Optimizing the Manufacture of High-Purity Niobium (and Copper) SRF Cavities Using the Forming Limit Diagram

Adrià Gallifa-Terricabras (adria.gallifa@cern.ch), Joanna Sylwia Święszek[1,2], Eduardo Cano-Pleite[3], Marco Garlaschè[1], Dorota Smakulska[1], Simon Barrière[1], Laurent Prever-Loiri[1], Stephan Pfeiffer[1], Ignacio Aviles Santillana[1], Manuele Narduzzi[4]

[1]CERN (CH), [2]Kraftanlagen Nukleartechnik GmbH (GE), [3]UC3M (ES), [4]Fermilab (US)

21st International Conference on Radio-Frequency Superconductivity (SRF 2023), Grand Rapids, US. 25-30 July 2023.

What do these parts have in common?

Seamless 1.3 GHz elliptical cavity (Cu substrate) made by hydroforming. Courtesy M. Yamanaka, A. Yamamoto, KEK (2023)

HL-LHC Crab Cavities RFD Pole forming trial, CERN (2022).

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Key parts of SRF cavities

Large deformation processes

FE simulations + FLD can provide useful insights

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Motivation:

- Master large deformations
- Assess process feasibility
- Increase productivity
- Reduce costs

Key parts of SRF cavities

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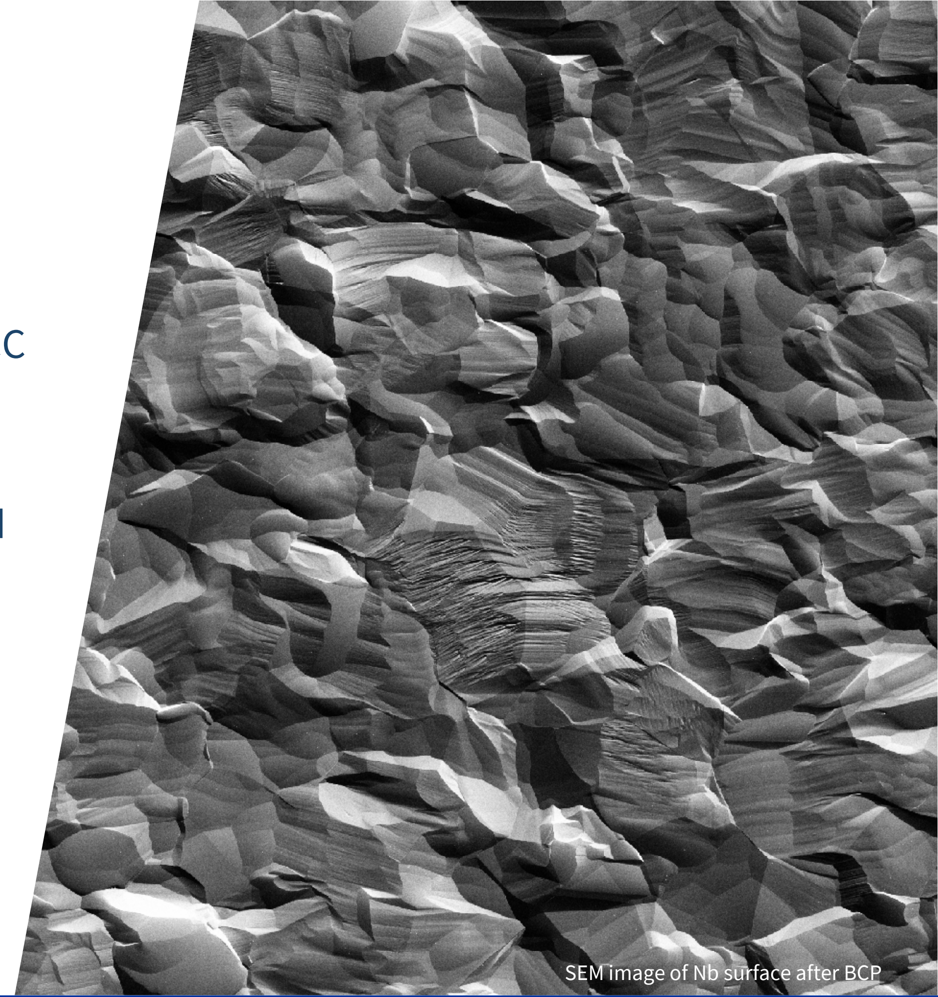
- **Future work** and Conclusions



SEM image of Nb surface after BCP

Failure… It's part of success

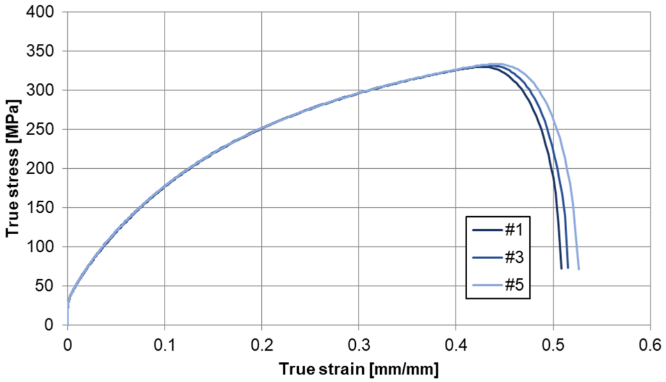
Inputs needed for FE simulation of metal-sheet forming process (e.g. hydroforming, deep drawing):

Initial part geometry, material model/properties, tooling/mold geometry, final geometry, forces/displacements/speeds involved, friction coefficients, …

But need of a crucial aspect → a Failure criteria

What is the maximum deformation a material (i.e. a Cu tube) can withstand?

- **Is it enough to consider the maximum strain after a tensile test?**

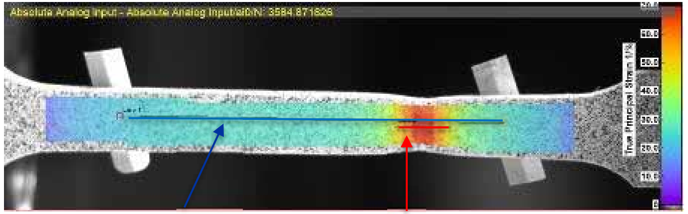


https://datagenetics.com/blog/december22013/index.html

‘Local’ vs. ‘macro’ strain & the role of the Strain Path

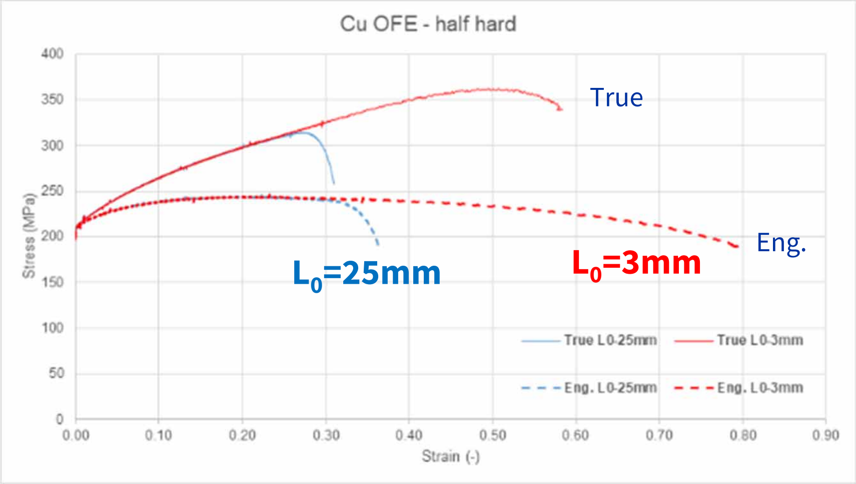
The **gauge length** size vs. the **necking size** matters:

Tensile test with DIC



Standard extens. L0=25mm

Local extensometer. L0=3mm



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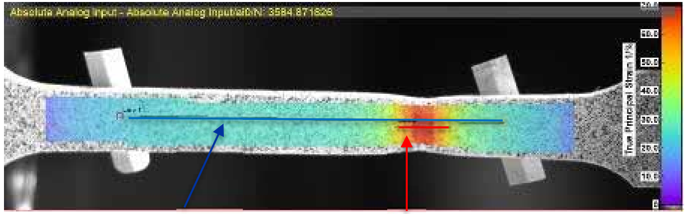

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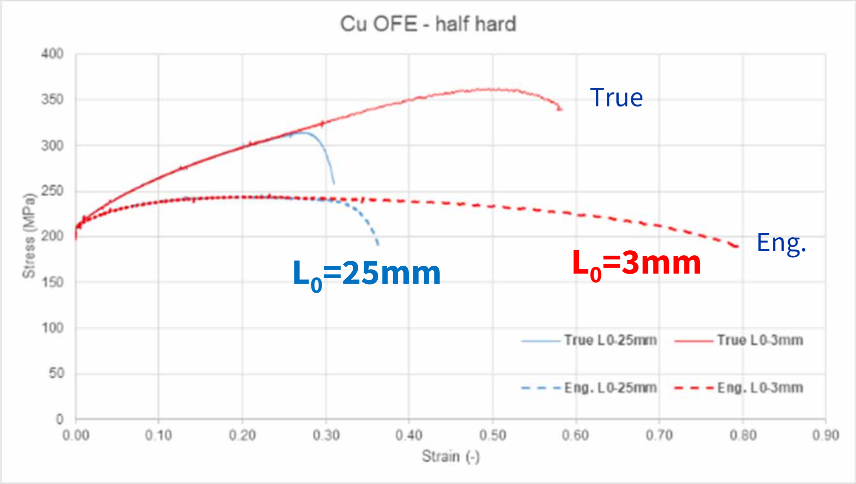
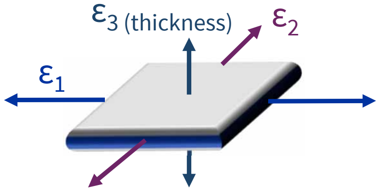
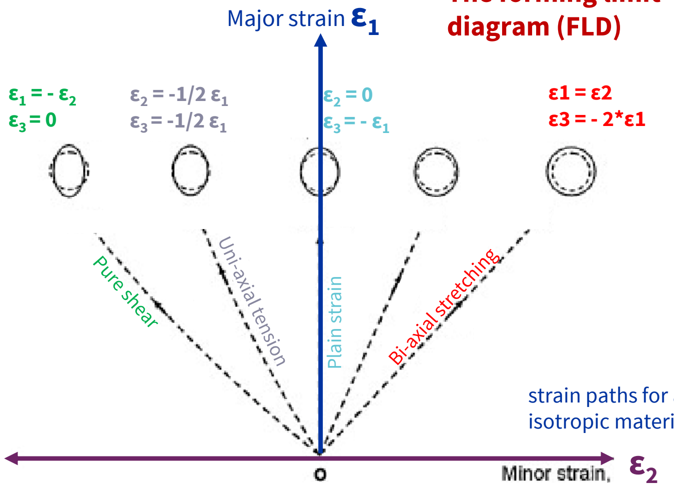


Relationship between ε_1 , ε_2 and ε_3 along the deformation process (i.e. **strain path**) matters:



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

The forming limit diagram (FLD)

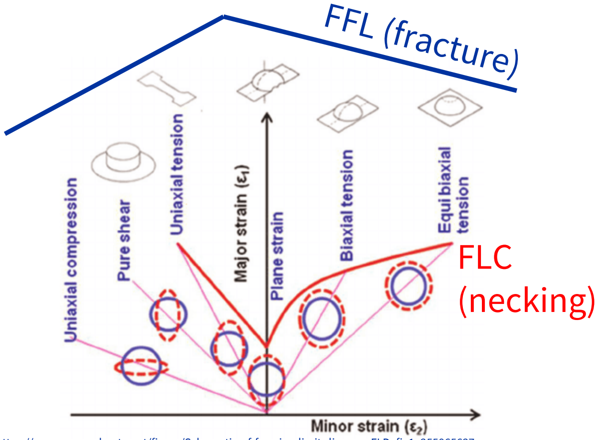


Adatped from: Kesvarakul, R., & Sresomroeng, B. Electrochemical Grid Etching Apparatus for Strain Analysis in Sheet and Tubular Blank.

The Forming Limit Diagram (FLD)

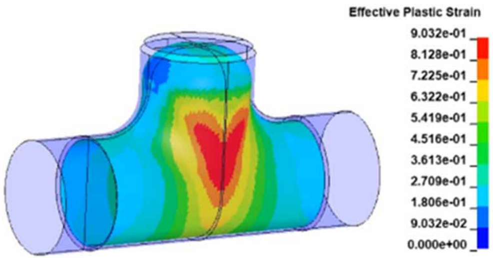
- **Failure criterion** that focuses on **strains** (goal for RF cavities: reach final shape while minimising forming + annealing steps)
- Adequate for **membrane-like materials** (thin-wall, shells.. for which D/t >>1), given that the strain path is linear (e.g. hydroforming).
- **Information about the strain path** (unlike 'effective plastic strain')
- Can include **failure by necking** (Forming Limit Curve, FLC) **or by fracture** (FFL, SFFL).
- **Established method** for failure detection in metal-sheet forming **in industry (ISO 12004-1 & 2)**
- **Obtained Experimentally** → Nakajima or Marciniak tests; or estimated theoretically from material parameters.

https://www.zwickroell.com/industries/materials-testing/sheet-metal-forming/cupping-test/forming-limit-curve-flc-iso-12004/



https://www.researchgate.net/figure/Schematic-of-forming-limit-diagram-FLD_fig1_255965627

By **FE simulations**:
Obtain **ε_1 – ε_2 pairs** for all elements → plot them in FLD



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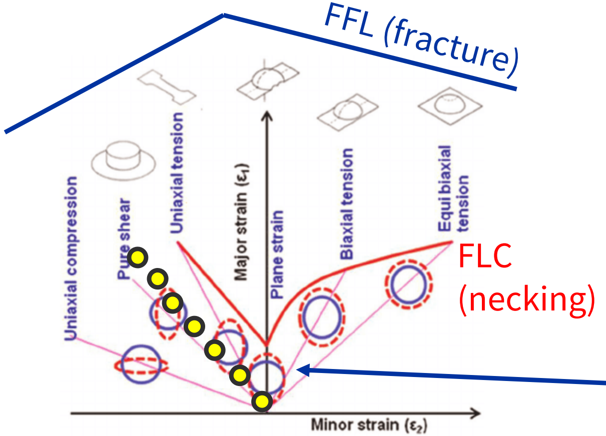

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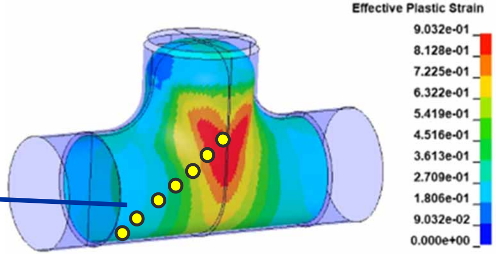

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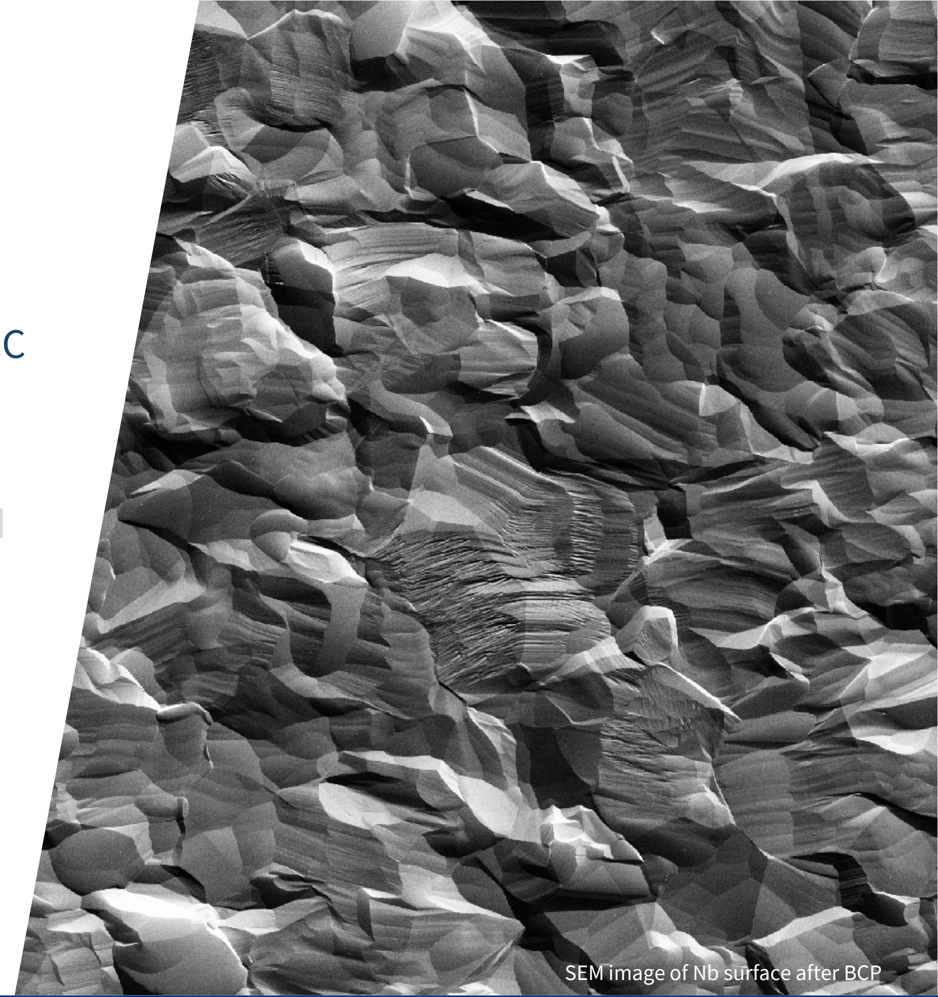

SEM image of Nb surface after BCP

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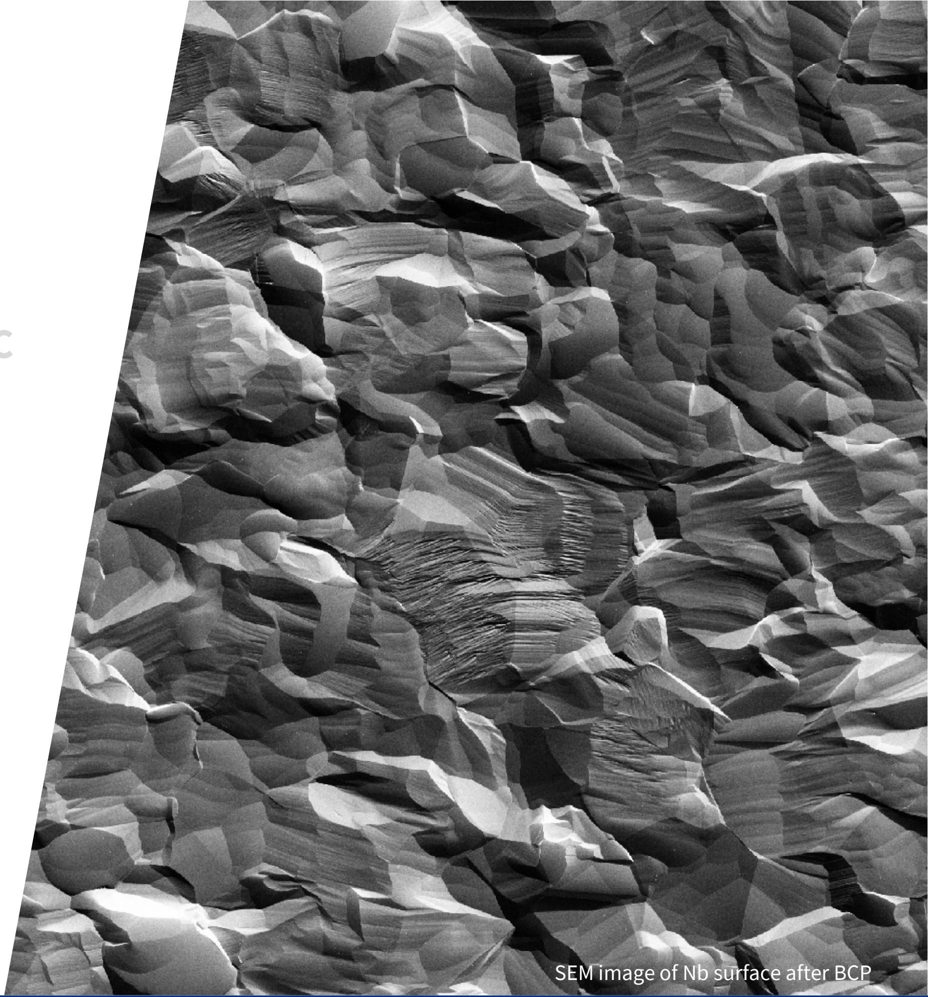

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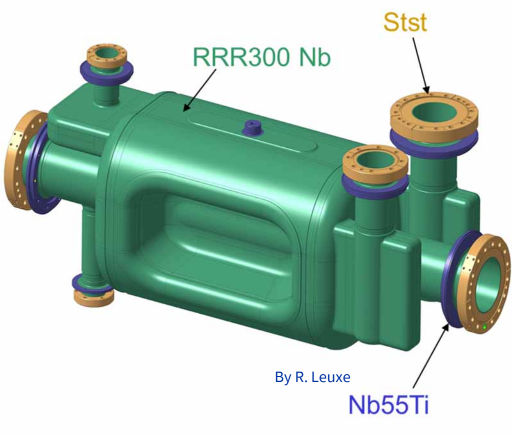
HL-LHC Crab Cavities

See talk by Katarzyna Turaj, "RF Performance Results of DQW for HL-LHC"

Series production ongoing nowadays

- 2 cavities/beam/Interaction point (at ATLAS and CMS)
- 16 cavities (in 8 cryomodules) in total
- Prototypes: development & manufacturing at CERN (EN-MME, SY-RF)
- Series cavities and Cryomodules → Intl. collaborations & Industry



RFD Crab Cavity, CERN, FNAL.

Multi-technology fabrication: Deep Drawing, Machining, EB Welding, Vacuum Brazing, BCP Surface Processing and high/low Temp. Heat Treatments..

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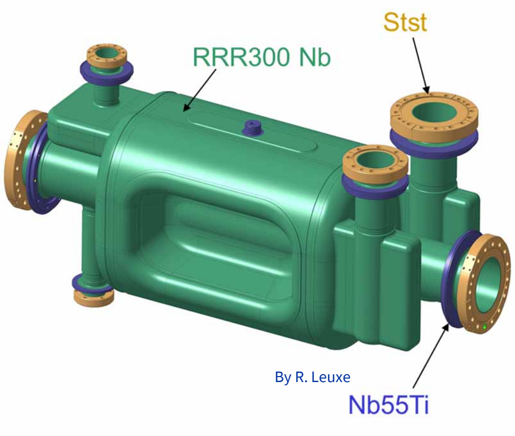

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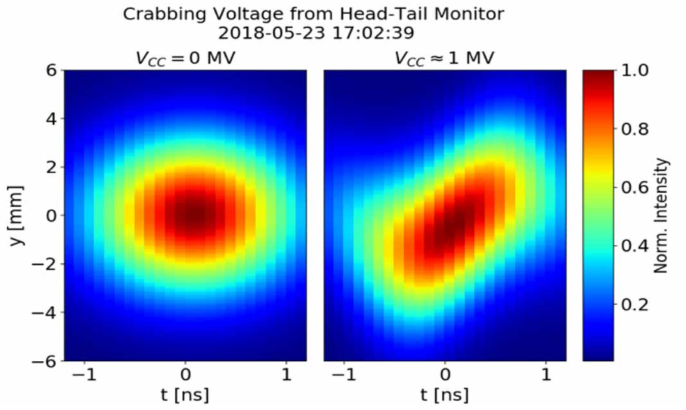
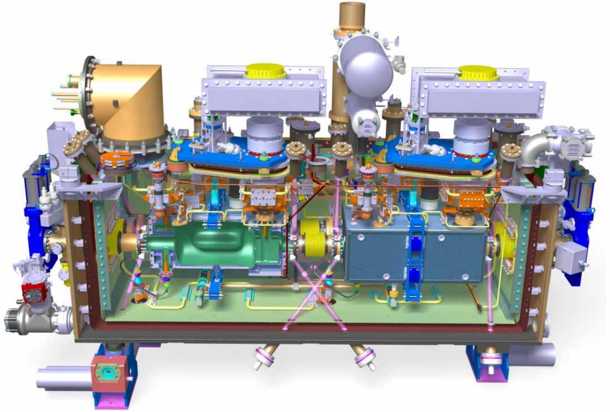


23 May 2018: first proton crabbing with 1 MV, R. Calaga.



The HL-LHC RFD Crab Cavity Cryomodule, T. Capelli.

Multi-technology fabrication: Deep Drawing, Machining, EB Welding, Vacuum Brazing, BCP Surface Processing and high/low Temp. Heat Treatments..

Challenges with RFD Pole forming

Min. thickness on corners ~ 2.3 mm

RFD pole forming trials for pre-series cavities, courtesy ZRI SRL.

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.

Challenges during deep drawing of RFD Pole – Benchmark at CERN

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

Challenges during deep drawing of RFD Pole

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

↓

Very different outcome!

Why?

Lot-1 (forming OK)

Lot-2 (forming NOK)

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

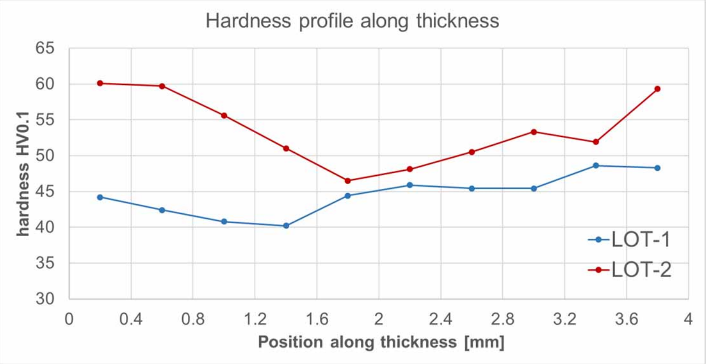
Materials investigation – Microstructure analysis

Lot-1 (forming OK)

ST
RD

Lot-2 (forming NOK)

thickness 4mm



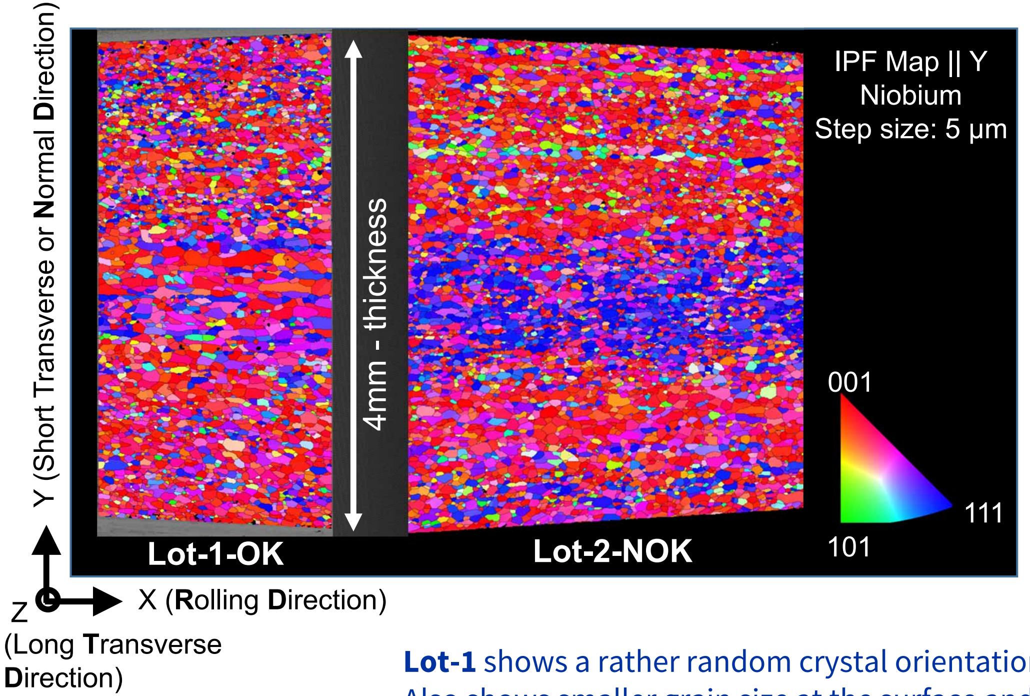
Both sheets show a recrystallized, similar microstructure.
Average grain size is very similar.

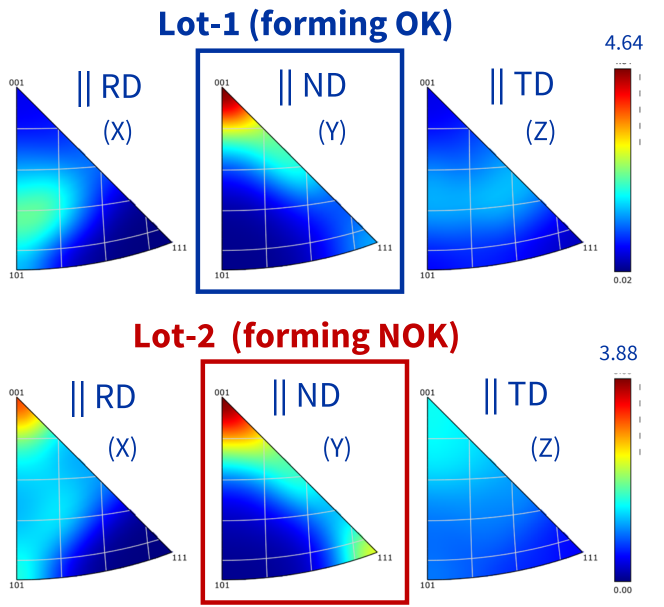
Lot-2 (NOK) presents a 'V-shape' hardness profile, presumably due to levelling or skin pass.

Influence of crystallographic orientation?

The supplier claimed that both lots have seen the same thickness reduction and multiple cross-rolling steps, with a final levelling operation.

EBSD – Crystallographic orientation and texture





Lot-1 shows a rather random crystal orientation || RD and || TD.
Also shows smaller grain size at the surface and slightly larger in the mid-thickness.
Lot-2 shows a more pronounced texture of type (001) in all directions.
Banded texture through thickness (|| ND): (001) band + (111) band at mid-thickness + (001) band.

Materials investigation – Mechanical tests

Lot 1 - OK

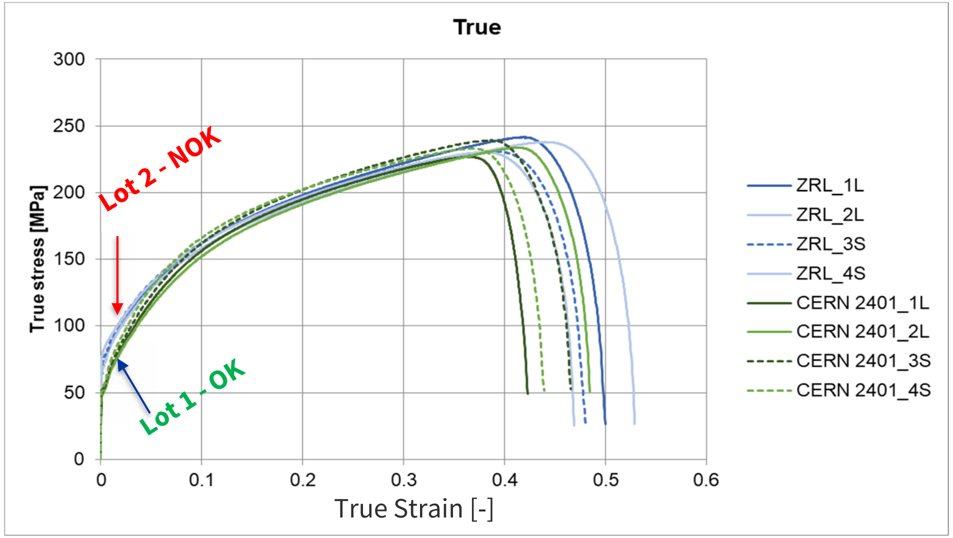
Specimen designation	$R_{p0.2}$ MPa	R_m MPa	A_g %	A_{25mm} %	$n_{0.02-0.20}$	$R_{p0.2}/R_m$
2082401_1L	*53.0*	*161.6*	*30.9*	*52.6*	**0.38**	**0.33**
2082401_2L	*49.5*	*159.4*	*33.0*	*62.3*	**0.38**	**0.31**
2082401_3S	*51.4*	*167.7*	*31.3*	*59.2*	**0.37**	**0.31**
2082401_4S	*53.6*	*166.6*	*27.9*	*55.1*	**0.35**	**0.32**

Material shows low Rp0.2 (<65 MPa)

Lot 2 - NOK

Specimen designation	$R_{p0.2}$ MPa	R_m MPa	A_g %	A_{25mm} %	$n_{0.02-0.20}$	$R_{p0.2}/R_m$
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 that shows bad formability complies with CERN Nb spec. 3300 Ed.4 and DESY Nb Spec.!

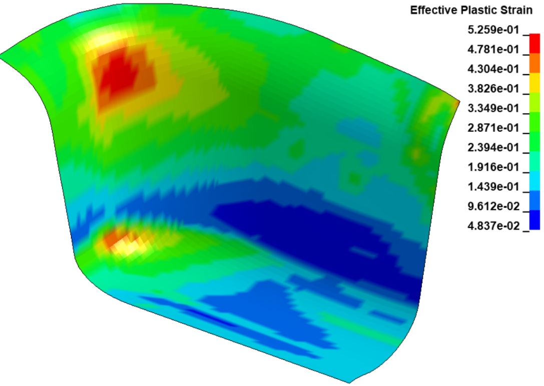


Strain hardening coefficient ‘n’ value seems to be significantly different, as well as the ratio Rp0.2/Rm

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.

Finite Element (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

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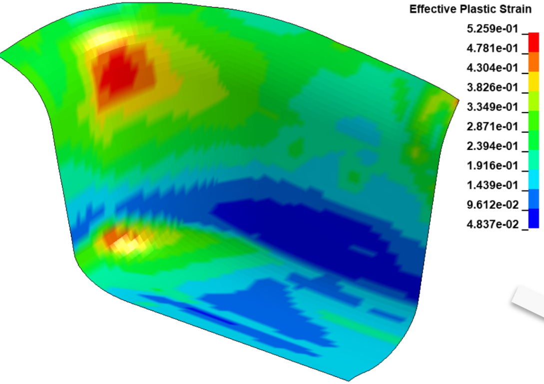

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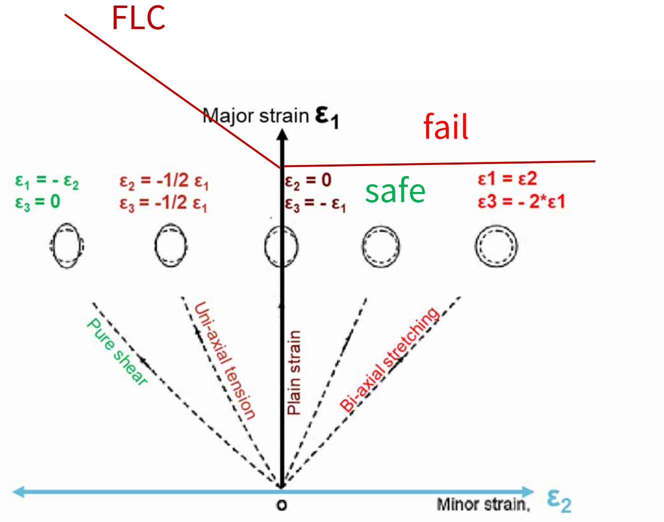

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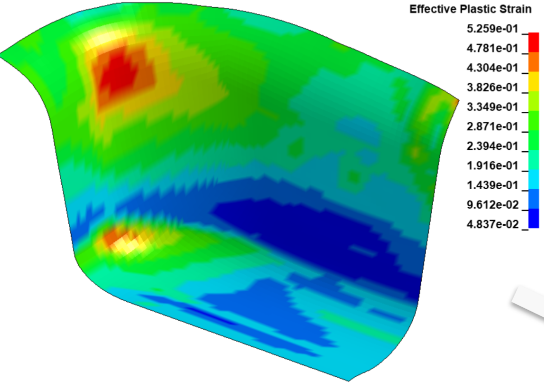

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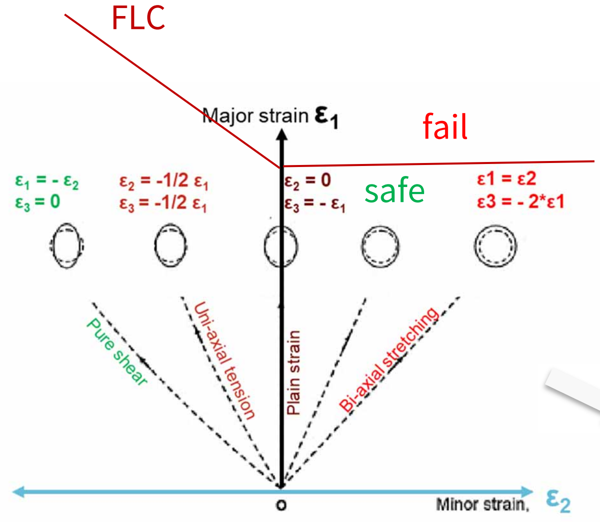
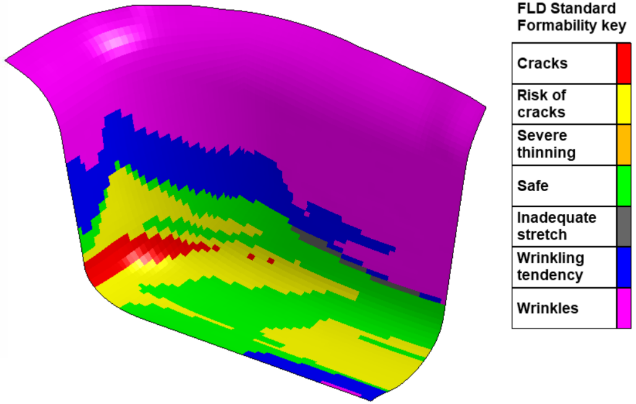
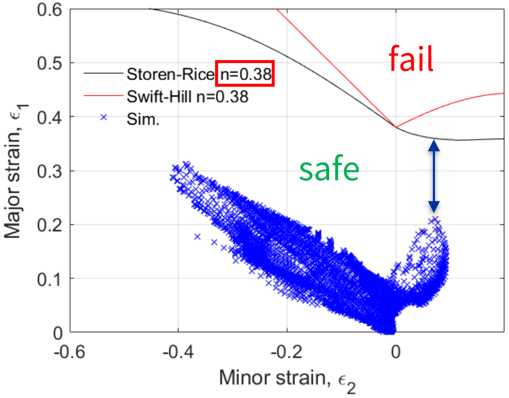




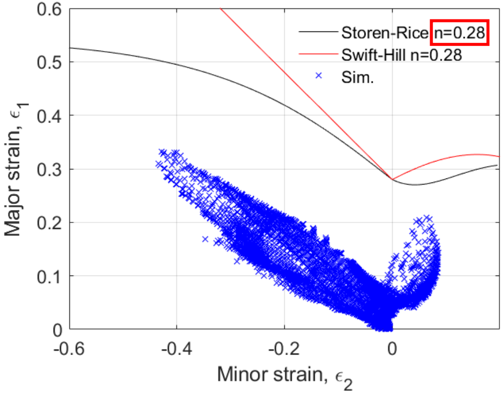
Simulations performed with LS-DYNA. Thanks to J. Swieszek & E. Cano-Pleite

Challenges with RFD pole forming

Lot 1 - OK



Lot 2 - NOK



Coefficient of Friction = 0.03

(Simplified case:
Strain rate sensitivity and anisotropy not considered in this example)

Thanks to J. Swieszek & E. Cano-Pleite

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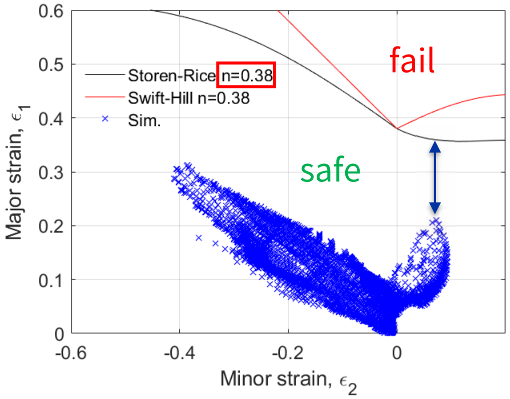

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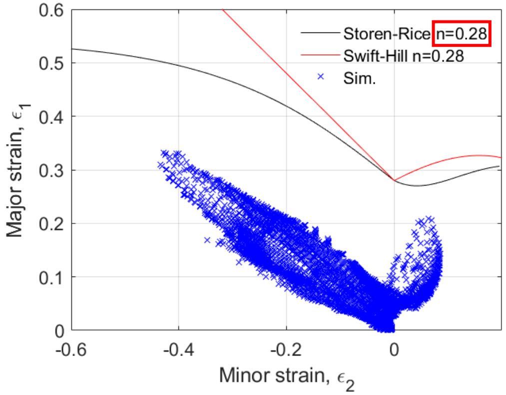
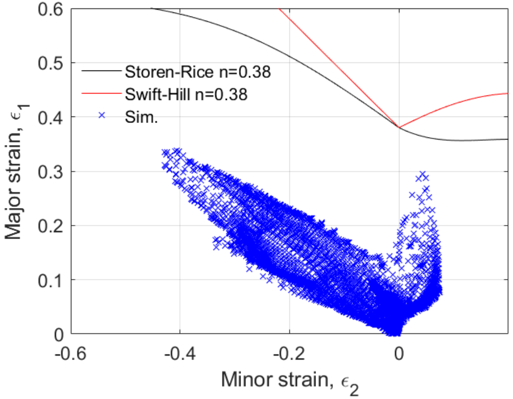


Coefficient of Friction = 0.18

(CoF estimated via experimental tests)

Lot 1 - OK



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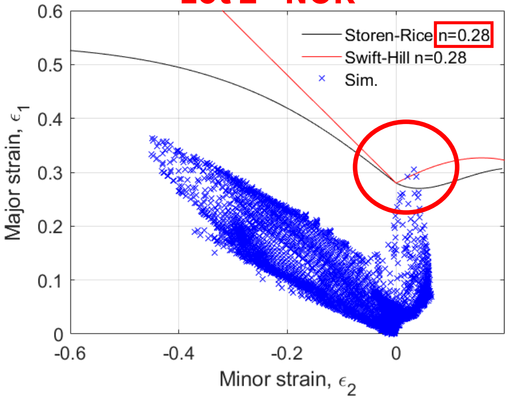

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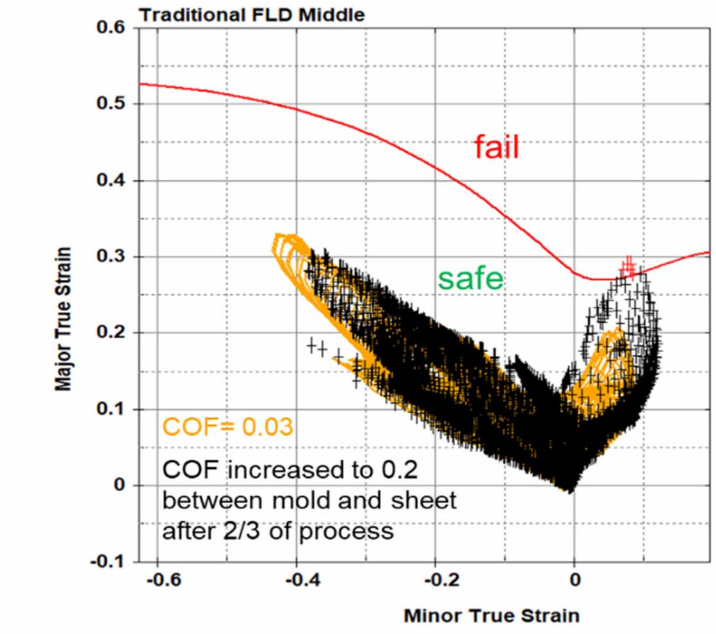
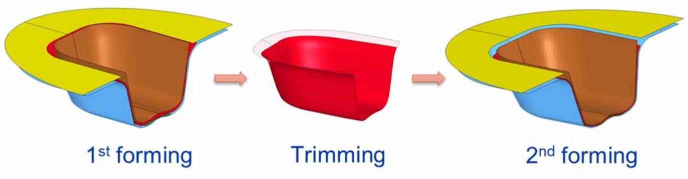
Potential ways of improving formability

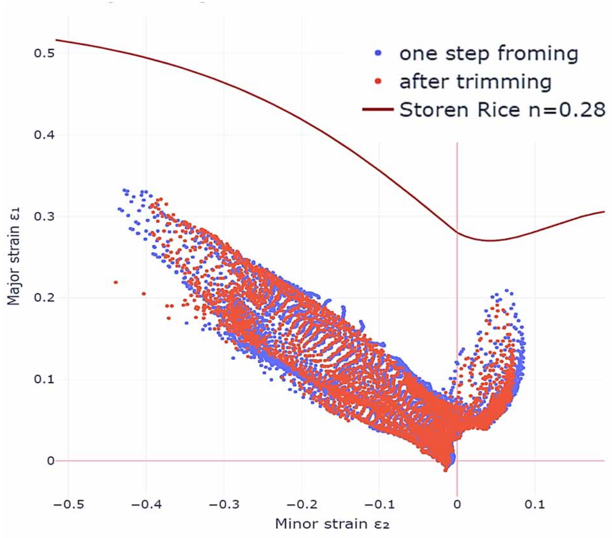
Improve lubrication (Reduce friction)



2 step process: Trimming leftover before reaching the final shape



(Solution proposed by ZRI SRL, AUP collaboration)

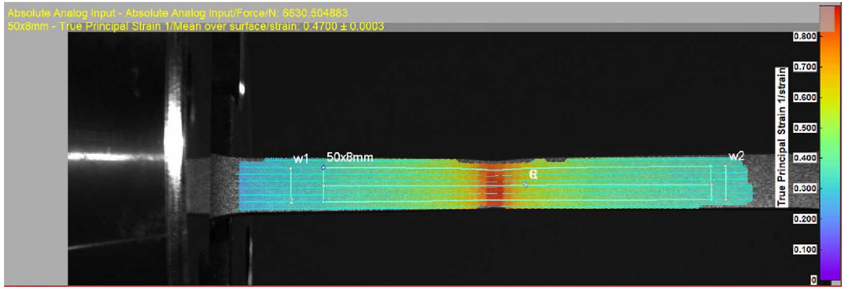


Ongoing work and future research

- Improved FLD for Nb → **need for experimental data for thick sheets (around 4 mm thickness)**

- **Refined material model for FE simulations**
  → include **anisotropy**, strain rate sensitivity

Solve **open questions**: **effect of trimming**, **effect of sheet orientation**, texture vs. formability → more accurate failure prediction



Tensile test with DIC

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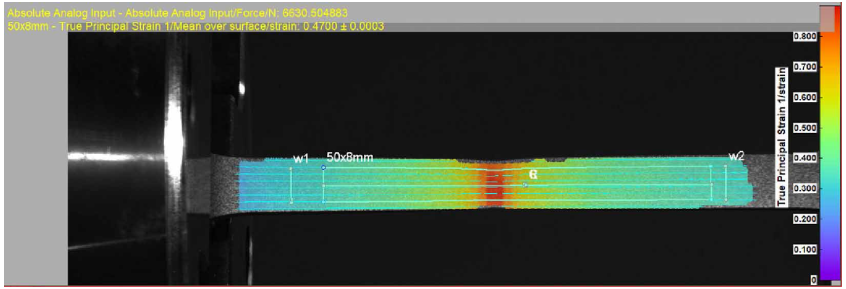
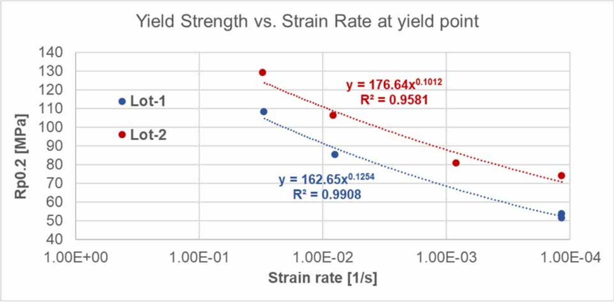


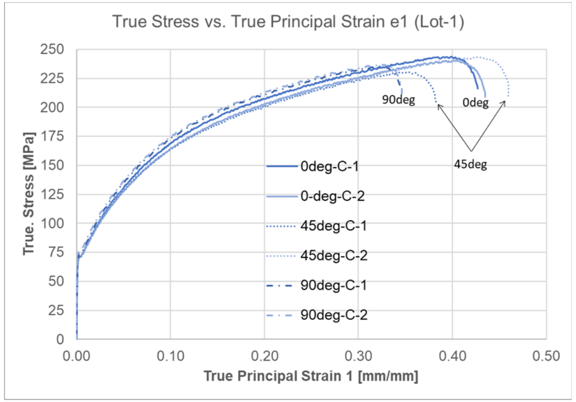
Tensile test with DIC

Preliminary results:

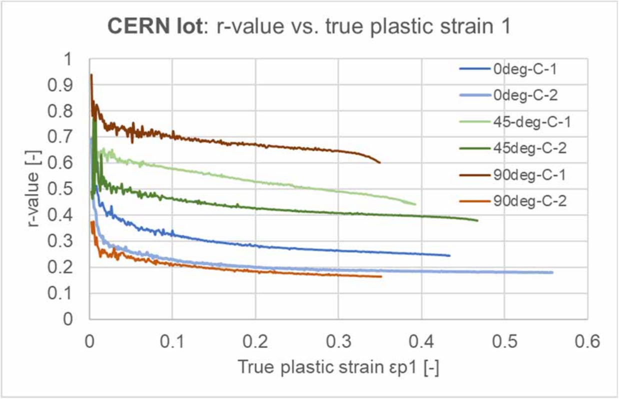
Strain rate sensitivity



Stress-strain curves @5E-3 1/s at 0, 45 and 90°



Anisotropy (R-values, or Lankford coefficients)



Ongoing work and future research: The 'SRFLD'

NOVEL APPROACH OF FAILURE FOR SRF APPLICATION: **SRFLD**

- **Evolving Forming Limit Diagram** to incorporate features of interest for both fabrication and SRF.
- A tool for **prediction** of **parameters of interest**, (final surface roughness, wall thickness..) **vs. strain path.**

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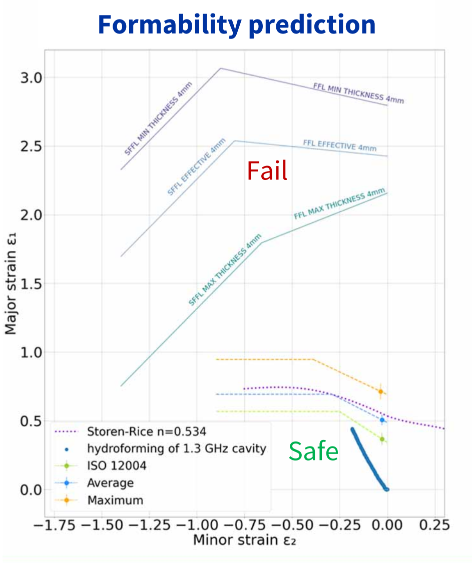

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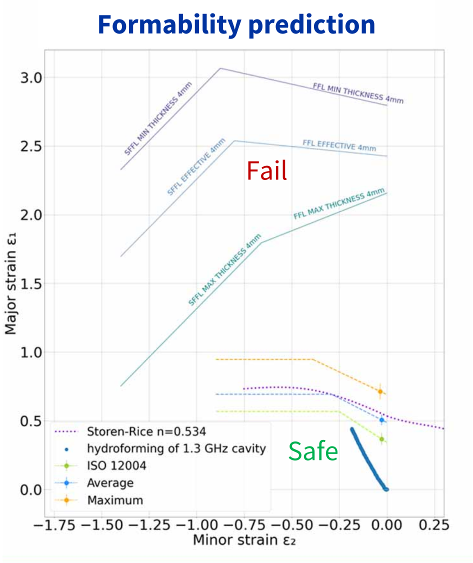

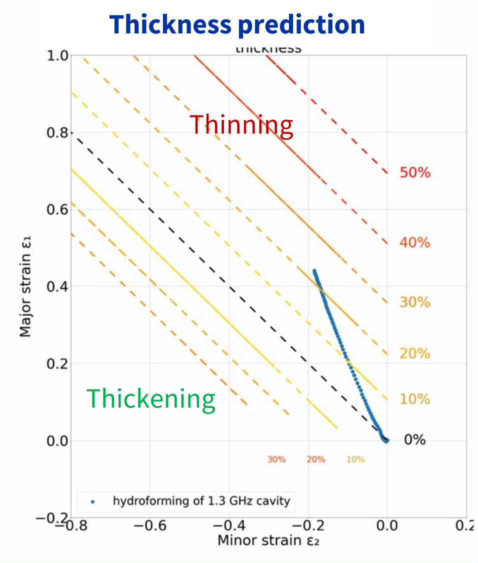

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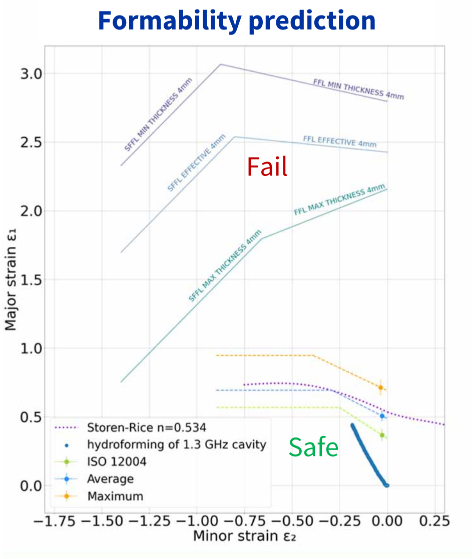

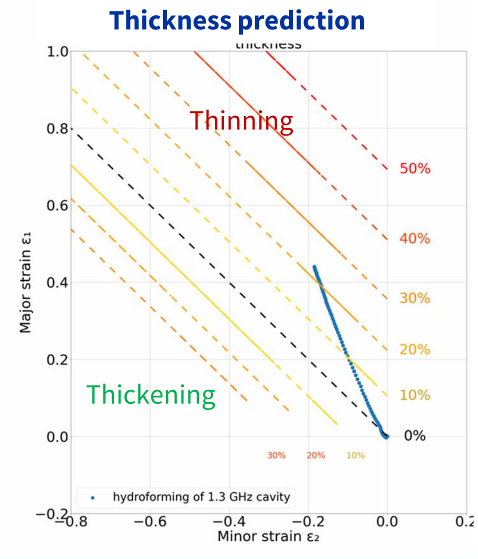

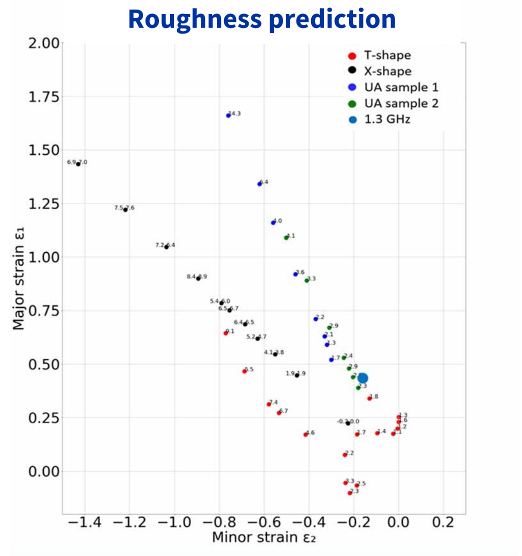

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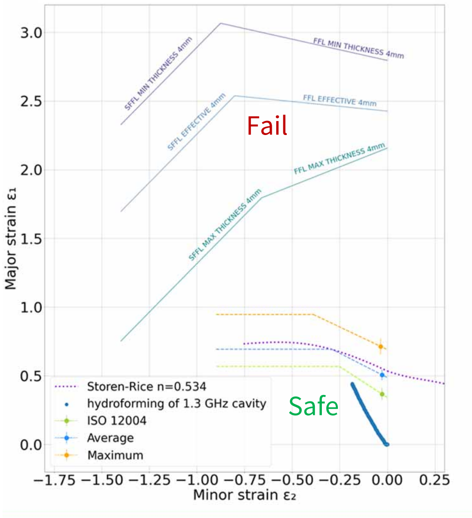
Powerful tool that can be used for many large deformation processes for SRF fabrication

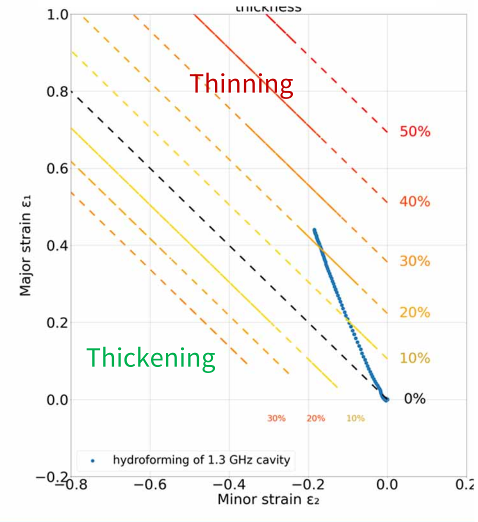
Regularly collecting data to improve the plots

See paper/poster by Joanna Swieszek

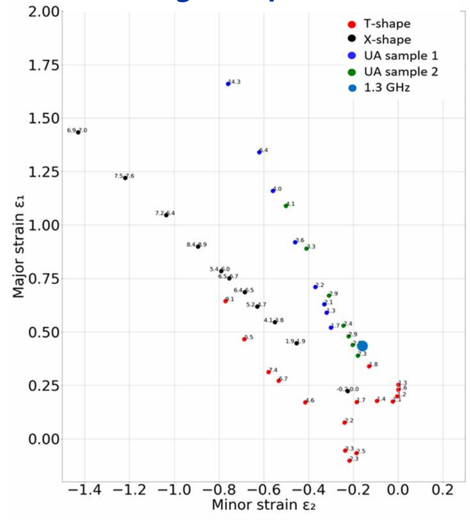
Formability prediction



Thickness prediction



Roughness prediction



Conclusions

- **FLD for Cu OFE is well mastered** and already helped to optimize **manufacturing of seamless 1.3 GHz cavities → developments towards 400 MHz ongoing**

- Nb is more complex: **FLD for Nb thick sheets** lacks of experimental data, **FE material model is being improved** (anisotropy, strain rate sensitivity…)
  - **Formability** of Nb seems influenced by **microstructure texture** at a microscopic level, which is translated in different macroscopic mechanical behaviour. Main differences in macroscopic mechanical properties are **strain hardening index *n*, Rp0.2/Rm, hardness profile**.
  - **Reducing friction** (improve lubrication) and leftovers **trimming before reaching final shape** are suitable methods for **improving formability** for a given material lot.
  - **Challenging to include certain material properties** (texture, strain hardening index) **in material specifications for Nb** if we want to keep it realistic in views of the current market situation.

- CERN keeps building **know-how** on **fabrication** processes, advanced **FEM simulations** and **material and failure characterization** (SRFLD,..).

- **FE simulations* + adequate failure criteria*, like FLD →** powerful tool to assess forming **process feasibility, increase productivity and reduce costs.**

***Backed up with accurate and targeted experimental data**

References and further reading

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Thanks for your attention

Optimizing the Manufacture of High-Purity Niobium (and Copper) SRF Cavities Using the Forming Limit Diagram

Adrià Gallifa Terricabras, **Joanna Sylwia Święszek[1,2], Eduardo Cano-Pleite[3], Marco Garlaschè[1], Stephan Pfeiffer[1], Simon Barrière[1], Laurent Prever-Loiri[1], Ignacio Aviles Santillana[1], Manuele Narduzzi[4]**

[1]CERN (CH), [2]Kraftanlagen Nukleartechnik GmbH (GE), [3]UC3M (ES), [4]Fermilab (US)

Adria.Gallifa@cern.ch

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