Electro-Hydraulic Forming of Niobium

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8th February 2016

ELECTRO-HYDRAULIC FORMING (EHDF)

Objectives:

- Produce symmetric and asymmetric RF cavities with EHDF;
- Thorough understanding of the EHDF process:

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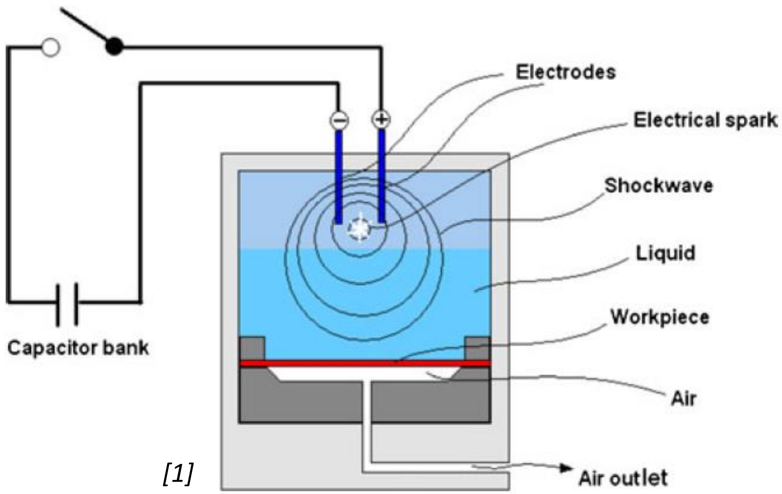
- Optimization of the process parameters: collaboration with BMAX;
- Forming: validate EHDF and compare this technology with spinning;
- Material behaviour: evolution of microstructure during high speed forming (change of grain orientation and dislocations behaviour)

Next Deadline: FCC conference 11th-16th April 2016

ELECTRO-HYDRAULIC FORMING (EHDF)

EHDF performed at BMAX



Parameters to be considered during EHDF:

- Position of electrodes;
- Input energy magnitude;
- Input energy duration;
- Chamber geometry;
- Type of material to be formed (thickness);

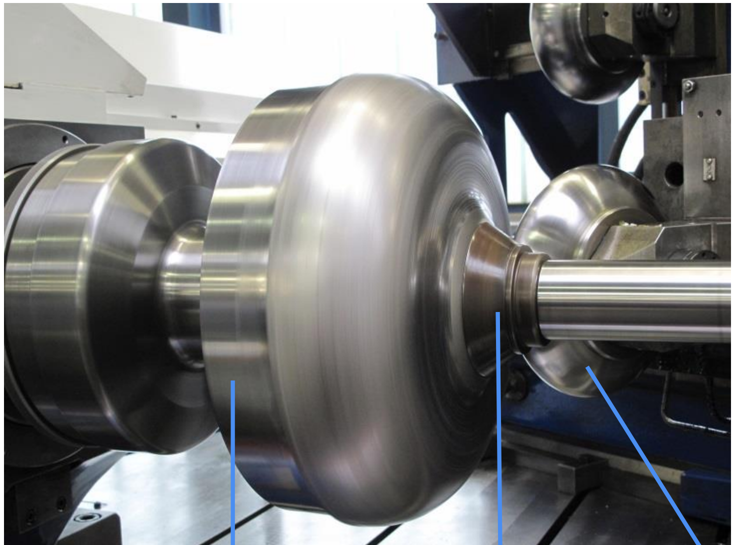
✓ Strain rate is determined by sheet/die interaction (max strain rates reported in literature $2 \times 10^4\ s^{-1}$);

✓ FEM modelling of EHDF: isotropic yield function + Johnson-Cook rate dependent model;

$$\sigma = \left[A + B \cdot \overline{\varepsilon_{pl}}^{n}\right] \cdot \left[1 + C \cdot ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$$

SPINNING

Spinning of half-cells



Mandrel

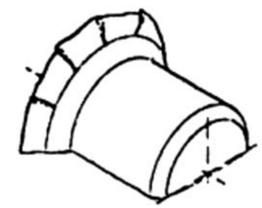
Tail stock

Forming Roller

Possible defects:

Wrinkle formation due to tangential compressive stresses

Circumferential cracks due to radial tensile stresses



Radial cracks due to tangential compressive stresses and bending stresses

Disadvantages of spinning compared to EHDF:

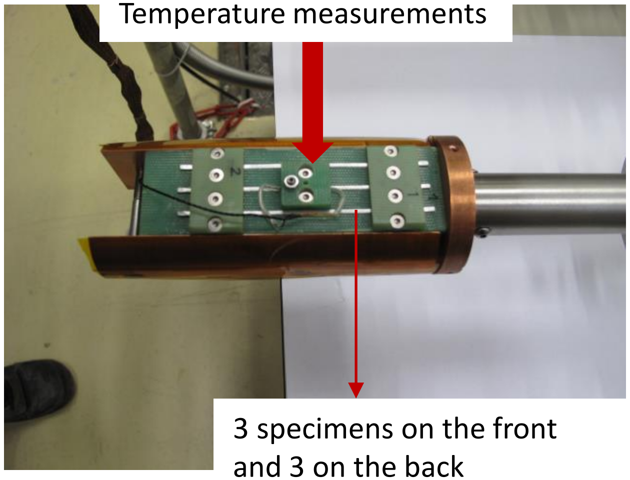
- Multiple steps required to shape blank into final profile without defects;
- Several steps of deformation can accumulate stresses causing wrinkles;
- Many parameters to be adjusted: Feed ratio, Roller path, Roller design, Spinning ratio;

Nb SHEET: RRR MEASUREMENTS

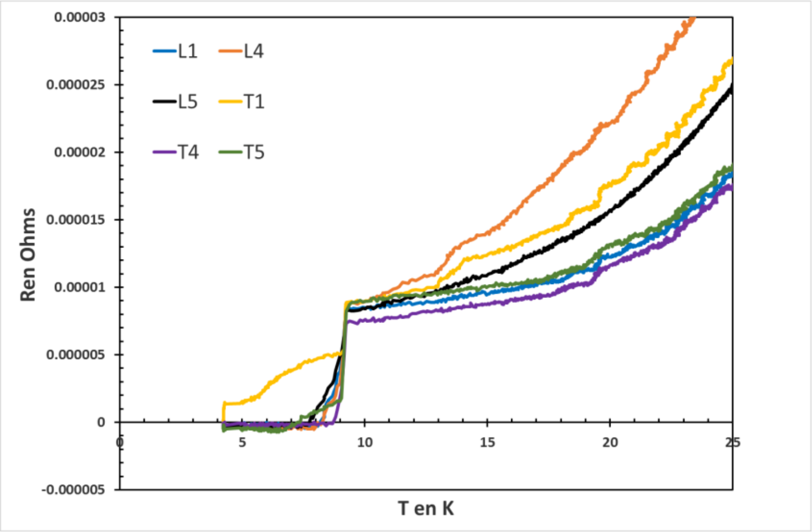
- 5 specimens cut in longitudinal direction of the Nb sheet;
- 5 specimens cut in transversal direction of the Nb sheet;

Raw Dimensions:
2mm x 2mm x 100mm

- Specimens were degreased and chemically attacked to remove 300 µm;



Resistivity versus temperature curves



- Applied current 5 A;
- Warm-up and cool-down procedure performed by using liquid He;

Nb SHEET: RRR MEASUREMENTS

- Best results obtained by regression of the resistivity vs temperature curves in the range 9.3K up to 17-20K;
- Best regression with exponential function: ρ(T) = a*exp(b*T) +c

$$RRR = \frac{R(295K)}{R(4.2K)}$$

Longitudinal Specimen	exponential interpolation RRR (from 9.2K to 17/20K) RRR=ρ(295K)/ρ(4.2K)	Transversal Specimen	exponential interpolation RRR (from 9.2K to 17/20K) RRR=ρ(295K)/ρ(4.2K)
L1	401	**T1**	375
L2	412	**T2**	358
L3	399	**T3**	373
L4	556 (*)	**T4**	351
L5	390	**T5**	318 (*)
Average Removing (*)	401	**Average Removing (*)**	364
STD	9	**STD**	12

✓ Values of RRR are > 300 along both directions (Ok for SPL requirements);

✓ Values of RRR declared by supplier 430 in average;

Nb SHEET: VICKERS HARDNESS AND GRAIN SIZE

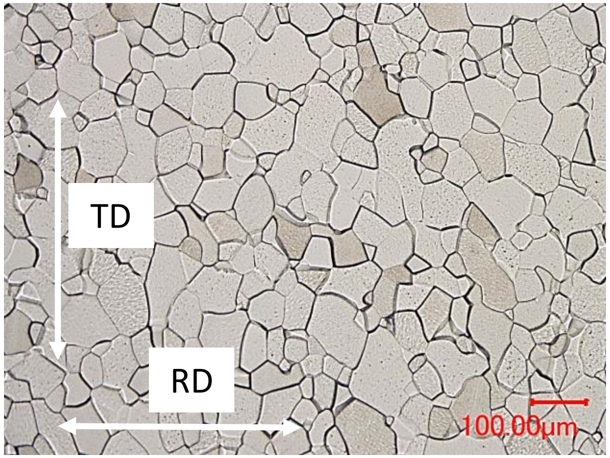
- Vickers Hardness HV10 should be max. 60 according to SPL requirements;

Average HV 10	STD
51	3

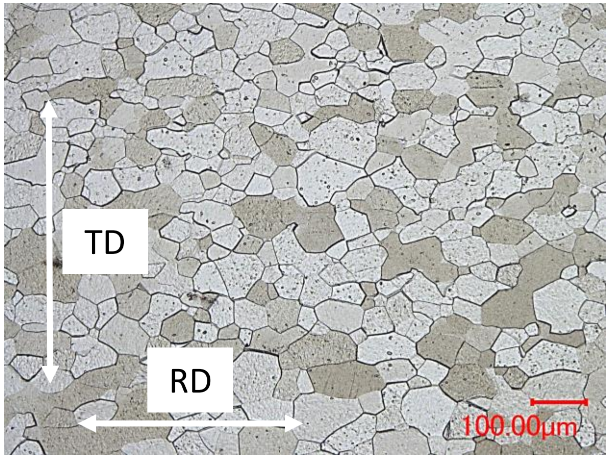
✓ The values meet the SPL requirements (average values declared by supplier: 47-52);

- Vickers Hardness HV0.2 through thickness: average value 57 and STD ± 4;

Microstructure on surface



Microstructure through thickness

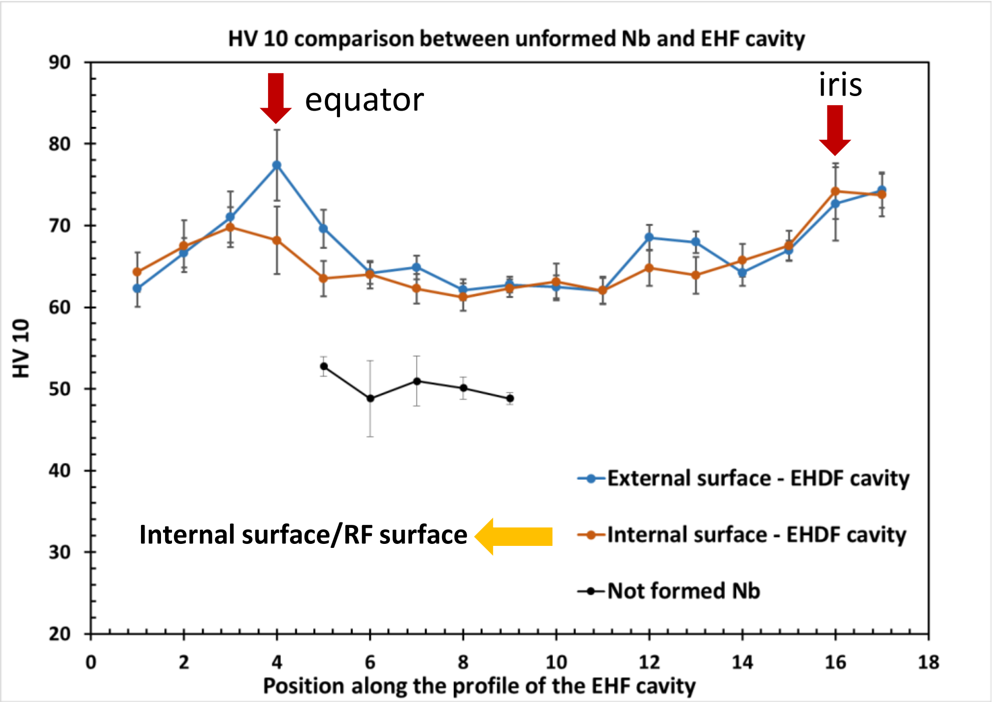


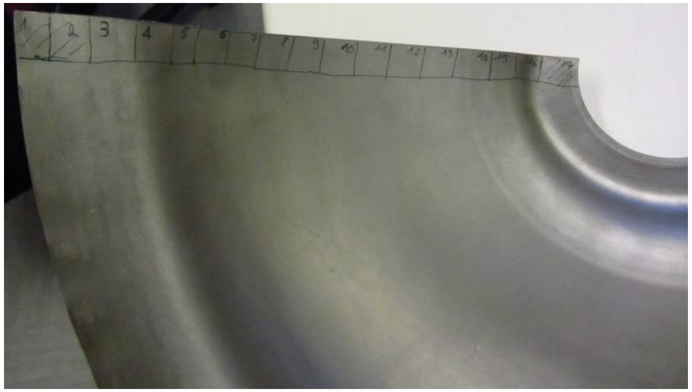
Average grain size number: 5 (Ø of grains 63 µm) (ASTM E112-96(2004)).

EHDF Nb CAVITY

- Vickers Hardness HV10 measured on the internal surface and external surface of the cavity;
- Internal surface is in contact with water during forming;
- External surface impacts the die during forming;

- Specimens extracted along the profile of the whole cavity;

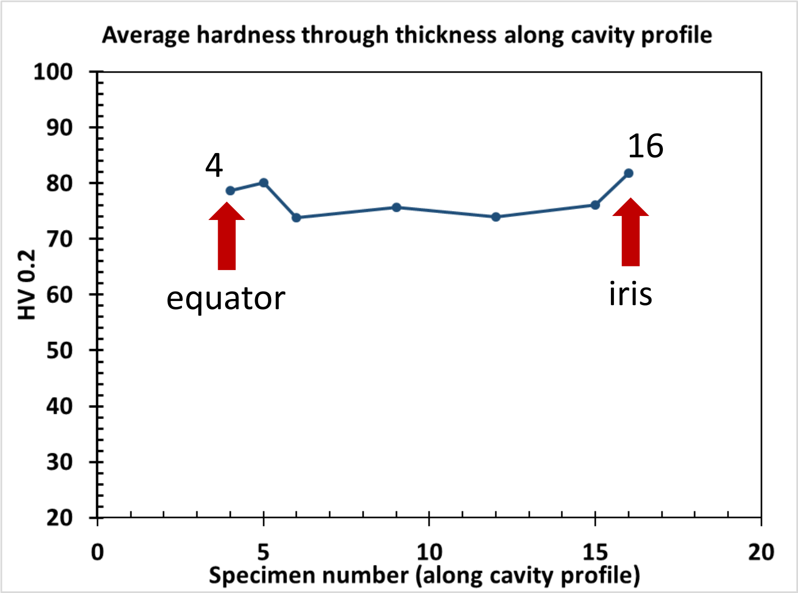


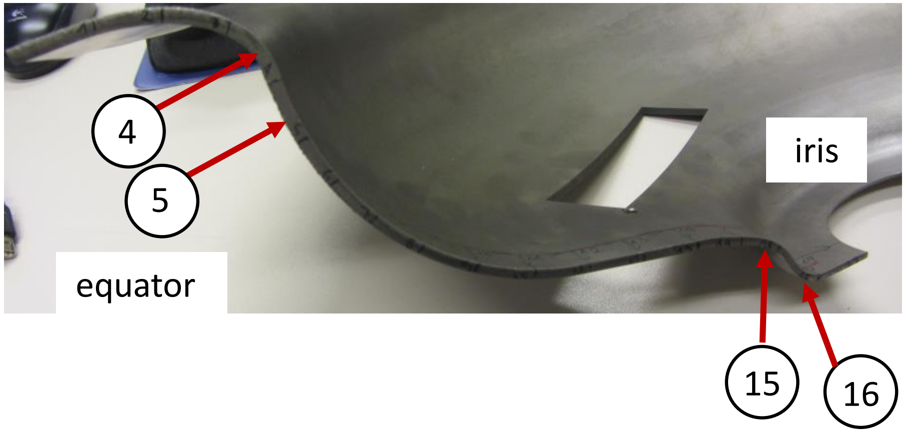


- ✓ Due to forming operation, the hardness on both surfaces raises from 50 to values 63-73;
- ✓ Peaks of hardness obtained for the iris and equator zones;
- ✓ External surface (impacting the die) has higher hardness close to the equator;

EHDF Nb CAVITY

- Vickers microhardness HV 0.2 performed through thickness on specimens position 4, 5, 6, 9, 12, 15 and 16 of the profile of the cavity;

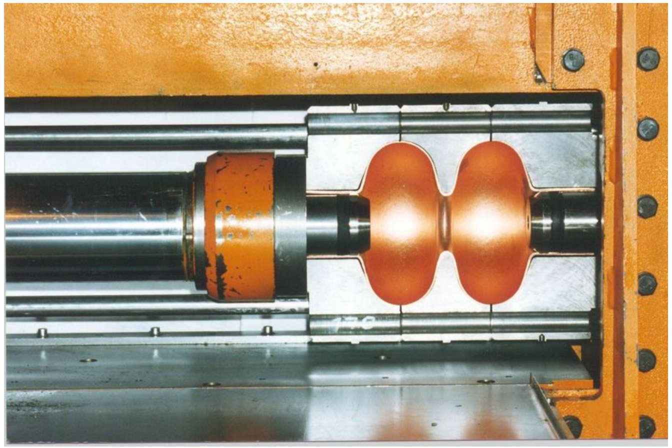


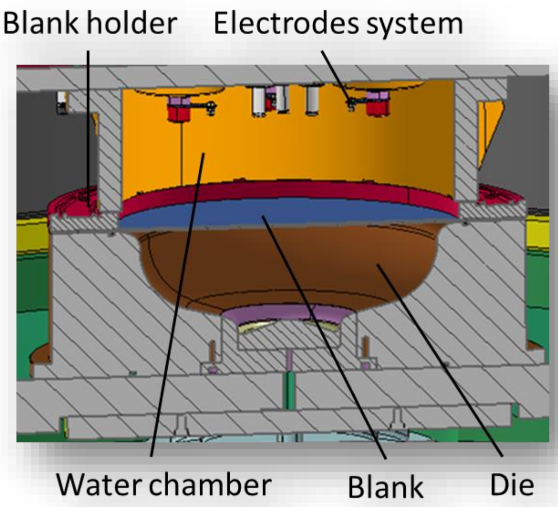


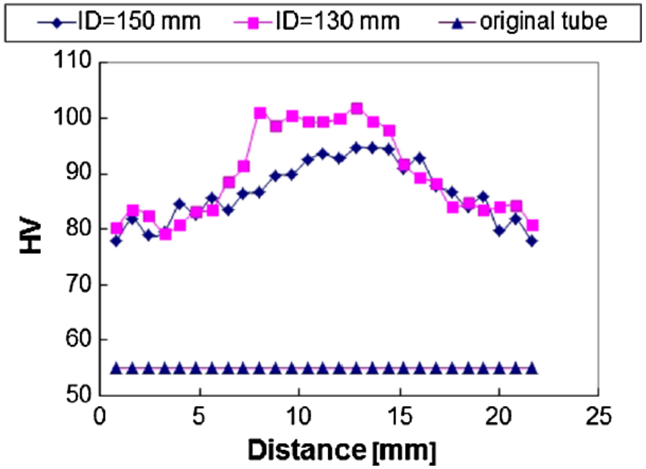
- ✓ The average through thickness hardness after EHDF is 75 HV, with peaks of 80 HV in the “critical” zones of equator and iris;
- ✓ Specimens in position 4, 5 and 15 should undergo dislocation analyses;
- ✓ Specimens in position 9 should undergo dislocation analyses for comparison;

EHDF Nb CAVITY: CONSIDERATIONS

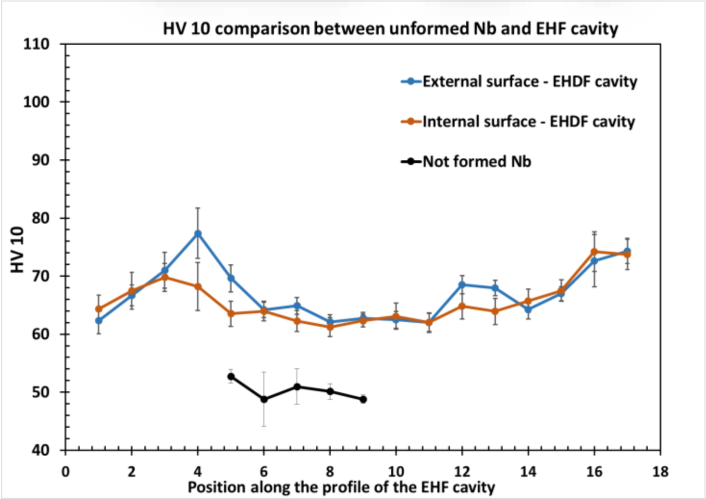
✓ Hardness obtained with EHDF is lower compared to other forming techniques:







HV10 of Hydroformed Nb tubes at DESY [1], [2]

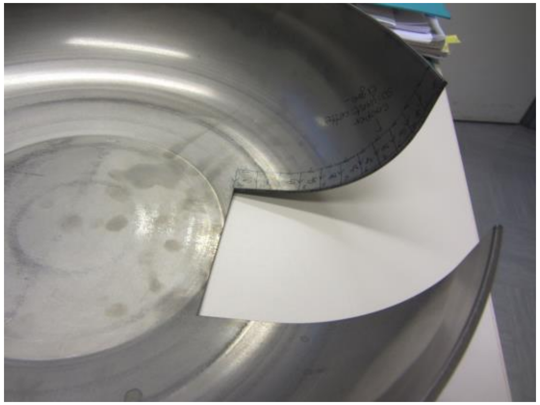


HV10 of Electro Hydroformed Nb cavities (CERN)

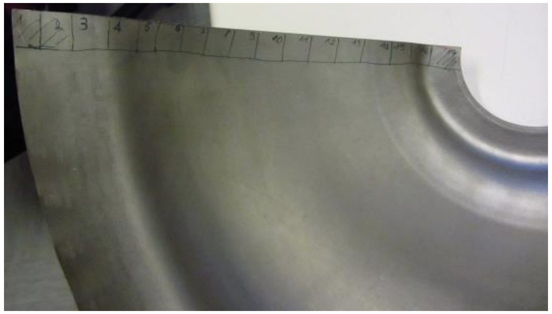
EHDF Nb CAVITY: CONSIDERATIONS

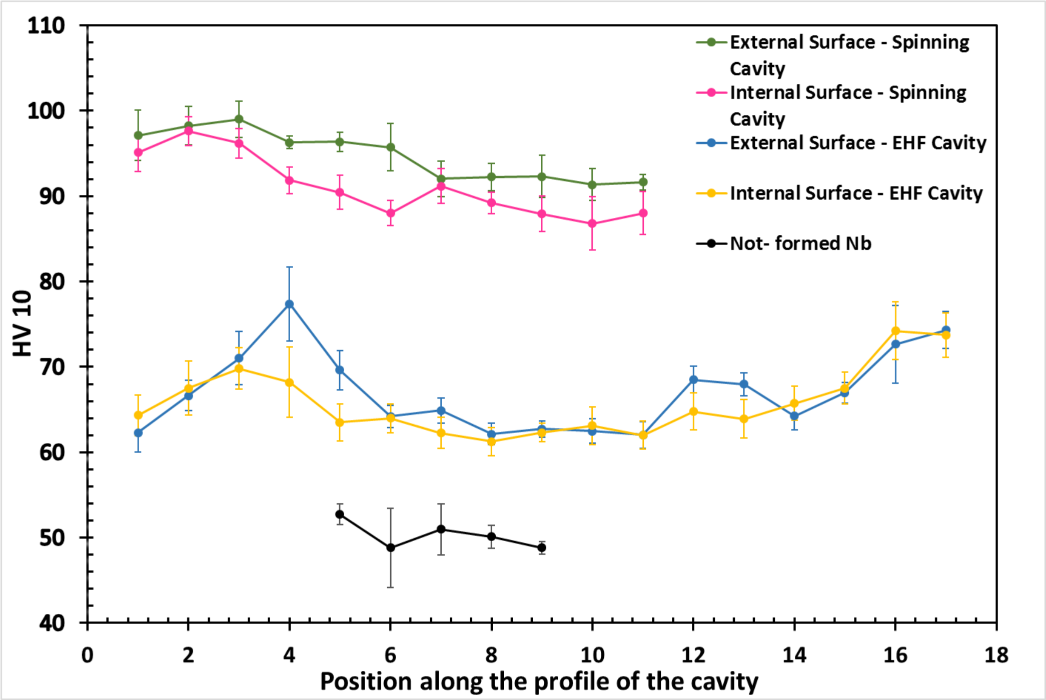
✓ Comparison between Spinning and EHDF:

First step of spinning



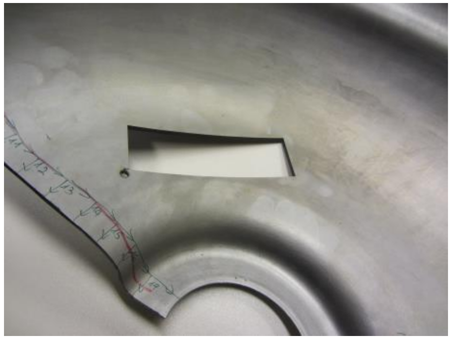
Electro-hydraulic forming





EHDF Nb CAVITY: CONSIDERATIONS

- RRR on EHF cavity:

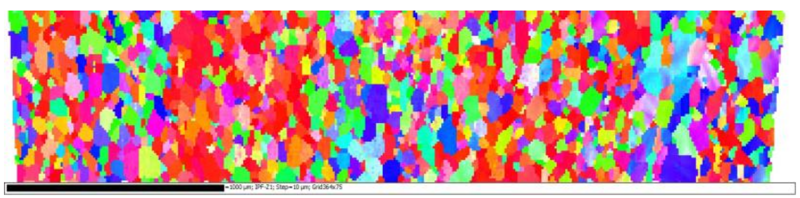


Specimen	exponential interpolation RRR (from 9.2K to 17/20K) RRR=ρ(295K)/ρ(4.2K)
A	286
B	276
C	274
D	290
E	320
F	283
G	297
H	298
I	299
Average	291

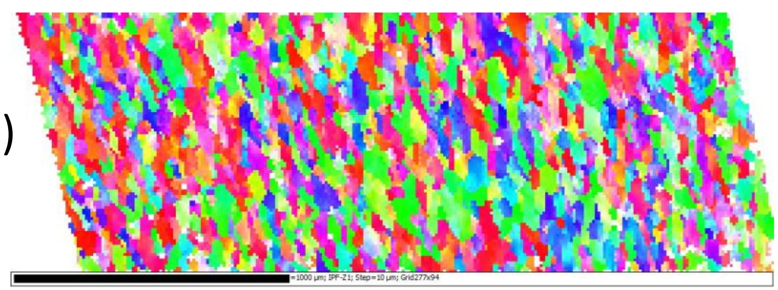
- Decrease of RRR from 380 to 291 due to increase of dislocations density after forming;

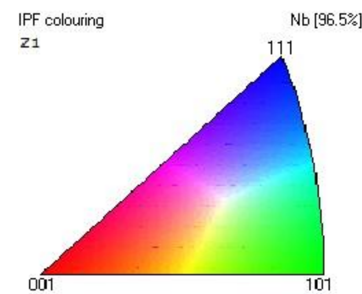
- EBSD:

Not-deformed Nb



EHDF Nb (pos. 15 – iris)





ONGOING WORK: CHARACTERIZATION

- Evolution of dislocations at high strain-rate[3]:
- More uniform dislocations distribution;
- Suppress formation of dislocations cells;
- For some materials, twinning might become predominant;

- EBSD to extract KAM parameter and see the strain distribution through thickness;

- Analysis of dislocations structures by TEM (collaboration with ETH Zürich);

- Nanohardness measurements through thickness of formed and not-formed niobium;

- Tensile tests at different strain rate and temperatures to extract parameters for JC model;

- Relate RRR with dislocation density;

BIBLIOGRAPHY

1. W. Singer, X. Singer, K. Twarowski, I. Jelezov, T. Khabibuline, A.Skasyrskaia, P. Kneisel, *“Hydroforming of NbCu Clad Cavities at DESY”,* The 10th Workshop on RF Superconductivity, 2001, Tsukuba, Japan;

2. W. Singer, X. Singer, I. Jelezov, P. Kneisel, *“Hydroforming of elliptical cavities”,* Physical Review Special Topics - Accelerators and Beams 18, 022001 (2015);

3. George T. (Rusty) Gray III, *“High-Strain-Rate Deformation: Mechanical Behaviour and Deformation Substructures Induced”,* Annu. Rev. Mater. Res. 2012. 42: 285-303;