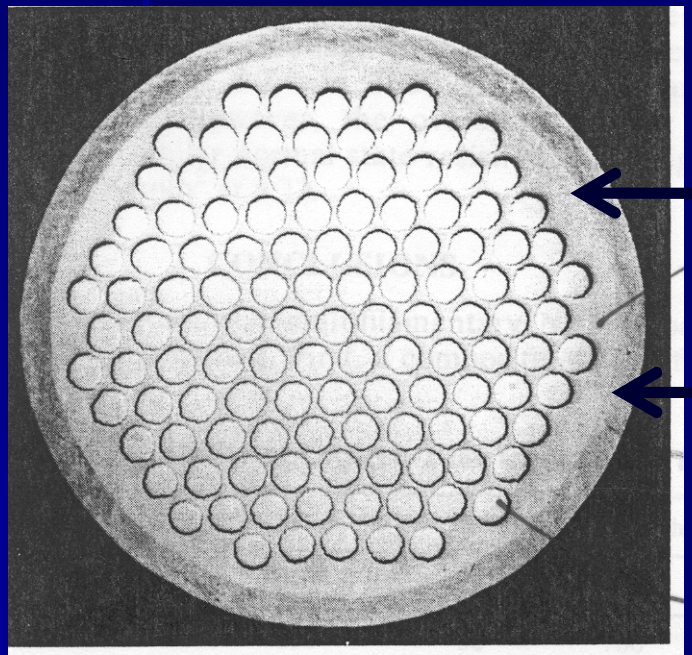


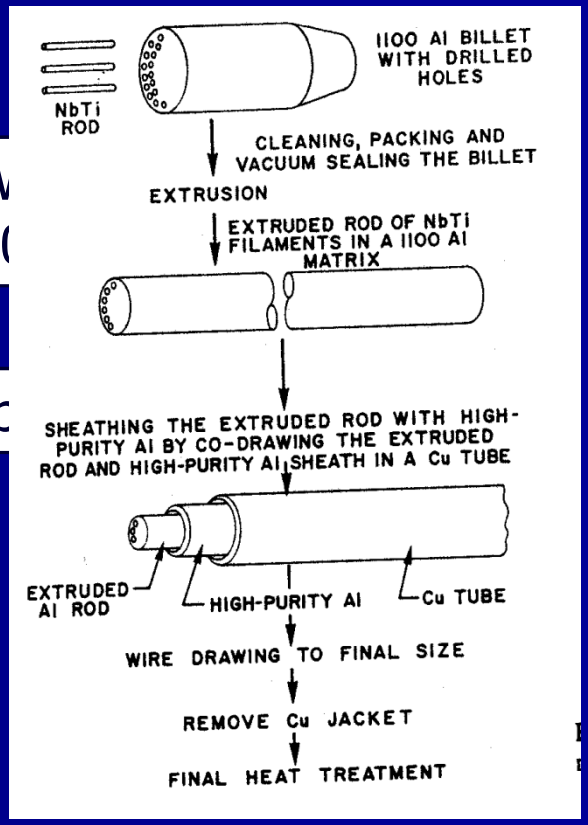
Fig. 2. Cross section of an Al-stabilized superconductor containing 121 NbTi filaments in an 1100 Al matrix sheathed in high-purity aluminum.

Embedding in EN AW
AW-6061 (EN AW-5

High purity Al "tub

RRR = 320

Critical current density at 5 T = 1630 A/mm^2



Al-stabilised Nb_3Sn multifilament SC

M. Thöner, H. Krauth, J. Rudolf, A. Szulczyk, *Aluminium Stabilized Nb_3Sn Superconductors,* Adv. Cryog. Eng. Mat. **34** (1988) 507

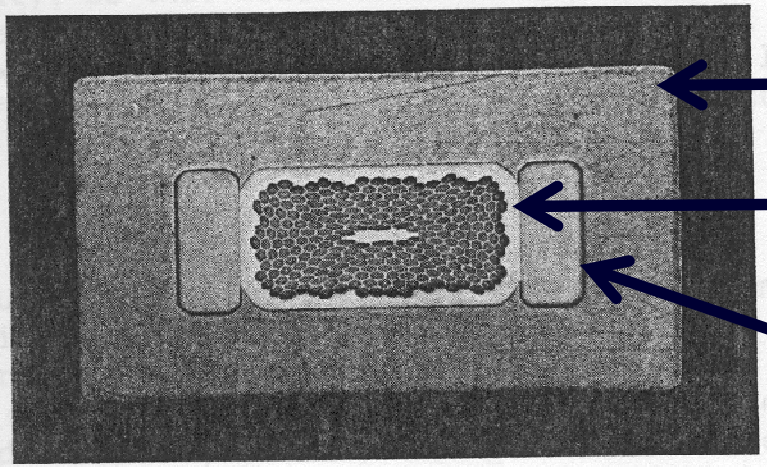


Fig. 3 Stabilized monolith NS 80000 (dimensions 6.6 x 3.6 mm^2) produced by coextrusion with Al and strengthening Duratherm.

High purity Al (RRR = 2500 to 5000)

Reacted "monolith" (80000 filaments in a CuSn matrix)

Duratherm reinforcement (Co-Ni-Cr alloy)

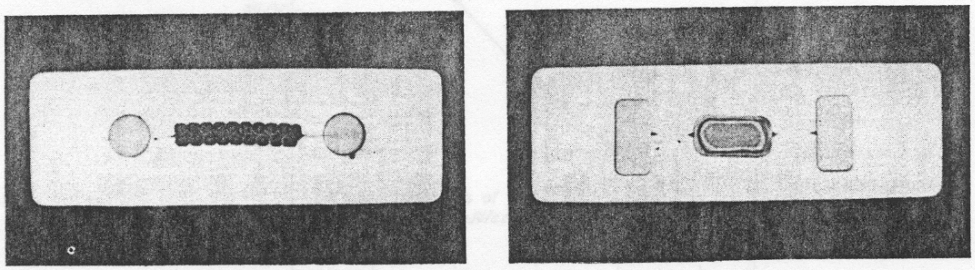


Fig. 2 Four types of Al stabilized Nb_3Sn composites (dimensions 16 x 5.24 mm^2) produced by coextrusion

Al added after the reaction treatment

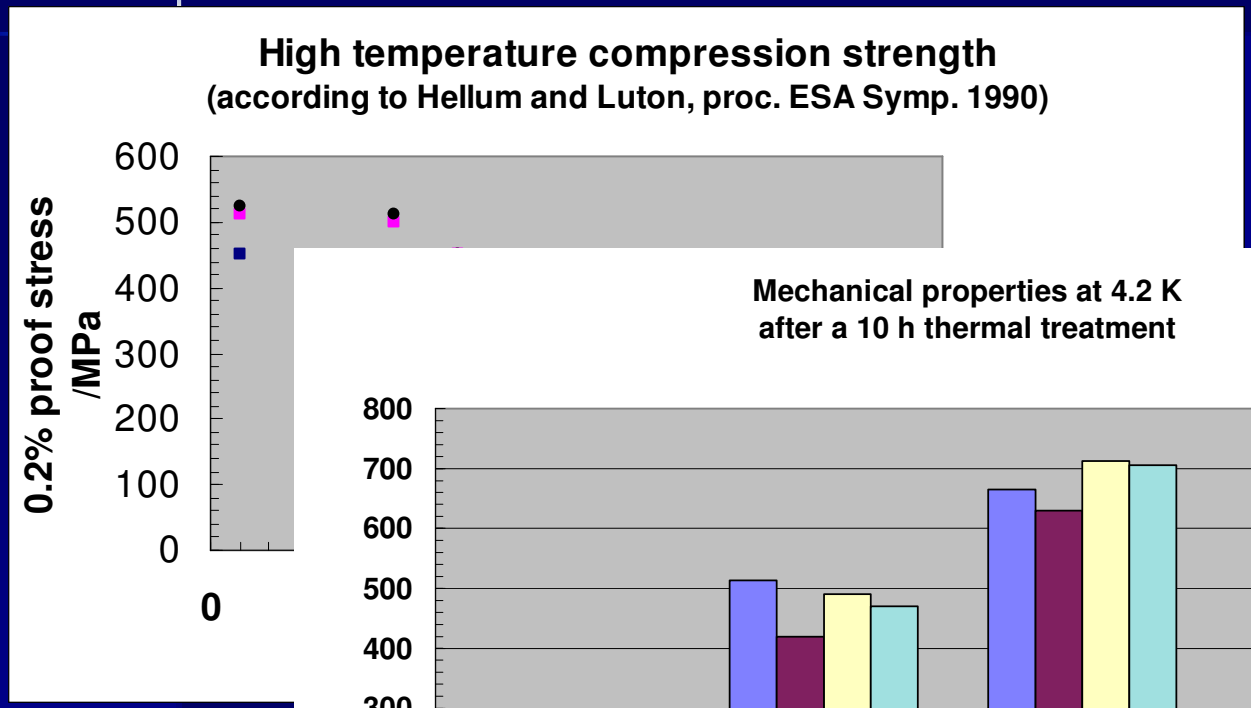
Simultaneous extrusion with reacted Nb_3Sn

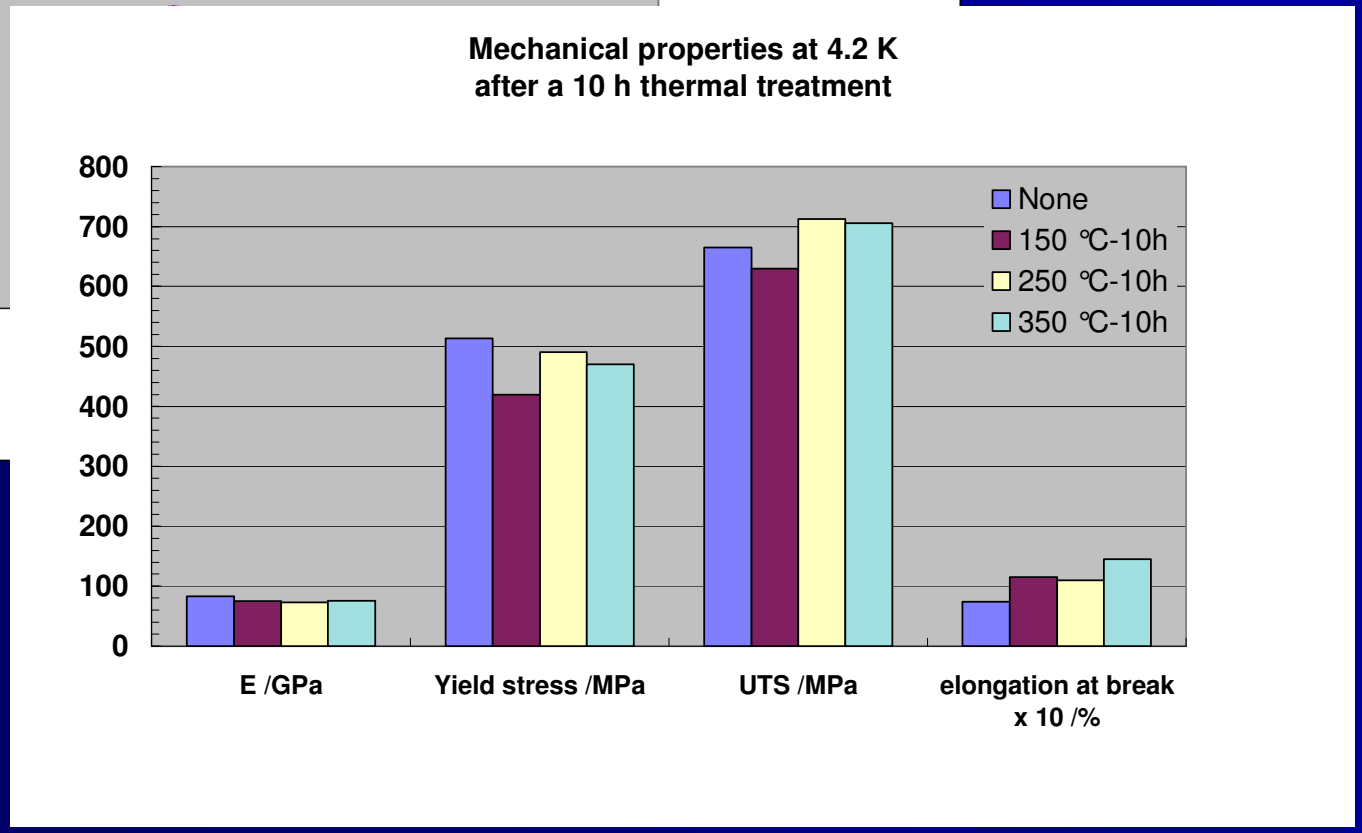
ngth up to 100 m (limited by length reacted Nb_3Sn)

R = 580 for the "80000" version

= 186 MPa at RT, idem

Aluminium alloy DS-Al-550





•S. SGOBBA, G. MARTIN and T. KURTYKA: *Mechanical Properties of a New Dispersion Strengthened Aluminium Alloy for Use at Very Low Temperatures*, Proceedings of the 5th European Conference on Advanced Materials, Processes and Applications, Maastricht 21-23 April 1997, vol. 1, p. 251-254

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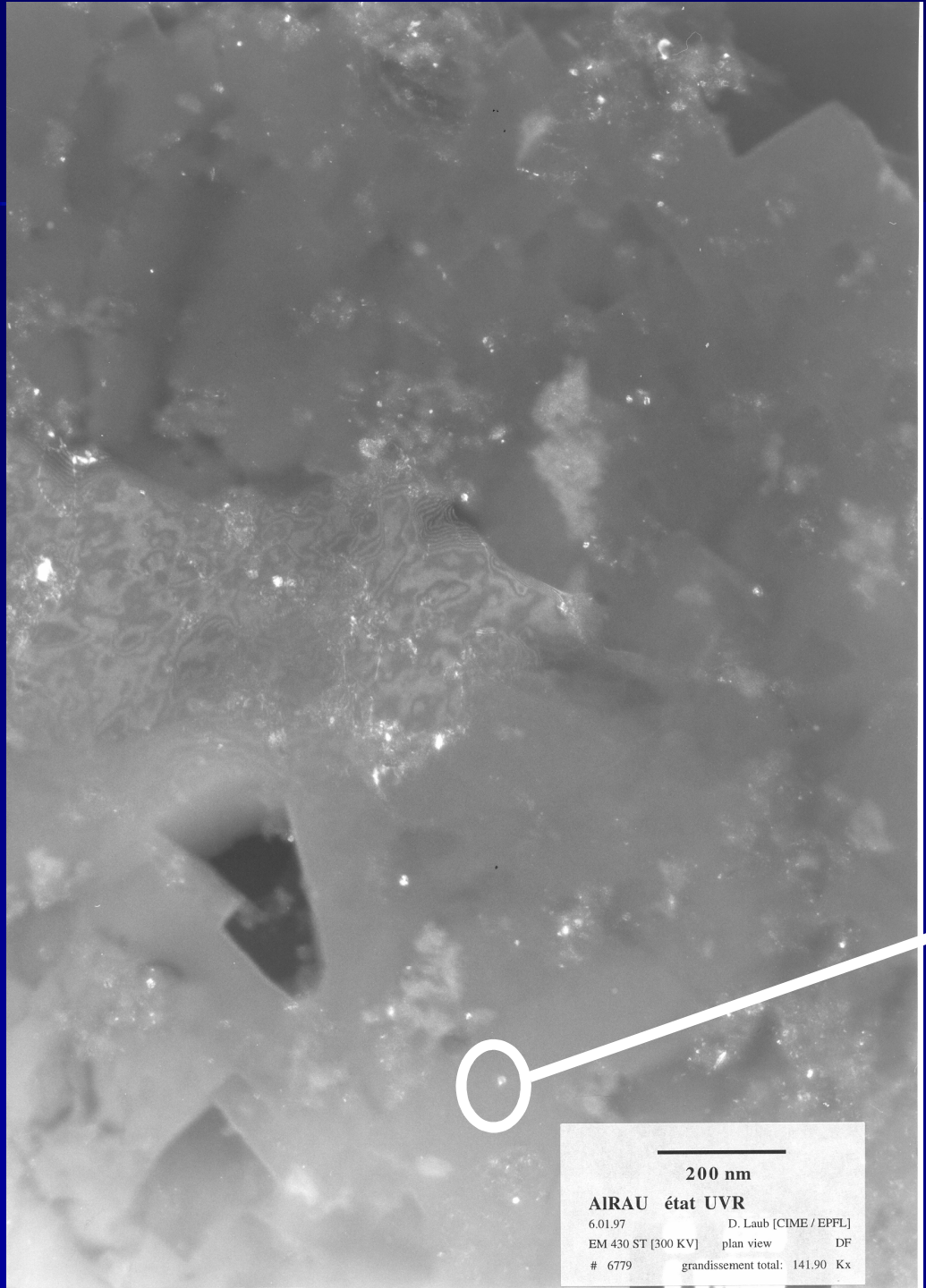
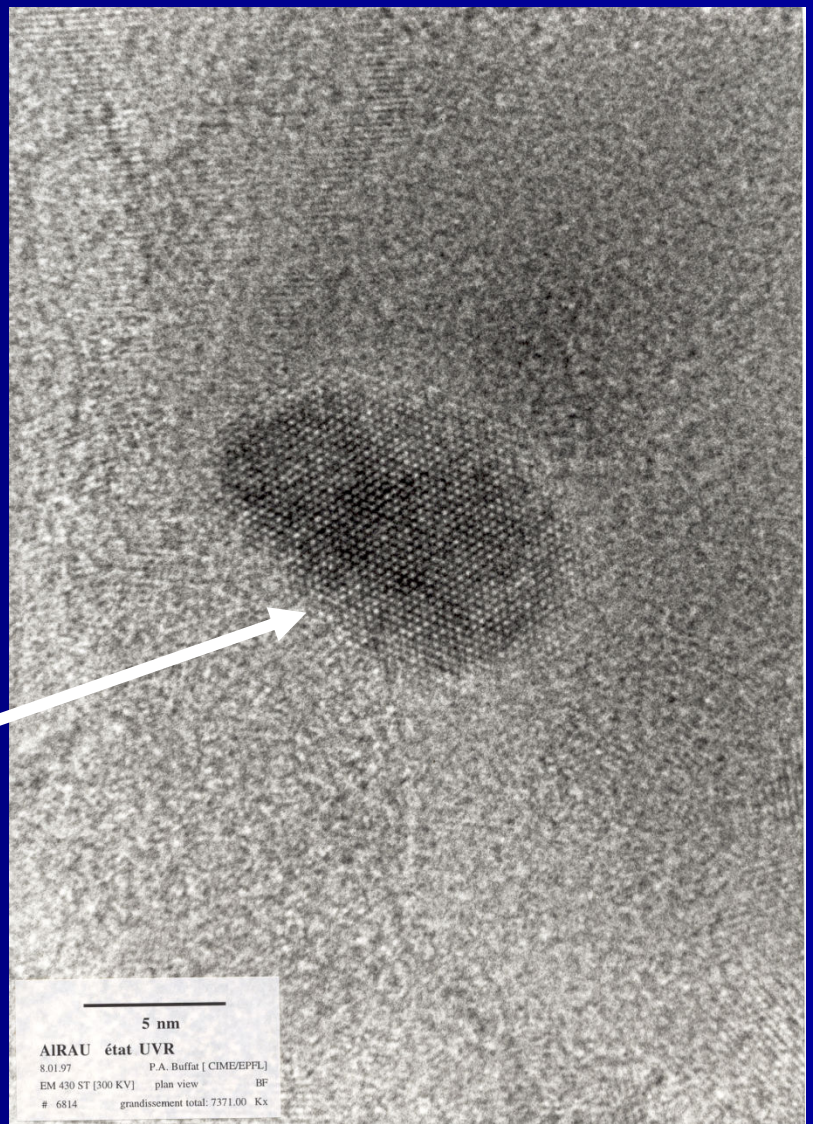
Particle size, 2 nm to 10 nm

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

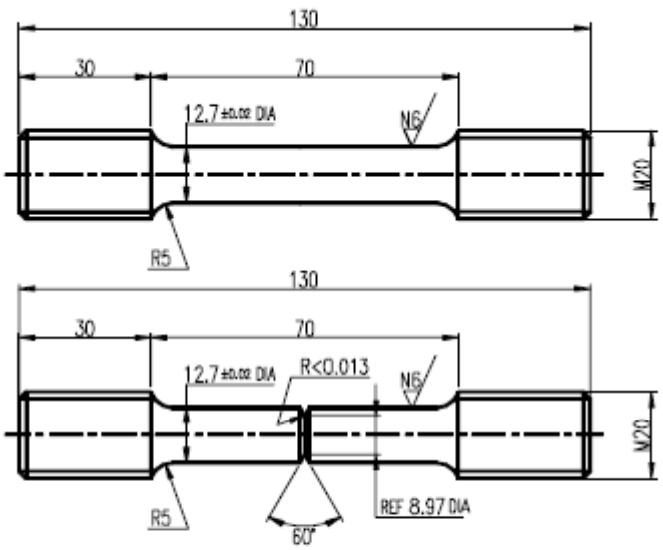


Fig. 3. Tensile and notch tensile design of the specimens. The design of the notch tensile specimens was done according to ASTM E 602-91.

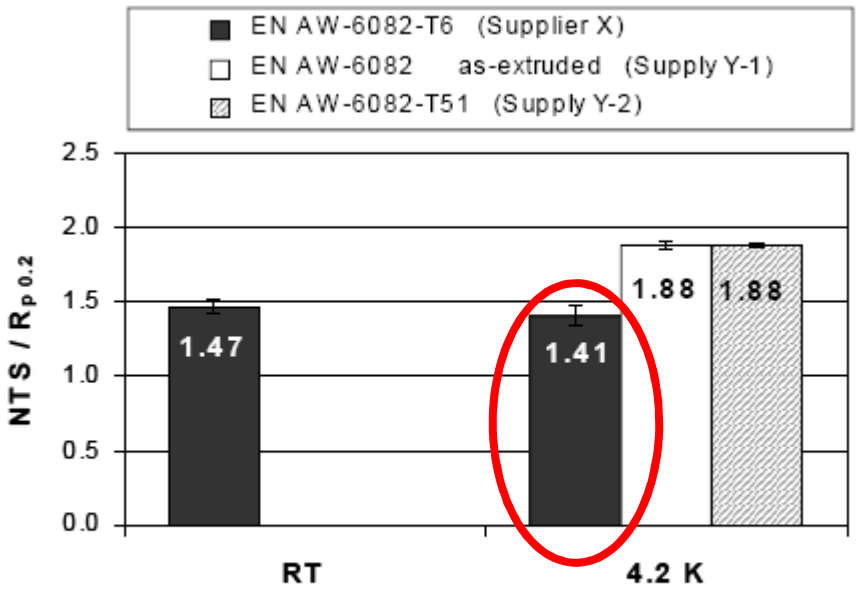


Fig. 5. Notch tensile strength over yield strength.

S. Sequeira Tavares, S. Sgobba,
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143–144 (2003) 584–590