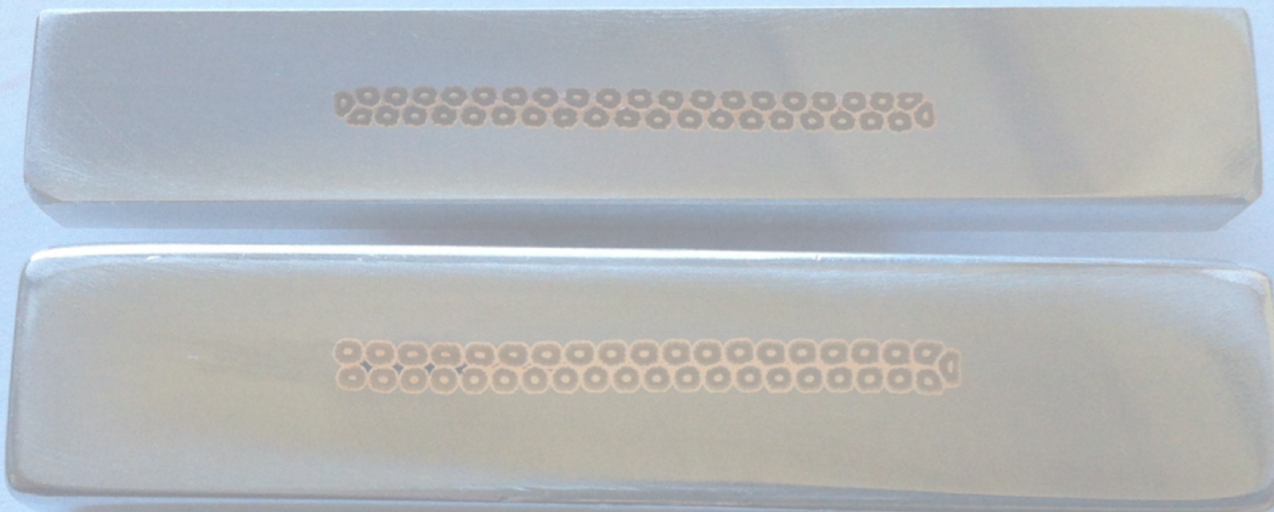
3MOrC2-07

Effect of thermo-mechanical processing on the material properties of a large size Al-Ni stabilized Nb-Ti/Cu superconducting cable



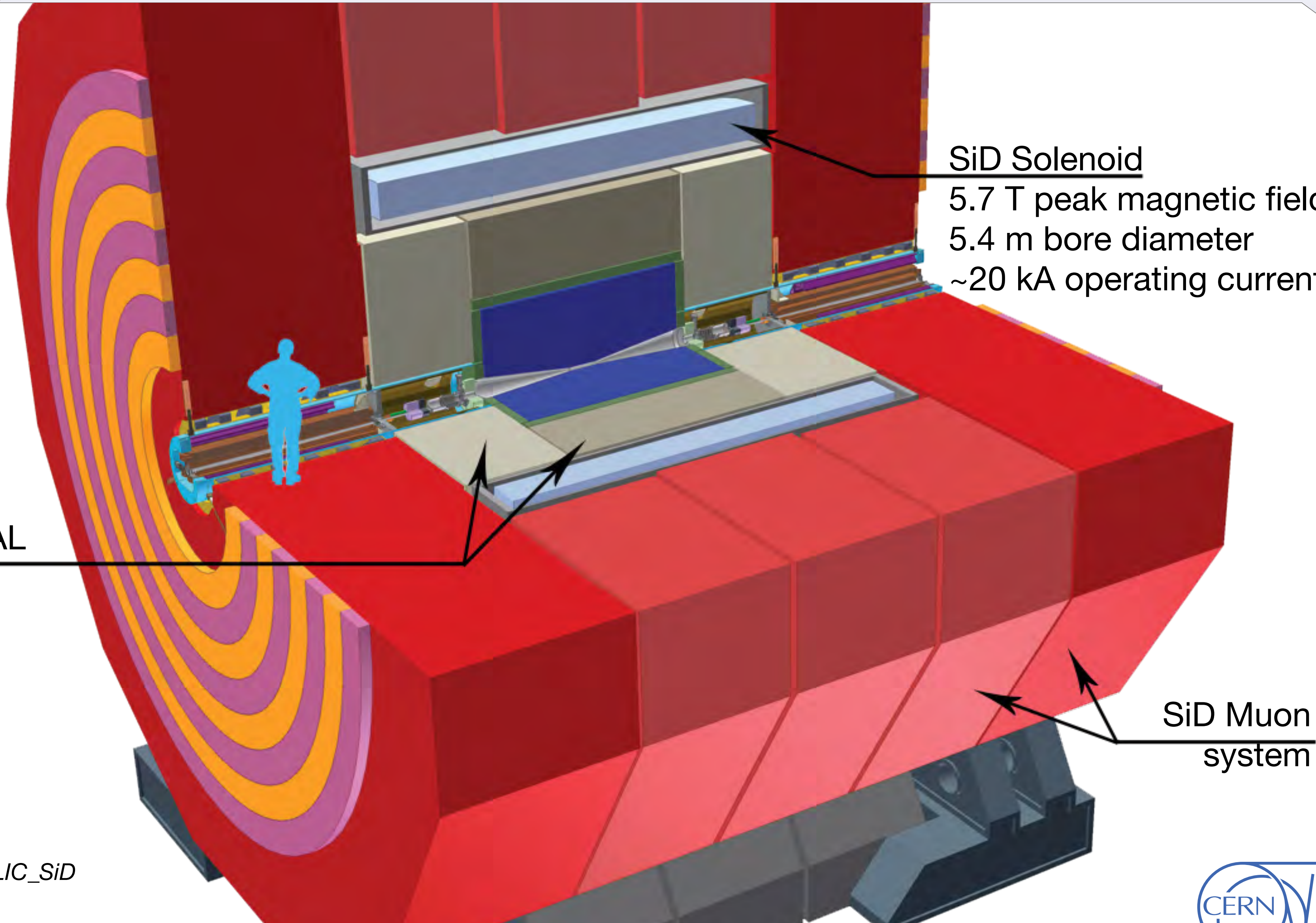
S.A.E. Langeslag

B. Curé, S. Sgobba, A. Dudarev, H.H.J. ten Kate,
J. Neuenschwander & I. Jerjen

CERN
UNIVERSITY OF TWENTE.

CEC/ICMC 2013, Anchorage
June 20th, 2013

WIDE BORE, HIGH-FIELD MAGNET



Wide bore, High-field Magnet

The self-supporting magnet structure needs to sustain a large hoop force as a result of the high peak magnetic field.

This requires for the conductor to exhibit challenging mechanical properties.

Goal is to develop a prototype for a 60 kA critical current, at 5 T class stabilized superconductor, operating at 4.2 K.

➜ Leading us to the development of a conductor with a ~2000 mm^2 cross-sectional area.

The stabilizer should feature a yield strength of >120 MPa at 4.2 K and a RRR of >500.

UNIVERSITY OF TWENTE.

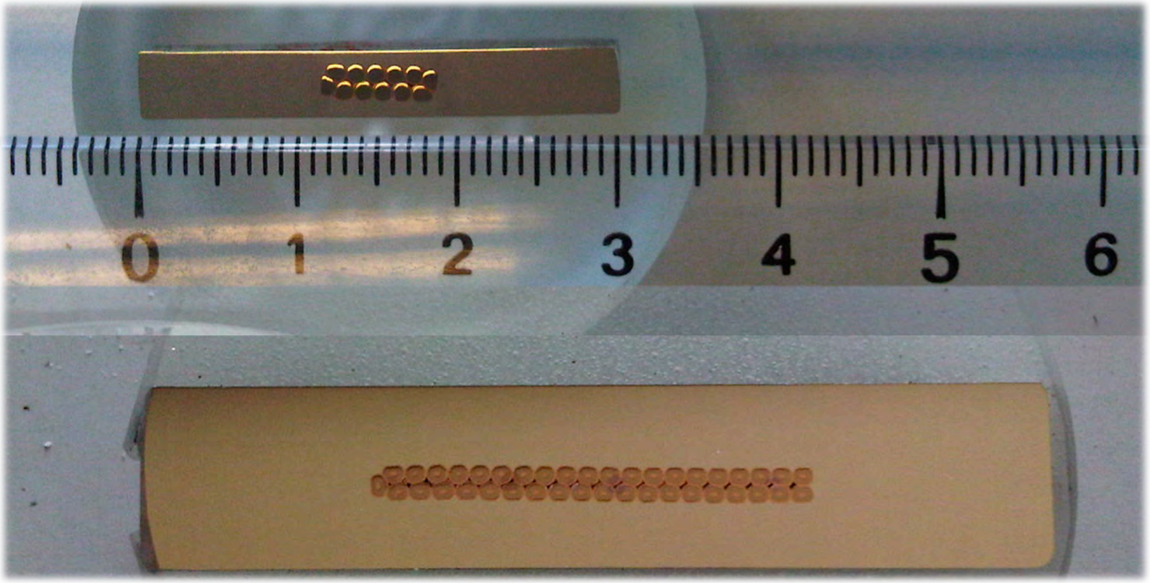
Scale-up towards a prototype for a 60 kA at 5 T, 4.2 K class conductor

Co-extrusion of a large 40-strand Nb-Ti/Cu superconducting cable with a precipitation type Al-0.1WT%Ni stabilizer.

Microalloying with Ni contributes to the strength of the stabilizer while avoiding significant degradation in RRR due to its low solid solubility in Al.

The Al-0.1WT%Ni material was made available by KEK, Tsukuba, Ibaraki (J).

S. A. E. Langeslag, B. Curé, S. Sgobba, A. Dudarev, and H. H. J. ten Kate; IEEE Transactions on Applied Superconductivity, vol. 23, no. 3, 4500504, 2013.



Al-0.1WT.%Ni stabilized ATLAS central solenoid conductor (top) & scaled-up Al-0.1WT.%Ni stabilized prototype conductor (bottom).

Co-extrusion of Al-Ni stabilized conductor

Leading to 200 m of 5N-Al co-extruded conductor and 100 m of Al-0.1wt%Ni co-extruded conductor.

Spool (3 m diameter) with co-extruded conductor

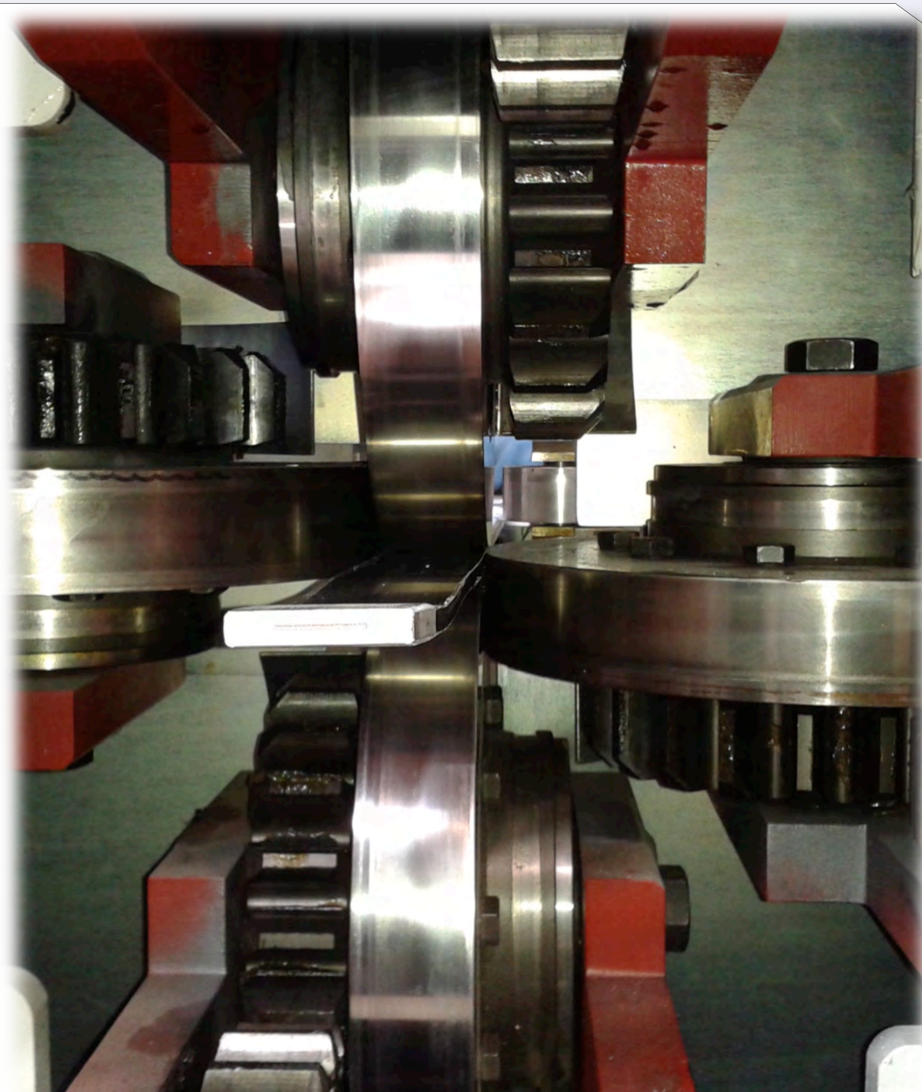
WORK HARDENING; BI-DIRECTIONAL ROLLING

Bi-directional (Turks head) rolling was preformed on a 50 ton DEM rolling mill at Criotec, Chivasso (I).

A set-up used for ITER cable-in-conduit production.

Rolling was conducted on 1.5 m samples, width constrained to preserve cable integrity and a realistic aspect ratio.

The rolling process was made possible by ENEA, Rome (I).



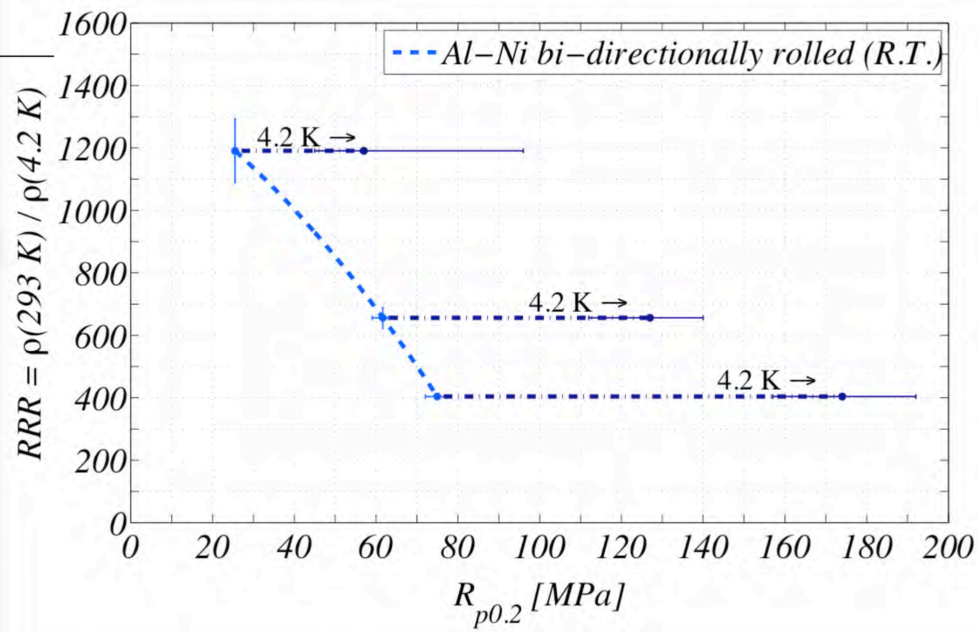
Four-roll rolling mill at Criotec (outlet)

TABLE 1. Properties of co-extruded Al-0.1wt%Ni as a result of various cross-section reductions due to bi-directional rolling

	Temp. [K]	RRR	$R_{p0.2}$ [MPa]	R_m [MPa]
As-extruded	293	1191	26	53
	4.2	-	57	303
20% single pass cold-rolled	293	656	62	67
	4.2	-	127	376
30% single pass cold-rolled	293	404	75	81
	4.2	-	157*	496

* deduced from two measurements

High workability of Al-0.1WT%Ni alloy in a production-scale work-hardening sequence.



Results for the co-extruded Al-0.1WT.%Ni conductor subjected to various work-hardening processes. $R_{p0.2}$ and R_m are 0.2% yield strength and ultimate tensile strength respectively.

TABLE 1. Properties of co-extruded Al-0.1wt%Ni as a result of various cross-section reductions due to bi-directional rolling

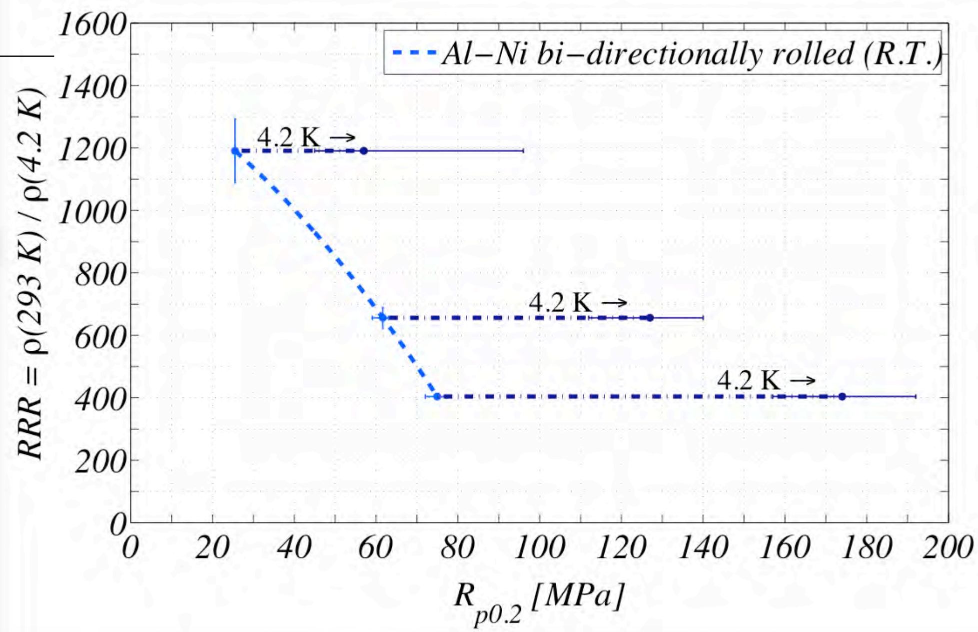
	Temp. [K]	RRR	$R_{p0.2}$ [MPa]	R_m [MPa]
As-extruded	293	1191	26	53
	4.2	-	57	303
20% single pass cold-rolled	293	656	62	67
	4.2	-	127	376
30% single pass cold-rolled	293	404	75	81
	4.2	-	157*	496

* deduced from two measurements

High workability of Al-0.1WT%Ni alloy in a production-scale work-hardening sequence.

Significant increase in $R_{p0.2}$ at 4.2 K

$R_{p0.2}$@ 4.2 K / $R_{p0.2}$@ R.T. of 2.1 - 2.3



Results for the co-extruded Al-0.1WT.%Ni conductor subjected to various work-hardening processes. $R_{p0.2}$ and R_m are 0.2% yield strength and ultimate tensile strength respectively.

TABLE 1. Properties of co-extruded Al-0.1wt%Ni as a result of various cross-section reductions due to bi-directional rolling

	Temp. [K]	RRR	$R_{p0.2}$ [MPa]	R_m [MPa]
As-extruded	293	1191	26	53
	4.2	-	57	303
20% single pass cold-rolled	293	656	62	67
	4.2	-	127	376
30% single pass cold-rolled	293	404	75	81
	4.2	-	157*	496

* deduced from two measurements

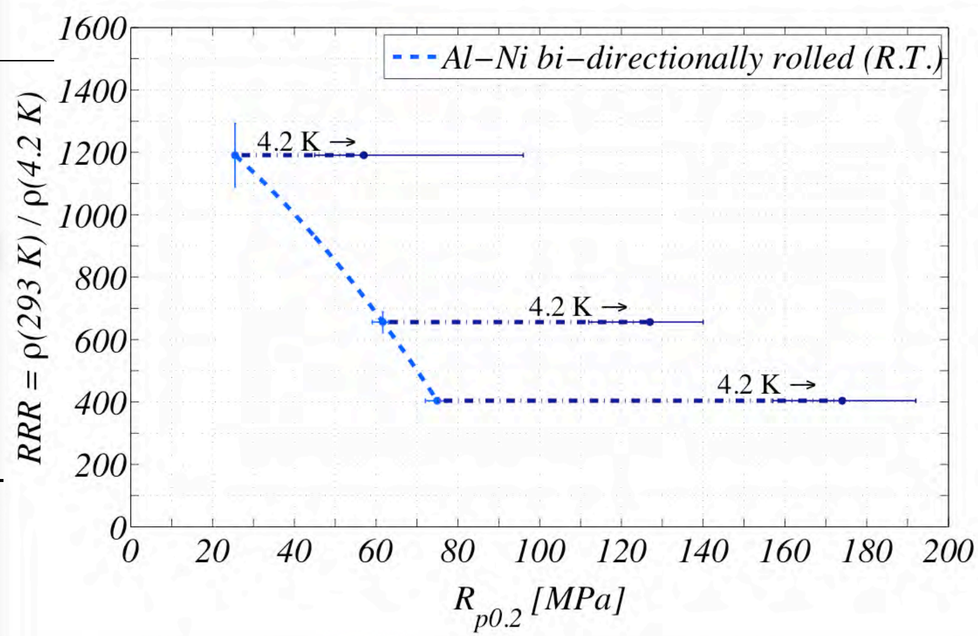
High workability of Al-0.1WT%Ni alloy in a production-scale work-hardening sequence.

Significant increase in $R_{p0.2}$ at 4.2 K

$R_{p0.2}$@ 4.2 K / $R_{p0.2}$@ R.T. of 2.1 - 2.3

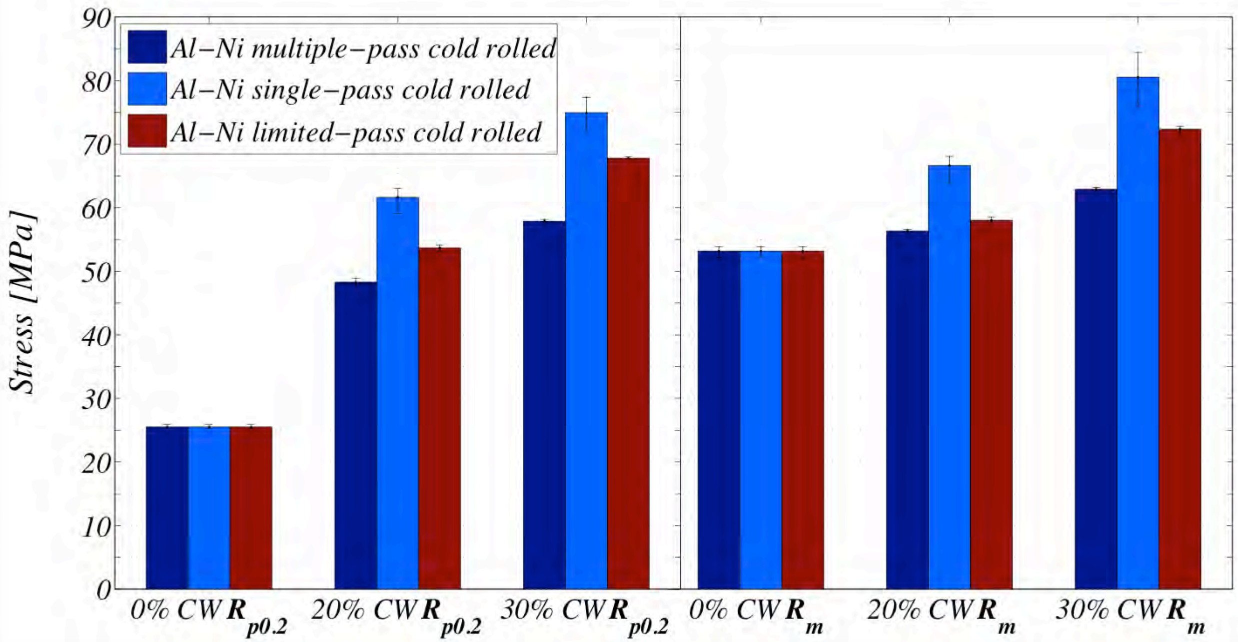
Roughly linear interaction RRR - $R_{p0.2}$

~120 MPa at 4.2 K when ~19% cold-reduced, maintaining RRR of ~700.



Results for the co-extruded Al-0.1WT.%Ni conductor subjected to various work-hardening processes. $R_{p0.2}$ and R_m are 0.2% yield strength and ultimate tensile strength respectively.

UNIVERSITY OF TWENTE.

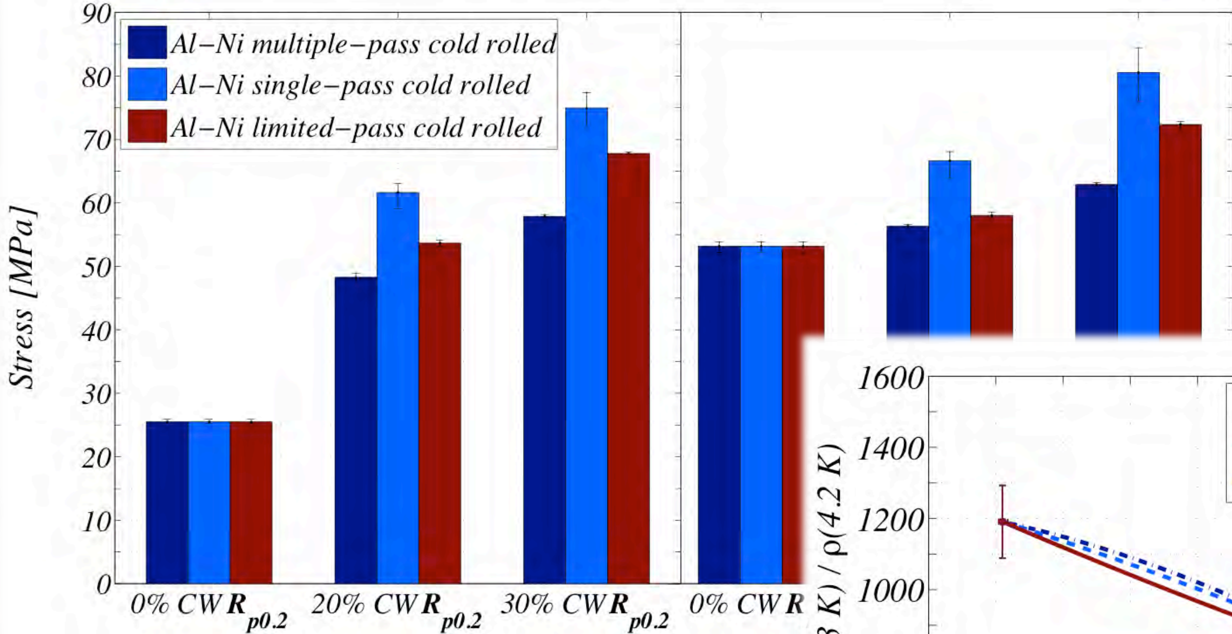


Tensile characteristics of the co-extruded conductor subjected to multiple-pass, single-pass and limited-pass cold rolling.

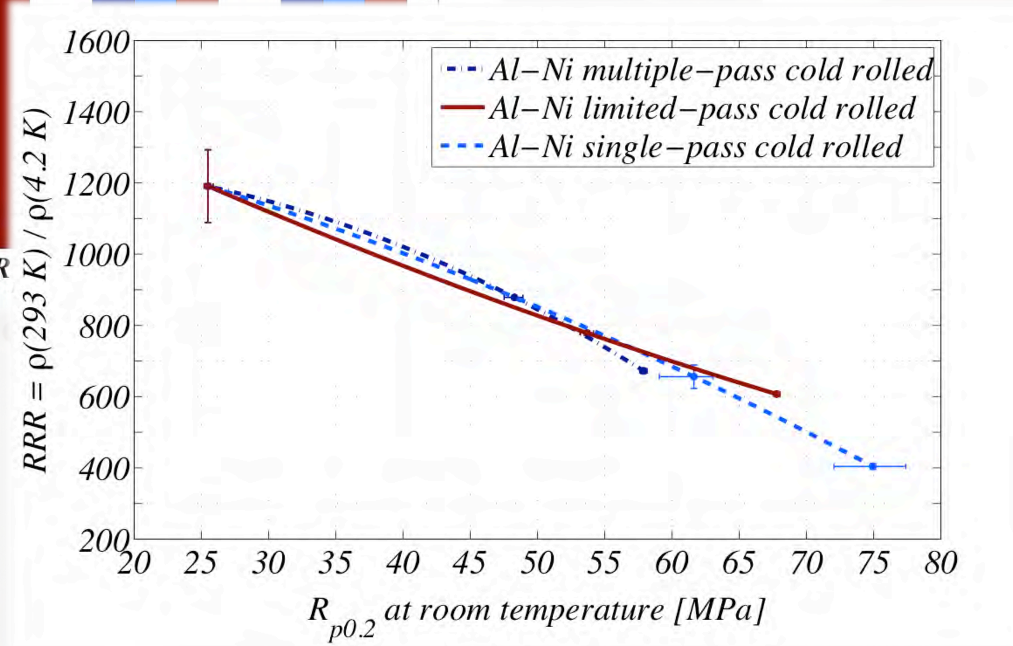
- Distinct decrease in mechanical properties with number of cold-roll passes.
- Process of recovery of dislocation pinning points in between passes in this dilute Al-Ni alloy.

UNIVERSITY OF TWENTE.

Work hardening; Results



- Similar relationship is visible between RRR and $R_{p0.2}$ for the various work-hardening processes.



RRR plotted as function of Rp0.2 for the various cold-worked states, for the different work-hardening processes.

- The mechanical and resistivity characteristics of Al-0.1wt%Ni are not only subject to the amount of work hardening, but also to the process.

UNIVERSITY OF TWENTE. CERN

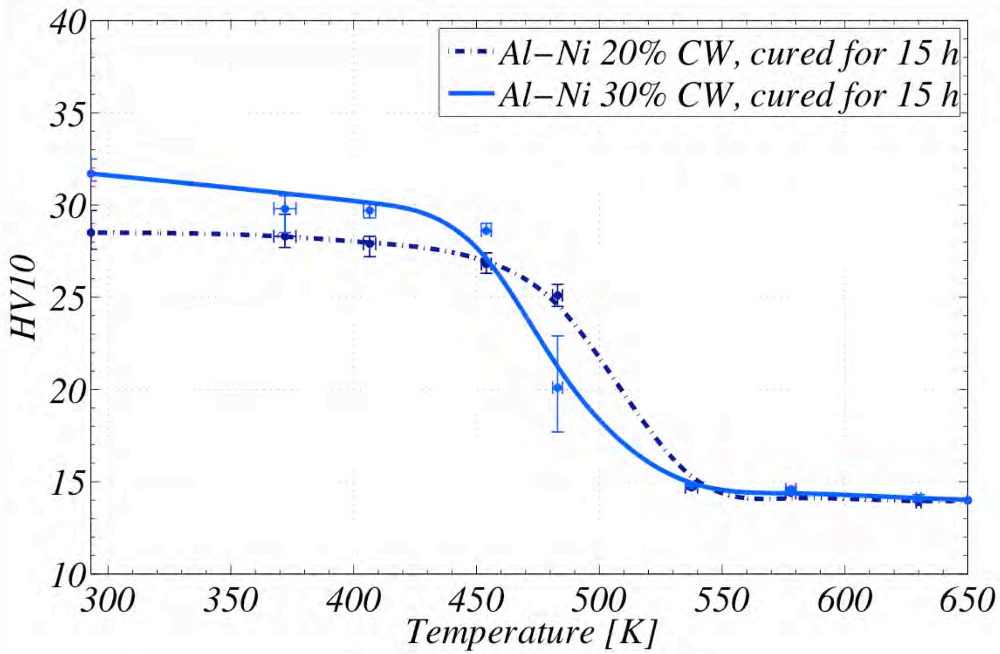
- Clear temperature range where recovery of lattice defects takes place; reversing work-hardening.

  ➜ 470 K – 530 K for 20% reduced
  ➜ 450 K – 510 K for 30% reduced

- Coil resin curing should not exceed temperatures (for 15 h) of:

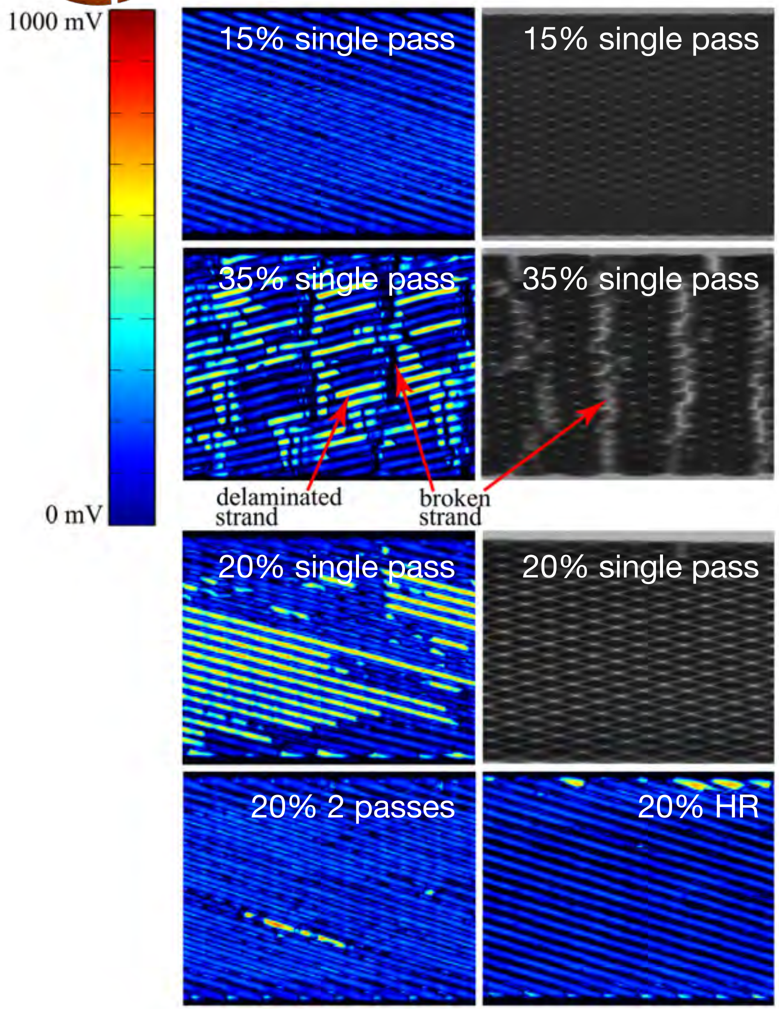
  ➜ 470 K for 20% reduced
  ➜ 450 K for 30% reduced

- No indication was found of precipitation hardening due to artificial aging.



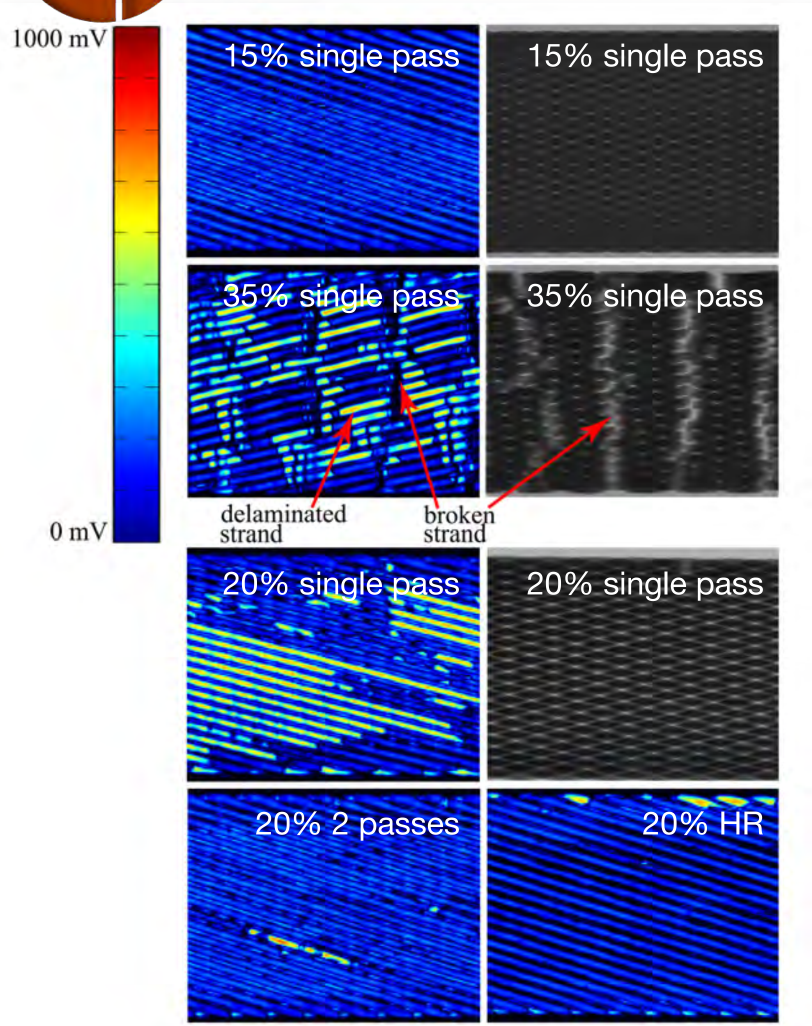
Hardness, HV10, of 20% and 30% single pass cold-rolled short samples subjected to various thermal treatments with a duration of 15 h.

UNIVERSITY OF TWENTE.



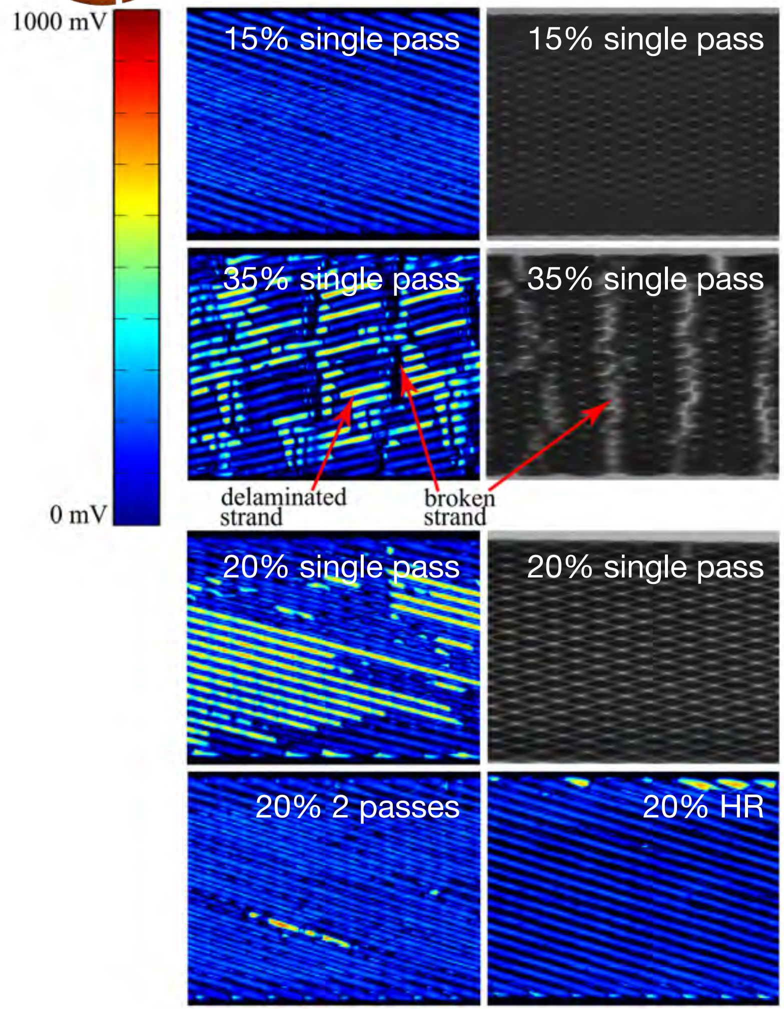
Ultrasonic C-scans (color) and X-ray radiography images (black & white) of the co-extruded, cold-rolled Al-Ni stabilized conductor. HR denotes homogeneously reduced.

- 35% reduced; major delamination, accompanied by strand breakage.
- Location of strand breakage is consistent with concave ripples on the surface.



Ultrasonic C-scans (color) and X-ray radiography images (black & white) of the co-extruded, cold-rolled Al-Ni stabilized conductor. HR denotes homogeneously reduced.

- 35% reduced; major delamination, accompanied by strand breakage.
- Location of strand breakage is consistent with concave ripples on the surface.
- Stress relieve between passes also affects the delamination intensity.
- Reduced delamination, located on the edges in the HR case.



Ultrasonic C-scans (color) and X-ray radiography images (black & white) of the co-extruded, cold-rolled Al-Ni stabilized conductor. HR denotes homogeneously reduced.

- 35% reduced; major delamination, accompanied by strand breakage.
- Location of strand breakage is consistent with concave ripples on the surface.
- Stress relieve between passes also affects the delamination intensity.
- Reduced delamination, located on the edges in the HR case.
- The here applied single-pass, high-force bi-directional rolling seems only feasible up to a 15% cross-section reduction.

A successful **co-extrusion of a record-size, ~700 mm², Al-0.1wt%Ni stabilized superconductor** has been achieved, and an extensive study on thermo-mechanical effects is performed.

The expected **increase in $R_{p0.2}$ with dilute Ni alloying is confirmed**, and the enhancement of the mechanical properties at 4.2 K is promising.

The material characteristics of Al-0.1wt%Ni are subject to both work-hardening amount as well as to certain parameters of the **work-hardening process.**

➜ An **optimal work-hardening sequence** needs to be developed.

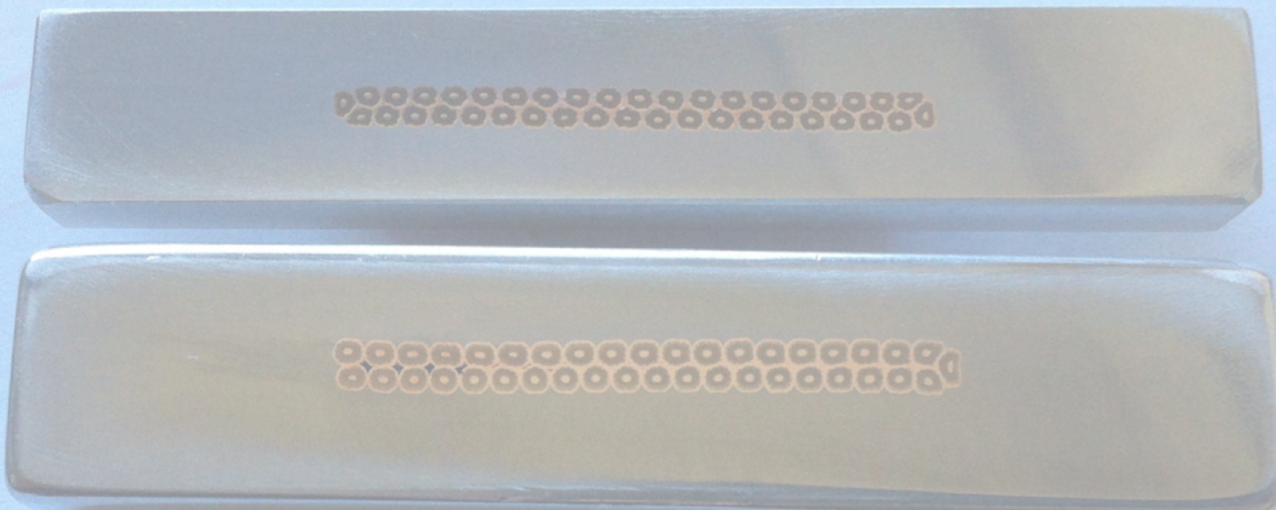
Recovery of work hardening exists between 450 K and 530 K (at 15 h) for the 20% and 30% work-hardened conductor.

➜ **Coil resin curing temperatures** should not exceed 450 K for a 30% cold-worked conductor and 470 K for a 20% cold-worked conductor.

Bonding quality measurements showed that high-force bi-directional rolling can only be performed without introducing defects to a 15% cross-section reduction (for this particular conductor).

UNIVERSITY OF TWENTE.

THANK YOU FOR YOUR KIND ATTENTION!

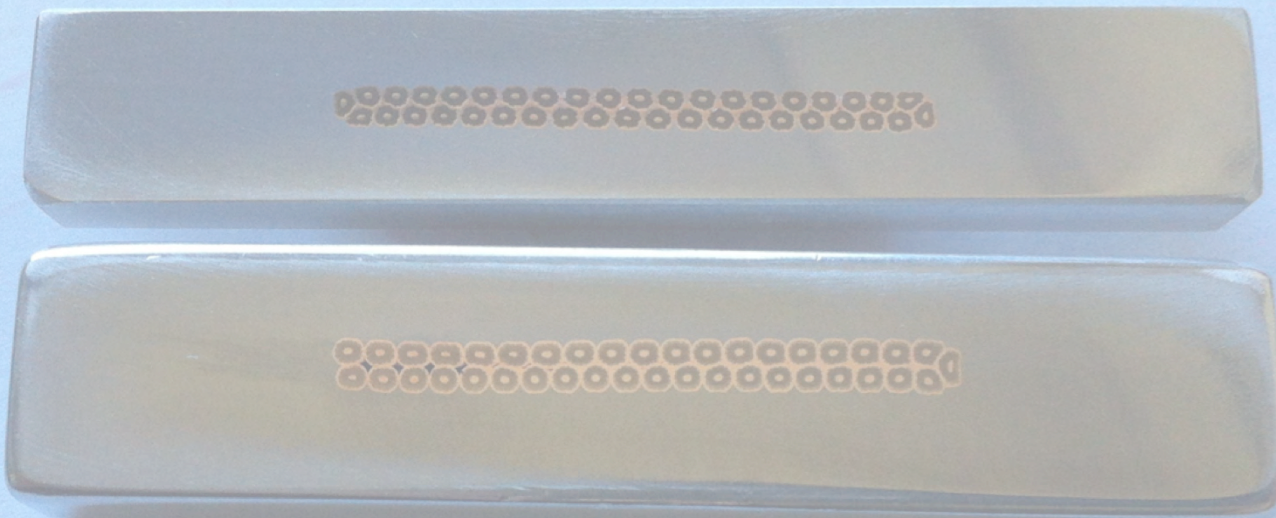


ACKNOWLEDGMENT:

Akira Yamamoto; KEK, Tsukuba, Ibaraki (J)
Antonio della Corte; ENEA, Rome (I)
Collaboration of Criotec, Chivasso (I)

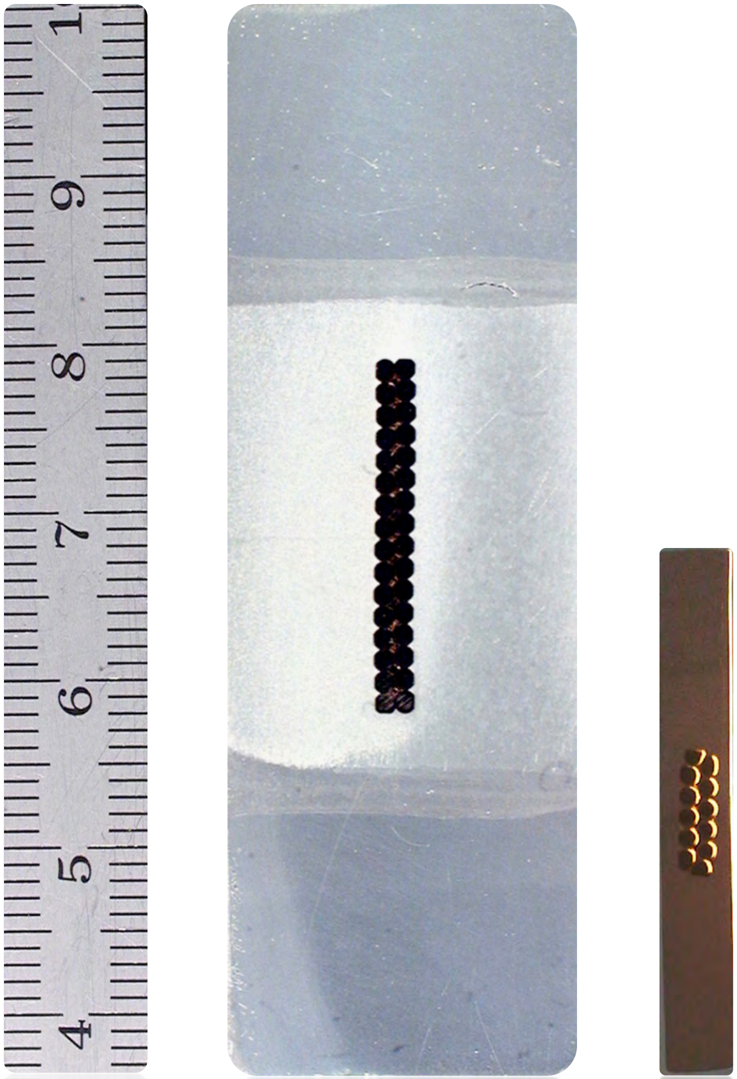
UNIVERSITY OF TWENTE.

Back-up



UNIVERSITY OF TWENTE.

Prototype for a 60 kA at 5 T class conductor



CMS (left) & ATLAS central solenoid (right) conductor

- Hybrid solution
  - preservation of resistivity properties ✓
  - mechanical reinforcement ✓
  - homogeneous deflection ~
  - conductor manufacturing ~
- Microalloying
  - preservation of resistivity properties ~
  - mechanical reinforcement ✓
  - homogeneous deflection ✓
  - conductor manufacturing ✓

Co-extrusion of Al-Ni stabilized conductor

Nexans Cortalliod (CH); Extrusion press

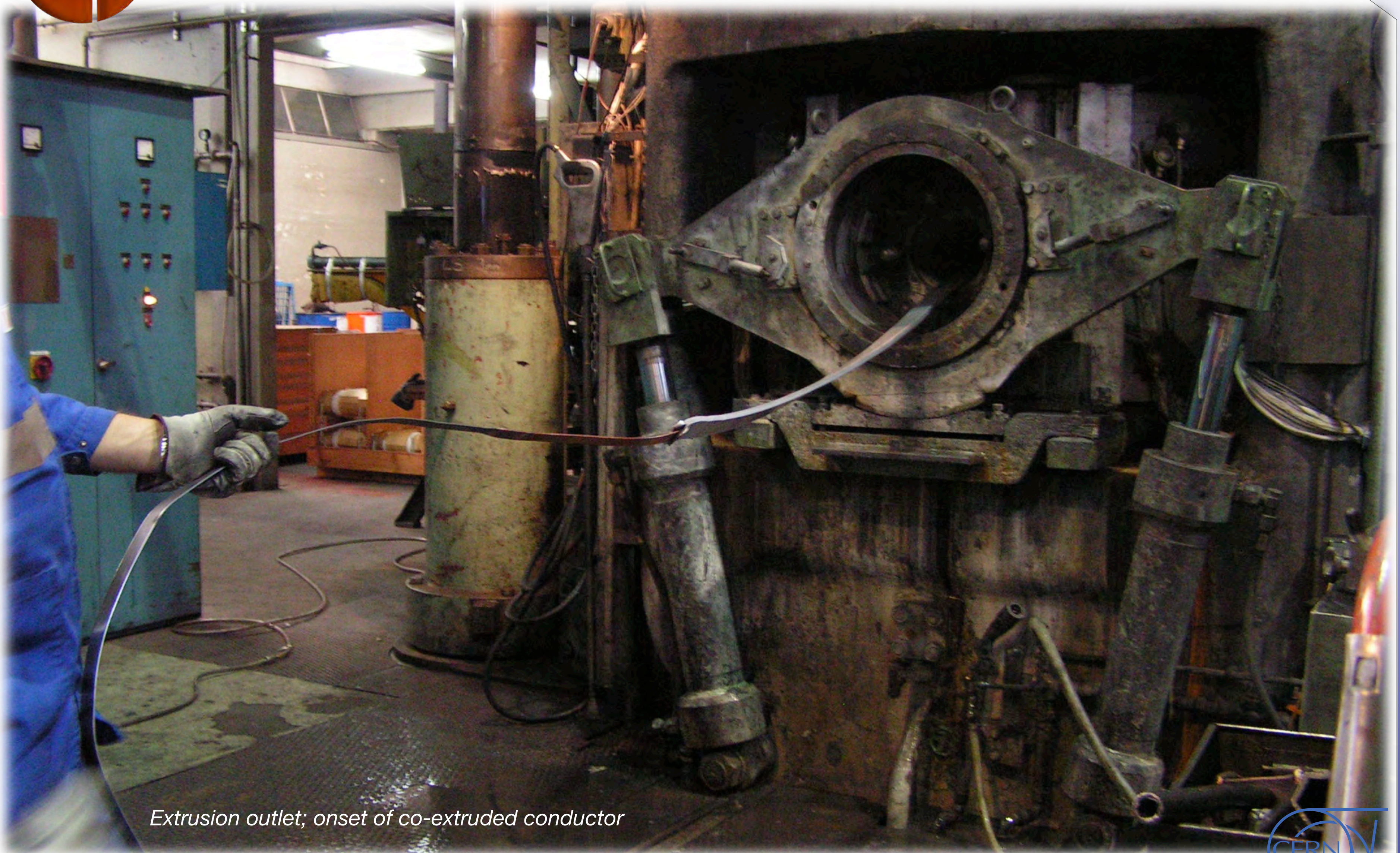
Continuous co-extrusion on a 3800 ton press at Nexans, Cortaillod (CH).

Using punch and die of the ATLAS BT conductor (57 x 12 mm^2).

Cable preheated and brushed to ensure good bonding.

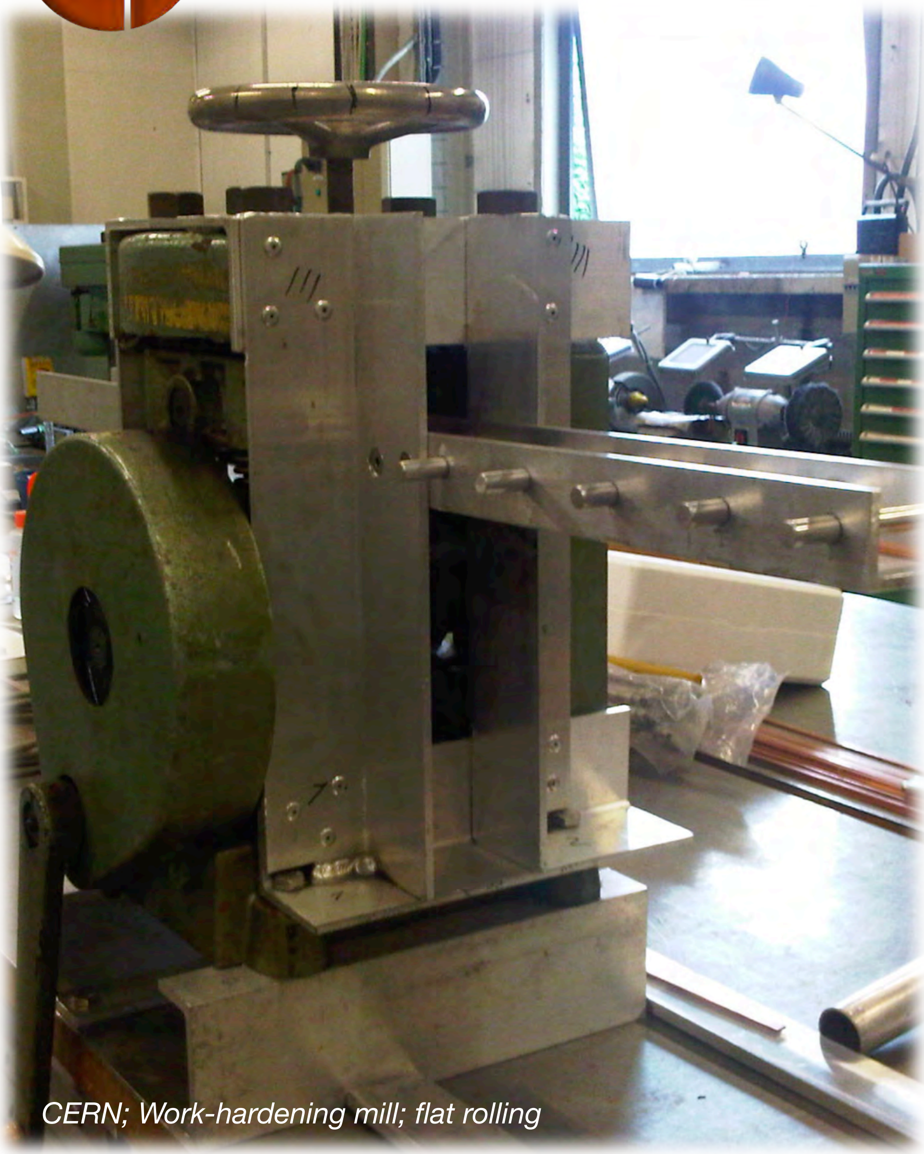
Temperature remained at a constant 400°C, while the pressure was increased with 20-25% with the introduction of Al-0.1wt%Ni, leading to a 1.5 m/min extrusion speed.

First meters from the die.....



UNIVERSITY OF TWENTE.

WORK HARDENING; MANUAL FLAT ROLLING



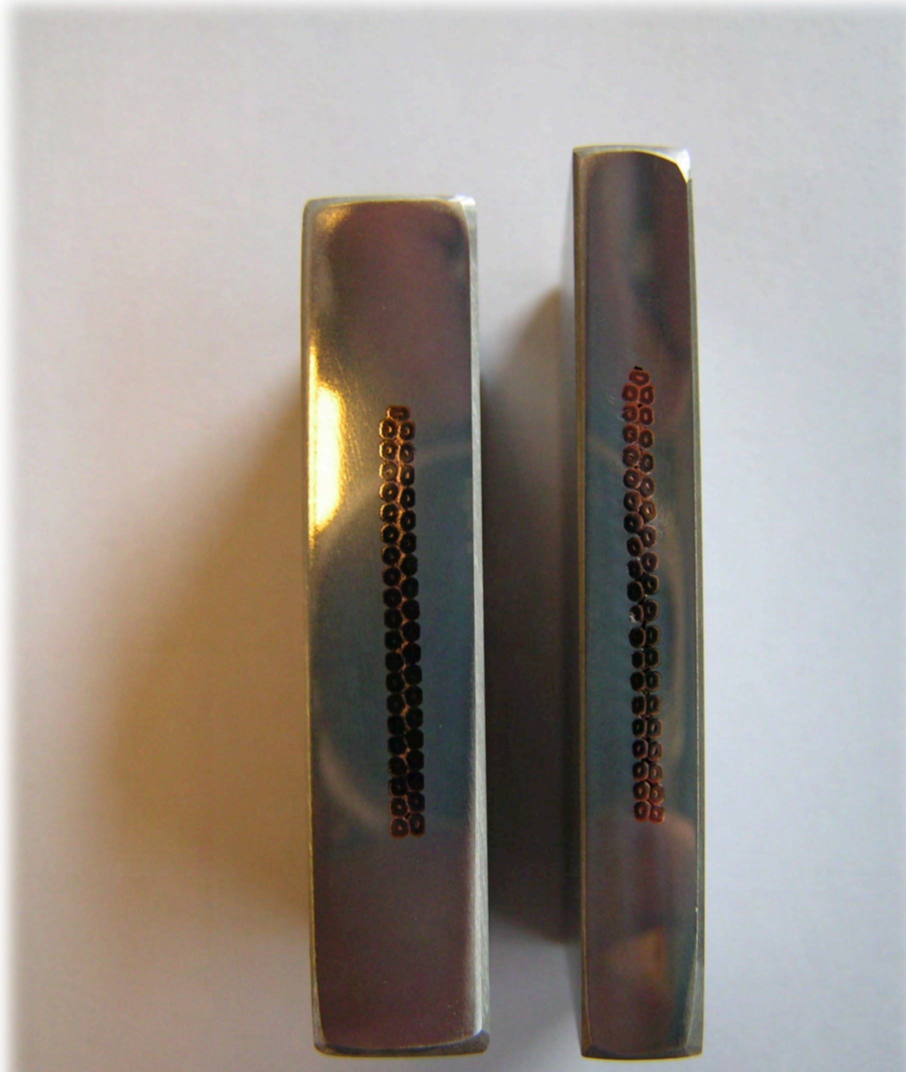
CERN; Work-hardening mill; flat rolling

Specimen; 0% (left) and 30% (right) work hardened

UNIVERSITY OF TWENTE.

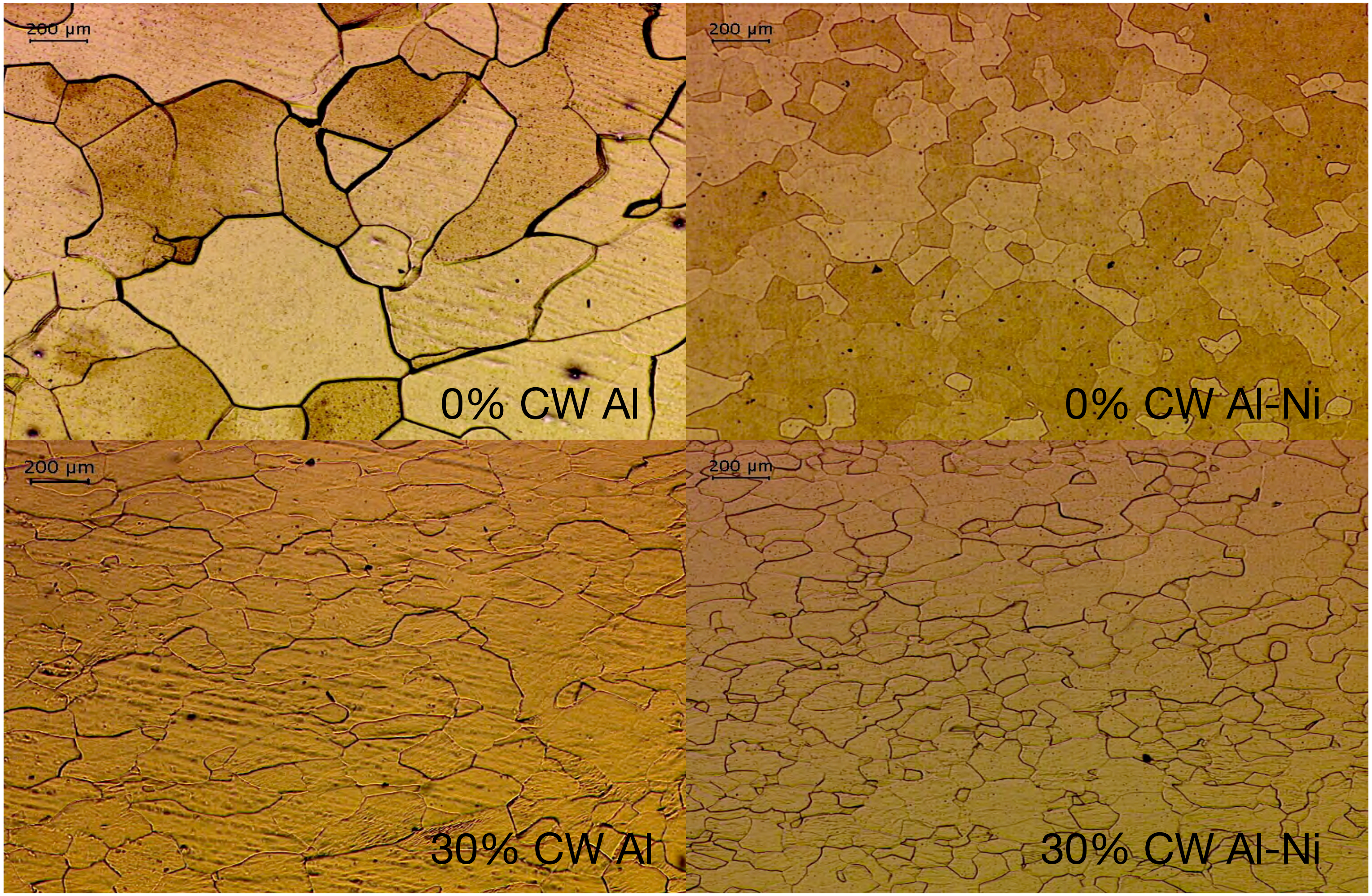
Specimens were extracted at 0, 15, 20, 25, and 30%.

Manual work hardening led to a significant amount of passes to reach a 30% work-hardened state.



Specimen; 0% (left) and 30% (right) work hardened

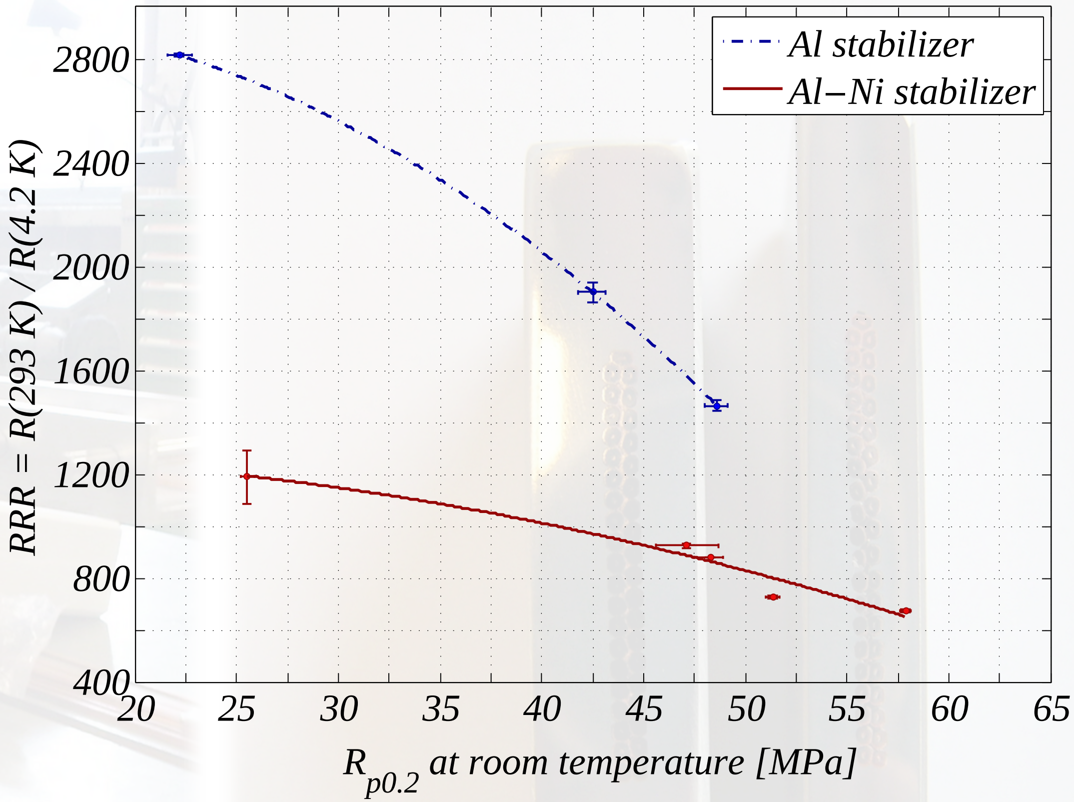
Prototype for a 60 kA at 5 T class conductor



Microscope pictures of HF/H_2O solution etched 5N-Al (left) & Al-Ni (right) specimens

UNIVERSITY OF TWENTE.

MANUAL FLAT ROLLING; RESULTS



	AlNi as-extruded	20% Cold rolled	30% Cold rolled
Yield Strength *(estimated [1])*	26 MPa at RT *(35 MPa at 4.2K)*	48 MPa at RT *(72 MPa at 4.2K)*	58 MPa at RT *(87 MPa at 4.2K)*
RRR	1191	879	673

[1] S. Sgobba, et al., 2006.
[2] K. Wada et al., 2000.
[3] K. Wada et al., 2000.
[4] A.Yamamoto, et al., 1999.

- The Al-Ni alloy extruded with Rutherford cable exhibited in the highest cold worked state of 30% an $R_{p0.2}$ of 58 and RRR of 673, which will result in an **$R_{p0.2}$ of 87 MPa at 4.2 K [1]** (promising results).

- The **obtained values are slightly lower** than the gross of measurements conducted on Al-0.1wt%Ni extruded in smaller cross-sections in the development of the ATLAS and CMS solenoid conductor.

- A cautious conclusion to be further verified is that **increased cross-section** extrusions result in **decreased work hardening effects**.

Comparison: for the ATLAS central solenoid conductor (20% cold-worked), the R.T. yield strength was found to be between 55 and 79 MPa and the RRR ~600 [1-4].

	AlNi as-extruded	20% Cold rolled	30% Cold rolled
Yield Strength *(estimated [1])*	26 MPa at RT *(35 MPa at 4.2K)*	48 MPa at RT *(72 MPa at 4.2K)*	58 MPa at RT *(87 MPa at 4.2K)*
RRR	1191	879	673

[1] S. Sgobba, et al., 2006.
[2] K. Wada et al., 2000.
[3] K. Wada et al., 2000.
[4] A.Yamamoto, et al., 1999.