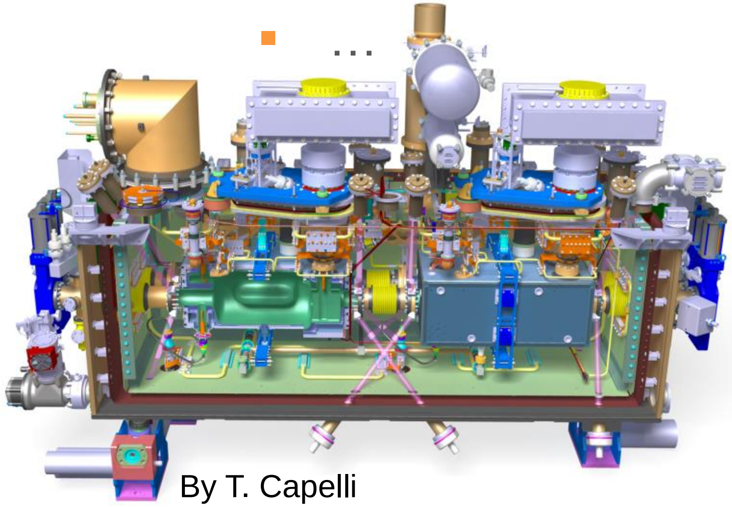
Materials testing & lessons learned for Crab Cavities

Adrià Gallifa Terricabras CERN EN-MME, on behalf of WP4

12th HL-LHC Collaboration Meeting · Uppsala · 19 - 22 September 2022

It’s a tight relationship…

- Materials
  - Nb RRR300
  - Ti alloys
  - Cu alloys
  - Stainless steel
  - Cryophy, mumetal
  - Ceramics (Al_2O_3)
  - Filler metals
  - …



By T. Capelli

- Components
  - Bare cavities
  - Brazed SS-Nb extremities
  - Tuning system
  - 2nd beam pipe
  - He tank
  - Ti-SS transitions
  - Outer Vacuum Vessel
  - Bellows
  - HOMs and antenna couplers
  - Cold & warm magnetic shield
  - Coaxial lines
  - RF feedthroughs
  - Gaskets
  - Fasteners
  - …

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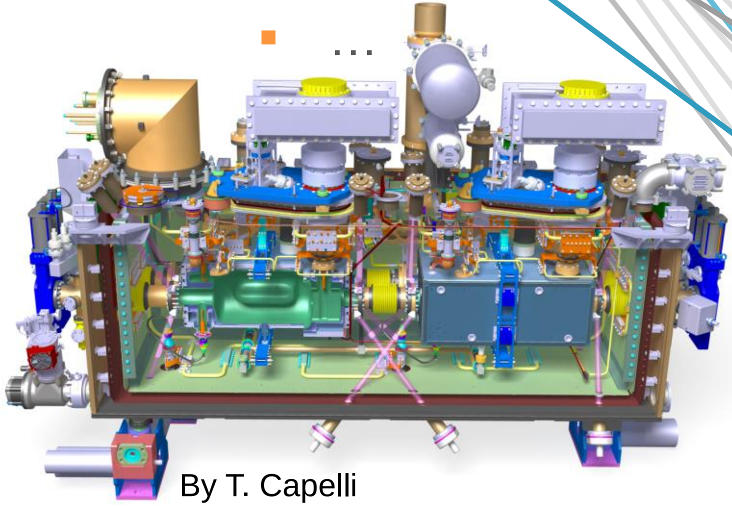
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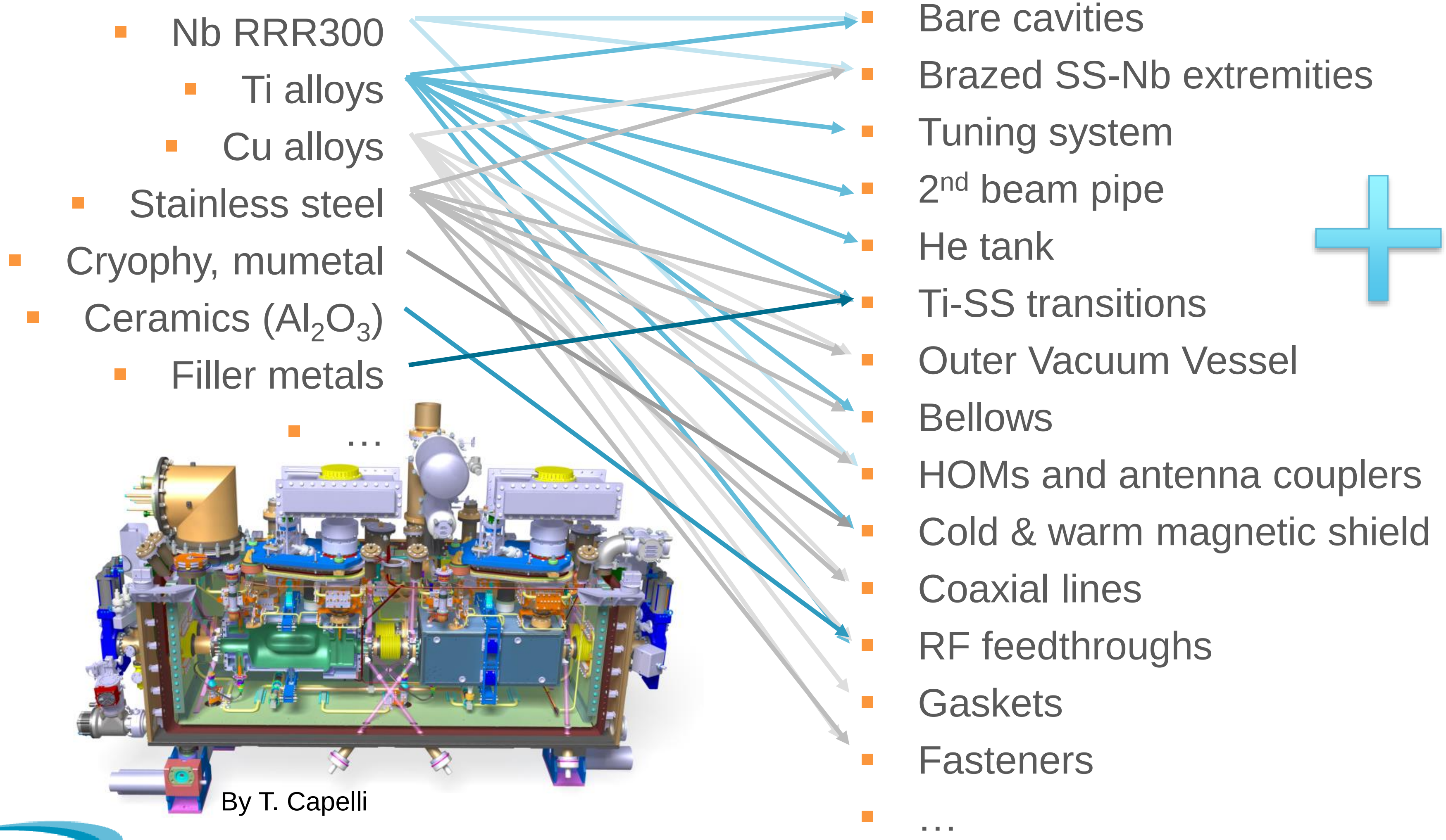

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By T. Capelli

Manufacturing process

- Cutting
- Deep drawing
- Machining
- Grinding
- Bending
- EB welding
- TIG welding
- Vacuum brazing
- Heat treatments
- Surface treatments
- ...

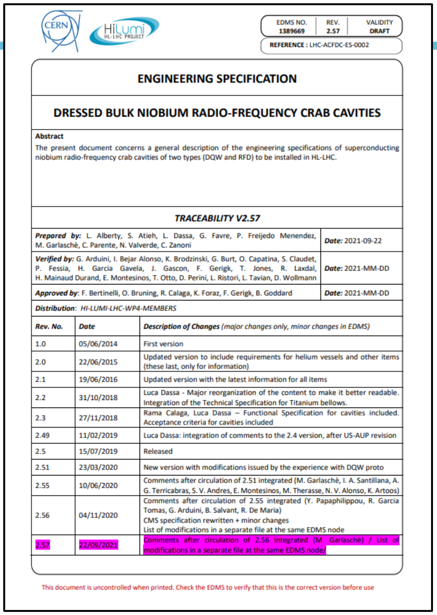
Our ‘holy’ documents

Engineering specifications for Dressed Crab Cavities (EDMS 1389669) / Cryomodule (EDMS 2043014) & sub-components

- Engineering requirements
- Materials to be used
- Qualification requirements + Acceptance criteria
- Quality, traceability
- Pressure Equipment Directive – PED 2014/68/EU
- CERN safety rules

CERN material specifications

- Materials acc. to standards in force
  ISO, EN, ASTM, and industry capabilities.
- Specific CERN requirements
- Technical quality ensured



EDMS NO.	REV.	VALIDITY
1389669	2.57	DRAFT

REFERENCE : LHC-ACFDC-ES-0002

ENGINEERING SPECIFICATION

DRESSED BULK NIOBIUM RADIO-FREQUENCY CRAB CAVITIES

Abstract

The present document concerns a general description of the engineering specifications of superconducting niobium radio-frequency crab cavities of two types (DQW and RFD) to be installed in HL-LHC.

TRACEABILITY V2.57

Prepared by: L. Alberty, S. Atieh, L. Dassa, G. Favre, P. Freijedo Menendez, M. Garlaschè, C. Parente, N. Valverde, C. Zanoni	***Date:*** 2021-09-22
Verified by: G. Arduini, I. Bejar Alonso, K. Brodzinski, G. Burt, O. Capatina, S. Claudet, P. Fessia, H. Garcia Gavela, J. Gascon, F. Gerigk, T. Jones, R. Laxdal, H. Mainaud Durand, E. Montesinos, T. Otto, D. Perini, L. Ristori, L. Tavian, D. Wollmann	***Date:*** 2021-MM-DD
Approved by: F. Bertinelli, O. Bruning, R. Calaga, K. Foraz, F. Gerigk, B. Goddard	***Date:*** 2021-MM-DD

Distribution: *HI-LUMI-LHC-WP4-MEMBERS*

Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
1.0	05/06/2014	First version
2.0	22/06/2015	Updated version to include requirements for helium vessels and other items (these last, only for information)
2.1	19/06/2016	Updated version with the latest information for all items
2.2	31/10/2018	Luca Dassa - Major reorganization of the content to make it better readable. Integration of the Technical Specification for Titanium bellows.
2.3	27/11/2018	Rama Calaga, Luca Dassa – Functional Specification for cavities included. Acceptance criteria for cavities included
2.49	11/02/2019	Luca Dassa: integration of comments to the 2.4 version, after US-AUP revision
2.5	15/07/2019	Released
2.51	23/03/2020	New version with modifications issued by the experience with DQW proto
2.55	10/06/2020	Comments after circulation of 2.51 integrated (M. Garlaschè, I. A. Santillana, A. G. Terricabras, S. V. Andres, E. Montesinos, M. Therasse, N. V. Alonso, K. Artoos)
2.56	04/11/2020	Comments after circulation of 2.55 integrated (Y. Papaphilippou, R. Garcia Tomas, G. Arduini, B. Salvant, R. De Maria) CMS specification rewritten + minor changes List of modifications in a separate file at the same EDMS node
2.57	22/09/2021	Comments after circulation of 2.56 integrated (M. Garlaschè) / List of modifications in a separate file at the same EDMS node/

This document is uncontrolled when printed. Check the EDMS to verify that this is the correct version before use

ORGANISATION EUROPÉENNE POU
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EUROPEAN ORGANIZATION FOR N

Materials Technical Specification
GS-IS & EN-MME

Technical Specif

Nº 2000 - Ed. 8
EDMS No: 79078

Oxygen-Free Electron
sheets

Cu-OFE

This document specifies the CERN technical requ
equivalent to UNS C10100 Grade 1, accordi
maximum oxygen content of 5 ppm.

ORGANISATION EUROPÉENNE PO
NUCLÉAIRE
EUROPEAN ORGANIZATION FOR

Materials Technical Specification
GS-IS & EN-MME

Material Specif

Nº 4055 - Ed.
EDMS Nº: 1485

Nb55Ti wrought products for
applications

This material specification establishes the requireme
and annealed condition to be used for the production

ORGANISATION EUROPÉENNE POU
NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NU

Materials Technical Specification
GS-IS & EN-MME

Material Specifi

Nº 3300 - Ed.
EDMS Nº: 10952

Pure niobium she
for superconducting ap

RRR 300 grad

This document specifies the CERN technical requ
(Nb) RRR grade sheets in fully annealed con
applications at CERN requiring a minimum RRR
conform to R04200-Type 5 as per ASTM B393 wi
requirements as specified herein.

ORGANISATION EUROPÉENNE POUR LA RECHERCHE
NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Materials Technical Specification
GS-IS & EN-MME

20.10.2014

Technical Specification

N°1006 – Ed.1
EDMS No: 1429406

Stainless steel sheets/plates
for vacuum applications

1.4435

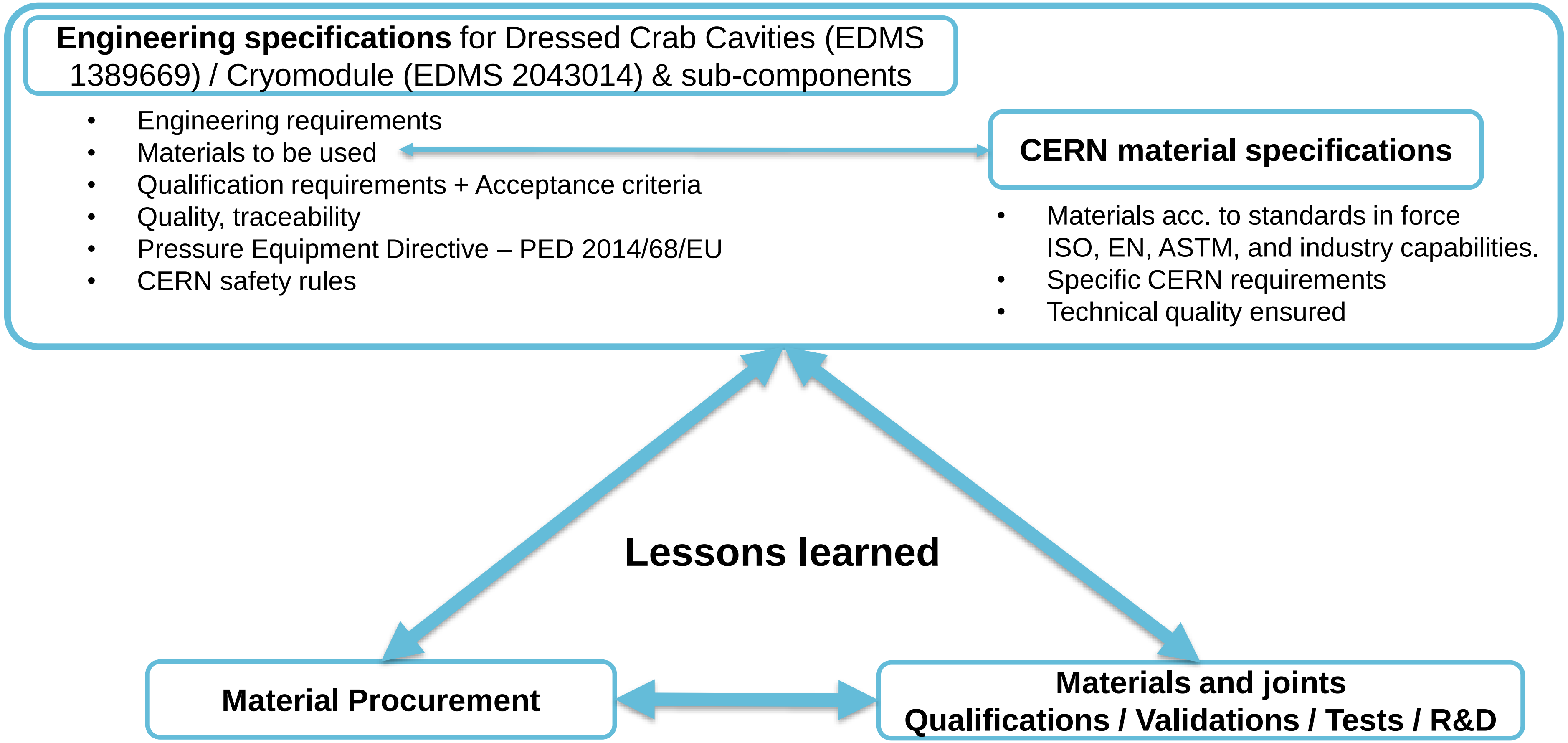
X2CrNiMo18-14-3

AISI 316L

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

Original : English

Our ‘holy’ documents



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Lessons learned

Material Procurement

Materials and joints Qualifications / Validations / Tests / R&D

QA: traceability, NCR, ECR..

Item concerned
Collaboration

Table of contents

Niobium: procurement status at CERN

	Items	Location	CERN Quality Check* Status
2018 - 2021	Nb and NbTi for DQW pre-series and series bare cavities	RI (working on series)	Done
	Nb for DQW HOMS pre-series	CERN	Done
2022	Nb **sheets** for DQW HOMs series (by Tokyo Denkai)	CERN	UT Done, the rest is pending
	Nb **plates** for DQW HOMs series (by Ningxia)	Shipping ongoing	Pending
	Nb **bars** for DQW HOMs series (by Ningxia)	Shipping Sept/Oct 2022	Pending

Summary report (ongoing) EDMS 2395238

*Quality check including UT, tensile tests, RRR measurements, metallographic check

Challenges with RFD pole forming

Min. thickness on corners ~ 2.3 mm

RFD pole forming trials for pre-series cavities.

Poles formed with **material from a specific batch** showed **orange peel** appearance and **excessive thickness reduction** on certain regions (+ wrinkles) → **shape accuracy not guaranteed**

CERN-FNAL agreed to perform a forming trial at CERN, comparing two different material batches.

See talks of M. Narduzzi and A. Ratti.

Challenges with RFD pole forming

Preparation of the RFD Pole forming trials held at CERN Main Workshop (May 2022).

RFD bare cavity pre-series
US-AUP collaboration

Challenges with RFD pole forming

- Same material supplier
- **2 different material lots**
- Same tooling
- Same operators
- Same press machine

⇩

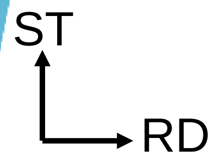
Very different outcome!

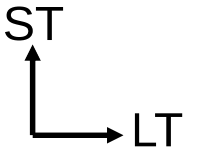
Lot 1 – forming OK

Lot 2 – forming NOK

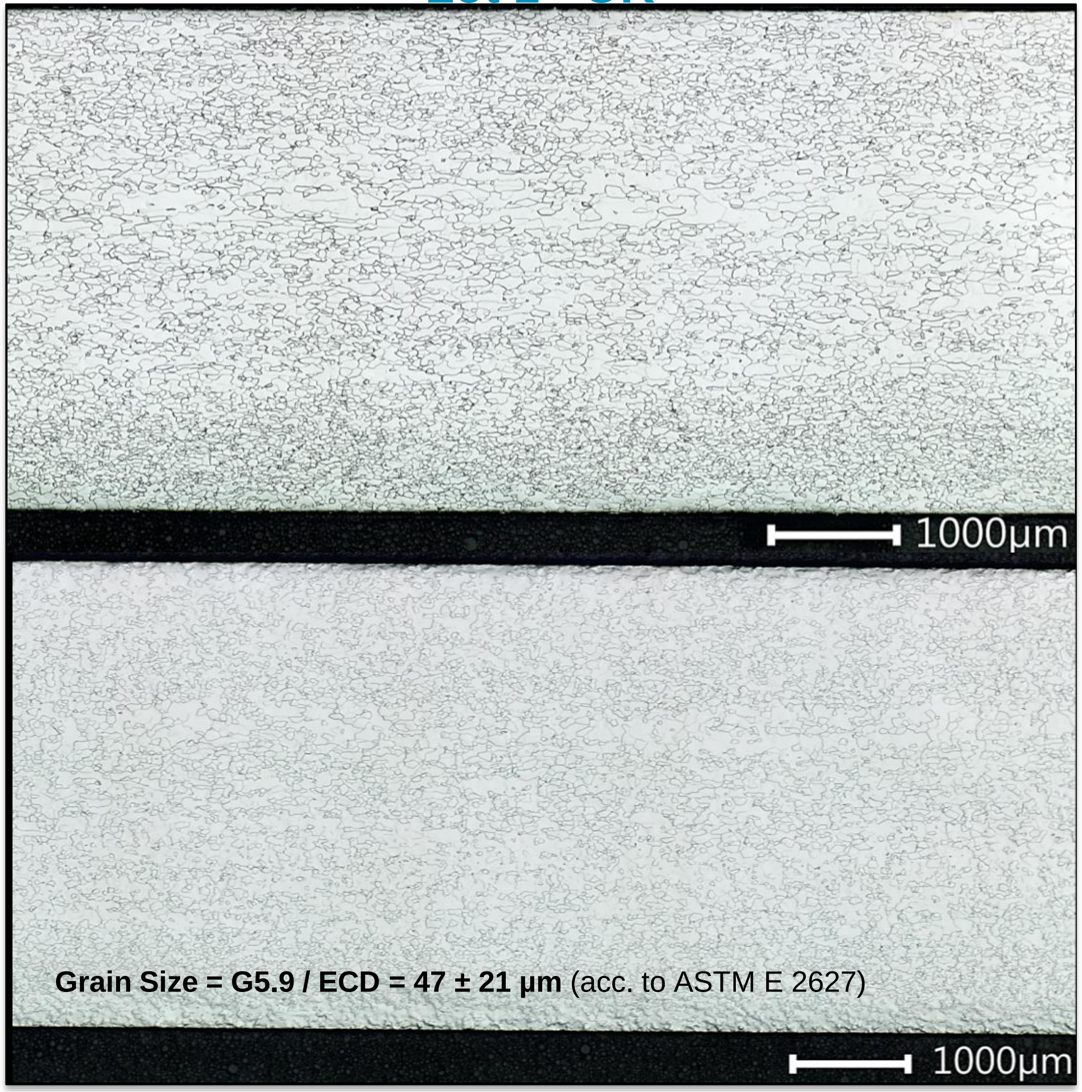
RFD Pole forming trials held at CERN Main Workshop (May 2022).

Materials investigation – Microstructure check



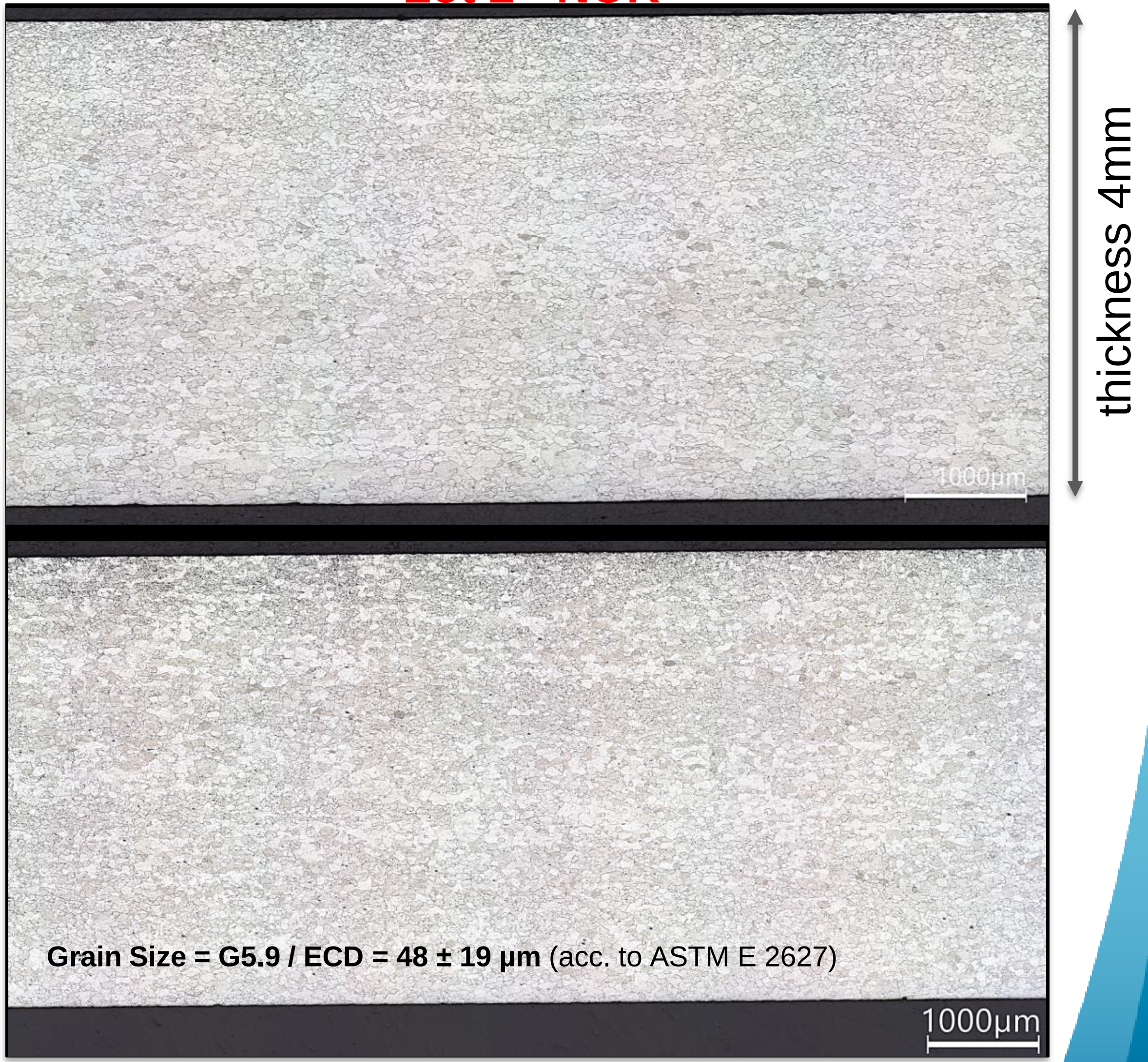


Lot 1 - OK



Grain Size = G5.9 / ECD = 47 ± 21 µm (acc. to ASTM E 2627)

Lot 2 - NOK



Grain Size = G5.9 / ECD = 48 ± 19 µm (acc. to ASTM E 2627)

Both sheets show a recrystallized, similar microstructure.

Materials investigation – Mechanical tests

Lot 1 - OK

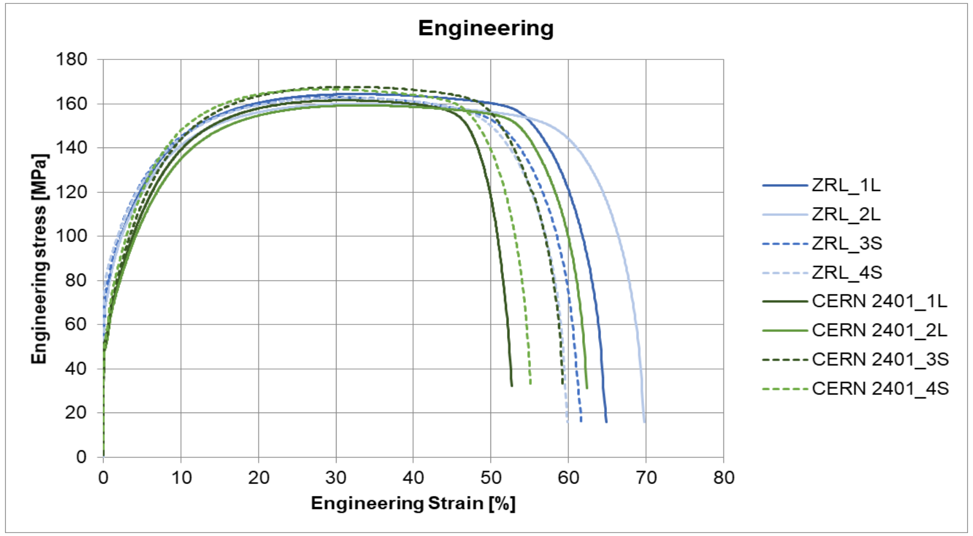
Specimen designation	$R_{p0.2}$	R_m	A_g	$A_{24,45mm}$	$n_{0.02-0.20}$	$R_{p0.2}/R_m$
	MPa	MPa	%	%		
2082401_1L	53.0	161.6	30.9	52.6	**0.38**	**0.33**
2082401_2L	49.5	159.4	33.0	62.3	**0.38**	**0.31**
2082401_3S	51.4	167.7	31.3	59.2	**0.37**	**0.31**
2082401_4S	53.6	166.6	27.9	55.1	**0.35**	**0.32**

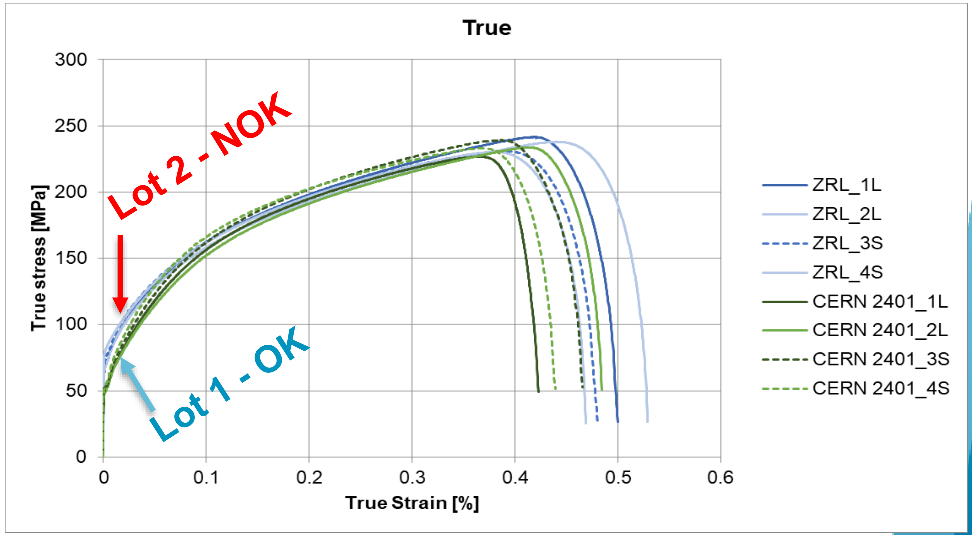
Material shows low Rp0.2 (<65 MPa)

Lot 2 - NOK

Specimen designation	$R_{p0.2}$	R_m	A_g	$A_{24,87mm}$	$n_{0.02-0.20}$	$R_{p0.2}/R_m$
	MPa	MPa	%	%		
ZRI_1L	68.7	164.5	32.4	64.9	**0.30**	**0.42**
ZRI_2L	69.1	160.0	32.3	69.7	**0.29**	**0.43**
ZRI_3S	74.0	163.0	29.5	61.6	**0.28**	**0.45**
ZRI_4S*	80.9	162.8	29.9	59.9	**0.28**	**0.50**

Material complies with CERN spec 3300 Ed.4!



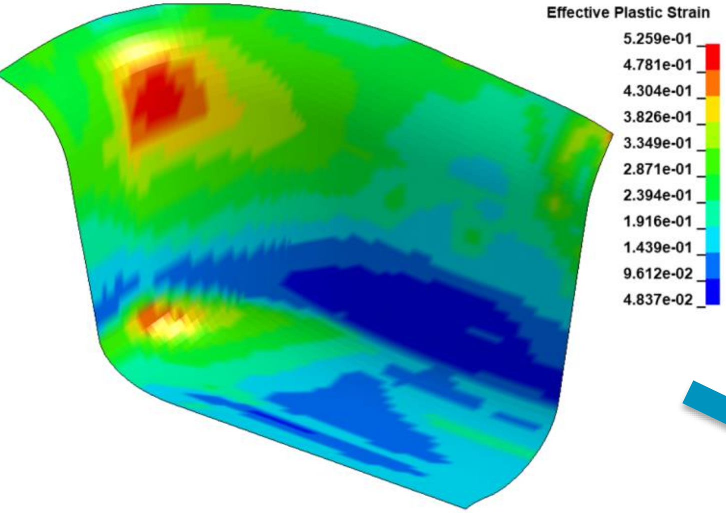


‘n’ value seems to be significantly different, as well as the ratio Rp0.2/Rm

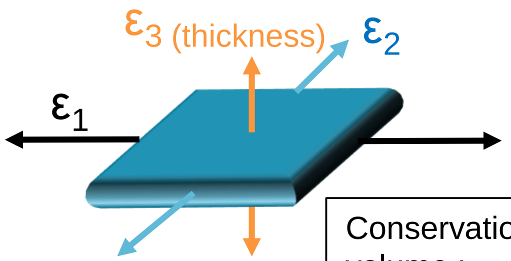
Note: Ag → elongation (engineering) at maximum force
$n_{0.02-0.20}$ → strain hardening index (interval from 0.02 to 0.2 true strain)
*: for sample ZRI_4S, the same test speed (0.05 1/min) was used during the whole test.

Challenges with RFD pole forming – FE simulations

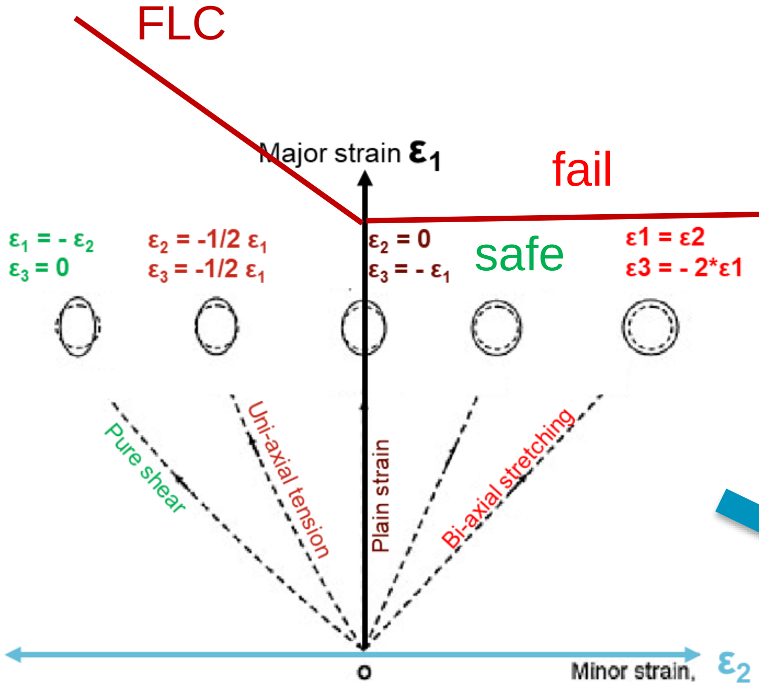
- FE simulations together with a failure criteria for membrane-like components (e.g. Forming Limit Diagram) can help understanding and optimizing the formability.



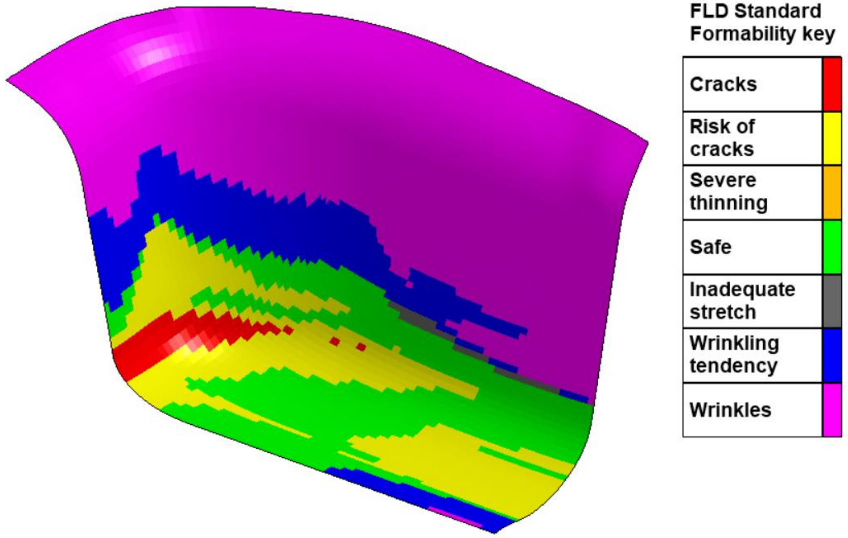
FE simulation with LS-DYNA, thanks to A. Amorim Carvalho, M. Garlasche



Conservation of volume :
$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$



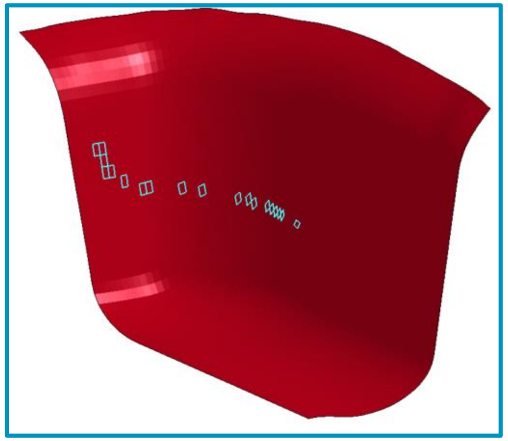
Relationship between ε_1 , ε_2 and ε_3 along the deformation process (i.e. **strain path**) matters:

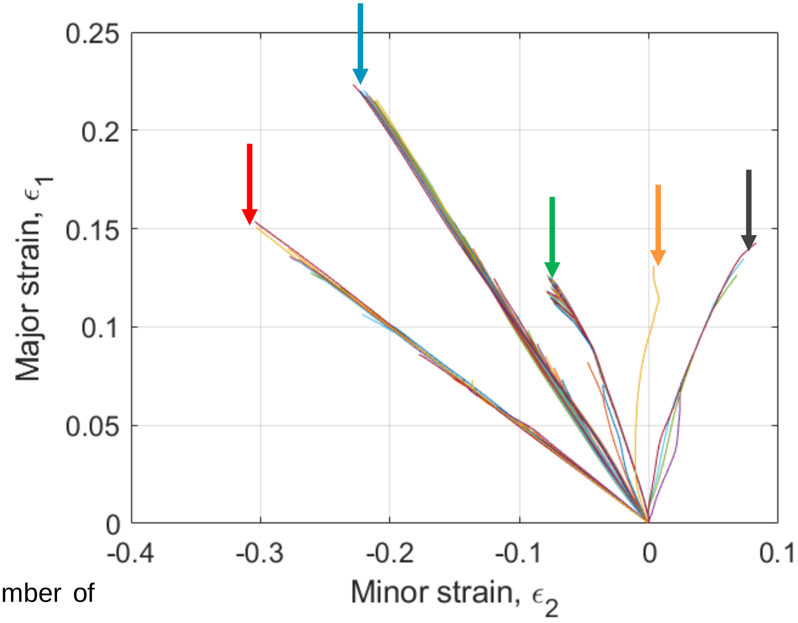


Thanks to J. Swieszek &
E. Cano-Pleite

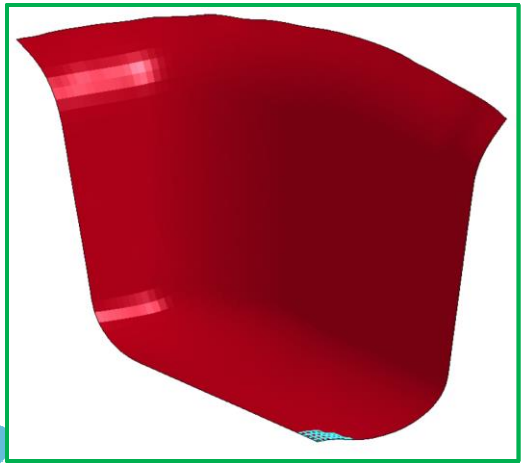
Challenges with RFD pole forming – FE simulations

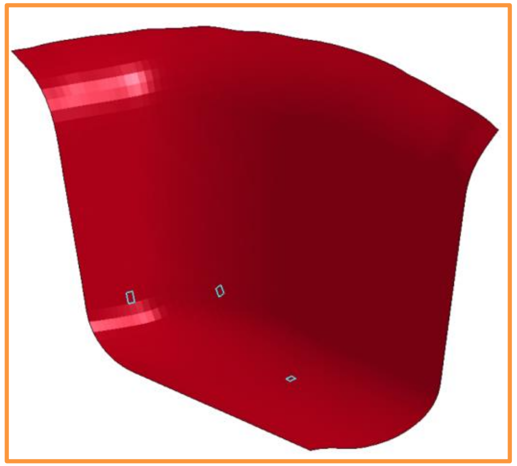

Uniaxial compression

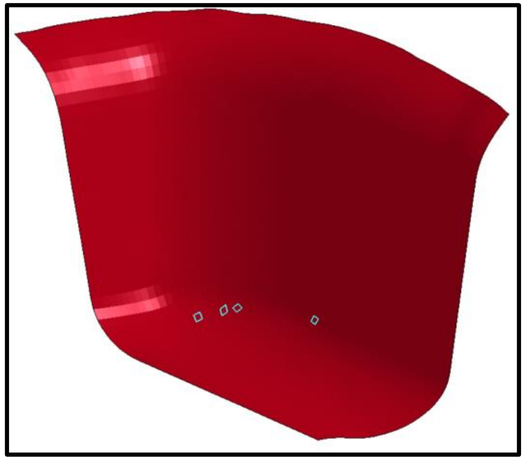

Pure shear



* Some elements were manually selected, the number of curves in the plot and the number of elements in the snapshots may not match.

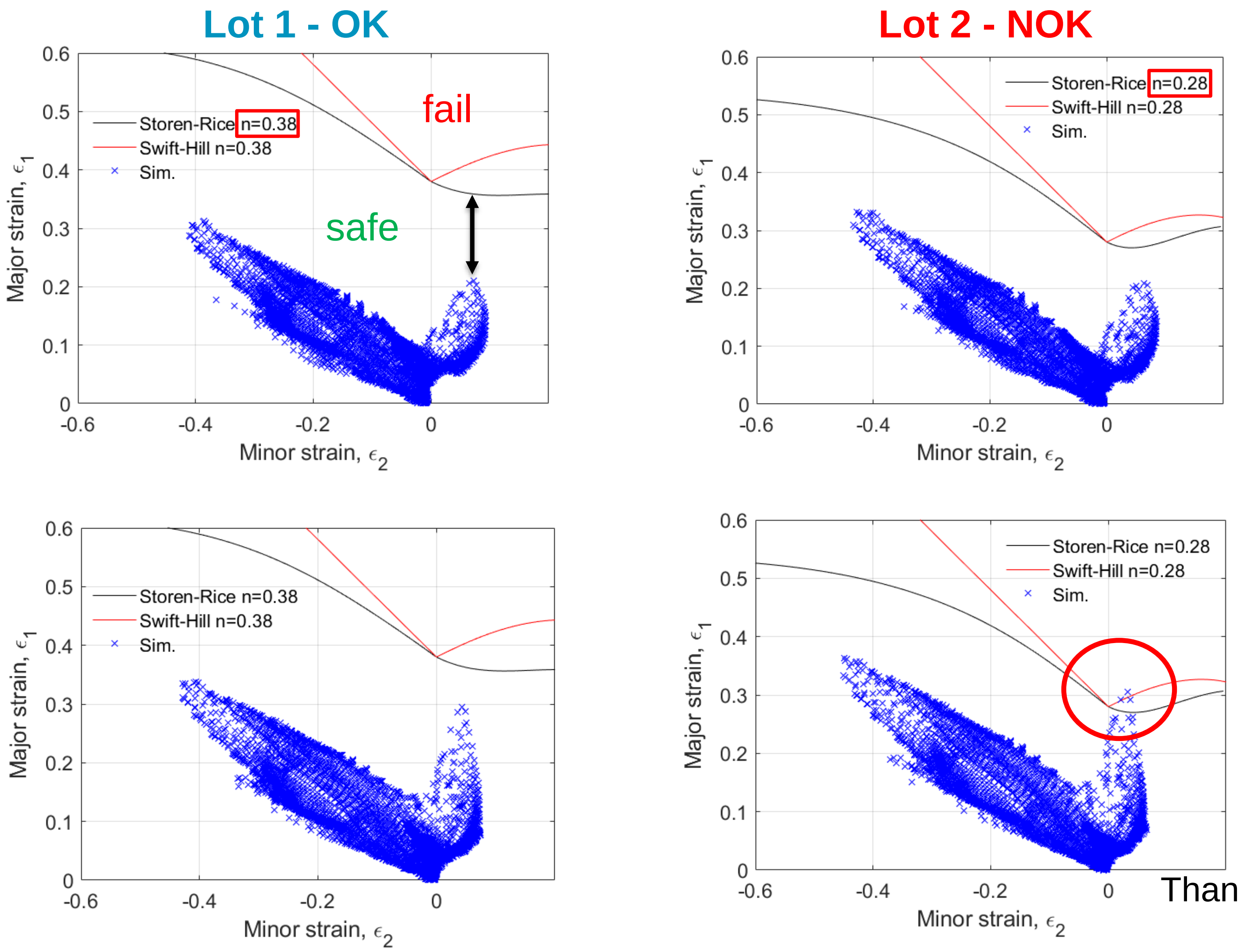

Uniaxial tension


Plane strain


Biaxial tension

Thanks to J. Swieszek &
E. Cano-Pleite

Challenges with RFD pole forming



Lot 1 - OK

Lot 2 - NOK

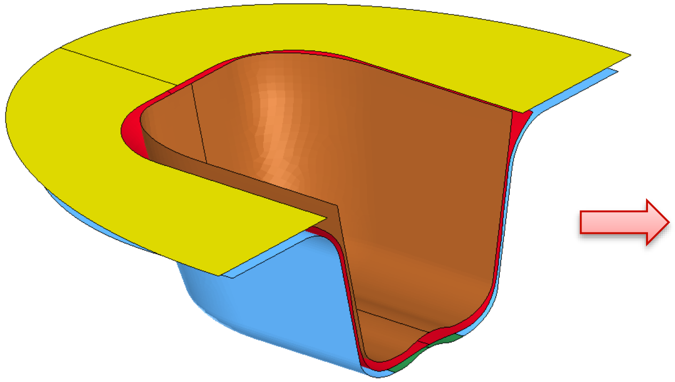
Coefficient of Friction = 0.03

Coefficient of Friction = 0.18

Thanks to J. Swieszek & E. Cano-Pleite

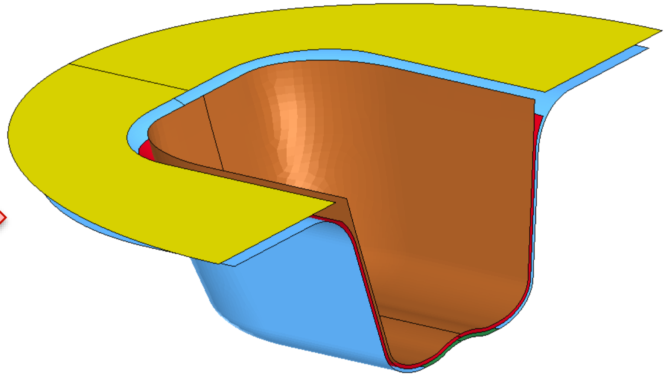
Modified 2-step forming process

- Initial forming up to 5-15 mm from the end of the punch stroke.
- Trimming so that at least the nominal shape +25 mm of material is available.



1st forming

Trimming

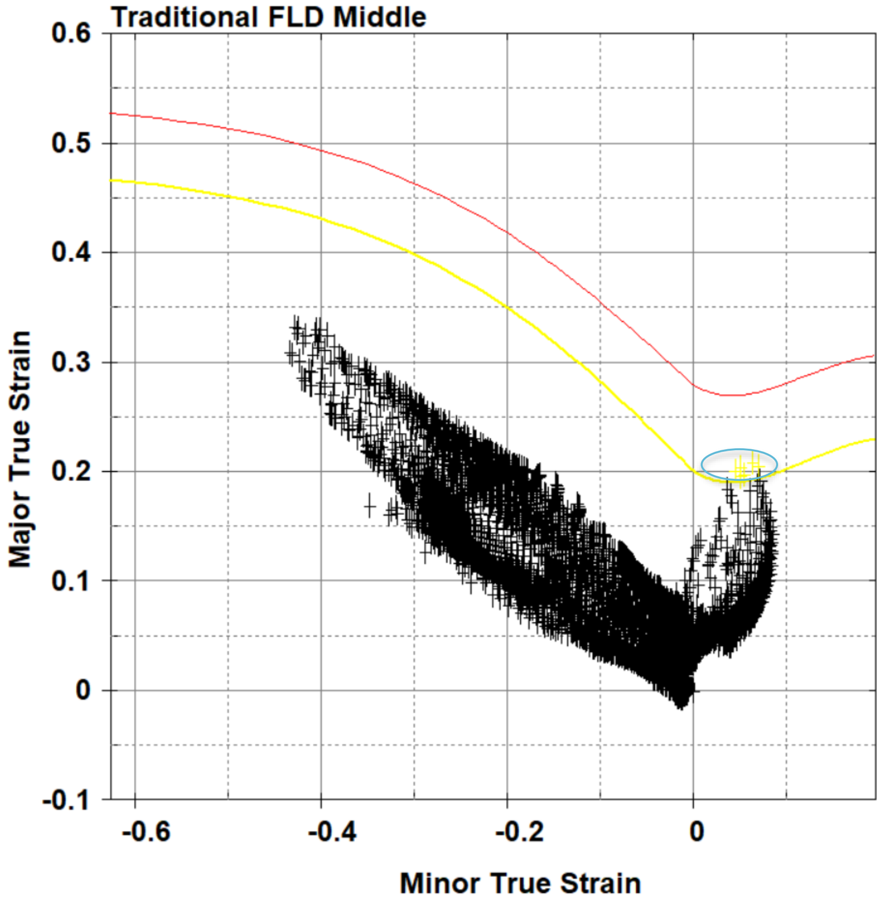


(Greasing +) 2nd forming

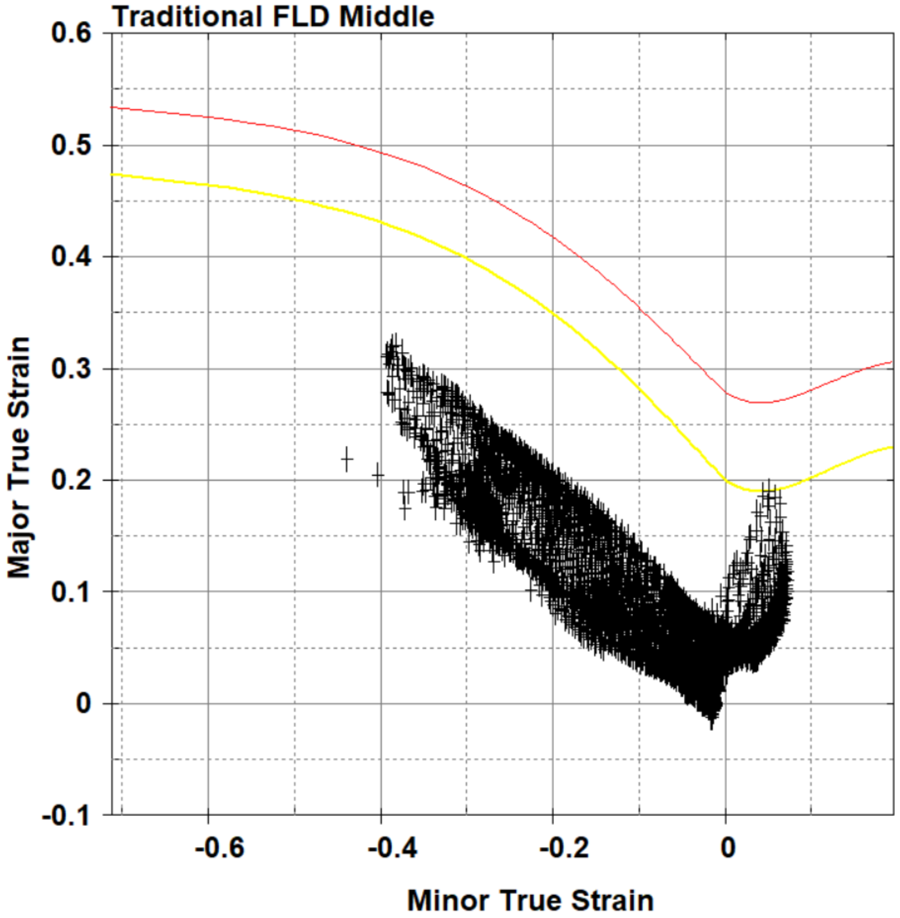
Thanks to J. Swieszek &
E. Cano-Pleite

Modified 2-step forming process

Original: single-step forming



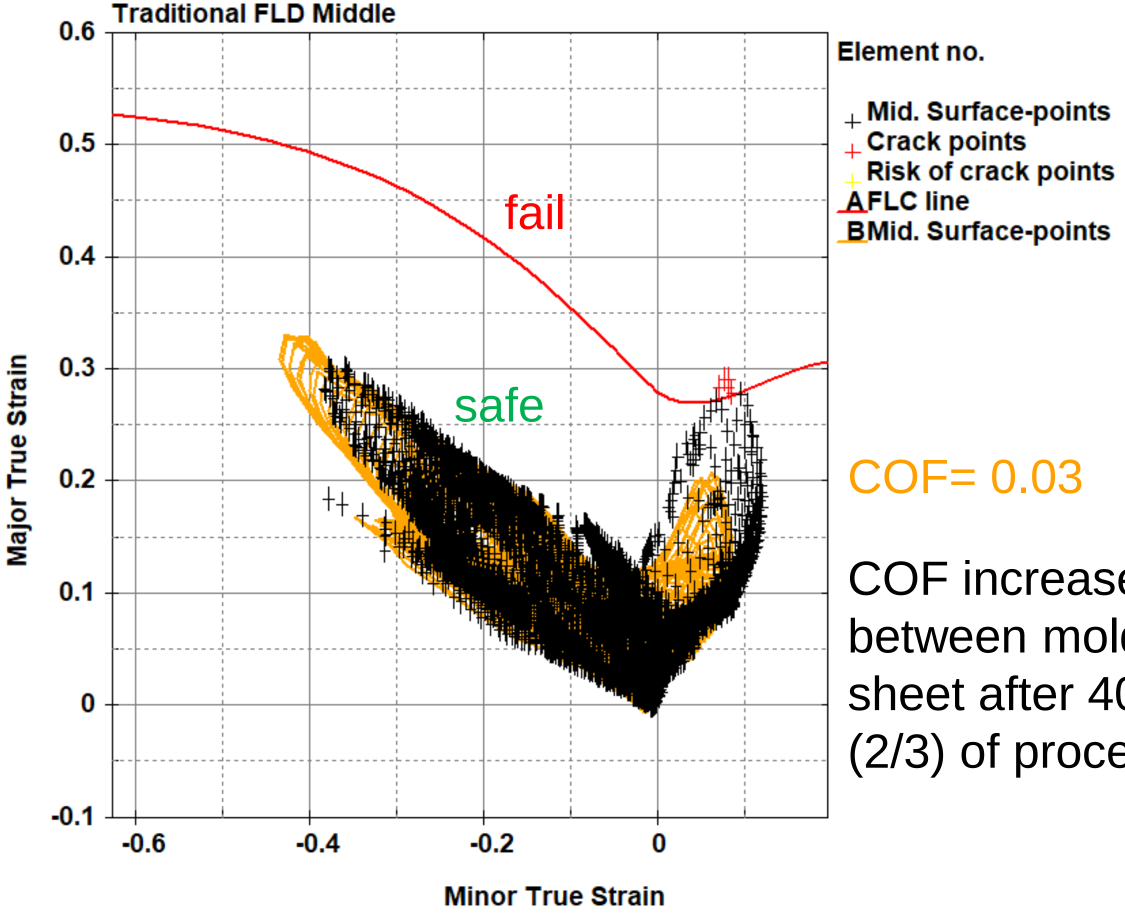
1^{st} step stop at 15mm + 2^{nd} step



The 2-step forming slightly reduces the value of strain in the conflictive region.

Thanks to J. Swieszek &
E. Cano-Pleite

Summary – Lot 2 NOK with increased CoF



COF= 0.03

COF increased to 0.2 between mold and sheet after 40 ms (2/3) of process

Thanks to J. Swieszek & E. Cano-Pleite

The **2-step forming** process is **beneficial** mainly due to the **reduction in friction of coefficient** !

The modified **forming procedure by the US-AUP contractor has been validated** by FE simulations.

Some mechanical properties would play a significant role (**Rp0.2/Rm** & **strain hardening coefficient n**).

Cryomodule : stainless steel specification challenges

The CERN austenitic SS specifications (i.e. 1.4435, 1.4429) focus on several critical points:

- **Chemical composition (grade) →**
  - **Avoid martensitic transformation** γ (austenite) $\Rightarrow$ α' (martensite) (spontaneous when cooling or strain induced). General rule: the more alloying elements the better.
  - **Keep low magnetic permeability** (given by initial ferrite + 'transformed' austenite → martensite).
  - Keep low P + S content → improve **weldability** (avoid hot cracking)
  - Co content → reduce **activation of cryomodule parts** (Derogation by HSE: up to 0.3 wt% allowed!)

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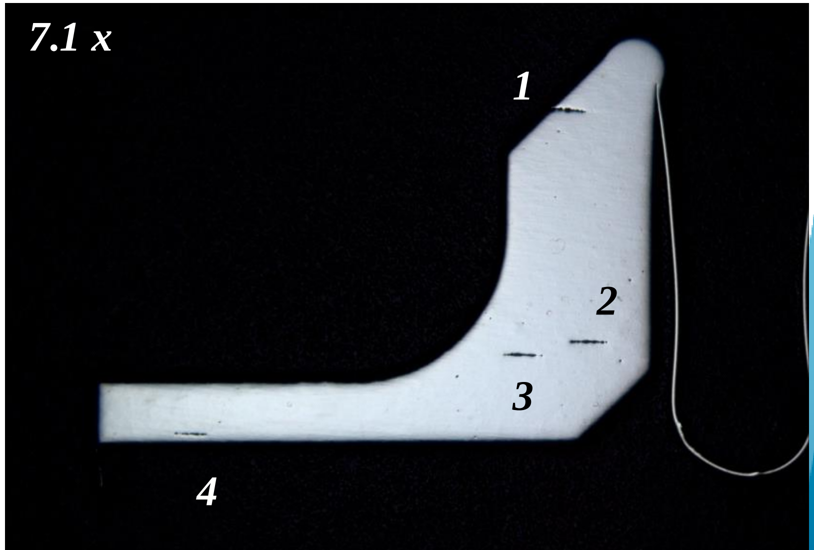
- **Grain size, inclusion content (& 3D forging)** → UHV applications
- **Mechanical properties and UT** → structural soundness
- **Certificate 3.1** (EN 10204) → ensure quality & traceability



S. Sgobba, Mini-CAS: Steels & Stainless Steels, 2020

Cryomodule : stainless steel specification challenges

via Delong equation - ferrite content estimation:

	Ferrite*	Rel. Magnetic permeability
1.4435 (CERN spec.)	0%	< 1.005
1.4441 (ISO 5832-1, EN 10088-3)	0%	~ 1.003 (mat. cert.)
1.4429 (CERN spec.)	0%	~ 1.003 (mat. cert.)
1.4404 (EN 10028-7, EN 10088-1)	4% , 6% , 8%	~ 1.3 , 1.5 1.6

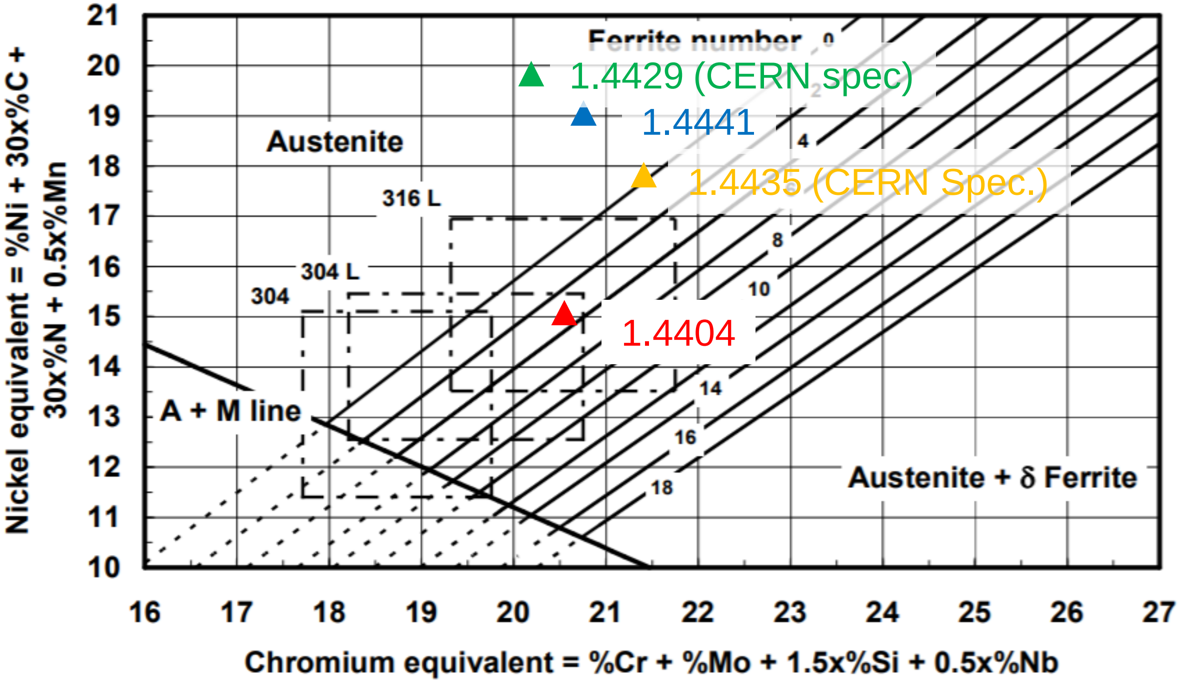
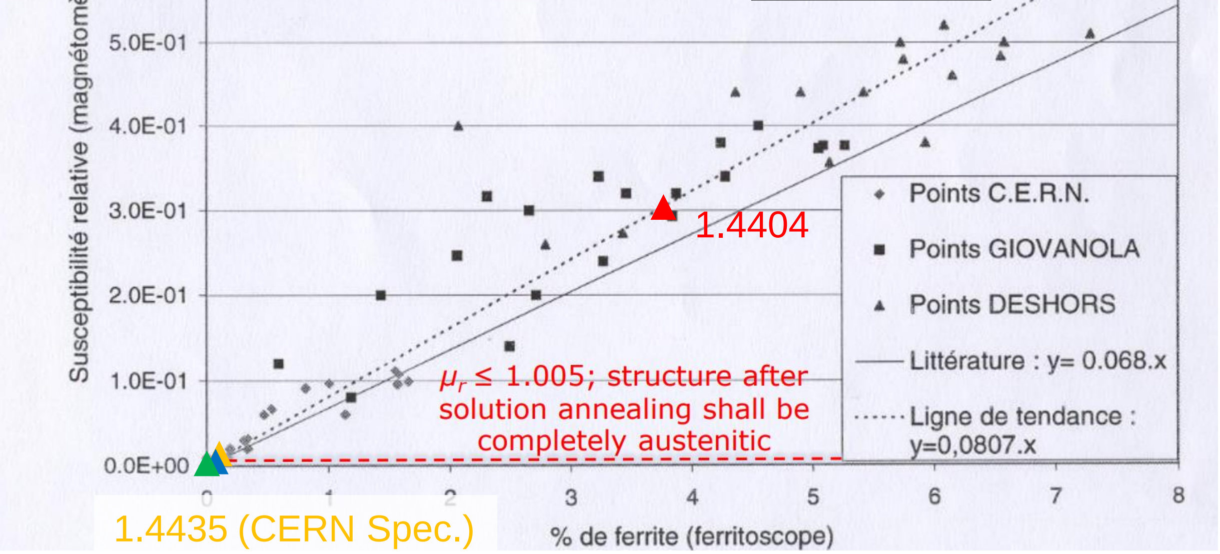


Fig. 5: Diagram for the determination of the ferrite content in austenitic stainless steel weld metal according to DeLong [41,42]. Diagrams more adapted to high N stainless steels are the ones of Hull [43] and Espy [44].



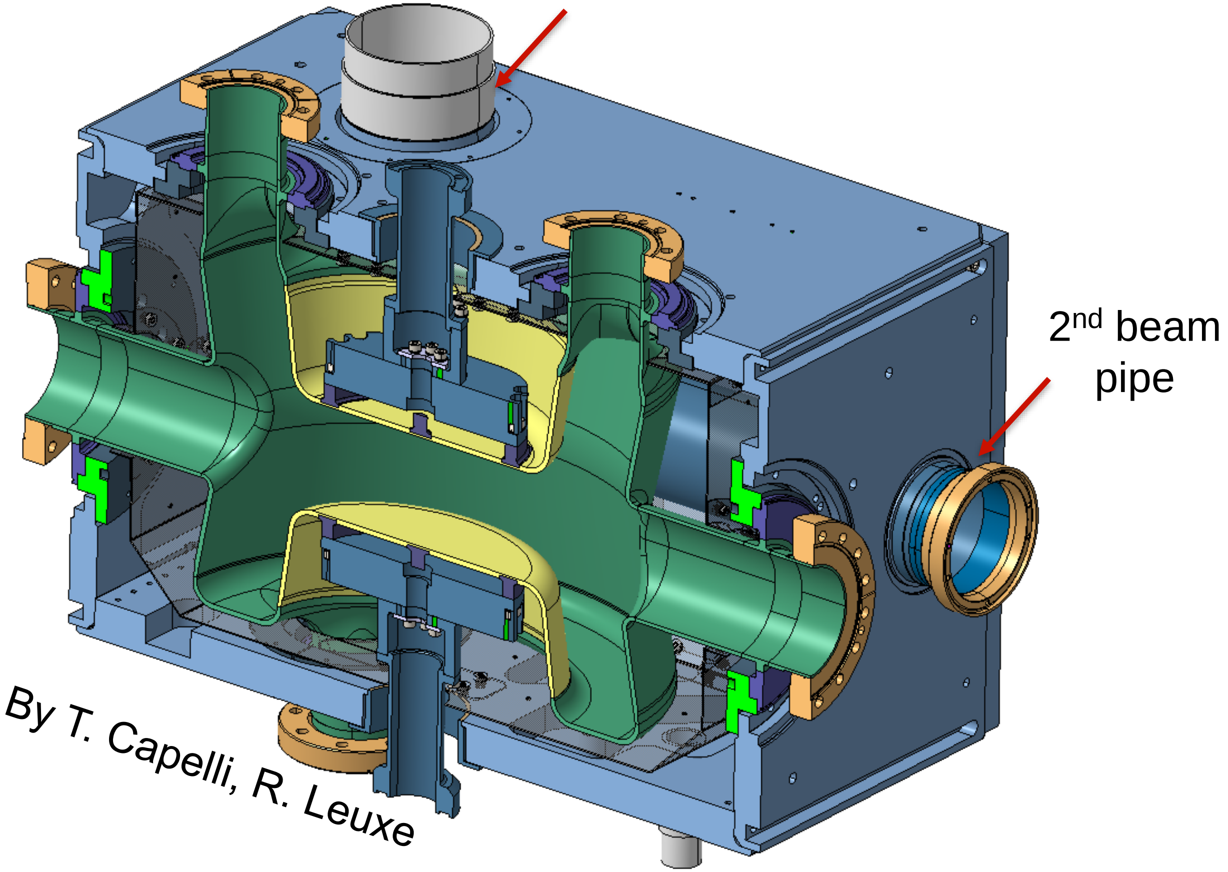
$\mu_r \leq 1.005$; structure after solution annealing shall be completely austenitic

Each ferrite % contributes ~0.08 to the relative magnetic permeability

- Anticipate the purchase of specific grades (1.4429, 1.4435, 1.4441..).
- Check carefully Material Certificate vs. Eng.Spec & Application (UHV, cryogenics, position w.r.t. cavities..).
- In case of any doubts contact WP4 cryomodule responsibles (M. Garlasche, T. Capelli)

Advanced techniques for characterizing parts and joints: update on several case studies

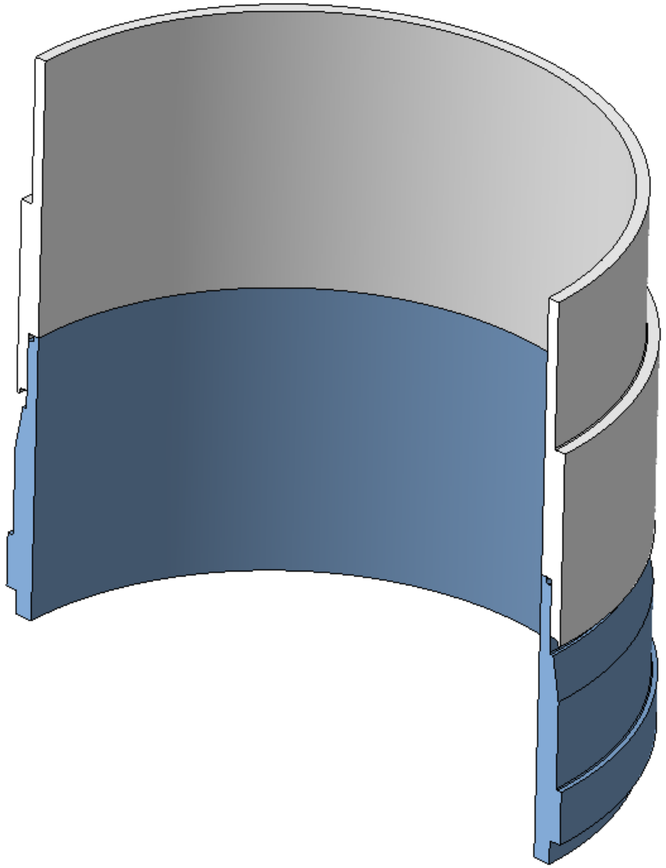
SS-Ti bimetallic transitions – new results


He tank - Cryolines

2nd beam pipe

By T. Capelli, R. Leuxe

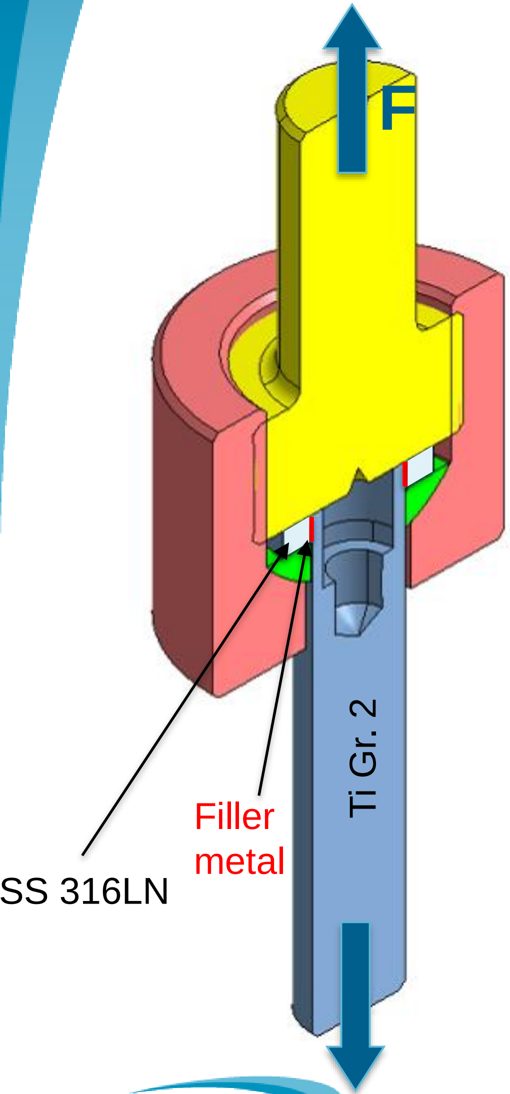
Brazing developed by F. Motschmann & MME-FW team

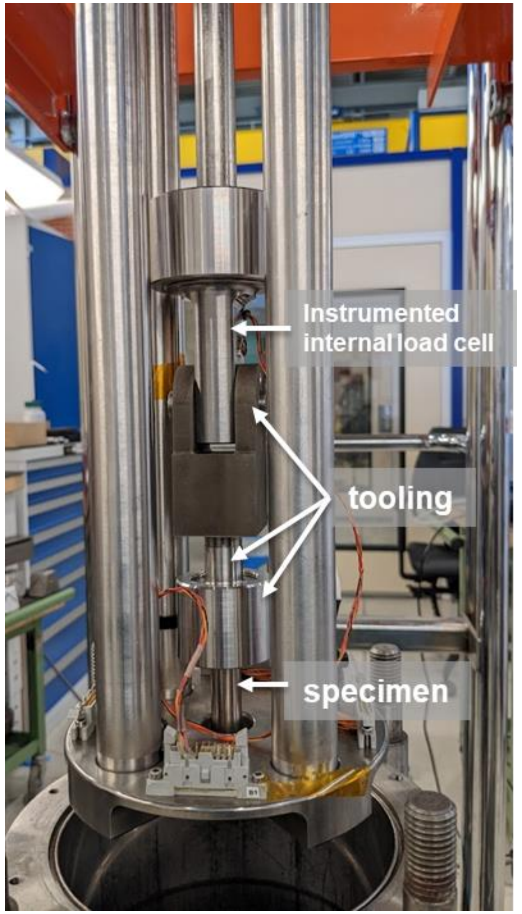


A dedicated qualification campaign was performed, see EDMS **2271509.**
But mechanical tests set-up at 4K was not optimized (shear + non-desired bending)

SS-Ti bimetallic transitions – tests at 4K

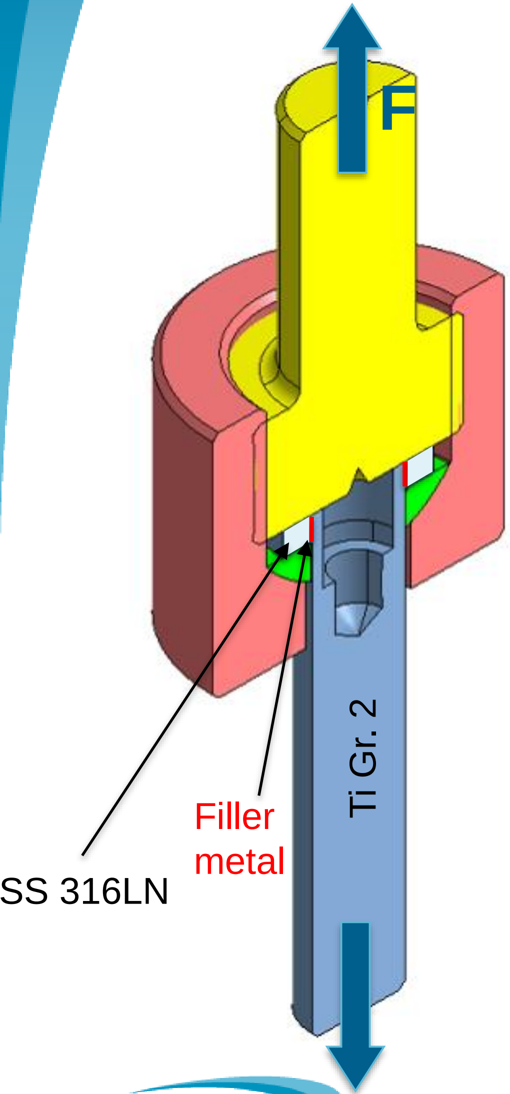
New dedicated specimens and tooling adapted from ISO 5187

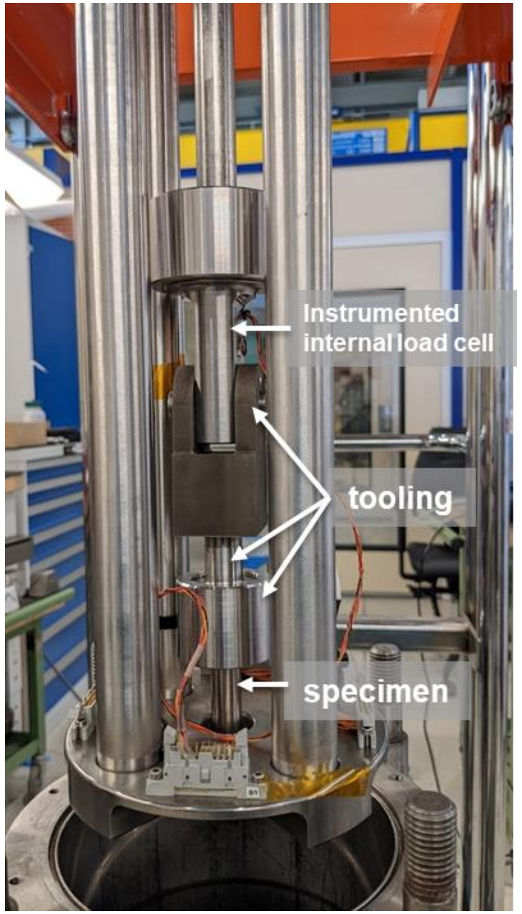


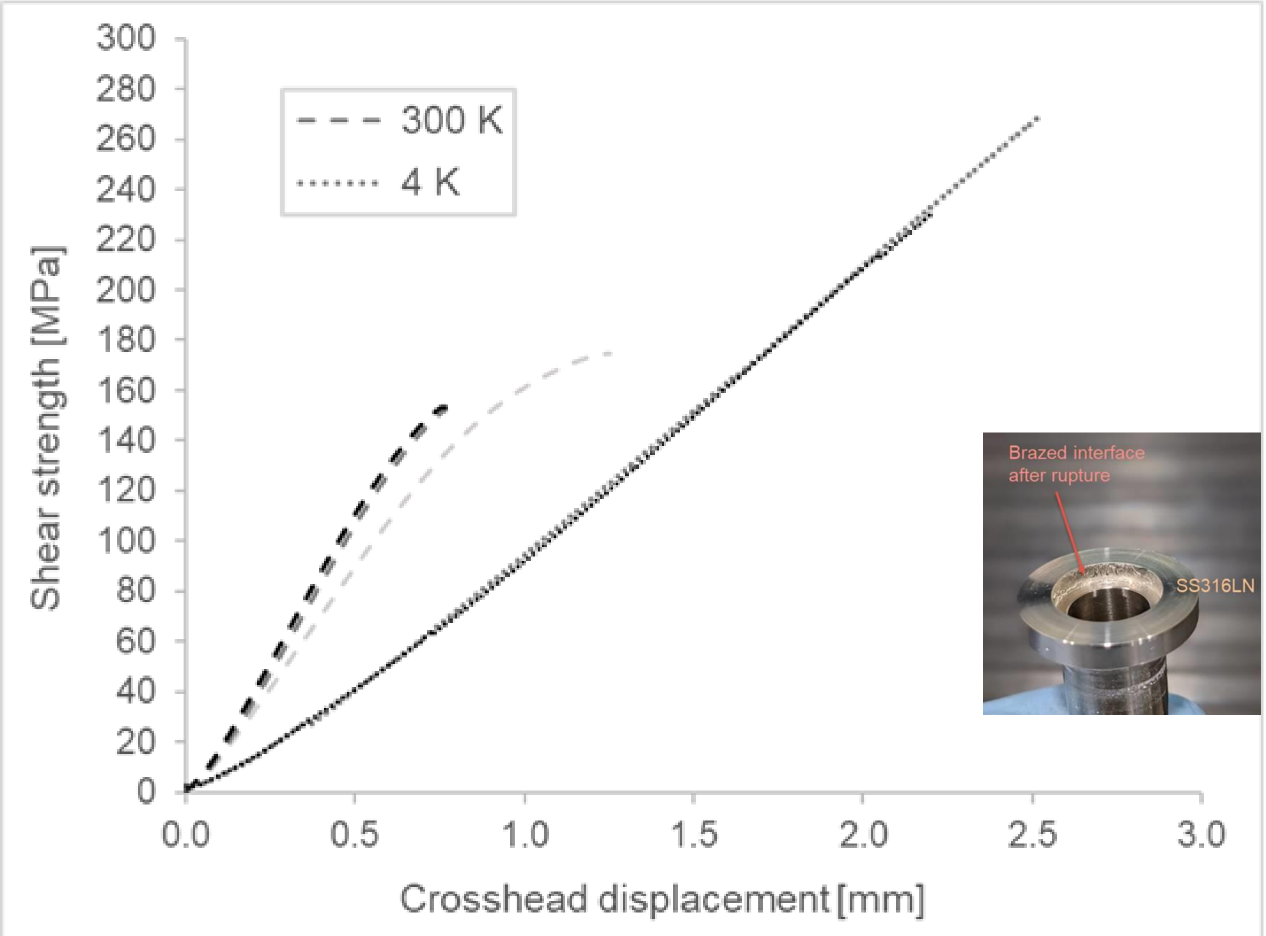


SS-Ti bimetallic transitions – tests at 4K

New dedicated specimens and tooling adapted from ISO 5187







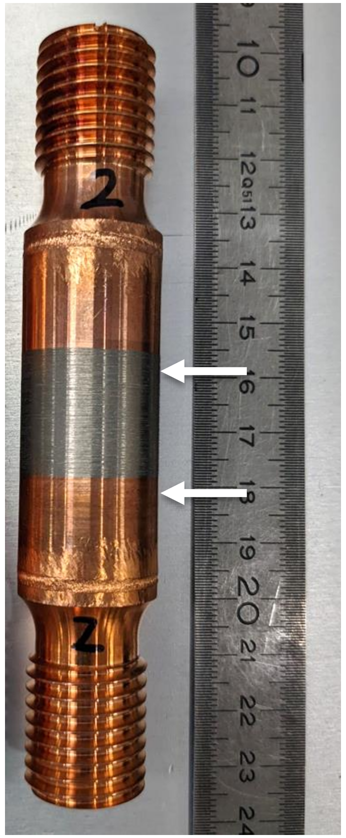
Mechanical tests at 4K show significant shear strength improvement (min. 231 MPa) with respect to tests at RT (min. 153 MPa)

“Vacuum Brazed Titanium-Stainless Steel Transitions for Cryogenic Applications”, Presented by F. Motschmann at the 13th International Conference on Brazing (LOT 2022), Aachen, Germany, 2022.
Full results to be published.

Cu-Nb Electron Beam Weld for the pick-up antenna

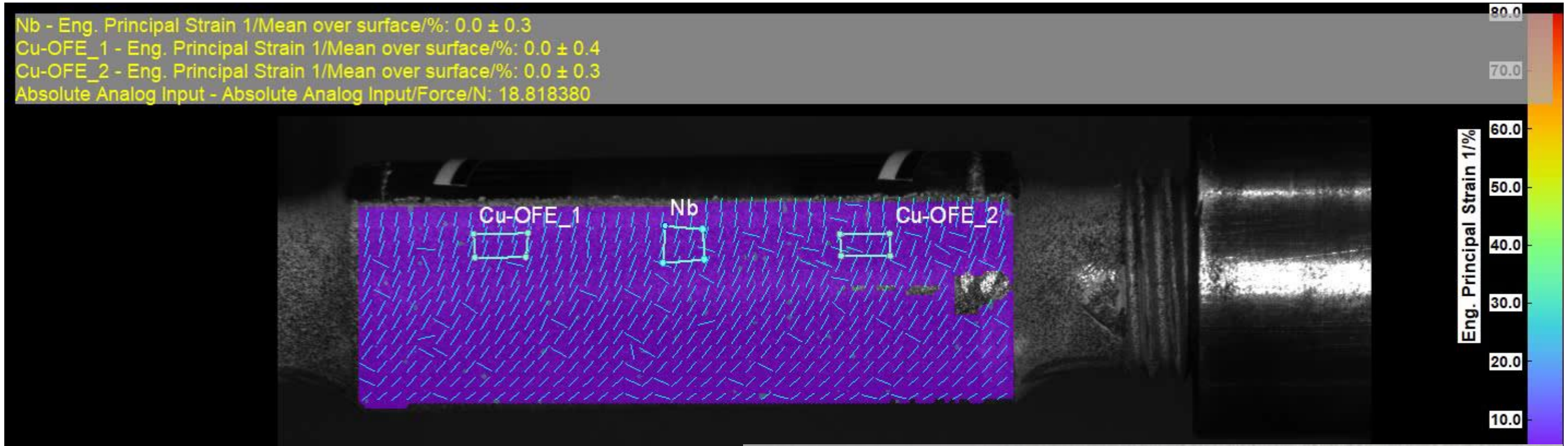
Courtesy of S. Barriere, T. Demaziere.

- Parts are leak tight but **mechanical robustness of interface was unknown**.
- New **dedicated specimens were conceived**.

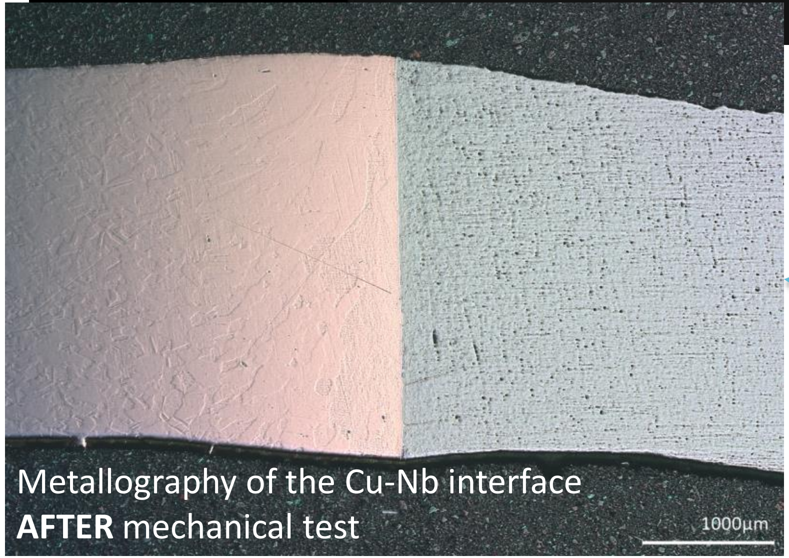


Cu-Nb EB weld by T. Demaziere.

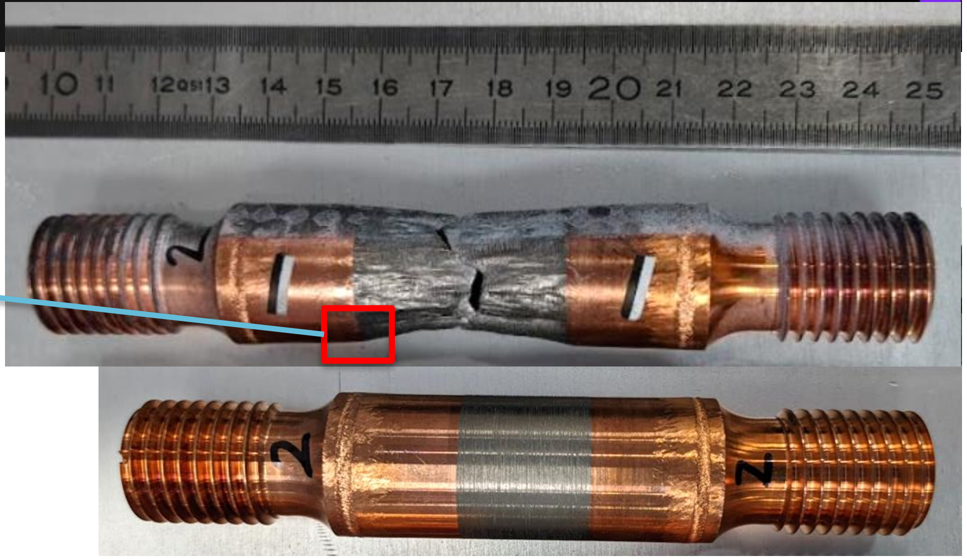
Cu-Nb Electron Beam Weld for the pick-up antenna - DIC



Nb - Eng. Principal Strain 1/Mean over surface/%: 0.0 ± 0.3
Cu-OFE_1 - Eng. Principal Strain 1/Mean over surface/%: 0.0 ± 0.4
Cu-OFE_2 - Eng. Principal Strain 1/Mean over surface/%: 0.0 ± 0.3
Absolute Analog Input - Absolute Analog Input/Force/N: 18.818380

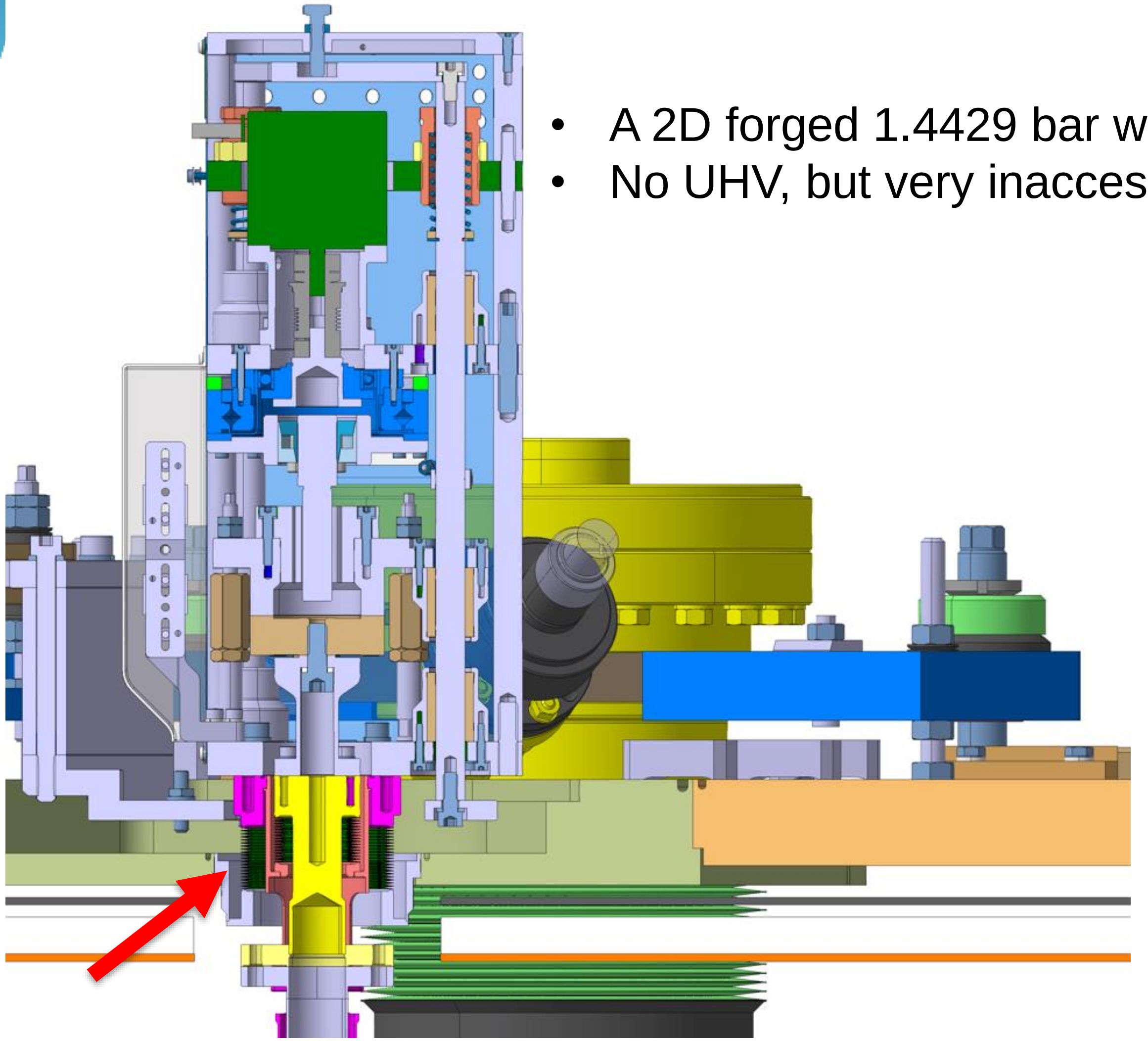


Metallography of the Cu-Nb interface
AFTER mechanical test

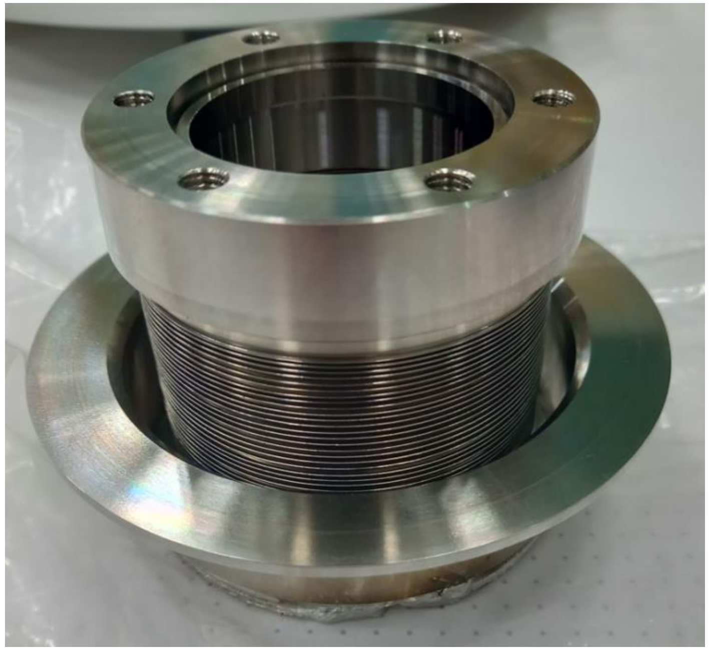


The Nb-Cu EB weld is mechanically sound and even compliant with the Nb-Nb EBW qualification requirements! (Rm > 118 MPa)

Tuner actuation bellows



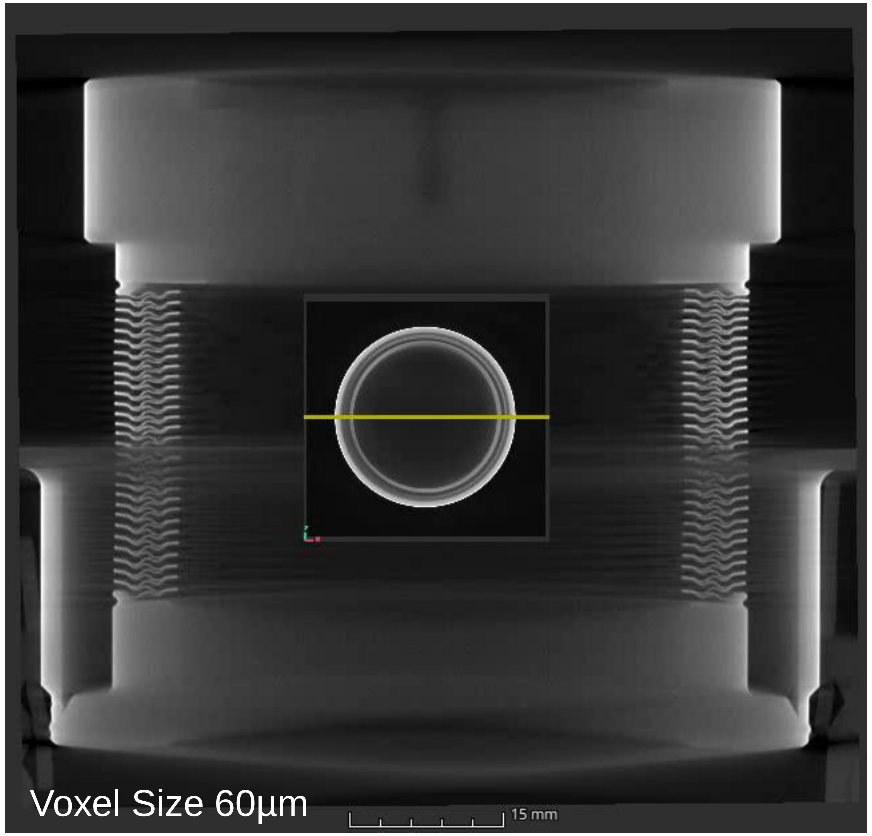
- A 2D forged 1.4429 bar was employed.
- No UHV, but very inaccessible part once is assembled.



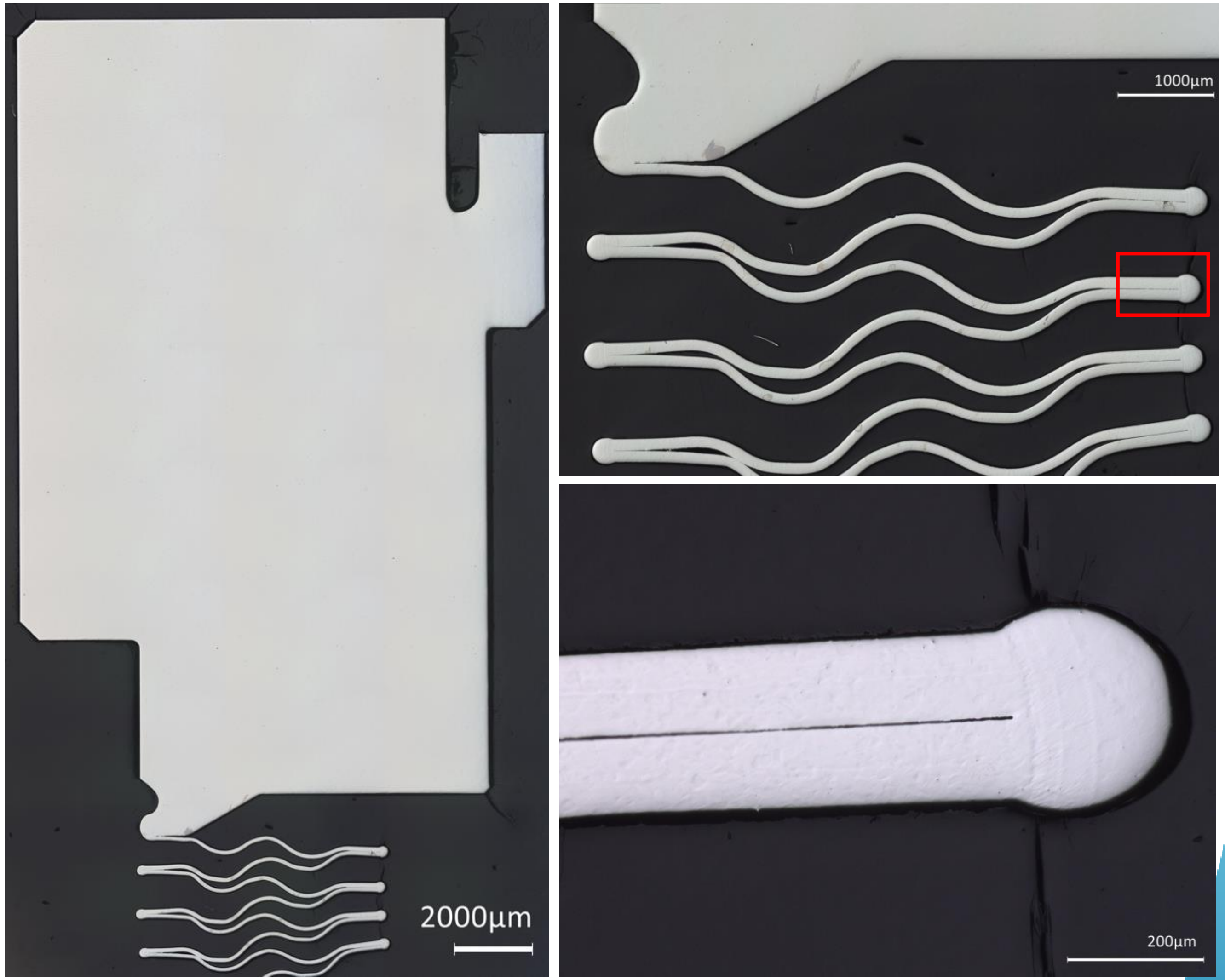
By K. Artoos, T. Capelli.

Tuner actuation bellows - µC Tomography and metallography

A 2D forged 1.4429 bar was employed.



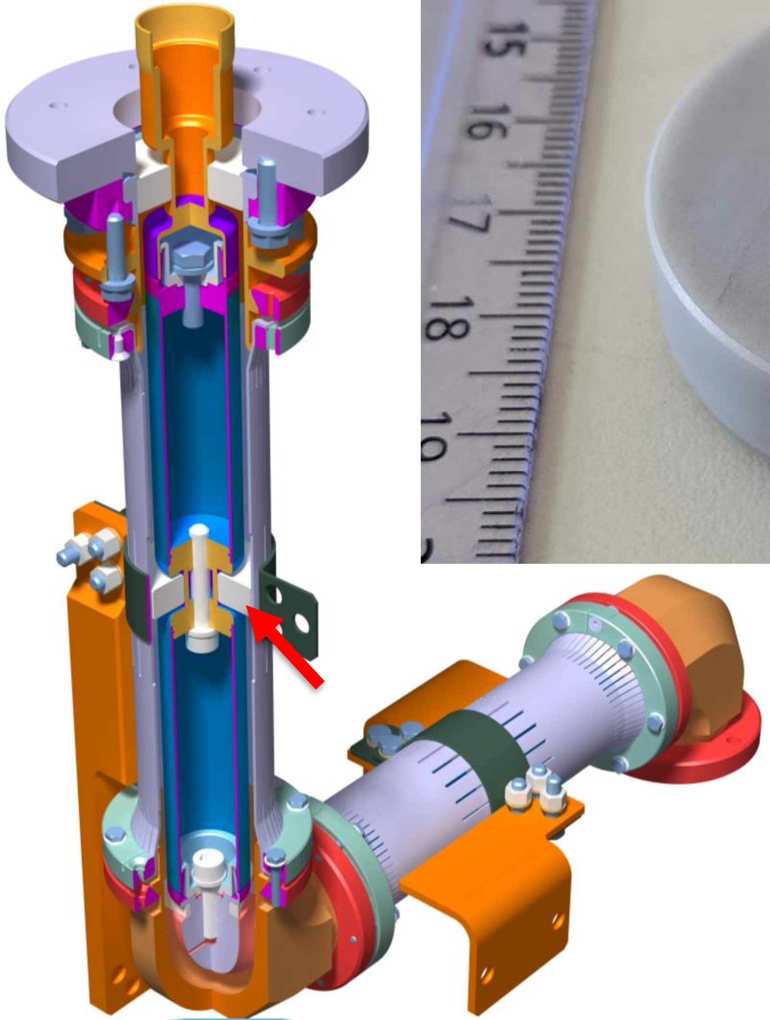
Thanks to M. Celuch



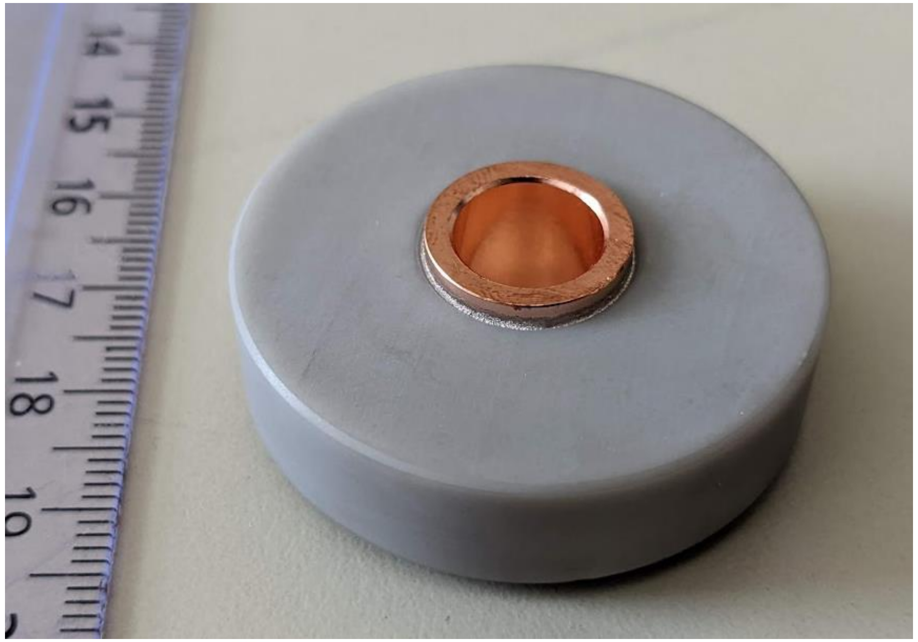
Very clean steel (316LN - 1.4429). Absence of aligned non-metallic inclusions despite being a 2D forged bar!

AlN-Cu brazed joints for coaxial lines - µC Tomography

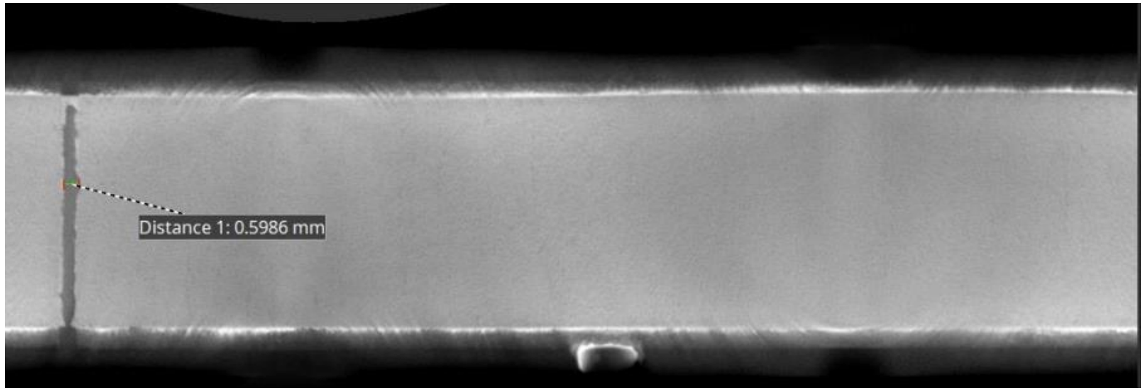
Brazing by F. Motschmann



By T. Capelli

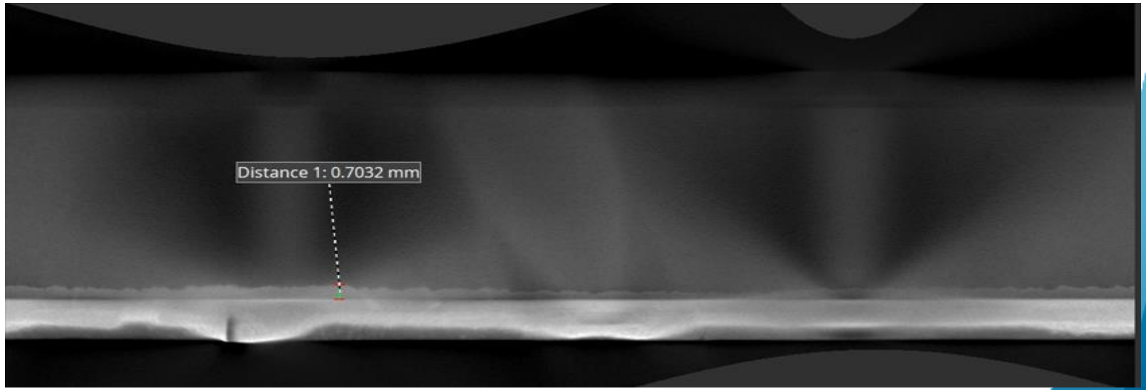


Foil 50 um



Vs.

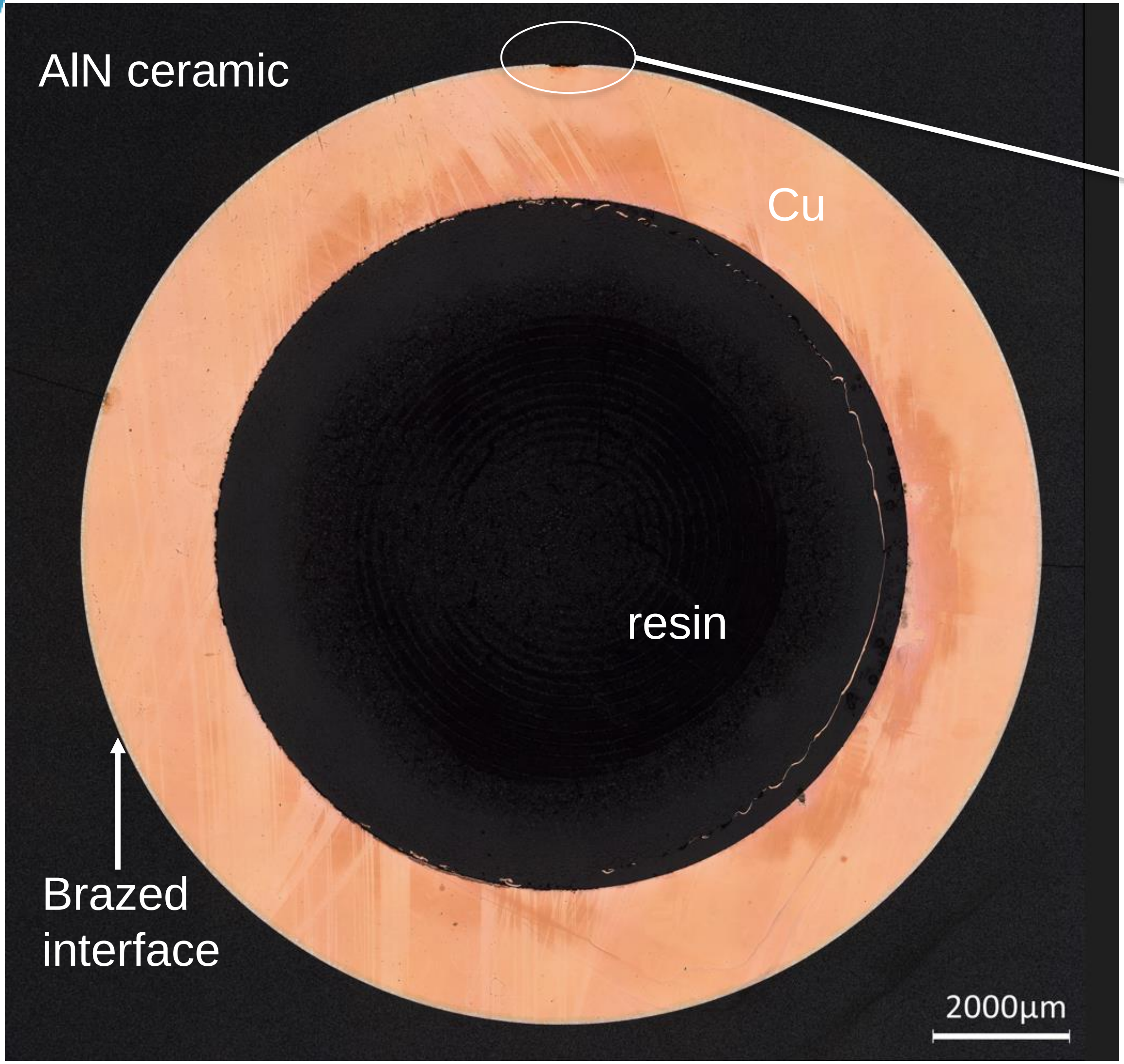
Wire D0.75 mm

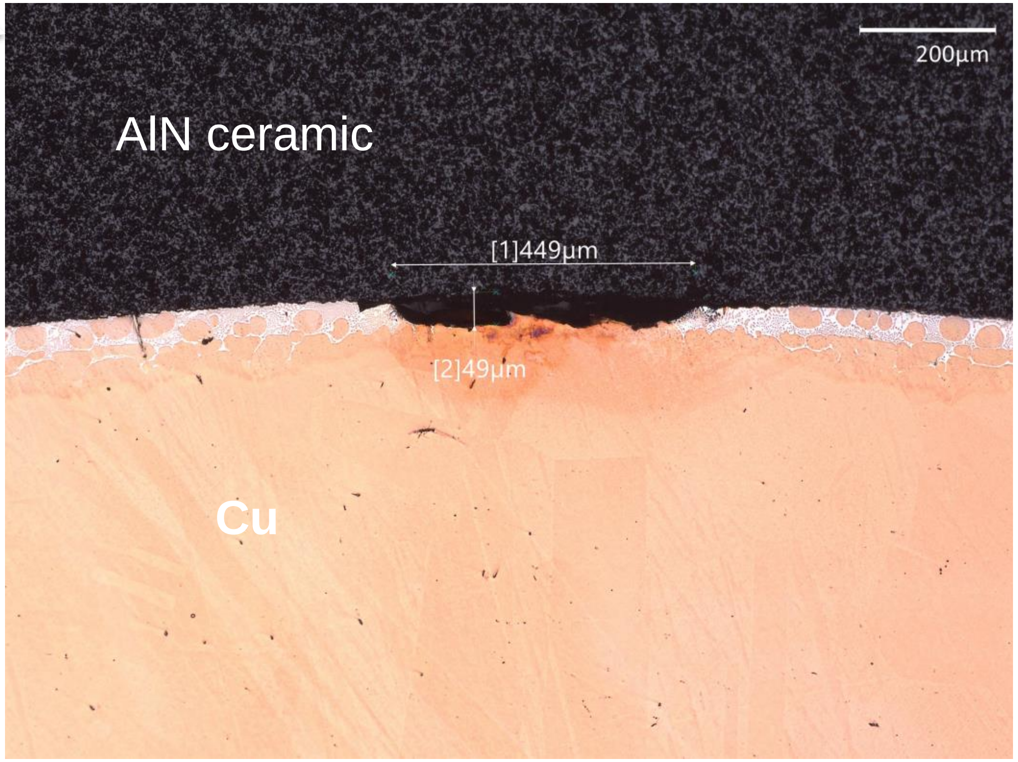


CT by M. Celuch.
EDMS 2736630

AlN-Cu brazed joints for coaxial lines

Brazing by F. Motschmann





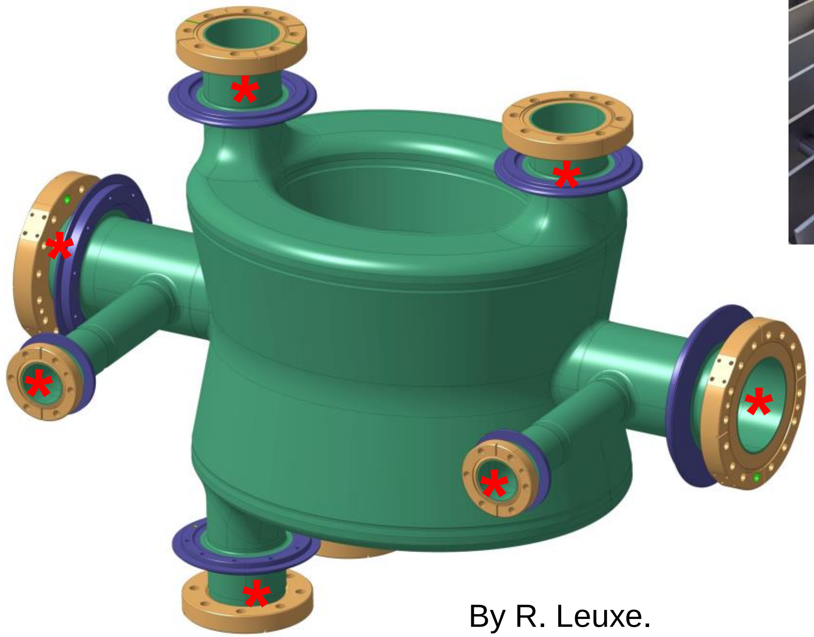
uCTomography allowed to easily identify defects and optimize the brazing strategy.

Thanks to K. Buchanan

Nb RRR drop during brazing heat treatment

CERN reference trials show a potential RRR drop up to 20%. **(e.g. RRR 300 → RRR 240)**
It is however possible to drop by a 70%-80% if the process and furnace cleanliness is not well mastered.
(e.g. RRR 300 → RRR 75)

Discontinuity in RRR → effect on RF performance?

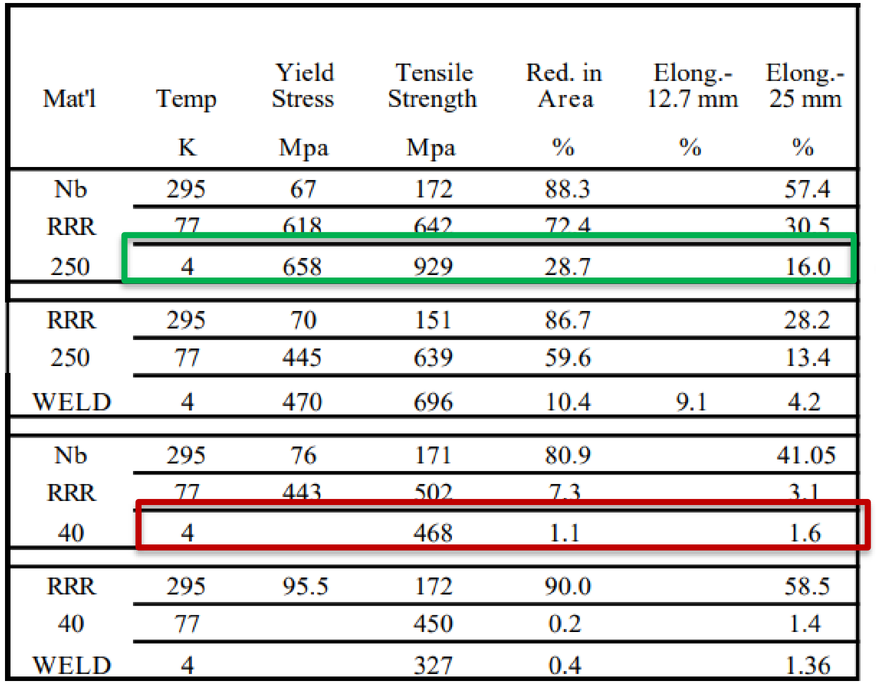


By R. Leuxe.

Brazed assemblies preparation, with Nb RRR witness samples. By F. Motschmann.

Lost of ductility at cryogenic temperatures?

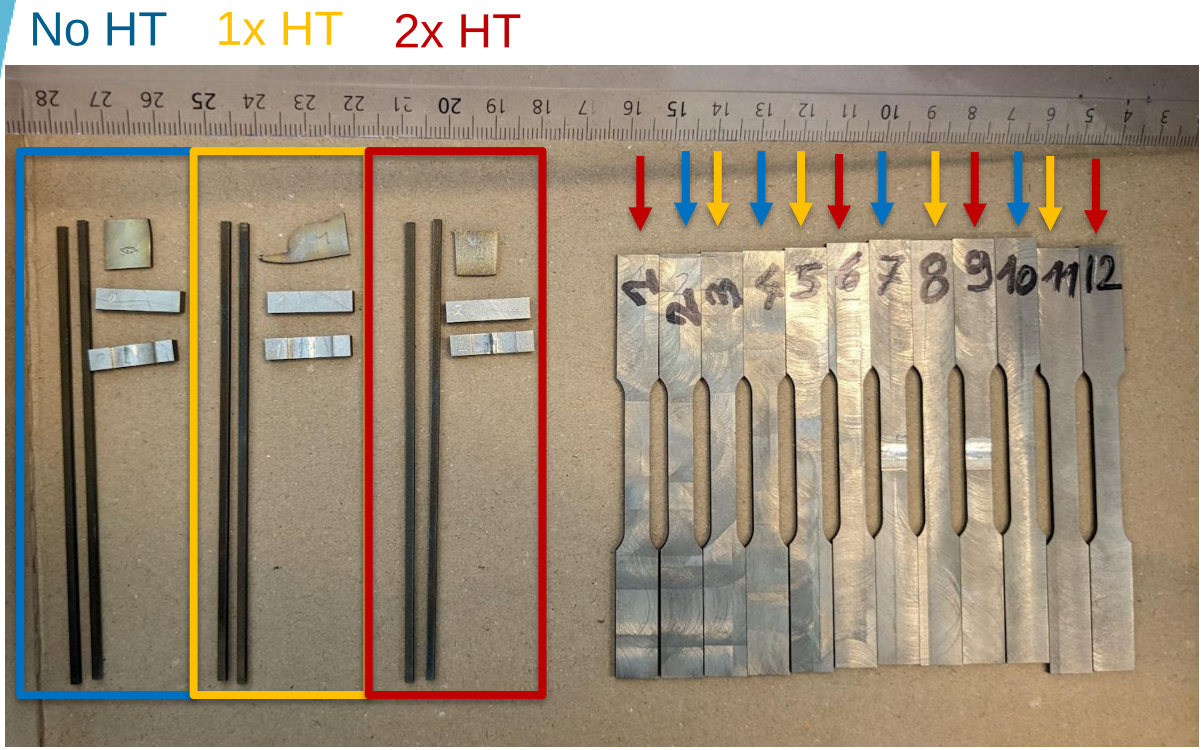
Table 2: Tensile test results.



Mat'l	Temp K	Yield Stress Mpa	Tensile Strength Mpa	Red. in Area %	Elong.- 12.7 mm %	Elong.- 25 mm %
Nb	295	67	172	88.3		57.4
RRR	77	618	642	72.4		30.5
250	4	658	929	28.7		16.0
RRR	295	70	151	86.7		28.2
250	77	445	639	59.6		13.4
WELD	4	470	696	10.4	9.1	4.2
Nb	295	76	171	80.9		41.05
RRR	77	443	502	7.3		3.1
40	4		468	1.1		1.6
RRR	295	95.5	172	90.0		58.5
40	77		450	0.2		1.4
WELD	4		327	0.4		1.36

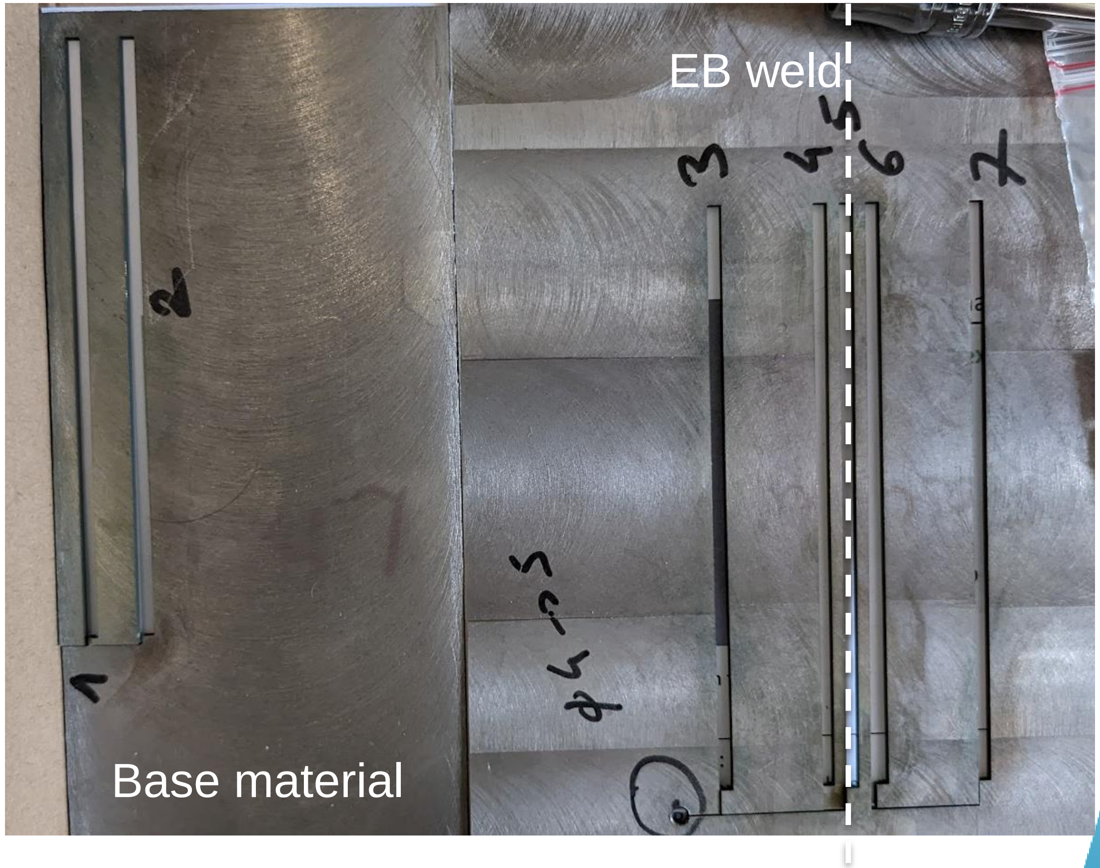
Walsh, R. P., et al. "Low temperature tensile and fracture toughness properties of SCRF cavity structural materials." *IX Workshop on RF Superconductivity” Santa Fe*. 1999.

Effect of 2x H degassing heat treatments



Compare Nb mech. properties in as-received, welded and cold rolled condition.

RRR after EBW US-AUP contractor



Assess RRR drop around the weld (0, 5, 20mm)

Conclusions

- A **material** is not a name/number only, but it has to be **purchased according to a specification** (international standard, CERN specification, other). Product quality can dramatically change.
- **CERN material specifications are in the safe side** regarding product quality. **Derogations** are possible to meet industry standard practices but have to be **assessed case by case**. Contact WP4 and MME colleagues in case of doubts.
- **All NbRRR300 and Nb55Ti** for the DQW Crab Cavities (including HOMs) has been purchased. Internal quality checks pending for Nb to be used for DQW HOMs.
- **FE simulations + Forming Limit Diagram** were employed to deeply **understand** the RFD pole **forming** and the **2-step forming** strategy employed by US-AUP contractor was **validated**.
- **Critical components** (e.g. bimetallic SS-Ti transitions, RF feedthroughs) **validation tests** are **completed** (or well advanced) for the series.
- We are still climbing the learning curve, but thanks to the **lessons learned and the know-how** curated and maintained by WP4 and EN/MME, performance of the crab cavities is beyond expectations.

HiLumi
HL-LHC PROJECT

Thanks for your attention.

And thanks to all WP4 colleagues and MME-MM colleagues.

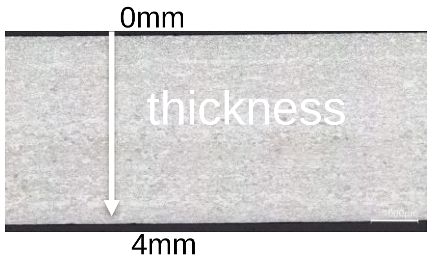
Initial materials and tensile test conditions

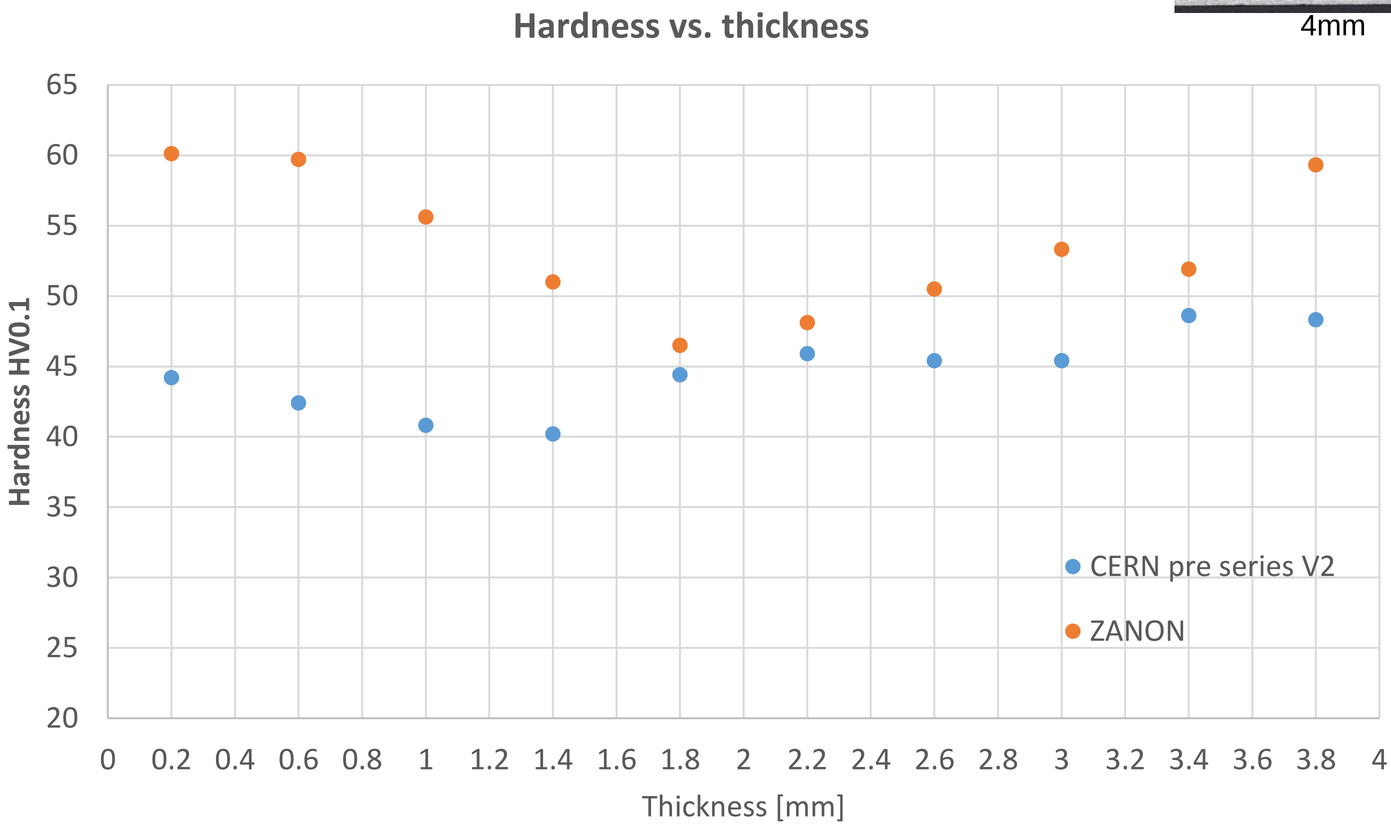
- ‘CERN’ material:
  - CA7420650 (pre-series v2) – sheet ID 2282401

- ‘Zanon’ material:
  - PO657756 (pre-series) – sheet ID 2411101

- Zanon material → Cutting by Micro water jet cut
- CERN material → Cutting by spark erosion
- ASTM E8 sub-size specimens
- 2x long (0 deg) and 2 x short (90 deg) specimens
- Test conditions ASTM B393

Hardness profiles



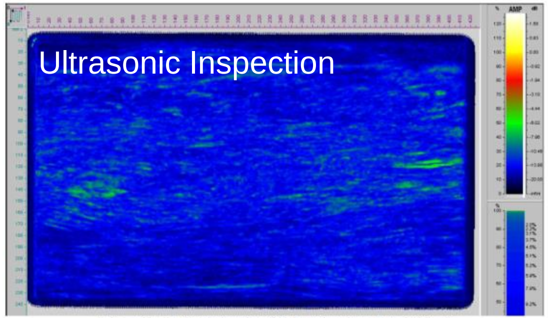


Measurements done by
J. Lequin-Souchon

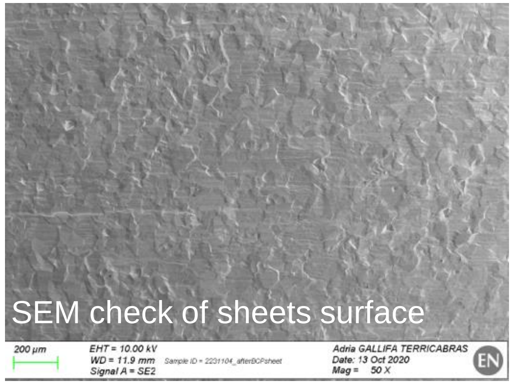
- ‘Zanon material’ presents a higher HV0.1 hardness average (53.6 ± 4.9) compared to ‘CERN material’ (44.6 ± 2.8).

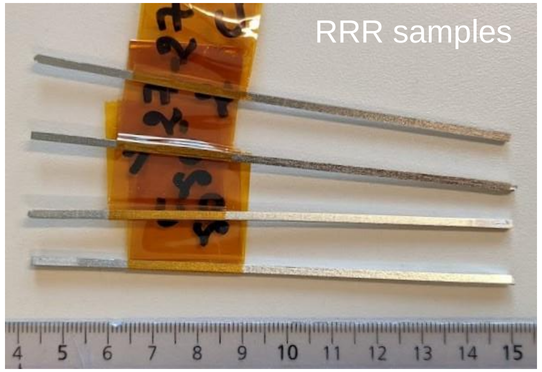
- ‘Zanon material’ hardness profile presents a more pronounced ‘V-shape’ presumably due to a levelling process, which would harden the surface.

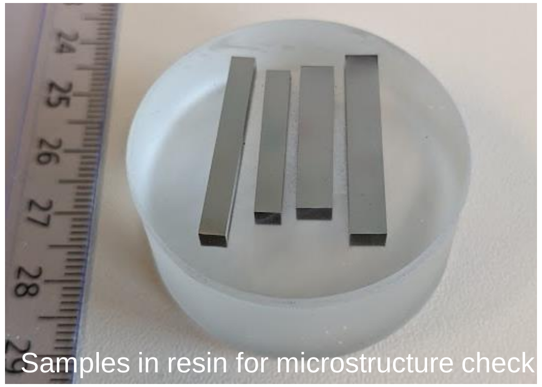
Figure 1. Detail of the exogenous substance on sheet ID 2221701.



Gain = 65 dB, for detection of indication class 5 at 100% SH







Assessment influence of 2x Hydrogen Degassing Heat Treatments on the mechanical properties of Nb RRR300.

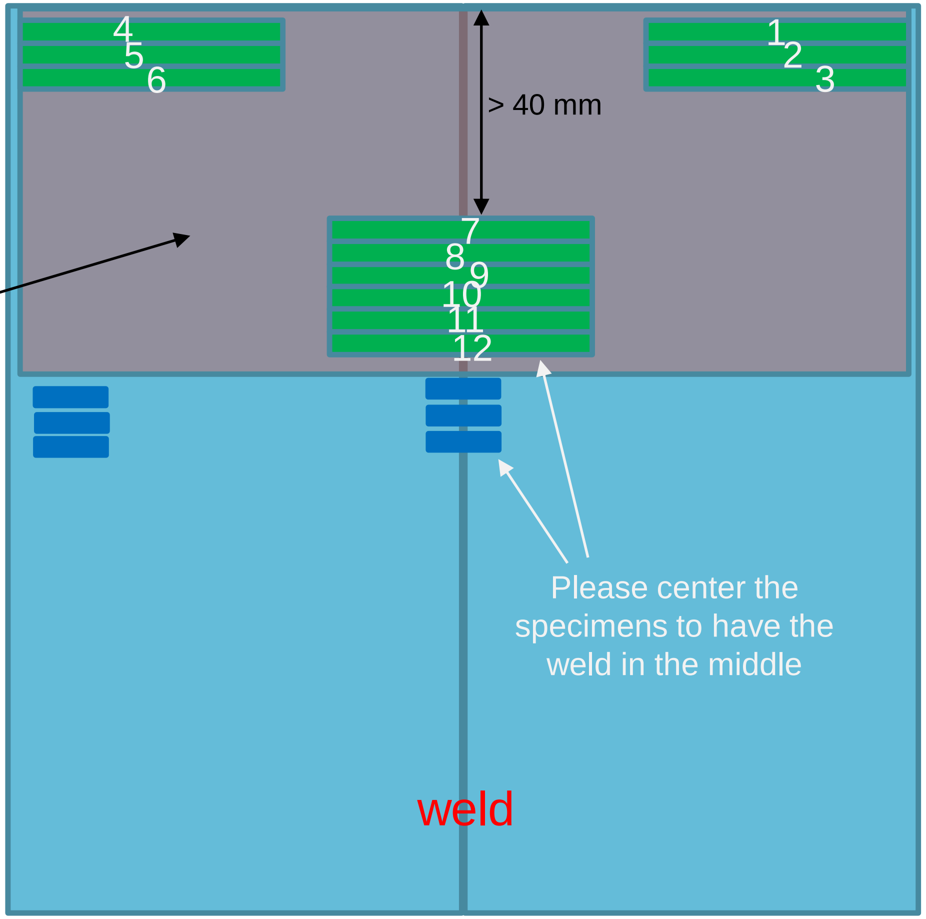
Specimens from sheet welded by Thomas	'state'	Additional samples: Cold rolled samples (50% thick. reduction)	No. of heat treatments (24h, 650C, vacuum) as per Eng. Spec.	Identification
2 x tensile specimens + 1 x coupon for hardness	Base material	1 rolled coupon for HV (Adria to cut)	0	B0-XX
2 x tensile specimens + 1 x coupon for hardness	Base material	1 rolled coupon for HV (Adria to cut)	1	B1-XX
2 x tensile specimens + 1 x coupon for hardness	Base material	1 rolled coupon for HV (Adria to cut)	2	B2-XX
2 x tensile specimens + 1 x coupon for hardness	Welded material		0	W0-XX
2 x tensile specimens + 1 x coupon for hardness	Welded material		1	W1-XX
2 x tensile specimens + 1 x coupon for hardness	Welded material		2	W2-XX

Summary:
12 x tensile specimens (ASTM sub- 🟩
6 x coupons hardness (5 x 20 x thickne 🟦)

Face milling (leave constant thickness of about 2mm) for tensile specimens.

If possible cut by: spark erosion or precision water jet cut. For hardness samples conventional cutting/machining also allowed.

Make BCP 30 per face, for all specimens, before doing the HT. (Adria will bring it to Serge).



Please center the specimens to have the weld in the middle

A. Gallifa, 16-05-202
BC: 69068

Specimens

- 0 HT: → please do not include them in the furnace
  - Tensile: x2 samples: **#4, #2, #7, #10**
  - RRR: x2 samples: **#XX, #XX**
  - Metallo: x 3 samples: **base #0, weld #0, cold rolled #0**

- 1 HT: → one hydrogen degassing heat treatment
  - Tensile: x2 samples: **#5, #3, #8, #11**
  - RRR: x2 samples: **#XX, #XX**
  - Metallo: x 3 samples: **base #1, weld #1, cold rolled #1**

- 2 HT: → two hydrogen degassing heat treatments
  - Tensile: x2 samples: **#1, #6, #9, #12**
  - RRR: x2 samples: **#XX, #XX**
  - Metallo: x 3 samples: **base #2, weld #2, cold rolled #2**