Material qualifications for Crab Cavities

Adrià Gallifa Terricabras – EN/MME/MM (CERN)
on behalf of Materials, Metrology and NDT team and HL-LHC WP4.

11th HL-LHC Collaboration Meeting, CERN, 19-22 October 2021

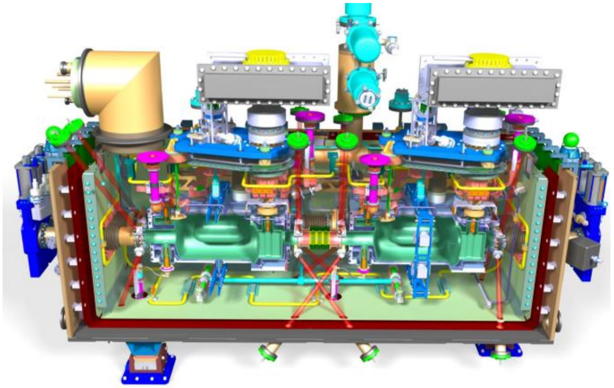
It's a tight relationship…

Materials

- Nb RRR300
- Ti alloys
- Cu alloys
- Stainless steel
- Cryophy, mumetal
- Ceramics (Al_2O_3)
- Filler metals: Ga-Pa-Ag
- …

Components

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



Teddy Capelli CERN/EN-MME HL-LHC Collaboration meeting

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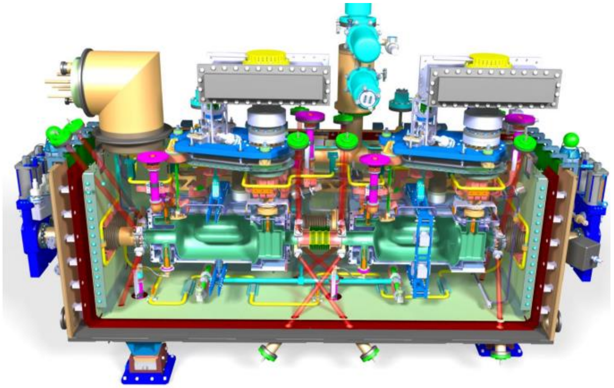

Teddy Capelli CERN/EN-MME HL-LHC Collaboration meeting

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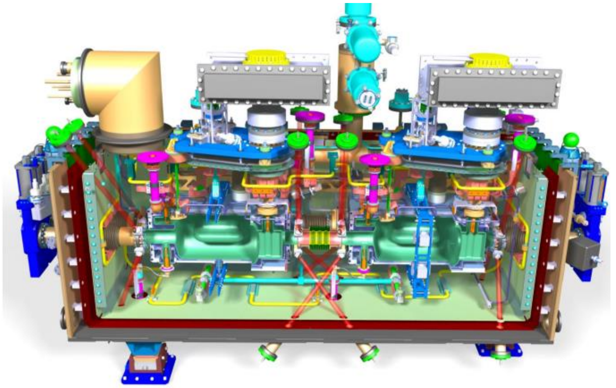

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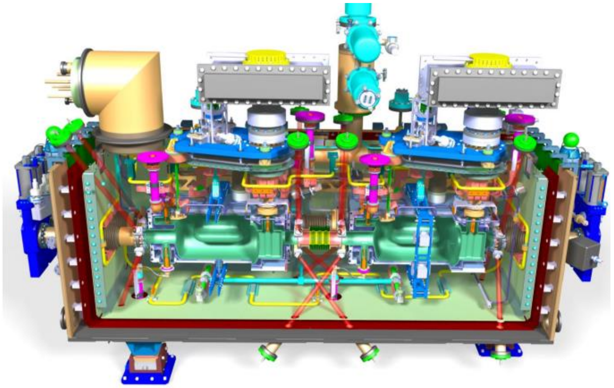

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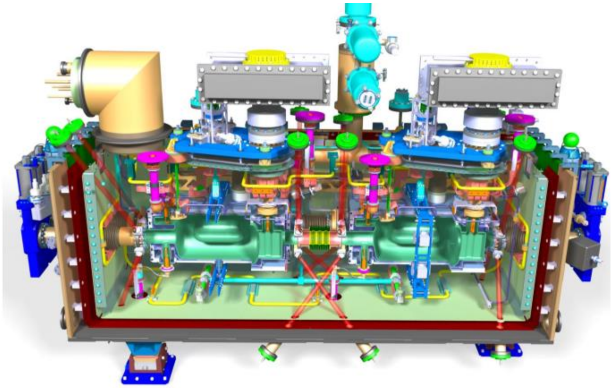

Teddy Capelli CERN/EN-MME HL-LHC Collaboration meeting

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\+

Manufacturing process

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

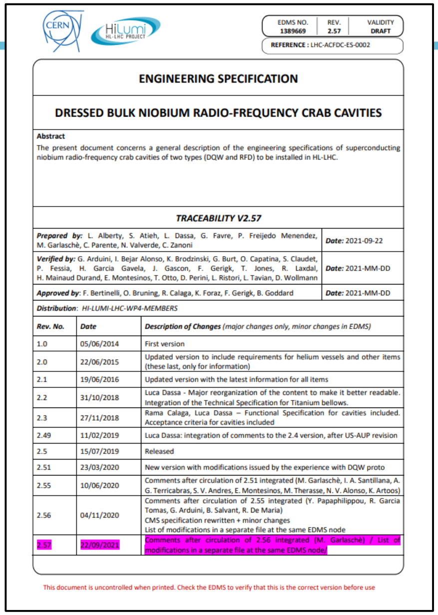
Our ‘holy’ documents

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

See talk by L. Dassa

Our ‘holy’ documents

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

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- Technical quality ensured

Lessons learned

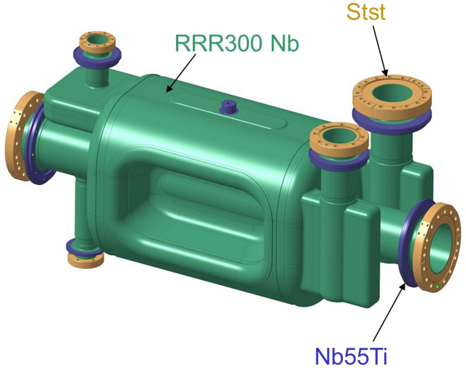
Material Procurement

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


Nb

Nb RRR 300

- Back in 2018 - 2020: after DQW SPS proto, **market survey and additional suppliers qualification:** Ningxia (CN), Tokyo Denkai (JP), Ulvac (JP).



Procurement challenges

- Cost: > 700 CHF/kg
- Lead time: > 4 months
- Limited amount of suppliers: 3 are qualified (not all produce all products!)

Technical challenges (CERN spec. is stringent, but guarantees high quality material)

- Achieve a specific yield strength (65MPa < Rp0.2 < 100 MPa) → Low yield strength was measured in the past → **important for strength assessment of the cavities according to PED.**
- Achieve a 'clean' surface → Abrasive particles embedded on the surface were detected → **prevent field emission 'hot spots' during operation.**

- For DQW series, systematic internal qualifications were performed consisting in:
  - **UT** (100%)
  - **Surface check by SEM (+thickness measurements)** (1-2/lot)
  - **Tensile tests** (~ 2 sheets/lot)
  - **RRR measurements** (1/each product type/shipment)
  - **Microstructure check** (1/each product type/shipment)

All NbRRR300 needed for DQW bare cavity series is already at CERN (sheets, plates).

See reception and internal qualification report in EDMS 2395238.

Nb reception and internal qualifications

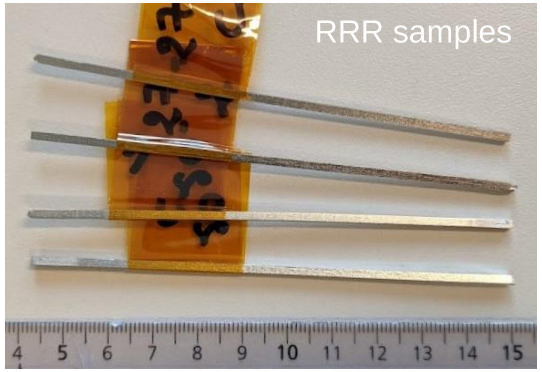
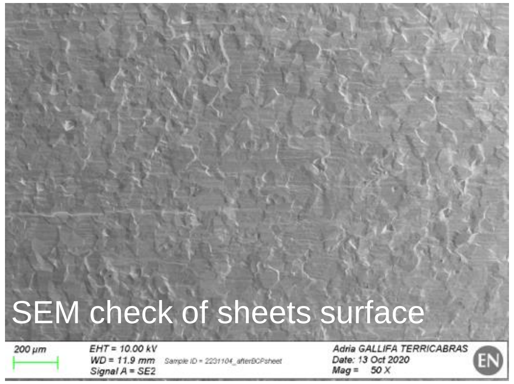
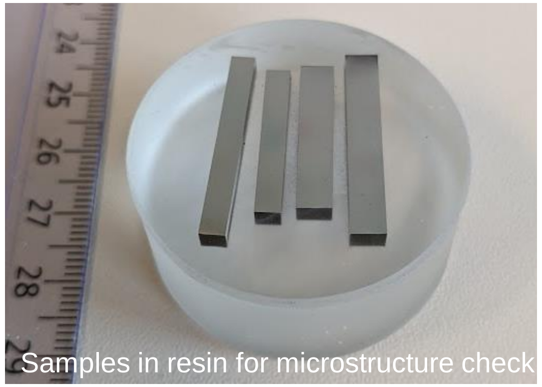
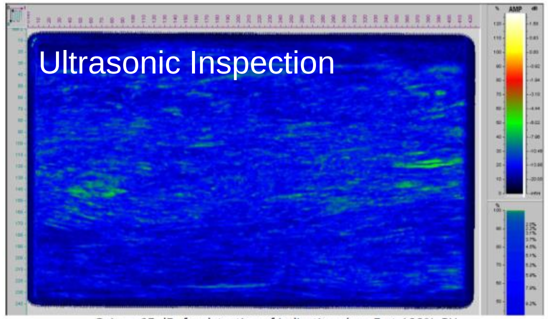


Figure 1. Detail of the exogenous substance on sheet ID 2221701.



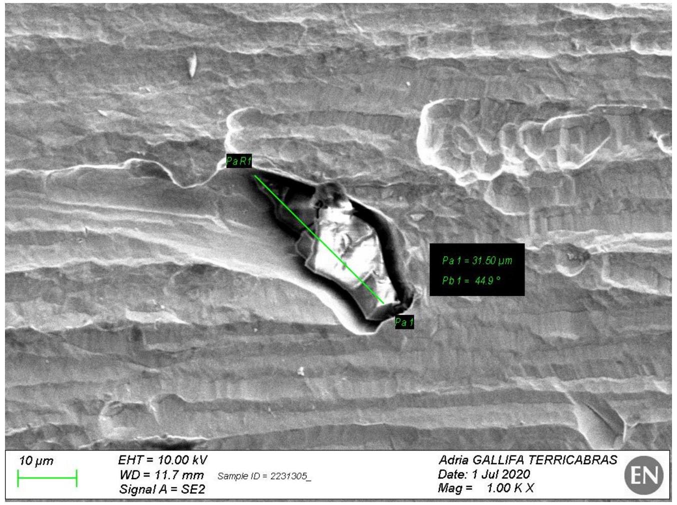




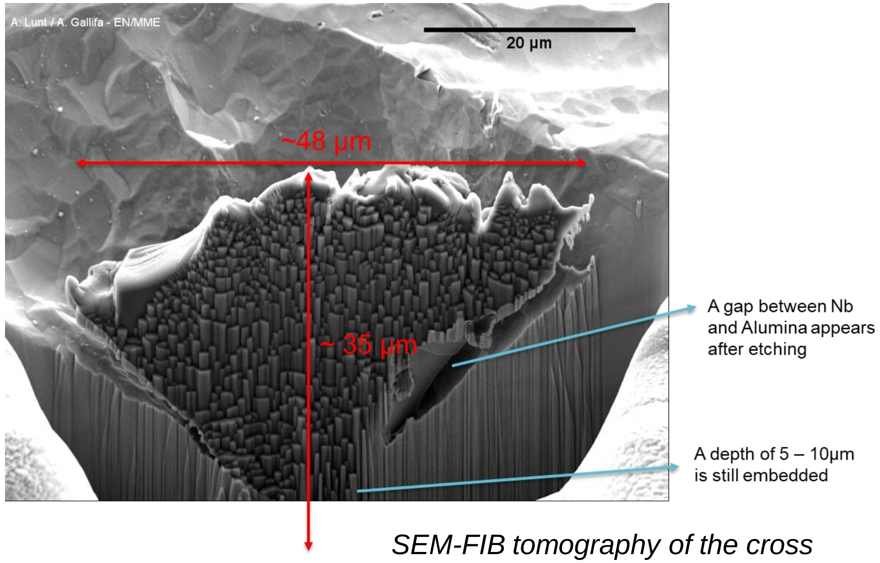
Gain = 65 dB, for detection of indication class 5 at 100% SH

Analyse Nb surface by SEM upon reception

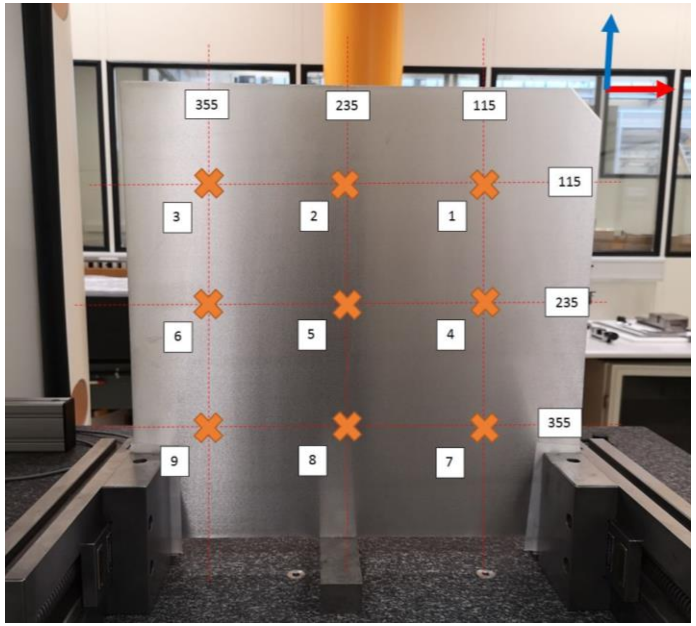
- Issue: Some sheets of both Nb orders for DQW series had alumina particles embedded on the surface.



Embedded Al2O3 particle on as-received Nb sheet.



SEM-FIB tomography of the cross section of an embedded Alumina particle on Nb. By A. Lunt



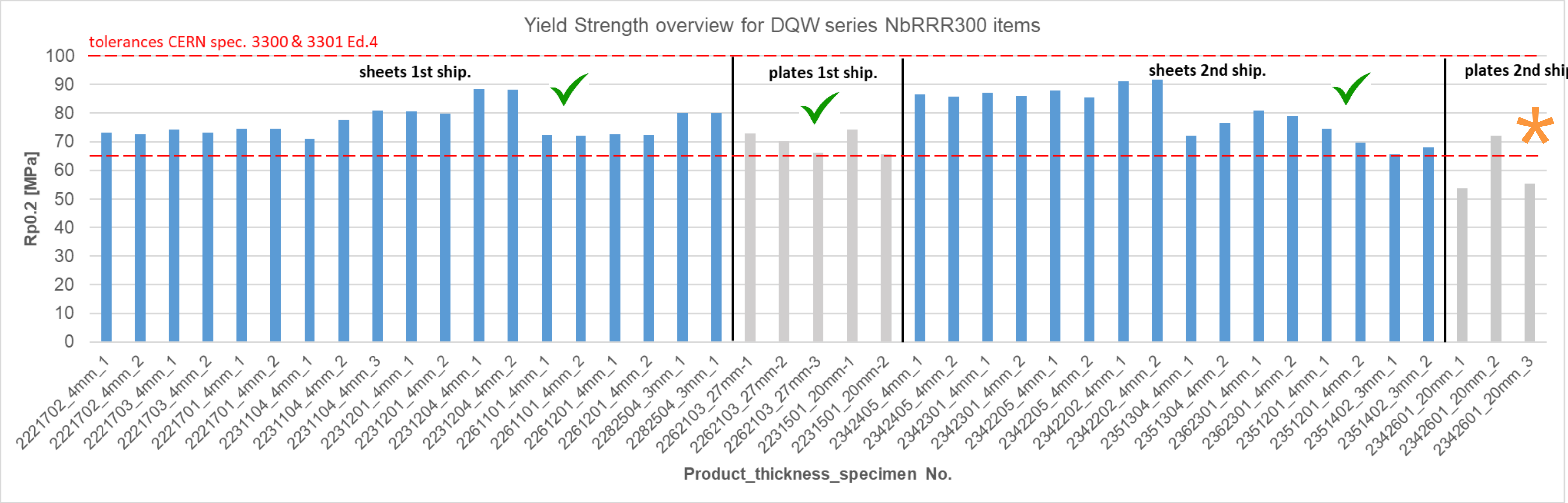
Thickness measurement on 9 points of a Nb sheet.

- 2x NCRs were created. Corrective actions: **perform BCP20 um (per face) before forming** operations (+ thickness measurements).

Thanks to S. Forel, B. Bulat and M. Burkowski

Microstructure check

Tensile tests overview: Rp0.2

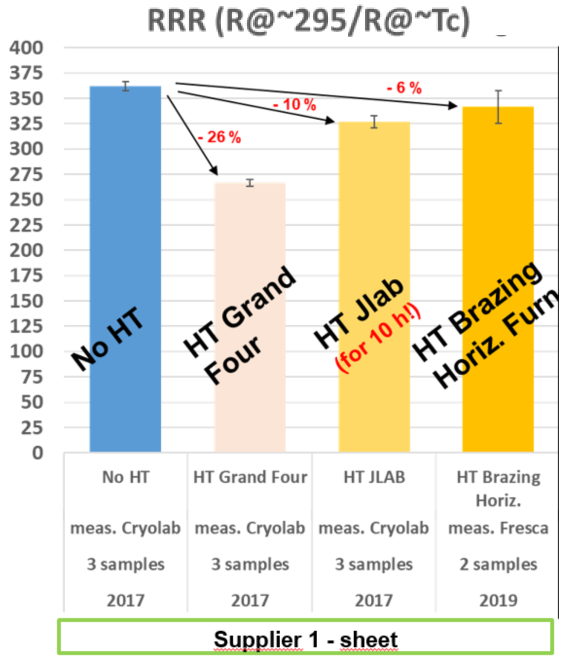


* A NCR was created and after a dedicated FEA strength assessment considering Rp0.2=50 MPa the 20mm thickness plates were accepted for the series production.

RRR degradation after heat treatments

- Thermal treatments can significantly degrade RRR:

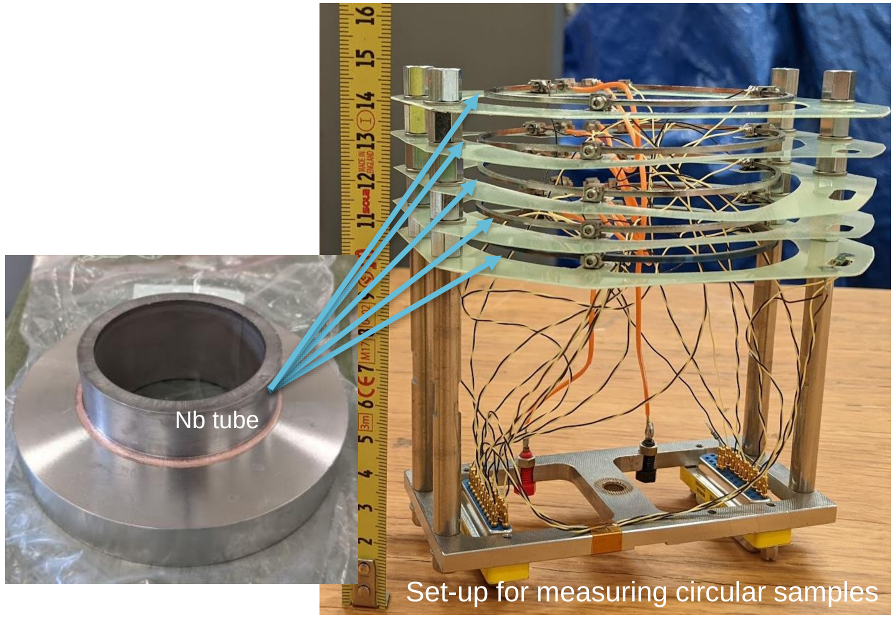
<u>Due to hydrogen degassing HT</u>



*Error bars represent one standard deviation

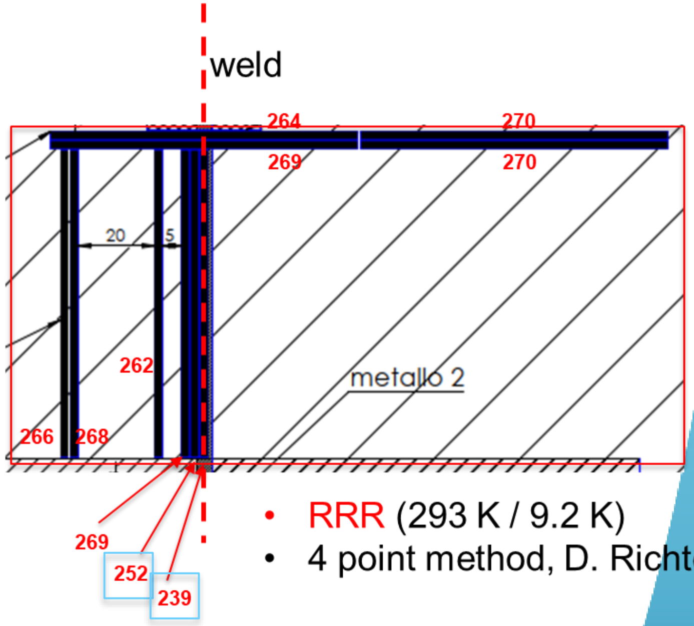
*Otherwise indicated, the HT consists in 650°C for 24h in vacuum.

<u>Due to Brazing cycles</u>



In collaboration with D. Richter TE-MSC

<u>Due to EB welding</u>



- RRR (293 K / 9.2 K)
- 4 point method, D. Richter

RRR degradation after HT

- Thermal treatments can significantly degrade RRR
  - EB welding → RRR samples are requested in the Eng. Spec (4.2.7.6)!
  - Hydrogen degassing HT
  - Brazing cycles

Recommended to check RRR, useful to improve heat treatment practices

Details as samples preparation, furnace manipulation and cleanliness, vacuum level and others can have a significant impact.

Thanks to P. Freijedo, D. Richter.
For further details contact A. Gallifa, F. Motschmann

Some references:

Singer, W., Singer, X., Tiessen, J., Wen, H. M., & Schölz, F. (2003, July). RRR degradation and gas absorption in the electron beam welding area of high purity niobium. In *AIP Conference Proceedings* (Vol. 671, No. 1, pp. 162-175). American Institute of Physics.

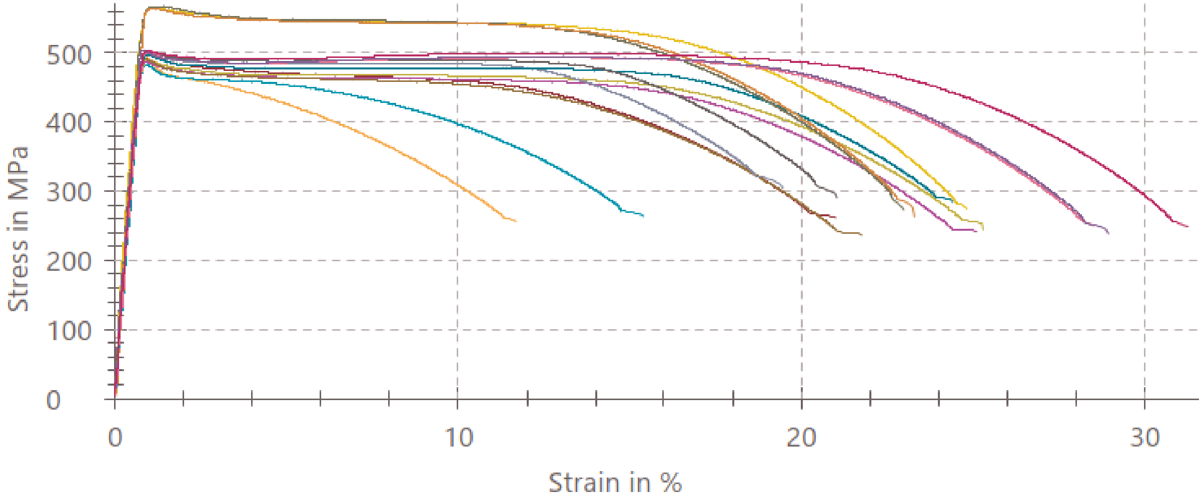
Alonso, N. V., Atieh, S., Santillana, I. A., Calatroni, S., Capatina, O., Ferreira, L., ... & Vacca, A. (2014). Electron Beam Welding and Vacuum Brazing Characterization for SRF Cavities. In *Proc. 27th Linear Accelerator Conf.(LINAC'14)* (pp. 932-934).


Nb55Ti

Nb55Ti reception and internal qualifications

- Additional pieces from the different lots were purchased for internal qualifications.
- Qualifications consisted in:
  - **Ultrasonic Inspection** (100%)
  - **Mechanical Tests** (1 item/lot and thickness)
  - **Microstructural check** (1 item/lot and thickness)

Additional pieces purchased for qualifications.



Tensile test curves for NbTi specimens.

All NbTi needed for DQW series is already at CERN (rings, rods, plates).

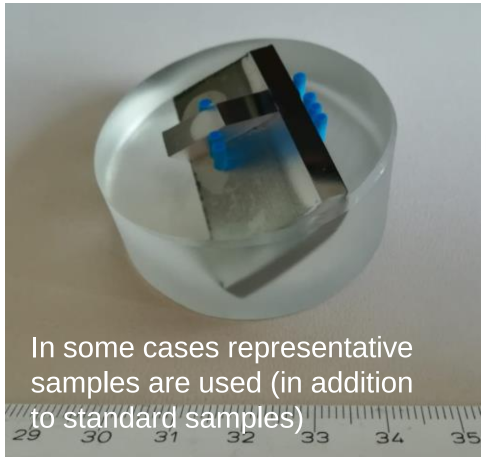
See reception and internal qualification report in EDMS 2395238.

EB welds

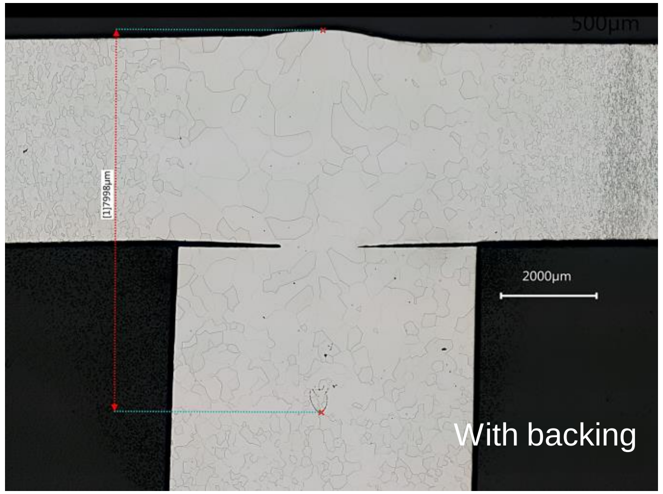
EB welds Nb-Nb and Nb-Nb55Ti

With T. Demaziere

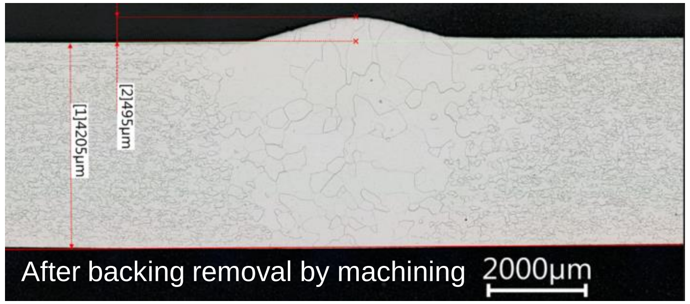
- **Welding Procedure Qualification Records** (according to ISO 15614-11 **and** Engineering Spec EDMS 1389669)



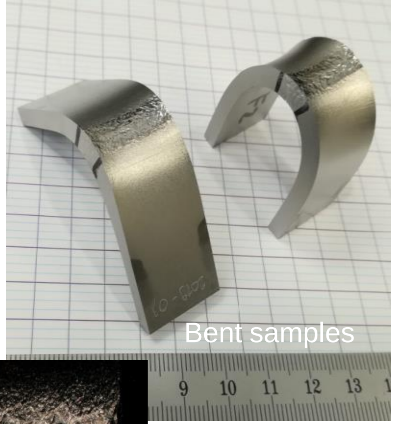
In some cases representative samples are used (in addition to standard samples)



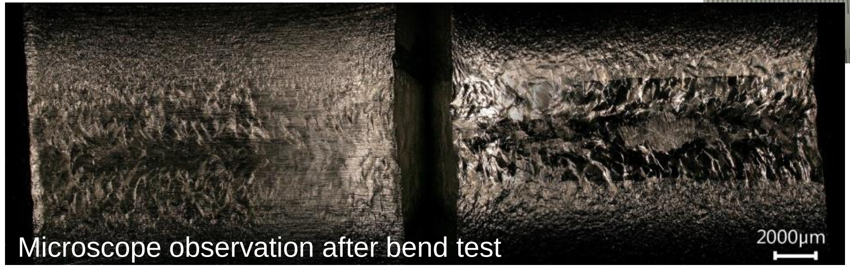
With backing



After backing removal by machining



Bent samples



Microscope observation after bend test

- **Effect of hydrogen degassing heat treatment on the mechanical properties of welds**

Percentage change of Rp0.2, Rp1.0 and Rm before vs. after HT.

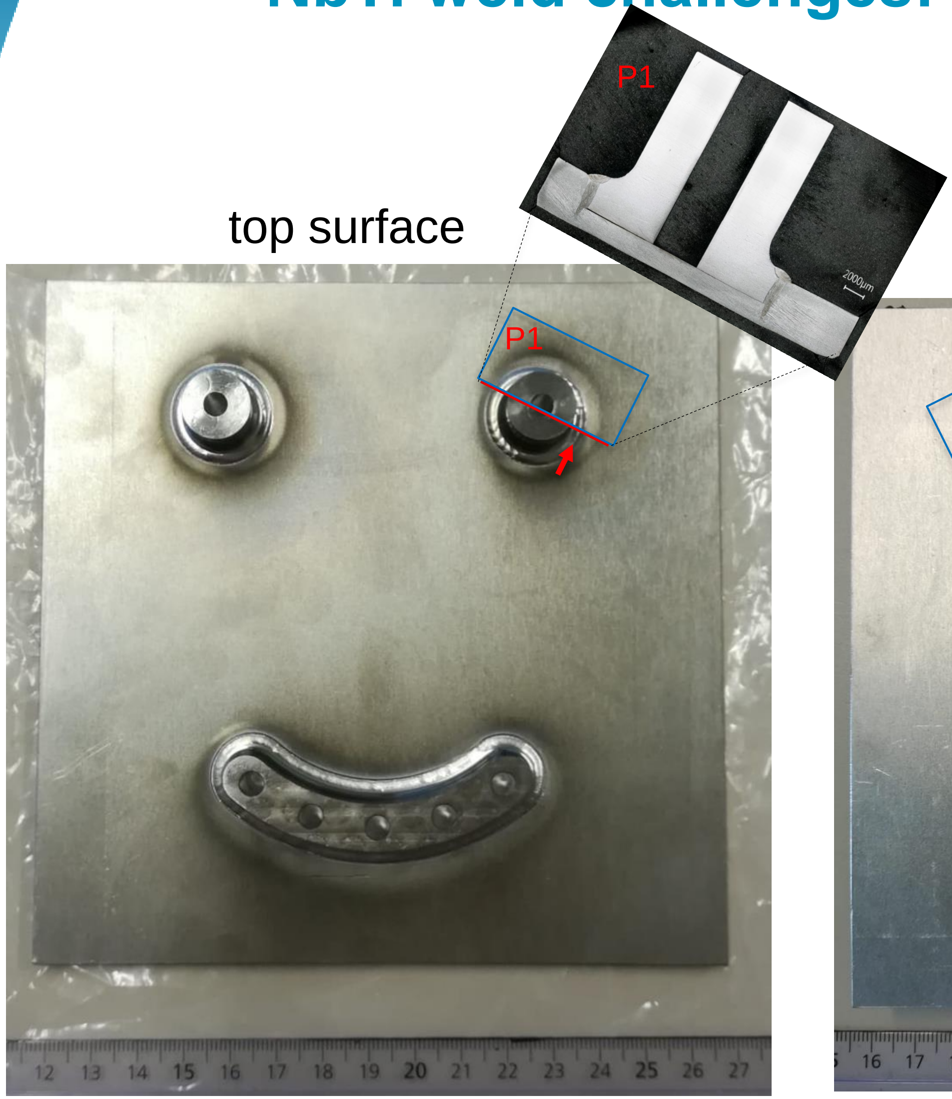
Qualif. ID	**Rp0.2 change**	**Rp1.0 change**	**Rm change**
WPQR-EBW-2019-01	-10%	-9%	-5%
WPQR-EBW-2019-03	-9%	-4%	-2%
WPQR-EBW-2019-04	-12%	-12%	-6%
WPQR-EBW-2019-05	-2%	-3%	-4%
WPQR-EBW-2019-07	-11%	-10%	3%
WPQR-EBW-2019-08	-18%	-17%	-6%
Average change	**-10%**	**-9%**	**-3%**

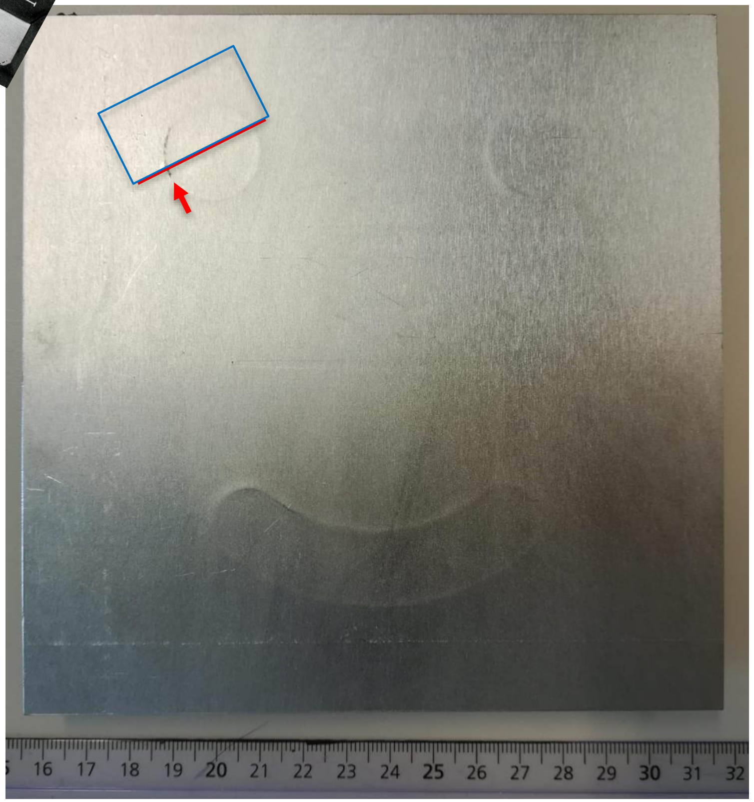
Specimens after transverse tensile tests

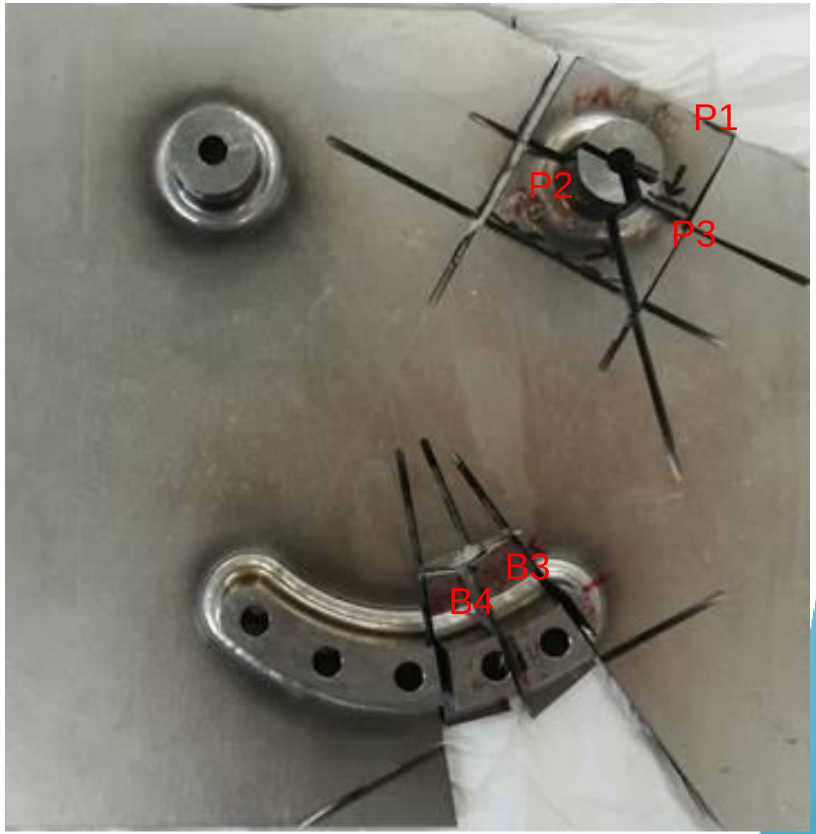
See full results in EDMS 2280803

NbTi weld challenges: example of the ‘Pin’ (tuning interface)

Confidential





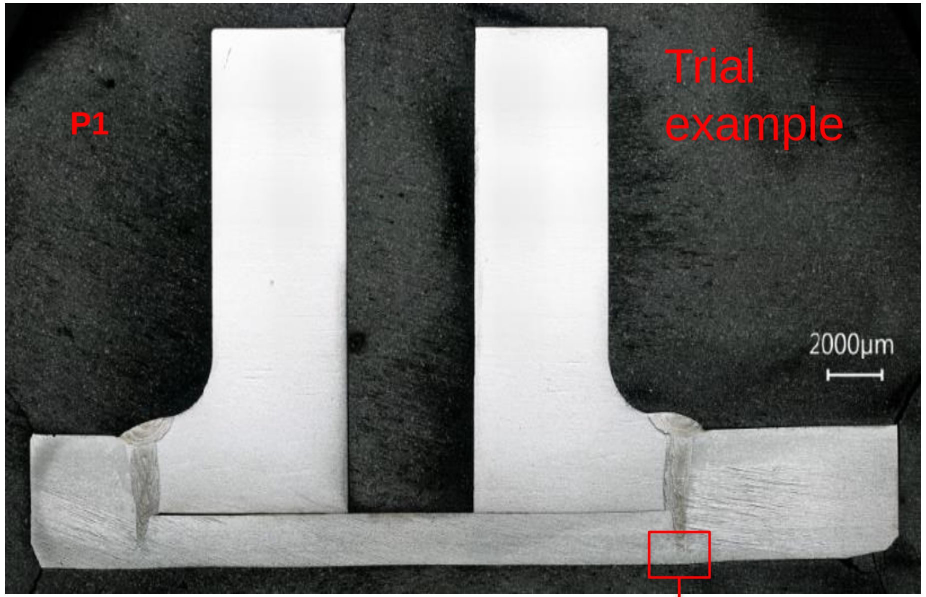


During manufacturing, NDT is not exploitable on the Pin and Banana.

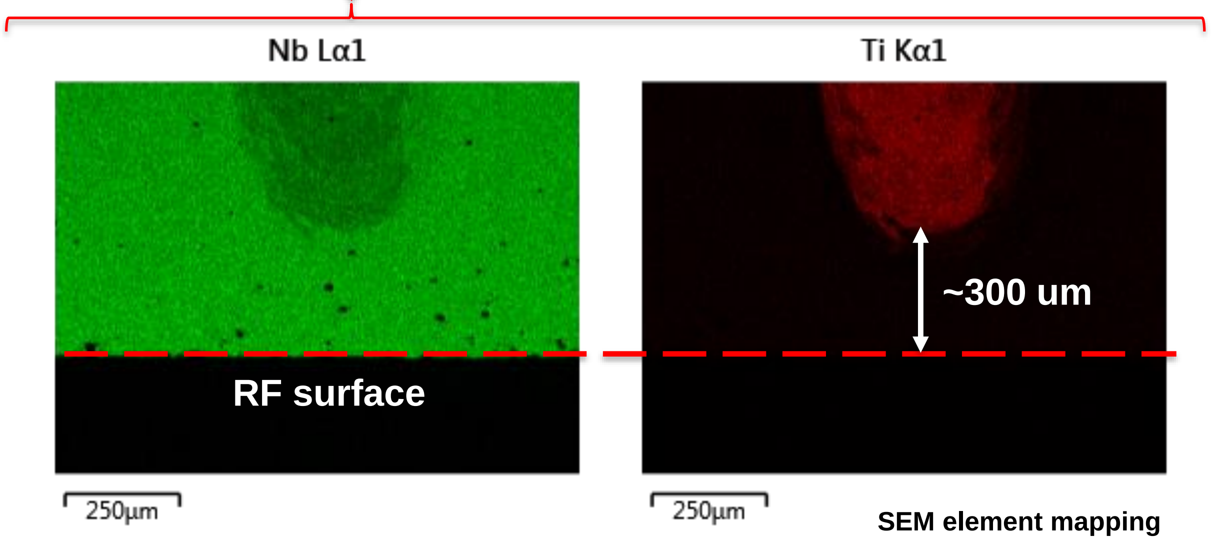
→ Several iterations needed to optimize penetration depth.

NbTi weld challenges: example of the ‘Pin’ (tuning interface)

Confidential



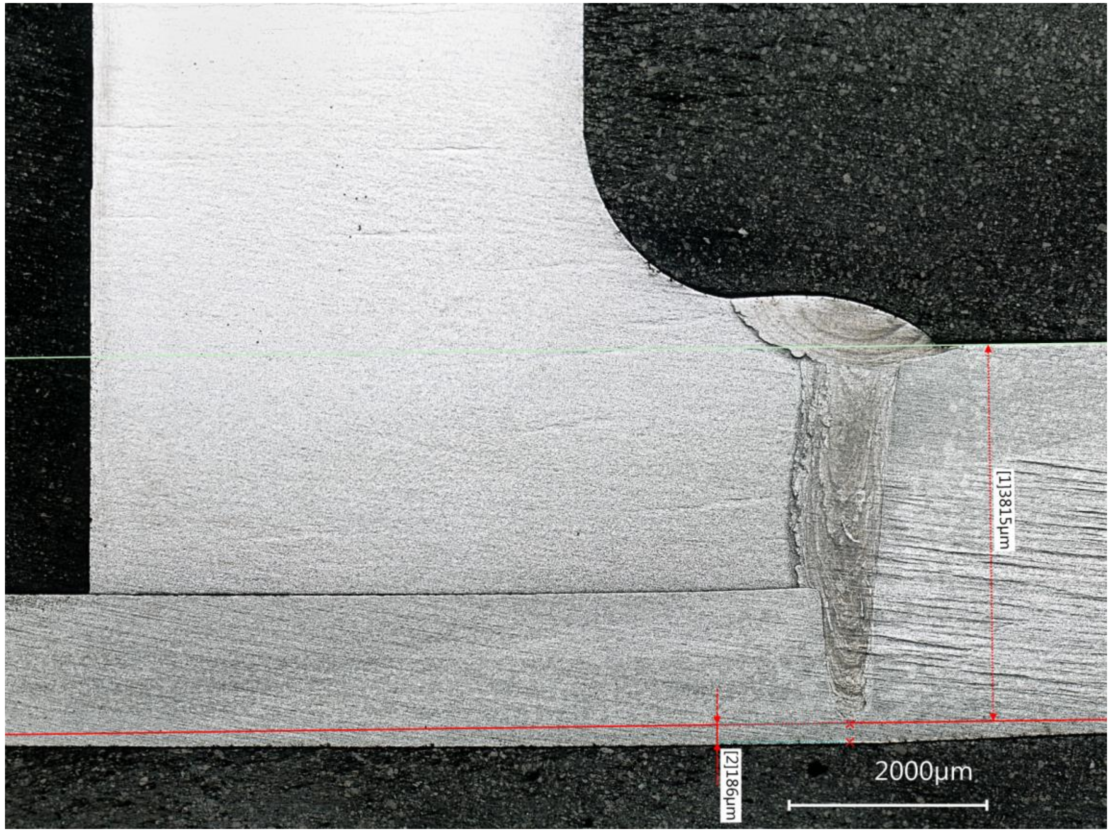
We shall keep the NbTi melt pool away from the RF surface!



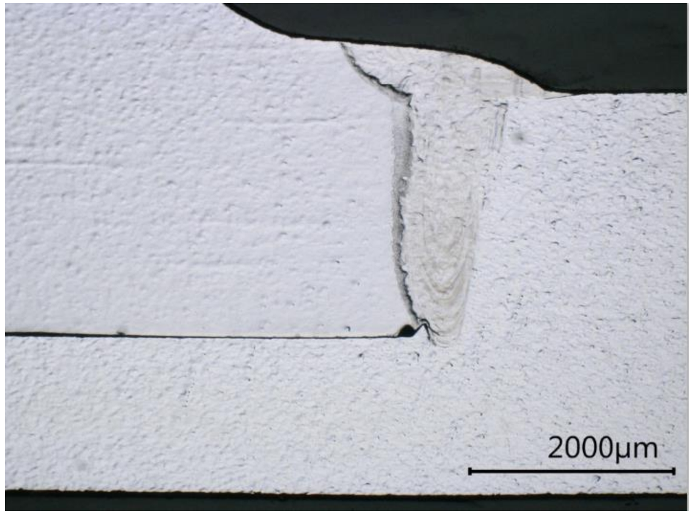
SEM element mapping

NbTi weld challenges: example of the 'Pin' (tuning interface)

Confidential



(adapting beam parameters, …)



First trial: Metalography P1, on the pin
Penetration depth 3.815 mm

After process improvement
Penetration depth ~ 2.8 - 3 mm

Metallographic cuts are crucial for improving (and qualifying) welds.

The Nb-NbTi welds typically require several trial and error iterations.

Image by M. Meyer

Ti Gr 2 procurement

- Crab Cavity project was relying on a Particular Material Appraisal (PMA) by DESY based on DIN specifications.
- A new PMA acc. to PED 2014/68/EU has been released together with CERN HSE team, in order to be able to use Ti Gr 2 acc. to ASTM/ASME standards.

2 MATERIALS UNDER THE SCOPE OF THE PRESENT PMA

This document presents the technical data needed to establish a Particular Material Appraisal (PMA) for the material **Titanium Grade 2[1]/2H[2]** specified according to the following US standards:

- ASME SB-265 (version 13 to 20a) Specification for Titanium and Titanium Alloy Strip, Sheet, and Plate
- ASME SB-348 (version 13 to 19) Specification for Titanium and Titanium Alloy Bars and Billets;
- ASME SB-861 (version 13 to 19) Specification for Titanium and Titanium Alloy Seamless Pipe;

and corresponding ASTM specifications with the additional requirements specified in §11.

Later versions of the aforementioned specifications are considered acceptable.

See talk by L. Dassa

EDMS NO.	REV.	VALIDITY
2370843	1.0	VALID

REFERENCE : LHC-ACFHT-SR-0001

PARTICULAR MATERIAL APPRAISAL (PMA)

TITANIUM GRADE 2/2H ACCORDING TO US SPECIFICATIONS

Abstract

The document details the Particular Material Appraisal (PMA) according to PED 2014/68/EU, annex I, sec.4.2 for Titanium Grade 2/2H according to US specifications: ASME BPVC.II.B, SB/B-265, SB/B-348, SB/B-861.

This document is written in the application of the European Directive 2014/68/EU regarding the technical documentation to be drawn up by the manufacturer of pressure equipment aiming conformity assessment.

Titanium commercial grades are not covered by European harmonised standards granting their use in pressure equipment.

In the framework of the HL-LHC WP4 'Crab Cavities & RF' project, the utilisation of material in agreement with US specifications requires a dedicated PMA which is described in this document.

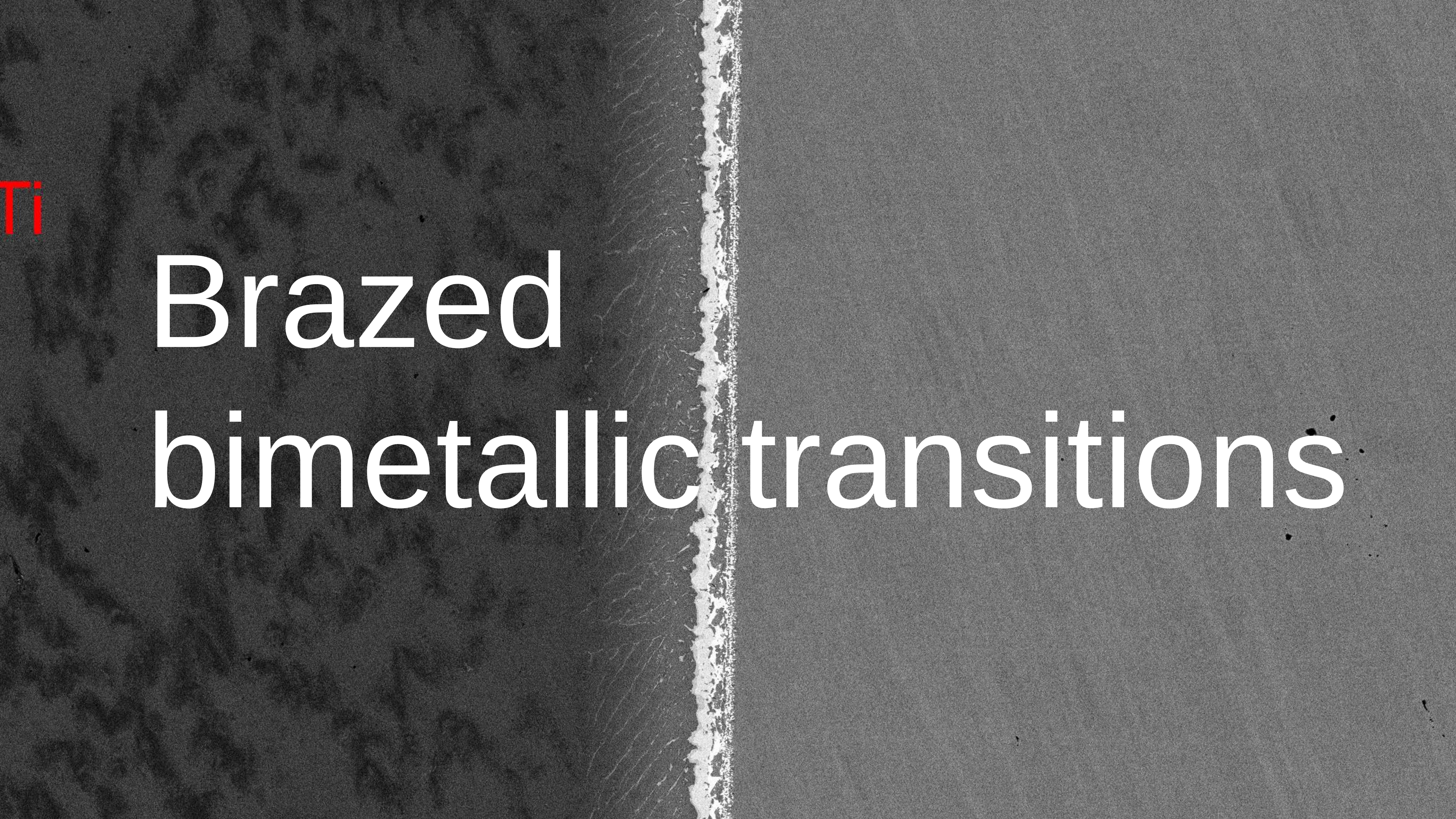
TRACEABILITY

Prepared by: L. Dassa, A. Gallifa Terricabras	***Date:*** 2021-02-24
Verified by: I. Aviles, S. Barriere, O. Capatina, M. Garlaschè, C. Gaignant, S. Marsh, S. Sgobba, N. Valverde, O. Williams	***Date:*** 2021-05-03
Approved by: R. Calaga	***Date:*** 2021-05-20
Distribution: N. Surname (DEP/GRP) *(in alphabetical order) can also include reference to committees*	

Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
0.6	2021-02-24	Revised version according to comments in EDMS during circulation of version 0.5. Sections 4 .2 and 4.3 added. Range of validity extended: versions 2013 to 2020 accepted
1.0	2021-05-20	1st Release version of the document

Page 1 of 23 Template EDMS No.: 1311288

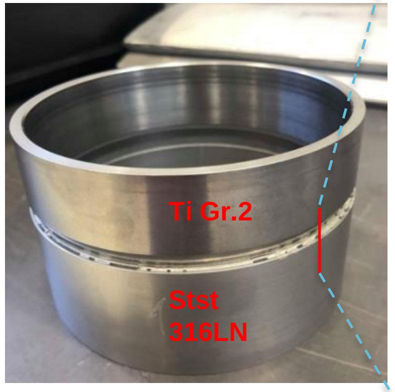
Brazed bimetallic transitions

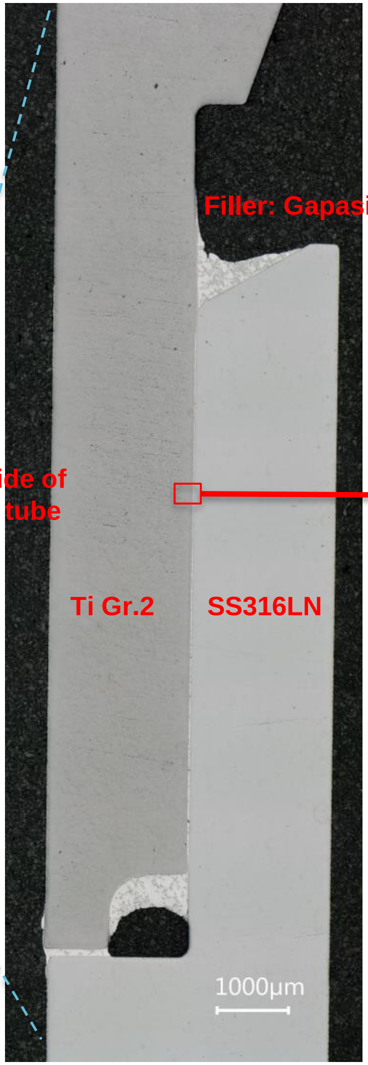


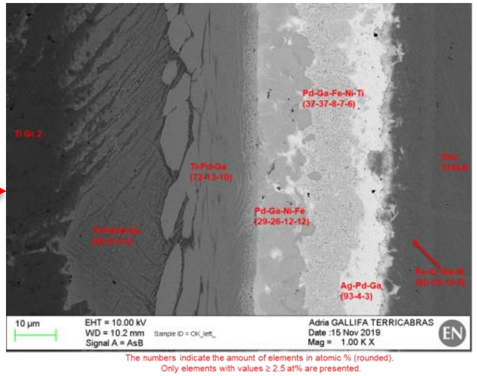
SS-Ti bimetallic brazed transition validation

5'small' + 5'big' test samples were validated

1. Leak tightness test
2. Ultrasonic test (UT) inspection
3. Thermal shock (TS) in liquid nitrogen (x5 times)
4. Leak tightness test after TS
5. Ultrasonic test (UT) inspection after TS
6. Visual test (VT) inspection
7. Metallograpy (OM and SEM)
8. Tensile tests
   1. 2x small tubes at RT
   2. 1x small tube at 77K
   3. 3x specimens cut from one big tube, tested at RT
   4. 3x specimens cut from one big tube, tested at 4K





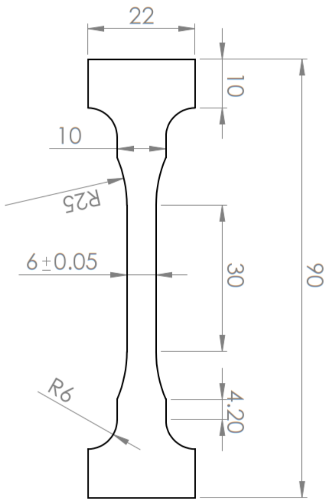


With F. Motschmann

SS-Ti bimetallic brazed transition validation

Tensile tests on real-size tube and on specimens extracted from a tube, at RT and cryogenic temperature.

Sample after rupture at the brazed region



Test conditions:

- Crossheads speed 0.4 mm/min (adapted from ISO 6892-1)
- 200 kN load cell
- Preload: 300 N

Extensive experience after internal tests:

- Leak tightness: 10/10 parts OK (before and after thermal shocks)
- Ultrasonic test inspection: 9/10 parts OK
- Mechanical tests
  - Small tubes at RT: Fmax ≥ 85 kN, Ultimate Shear Strength ≥ 116 MPa
  - Small tube at 77K: Fmax ≥ 143 kN Ultimate Shear Strength ≥ 190 MPa
  - Specimens cut from big tube, at RT: Ultimate Shear Strength ≥ 72 MPa
  - Specimens cut from big tube, at 4K: Ultimate Shear Strength ≥ 84 MPa

+ qualification with a notified body

apave

Further information EDMS 2271509

For further details contact
F. Motschmann, T. Demaziere.

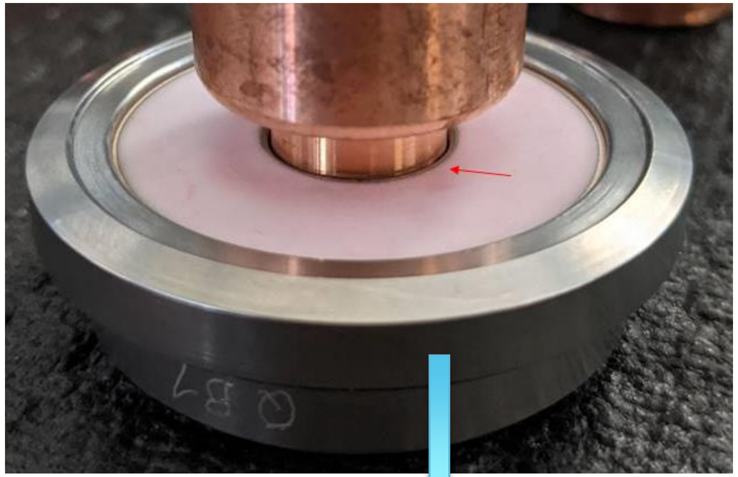
RF feedthroughs

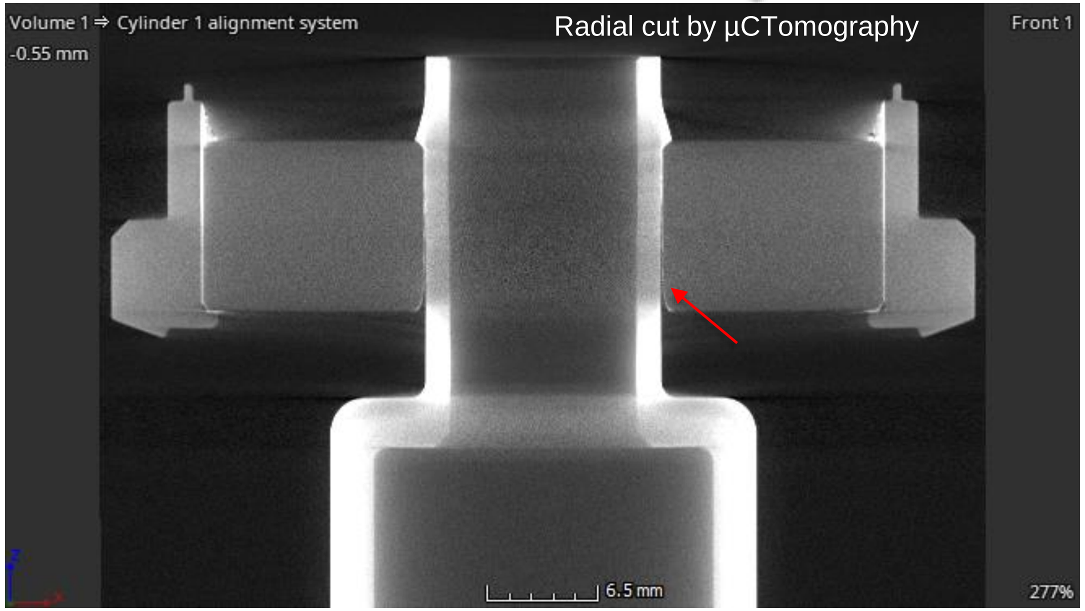
RF feedthroughs

See talk by E. Montesinos

Validation Test Plan (after brazing)

- Leak Test
- Penetrant Testing
- Mounting on ‘mock-up’ chamber
- Thermal Shock in liq. N_2
- Leak Test
- Penetrant Test
- NDT
- Metallographic / microscope check





Acceptance criteria for series needs to be discussed.
Remark: As NDT, Ultrasonic Testing is preferable, but depending on the geometry µCTomography could be envisaged.

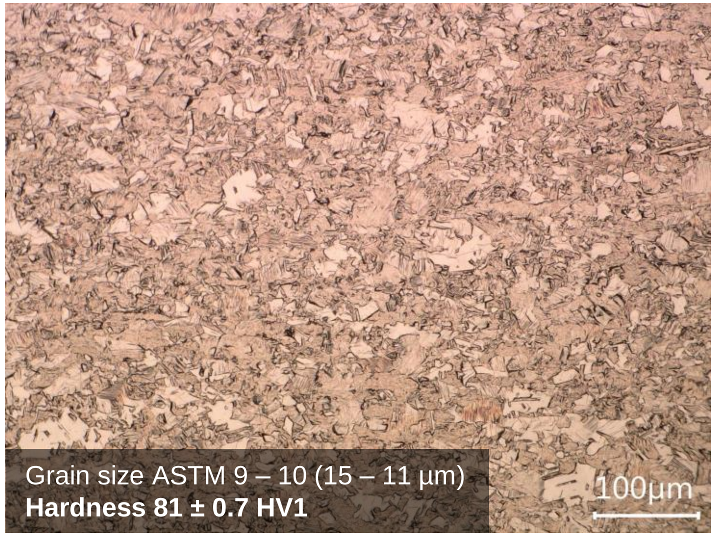
With F. Motschmann and M. Crouvizier.
Thanks to S. Bonnin, A. Porret.


Cu

Cu OFE vs. Cu OFS for RF gaskets

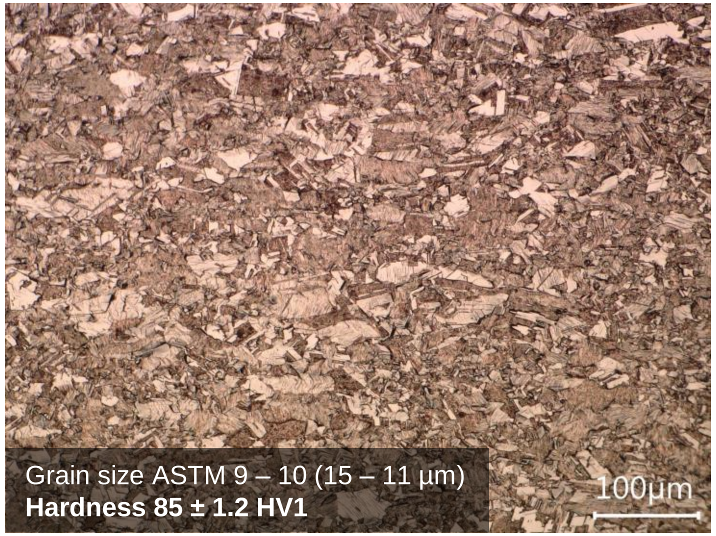
As-received (half hard) | HT 600°C for 2h in vacuum

OFE

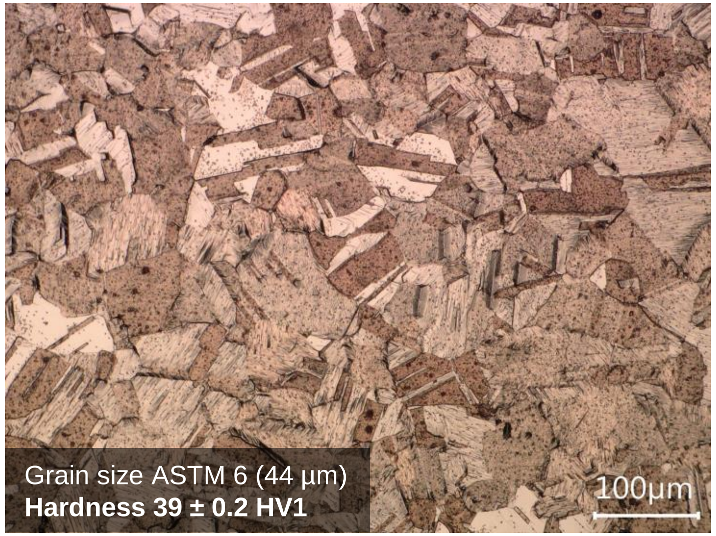


→

OFS
Ag ~0.10wt%

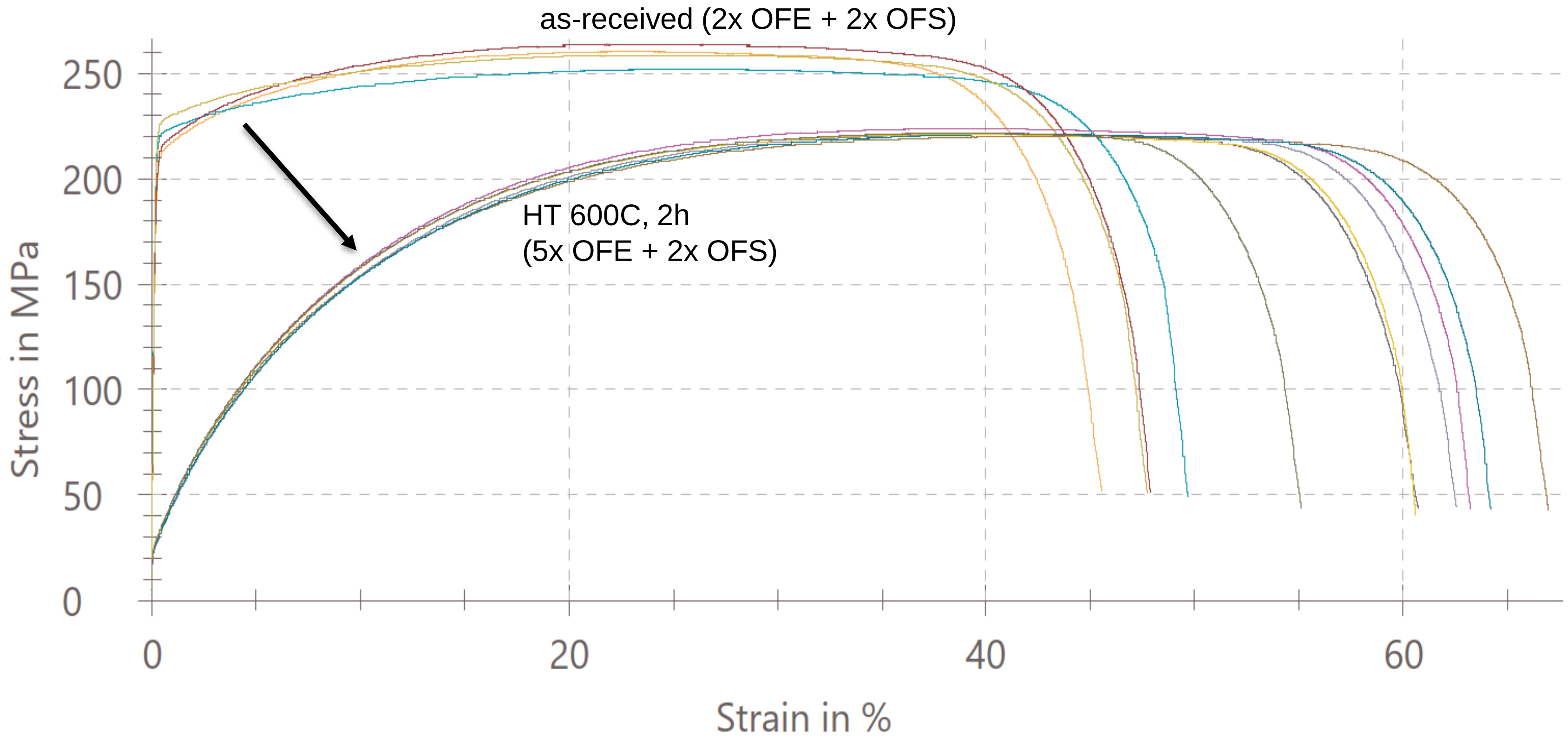


→

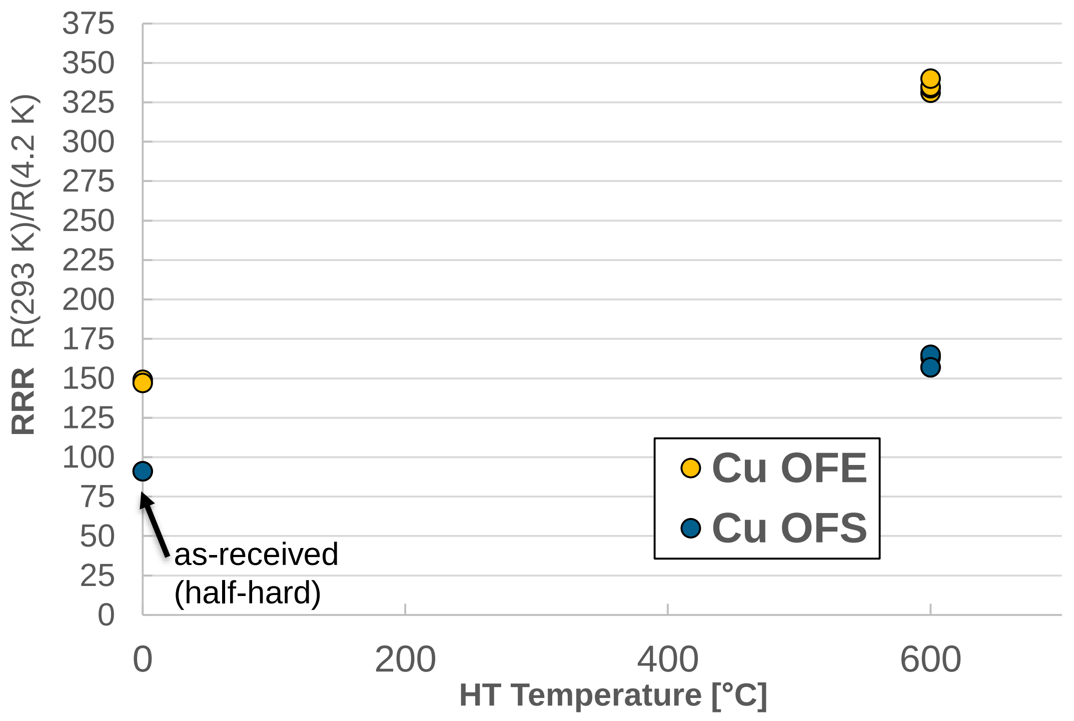


3 x hardness measurements in mid-thickness / Grain size values show the range measured within 5 fields / polishing up to 1 µm, etching with HNO3 50% vol.

Cu OFE vs. Cu OFS for RF gaskets – Tensile tests



Cu OFE vs. Cu OFS for RF gaskets - RRR



The graph contains a total of 12 data points:

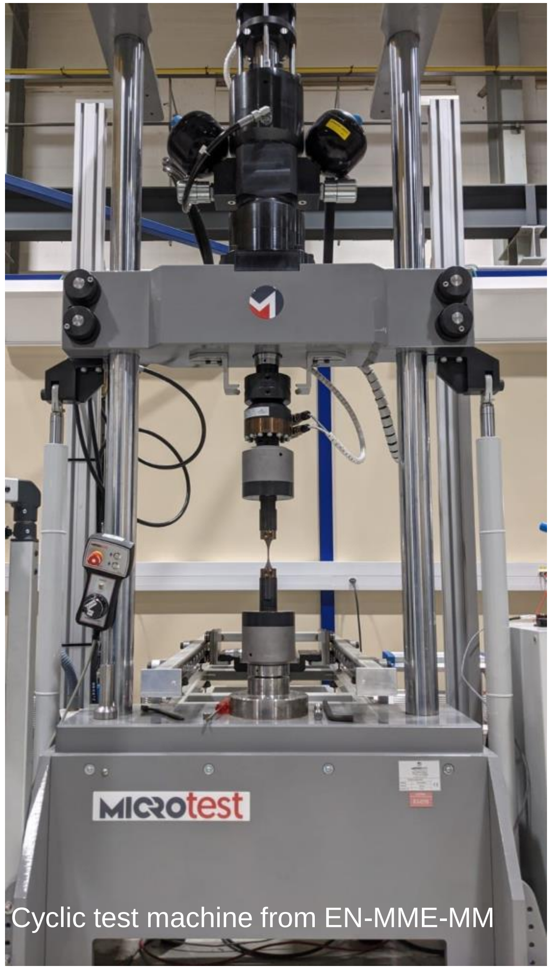
- OFE: 2 x samples as-received, 4 x samples after HT 600C

- OFS: 2 x samples as-received, 4 x samples after HT 600C

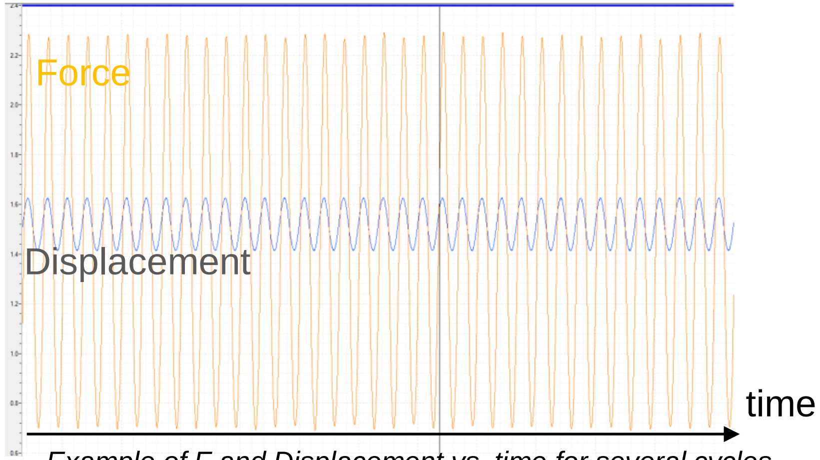
- In **as-received** condition, **Cu OFE has a higher RRR than OFS by a factor 1.6**
- **After HT** at 600°C for 2 hours, **Cu OFE has a higher RRR than OFS by a factor 2**
- The difference is **due to the resistance at 4.2 K** (at RT there is no significant difference)

Some future tests and R&D

- Ultrasonic parameters (attenuation..) vs. mechanical properties of NbRRR300
- Fatigue tests on NbRRR300



Cyclic test machine from EN-MME-MM



Example of F and Displacement vs. time for several cycles.

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.
- On **critical materials** for the project (e.g. NbRRR300) it is important to perform **internal quality control tests** and give feedback to suppliers.
- **Raw materials** for the bare **DQW series** (**NbRRR300, Nb55Ti**) are **already at CERN**. After internal tests, all items are **validated for production**.
- **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.

Thanks to all MME and WP4 colleagues!

And special thanks to I. Aviles, N. Valverde, L. Dassa,
S. Barriere, M. Garlasche, T. Demaziere, F. Motschmann, K. Eiler, P. Freijedo,
S. Forel, D. Richter, A. Eychenne, G. Arnau, S. Bonnin,
M. Haavarstein, M. Pentella.

HiLumi HL-LHC PROJECT

Questions?

Backup slides

Ti alloys: why to use Ti Grade 23?

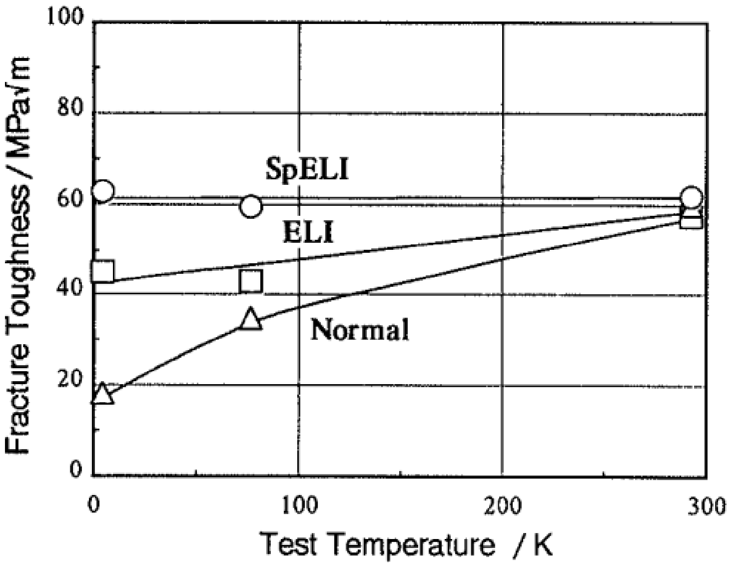
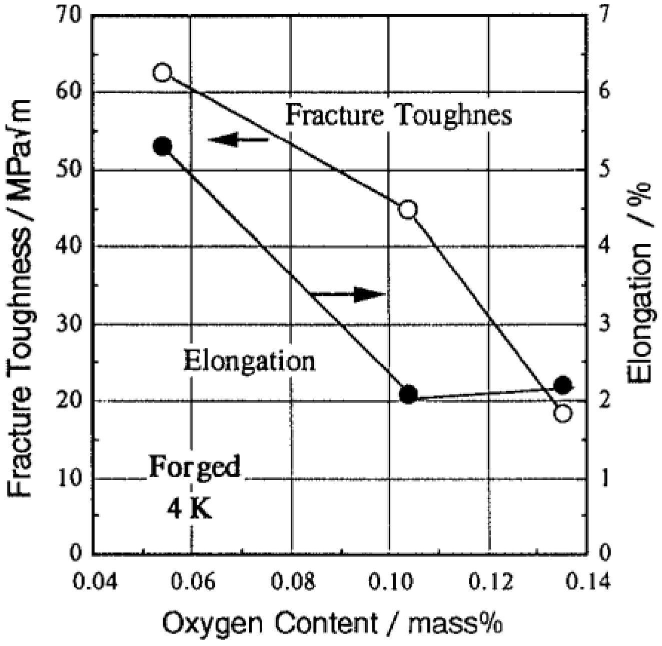


Fig. 6. Temperature dependence of fracture toughness, K_{IC}(J



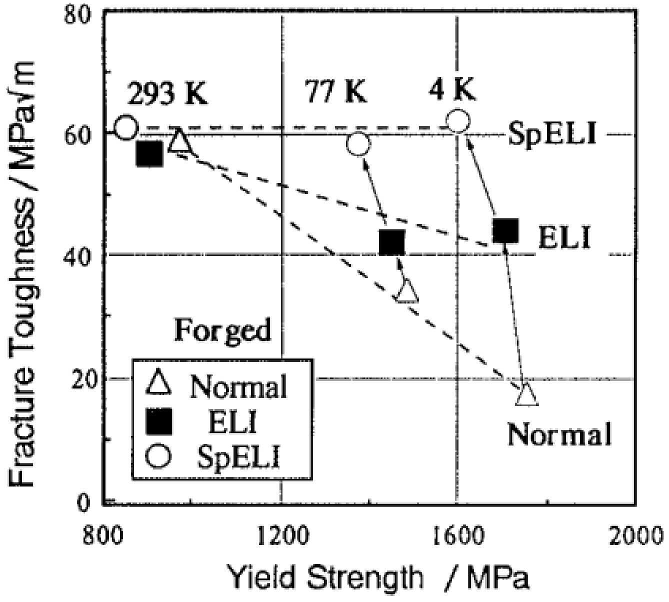


Fig. 7. Interrelationship between the fracture toughness of forged materials and other factors: (a) oxygen content and (b) yield strength. Elongation is also plotted in (a).

Nagai, K., Yuri, T., Ogata, T., Umezawa, O., Ishikawa, K., Nishimura, T., ... & Ito, Y. (1991). ***Cryogenic mechanical properties of Ti-6Al-4V alloys with three levels of oxygen content****. ISIJ International, 31(8), 882-889.*

The fracture toughness and ductility for Extra-Low-Interstitial (ELI) grades, like Ti Grade 23, at cryogenic temperatures are significantly superior than for non-ELI grades, like Ti Grade 5.

SS-Ti bimetallic qualifications (acc. to Eng. Spec. v2.57)

Table 27: Standards applicable to brazing qualifications

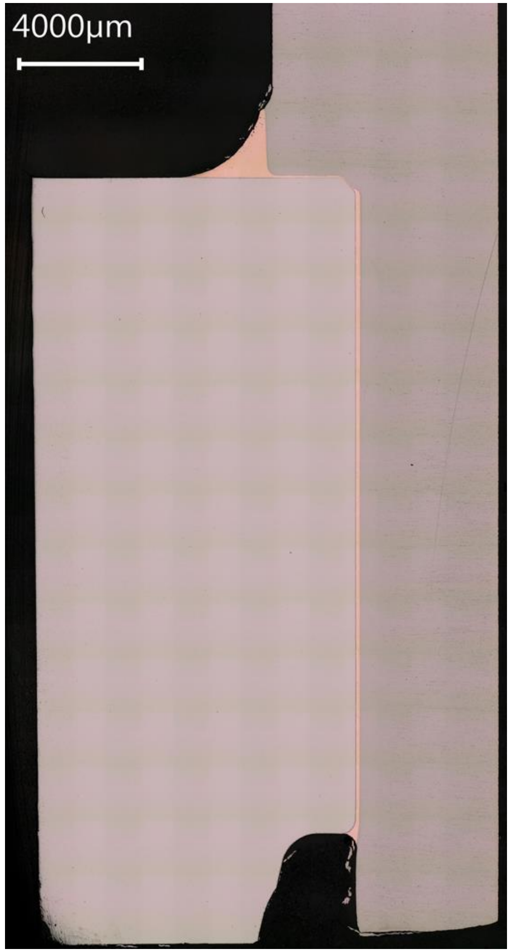
Description	Standards	
	American	European
Brazing Qualification (BPQR&BPS)		
Brazing	Qualification shall be performed on samples as much as possible close to the production components (see 8.1 of the EN 13134). A different qualification shall be produced for every combination of brazing procedure variables (as defined in EN 13134), required for the production of the cavity. No standard samples required by ASME are needed. The following tests are required for each qualification, considering only 1 sample subjected to all the following tests in the specified order: • 100% Visual inspection • Thermal shocks (at LN2 temperature) x 5 times, each of them followed by warming to ambient temperature + final drying • Helium leak test (refer to Section 4.3.5). • 100% UT by immersion according to §4.2.6.4 • Metallographic examination (on 2 sections of same sample) according to EN 12797 • Shear test with test conditions and documentation acc. to EN 12797, geometry as close as possible to final product (to be agreed with CERN) Documentation shall list be done according to the Annex B/C/D of the EN13134.	
Personnel Qualifications (BPQ)		
Brazing	ASME BPVC Section IX Part-QB	EN ISO 13585

After the internal validation experience, the qualification requirements are integrated in the Engineering Specification.

See talk by L. Dassa

Brazing qualification/validation of AUP brazed flanges (SS - Nb)

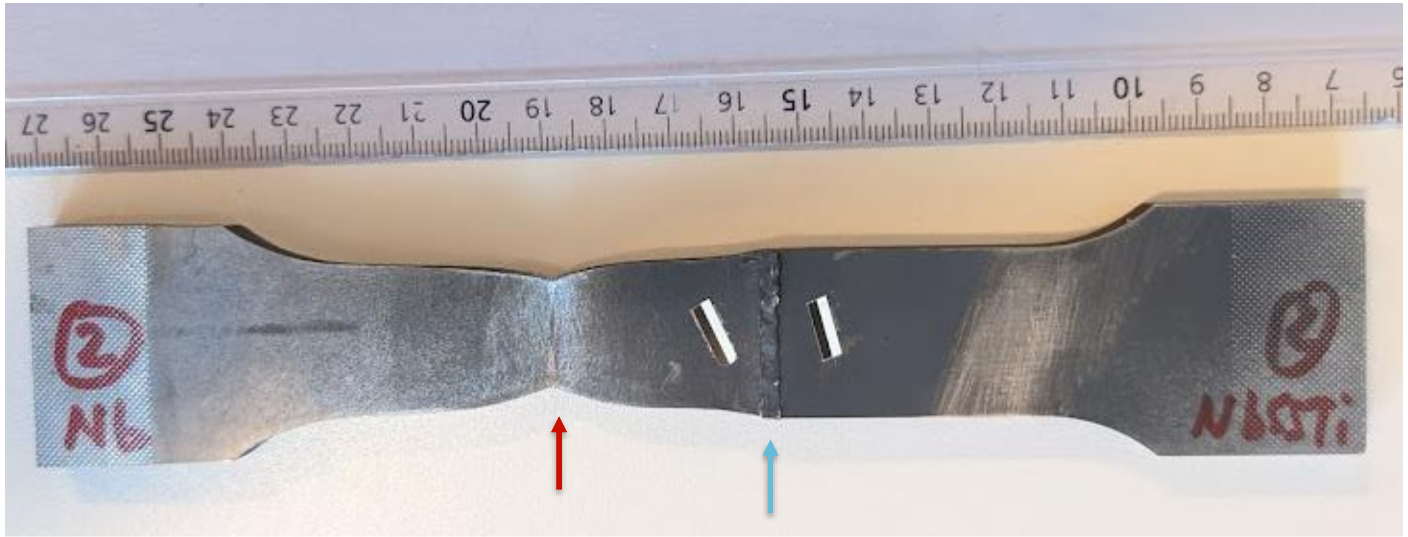
Acc. to Eng. Spec. for dressed cavitites EDMS 1389669 v2.56, table 11:



- Hydrogen degassing heat treatment (600C, 10h) Done
- 100% Visual inspection Done
- Thermal shocks (at LN2 temperature) x 5 times Done
- Helium leak test Done
- 100% UT by immersion Done
- Metallographic examination (on 2 sections of same sample) Done

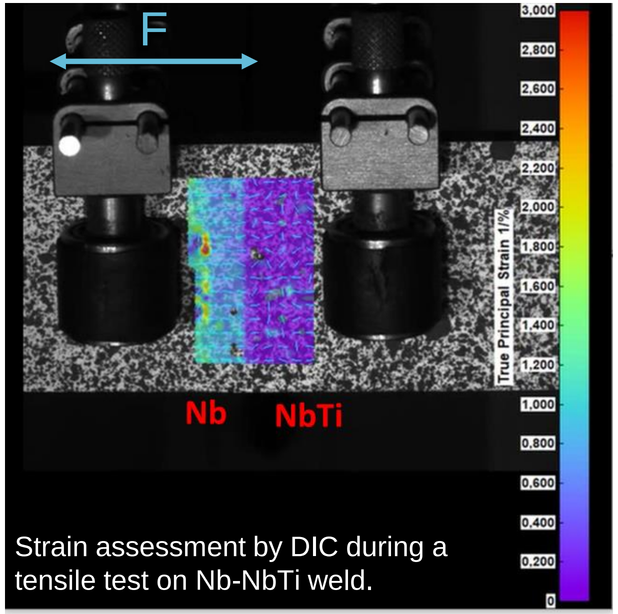
Reports stored in EDMS 2566930

Nb-NbTi EB welds



rupture

weld



Strain assessment by DIC during a tensile test on Nb-NbTi weld.

Legend	No.	Specimen no.	a_0 mm	b_0 mm	S_0 mm^2	L0 ST mm	L_c mm	m_E GPa	$R_{p0.2}$ MPa	A_g %	$A_{16,45mm}$ %	F_m kN	R_m MPa
	3	1	8.1	24.95	202.10	16.45	80	61	85	3.91	4.6	32.79	162
	4	2	8.09	24.97	202.01	16.45	80	47	95	4.88	6.2	33.94	168

The NbTi part is much more stiff than the Nb. The specimens break in the middle of the Nb part.

EDMS 2610033

Nb55Ti reception and internal qualifications

- Indications are sometimes identified by Ultrasonic testing:
  - Nb-rich regions
  - Microstructure inhomogeneities

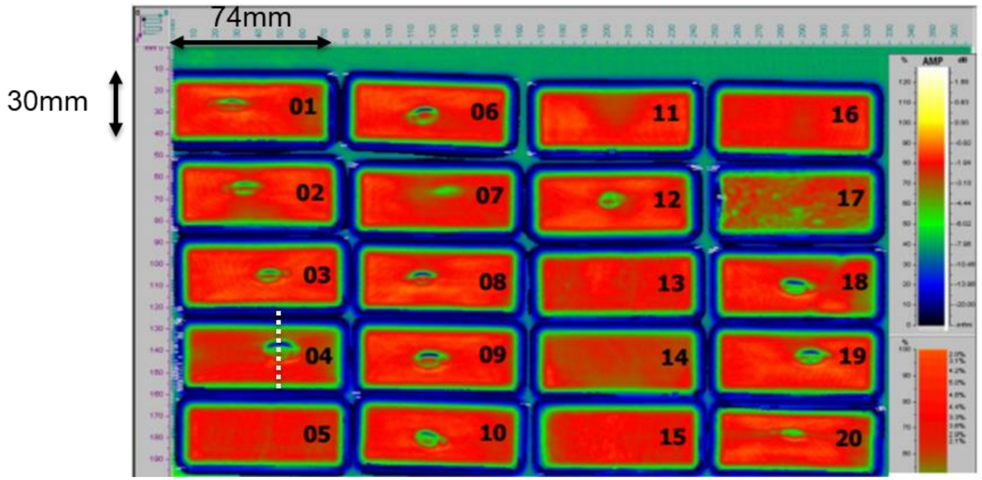
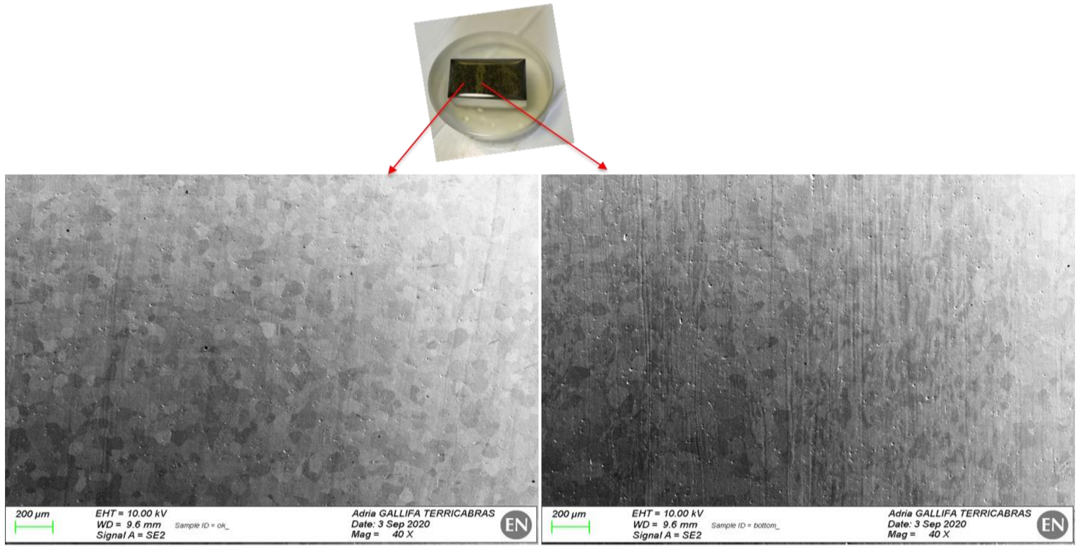


Figure 1. C-Scan Images – homogeneity of BWE of 18 mm thickness for NbTi pieces 1951201 to 1951240.



Hardness ~154 HV1 (avg. of 3 points)

Hardness ~ 161 HV1(avg. of 3 points)

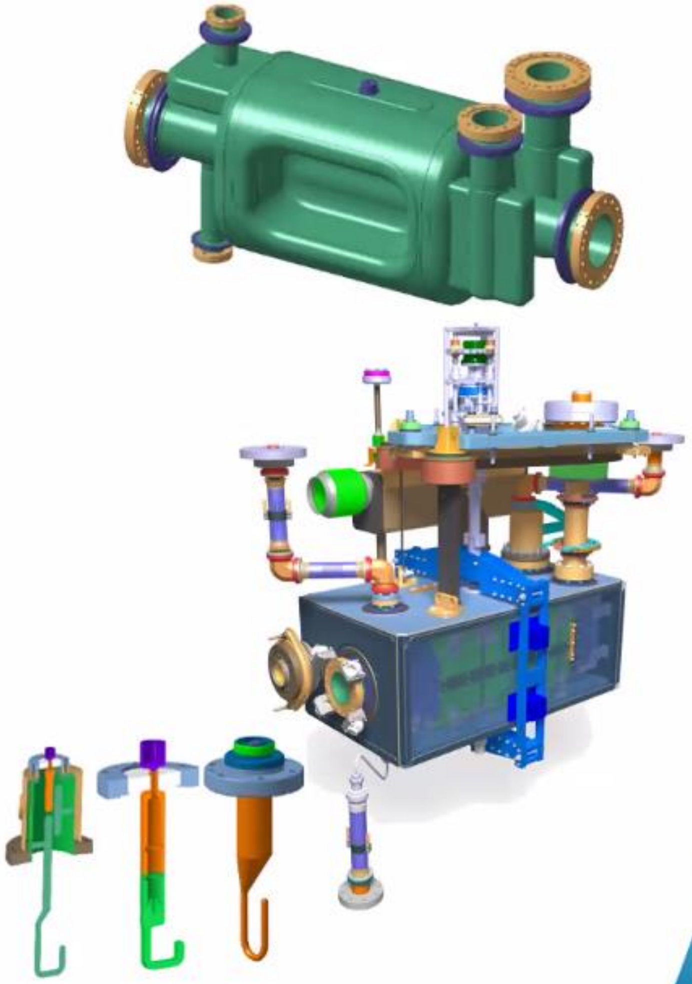
The defects encountered until now are considered non-critical for the Nb55Ti application, but they have to be studied case by case. Several NCR have been prepared to keep traceability.

Thanks to G. Arnau, S. Bonnin

Reminder: Dressed Cavity Geometries

Double Quarter Wave

RF Dipole



$$f_0 = 400\ \mathrm{MHz}$$

$$\mathrm{V_T} = 3.4\ \mathrm{MV/cavity}^*$$

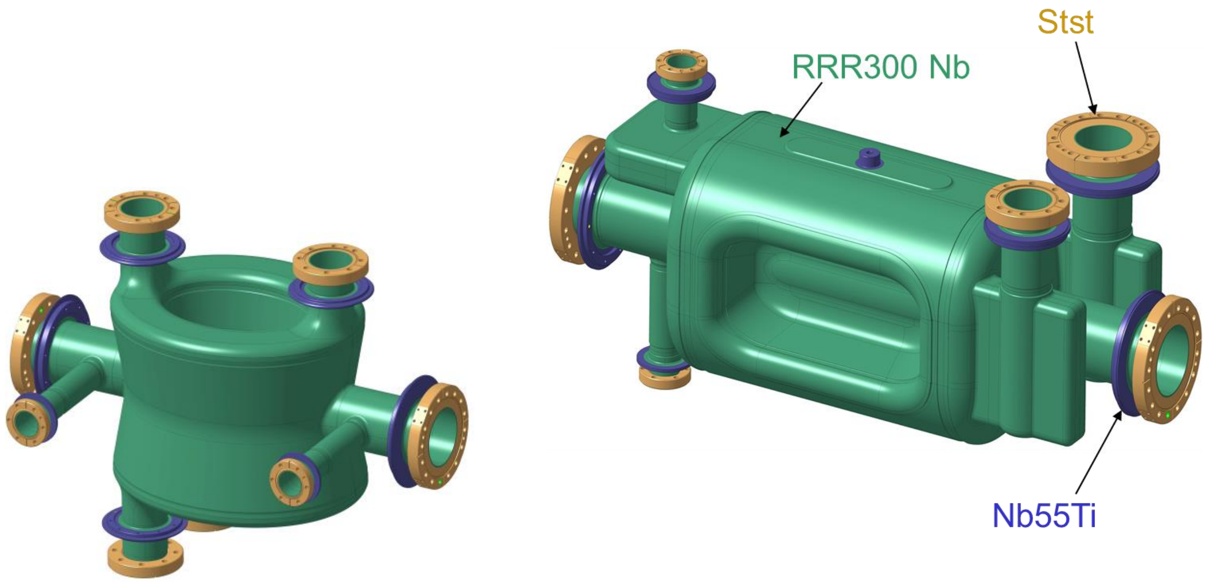
$$(\mathrm{E_p}, \mathrm{B_p} < 40\ \mathrm{MV/m}, 70\ \mathrm{mT})$$

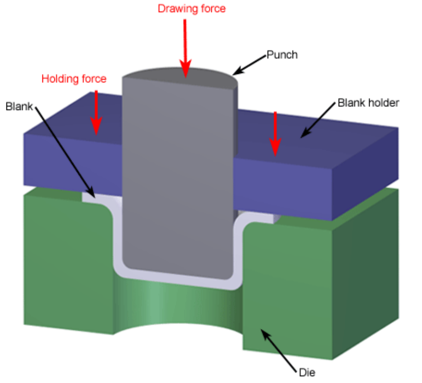
Beam aperture = 84 mm

Common FPC = 40 kW-CW

Operating Temp = 2 K

*Engineering spec: 4.1 MV dressed for 20% margin





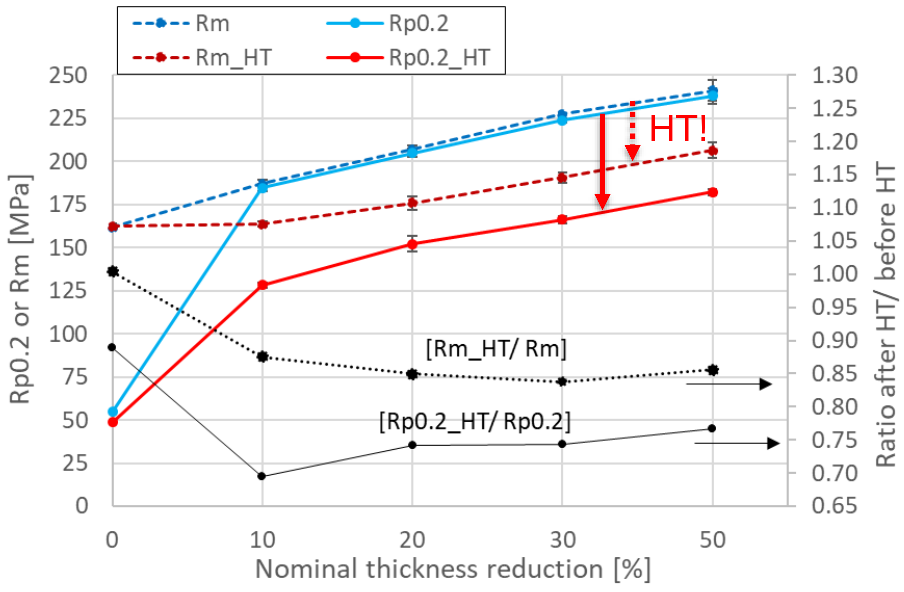
→ **Non-axisymmetric cavities** made of **ultra-high purity Nb (RRR300)**.

→ The main **components** of the CC are **plastically deformed** during manufacturing operations (i.e. **deep drawing**).

→ The CC are **submitted to** a hydrogen outgassing **heat treatment** **(HT) at 650º C** during **24 hours**.

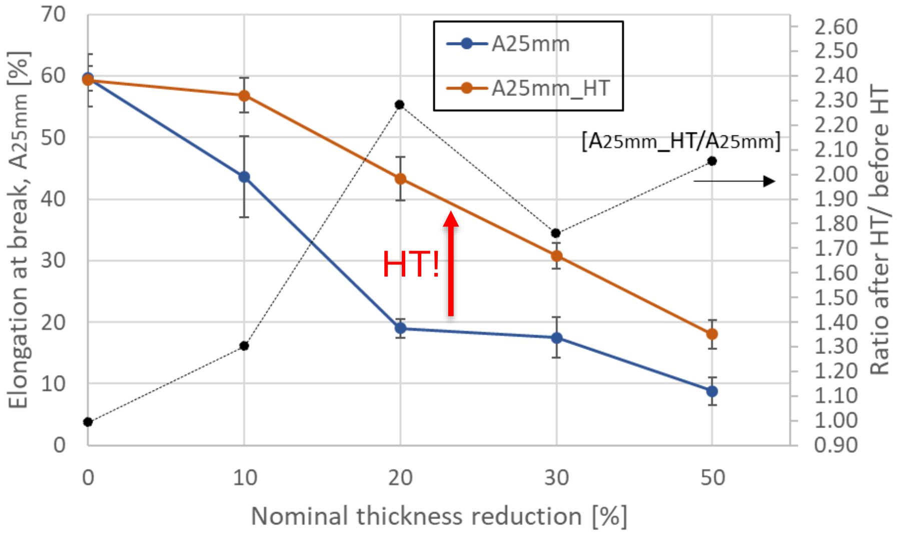
Mechanical properties of Nb after cold work and heat treatment

Yield strength (Rp0.2) and Ultimate strength (Rm) vs. Thickness reduction

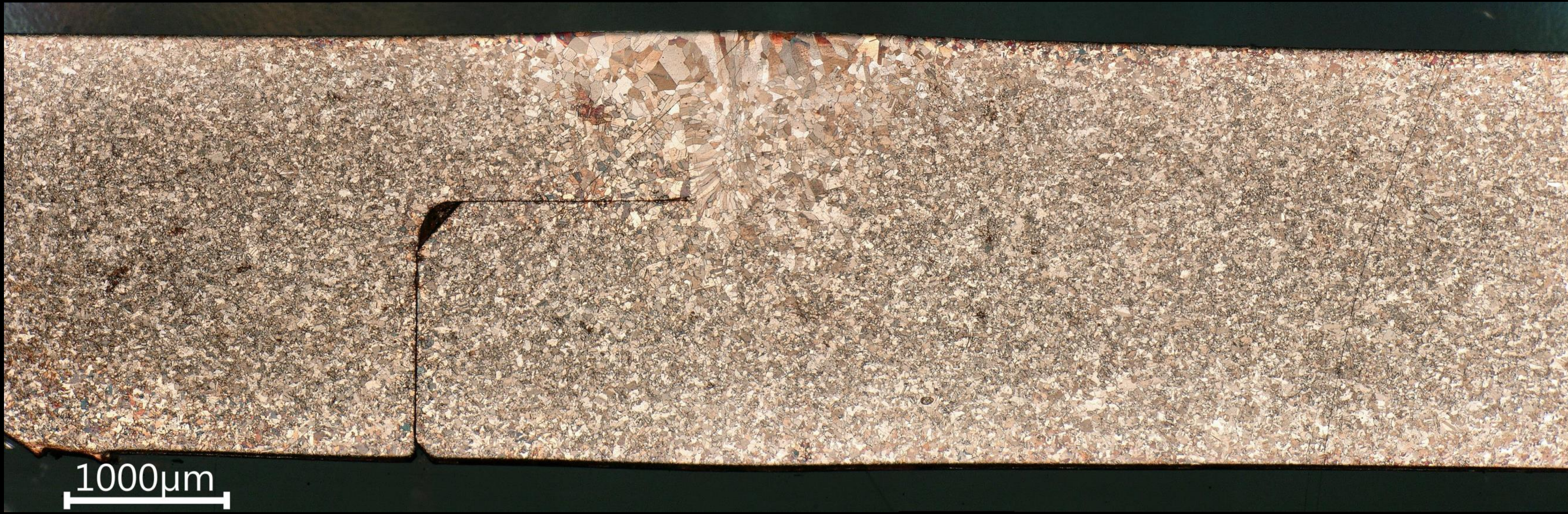


*Error bars represent one standard deviation

Elongation at break (A%) vs. Thickness reduction

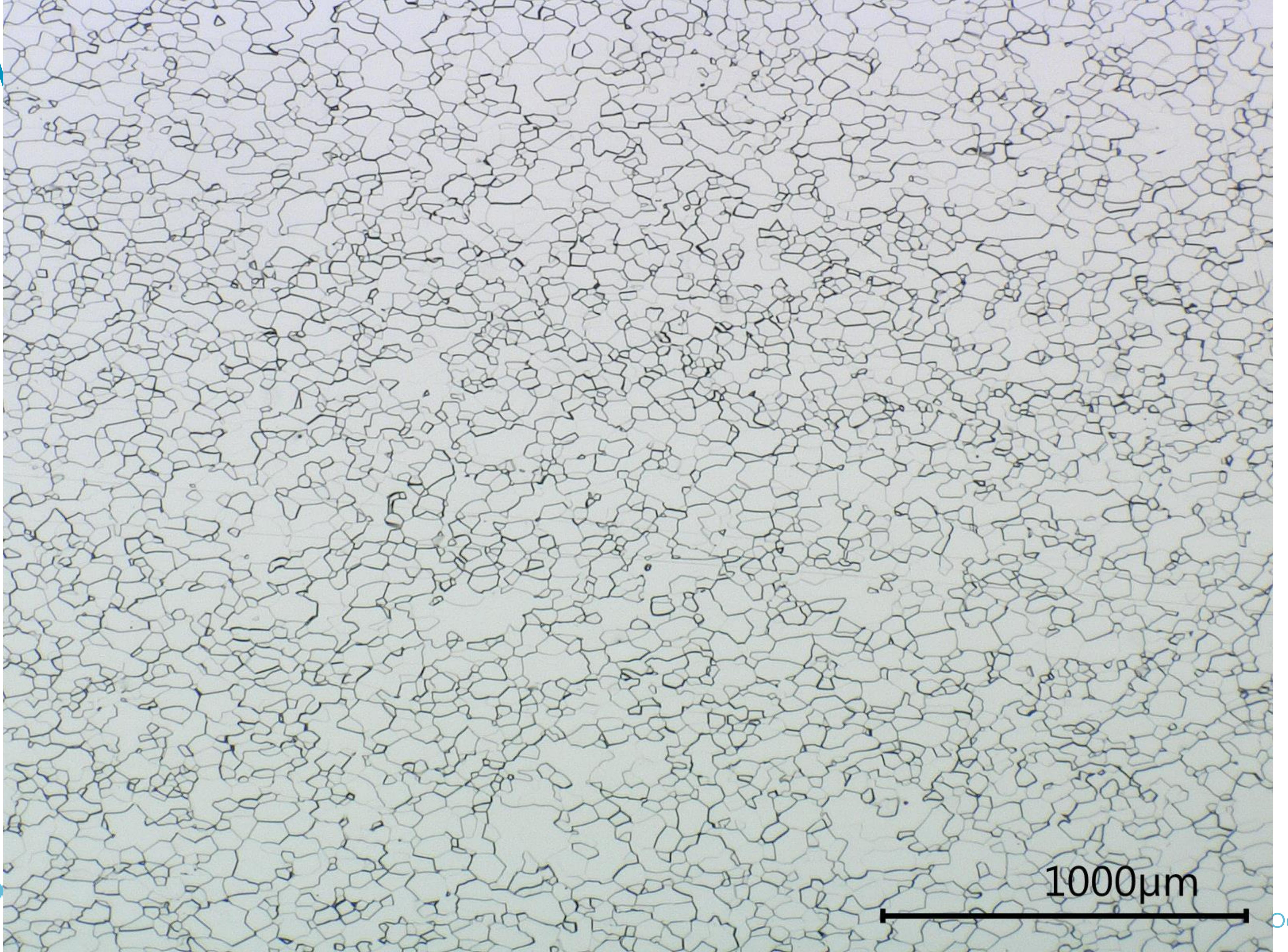


- **No full recrystallization after heat treatment - 650^{O}C, 24h - for none of the levels of plastic deformation studied**.
- Some of the cavity **components with lower Rp0.2 and Rm** would be **the ones non-plastically deformed during the manufacturing process!**



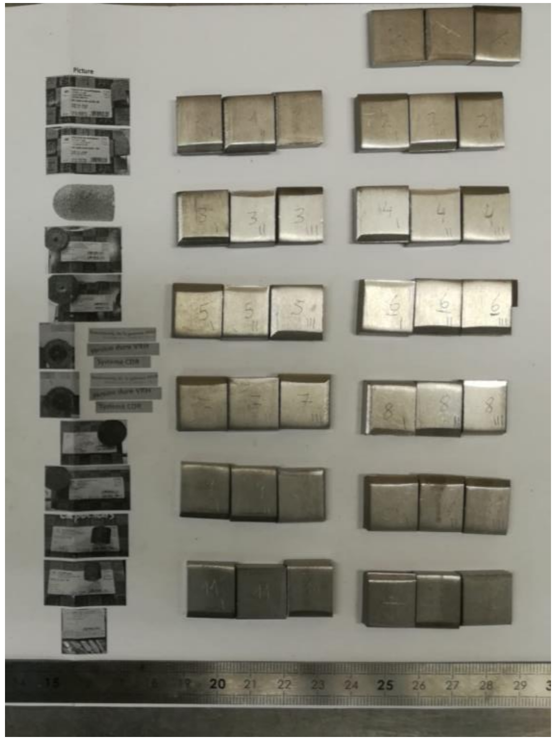
EB welds for HOMs

M



Studies of Nb surface cleanliness after use of several tooling & lubricants

- Check surface after using several grinding tools (compare different brands, abrasive media, grit size…).
- Determine minimum BCP thickness removal to eliminate embedded abrasives.



Sample #	Short name	Description	Abrasive material	Grit size (FEPA P)	eq. Grain size [µm]	Picture	BCP removal before	SEM analysis as-grinded	Comments as-grinded	BCP removal [µm]	SEM after BCP20	Comments after BCP20	embedded particles detected?
0	NO	NO_POLLUTION				-	30	manual	[illegible]	20	manual	[illegible]	NO
1	CAP 80	Palicap PC 1626 C SIC-COOL 80	SiC	80	201		[illegible]	manual - Automatic Particle Analysis (APA)	[illegible]	20	manual	[illegible]	[illegible]
2	CAP 150	Palicap PC 1626 C SIC-COOL 150	SiC	150	100		[illegible]	[illegible]	[illegible]	20	[illegible]	[illegible]	[illegible]
3	CO 120	Palicap PC WRC 1626 CO-COOL 120	corundum	120	125		[illegible]	[illegible]	[illegible]	20	manual	[illegible]	[illegible]
4	VRW 180	COMBIDISC CDR VRW (soft) Ø50 A 180	corundum	180	82		[illegible]	manual	[illegible]	20	manual	[illegible]	NO
5	VRW 280	COMBIDISC CDR VRW (soft) Ø75 A 280	corundum	280	52		[illegible]	manual	[illegible]	20	manual	[illegible]	NO
6	VRH 100	COMBIDISC CDR VRH (hard) Ø50 100G	corundum	100	162		[illegible]	manual	[illegible]	20	manual	[illegible]	[illegible]
7	VRH 240	COMBIDISC CDR VRH (hard) Ø75 240F	corundum	240	58		[illegible]	manual	[illegible]	20	manual	[illegible]	[illegible]
8	PNER	COMBIDISC CDR PNER-W 5006 C fine 50x6mm	SiC	320 - 600	46 and lower		[illegible]	manual	[illegible]	20	manual	[illegible]	NO
9	CK 180	COMBIDISC CDR 50 A 180 CK	SiC or corundum	180	82		[illegible]	manual	[illegible]	20	manual	[illegible]	[illegible]
10	GSB 60	GSB 2220 SIC 60	SiC	60	269		[illegible]	manual	[illegible]	20		[illegible]	[illegible]
11	GSB 150	GSB 2220 SIC 150	SiC	150	100		[illegible]	manual	[illegible]	20		[illegible]	[illegible]
12	PF 80	Poliflex PF KE 1025 6 AN 80 TX	corundum	80	201		[illegible]	manual	[illegible]	20		[illegible]	[illegible]

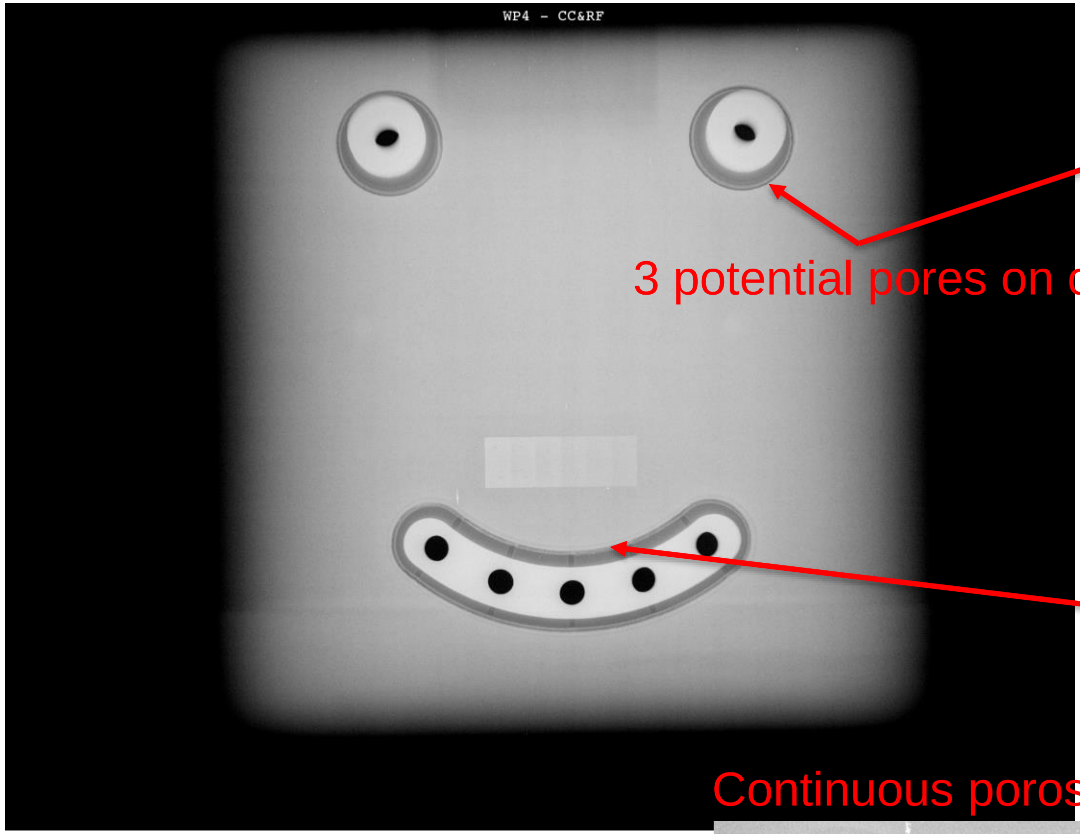
* All 39 (13 x 3) samples used have a squared dimension of about 1 cm2, they come from Ningxia sheet ID 502101 (CA6305450) and have seen a BCP of 30 micron per side (in order to clean the surface) before griding

Color Legend:

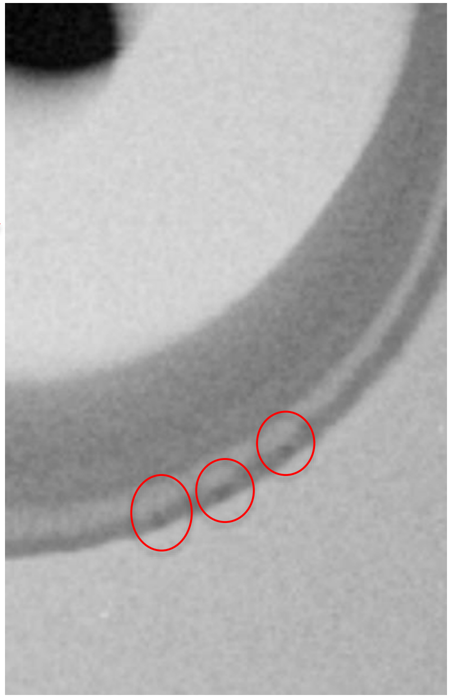
Summary table: EDMS 2258373

Thanks to M. Garlasche, L. Prever-Loiri, K. Eiler, A. Amorim Carvalho

X-ray radiography on Pin

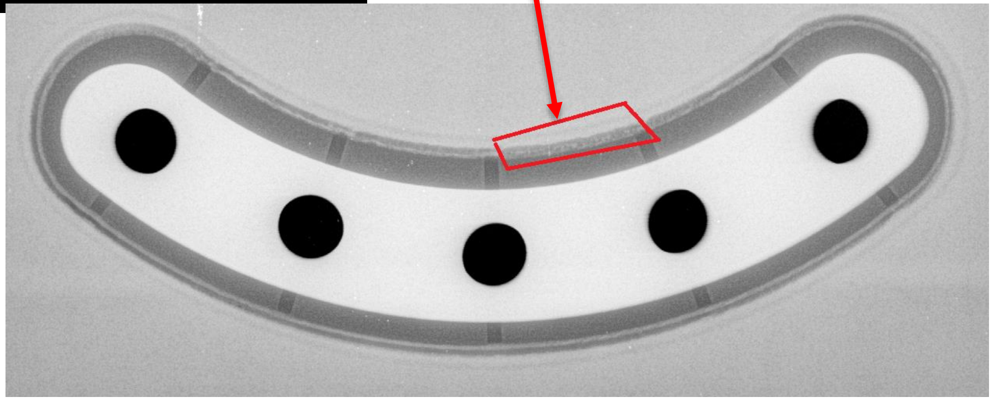


By Markus Viig Haavarstein EN-MME-MM



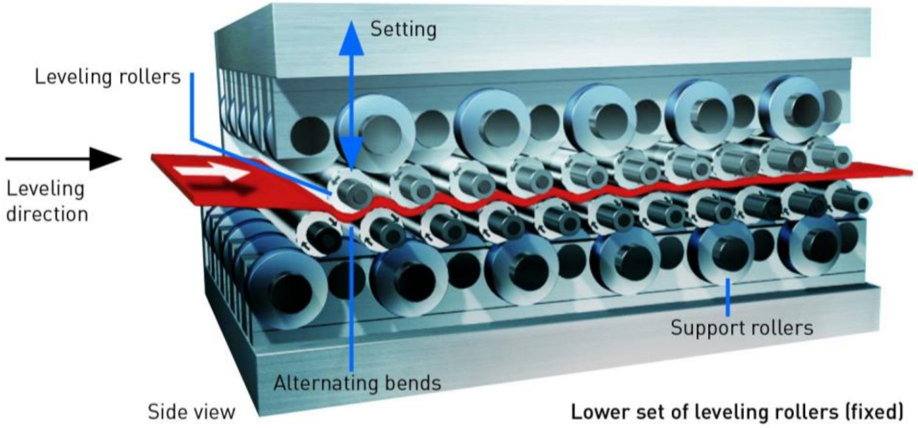
3 potential pores on one pin

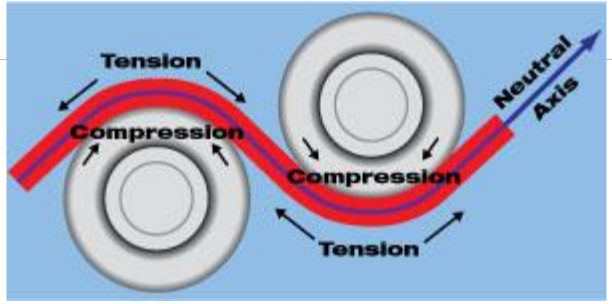
Continuous porosities in the banana?



Ways to increase Rp0.2 in rolled products

Levelling

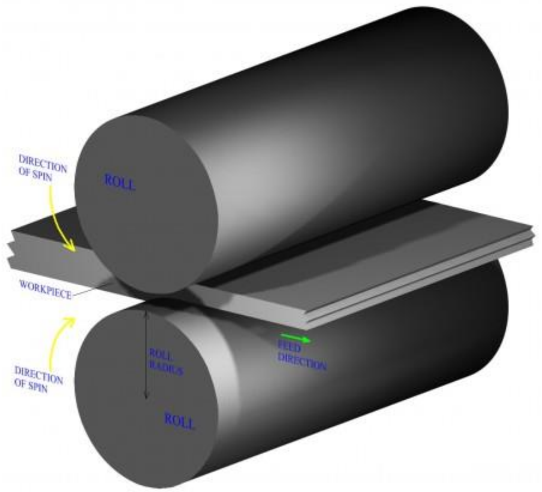




https://www.thefabricator.com/

Skin pass

Generally < 2% thickness reductions



https://thelibraryofmanufacturing.com