Mechanical characterization of REBCO CC layer materials at the microscale

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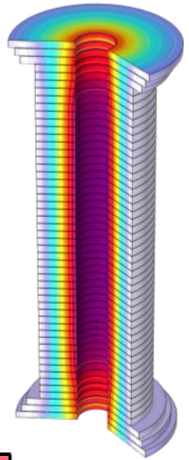
10.36227/techrxiv.172962986.60466462/v1

Outline

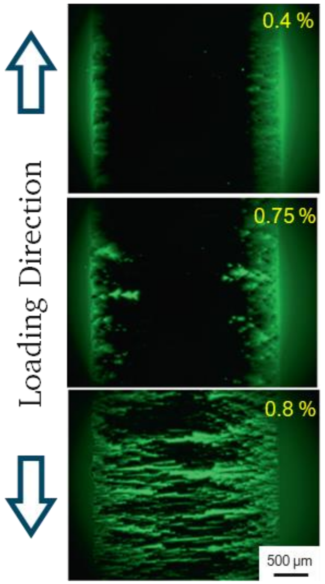
- Background
  1. Nanoindentation
  2. Micropillar compression
  3. Micropillar splitting
- Conclusions & Next steps
- Discussion

Why material properties ?

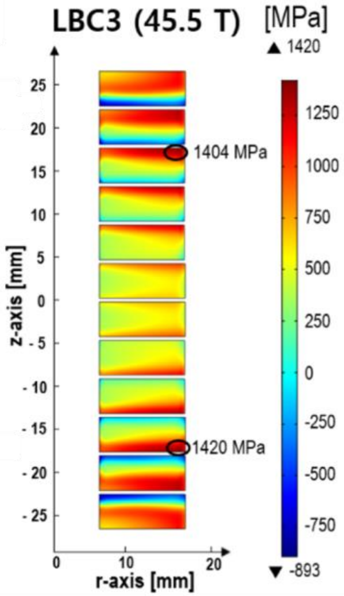
- High field → **high stresses** $p_m = \frac{B^2}{2\mu_0}$ $p_m(50\ \mathrm{T}) \sim 1\ \mathrm{GPa}$
  - Plastic deformation
  - Delamination



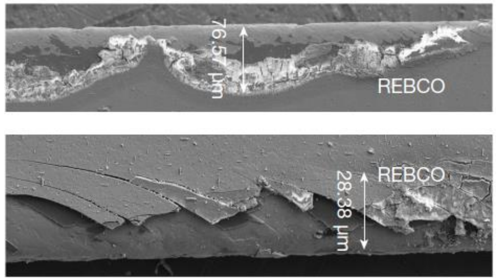
For the 40 T FC Solenoid:
extensive material characterization & modeling



Y.H. Zhou et al – Nature Communications (2021) 12:3110



Xinbo Hu et al 2020 Supercond. Sci. Technol. 33 095012



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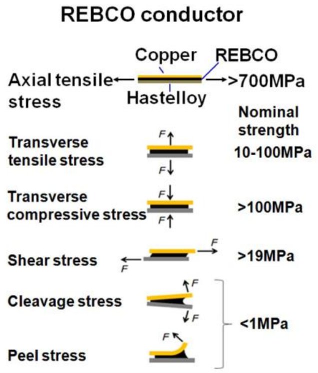
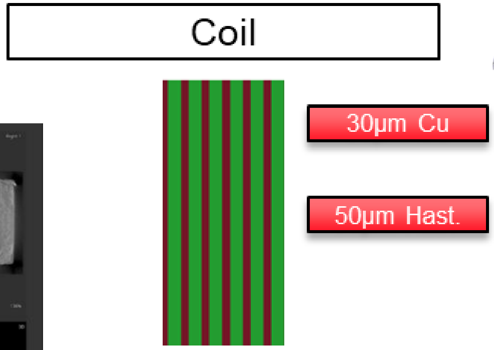
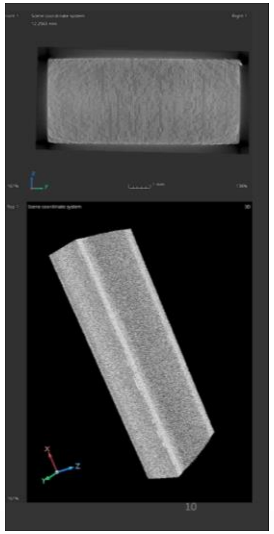
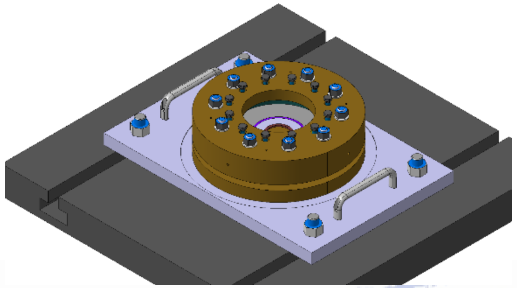


H. Maeda et al, IEEE TAS, VOL. 24, NO. 3,2014



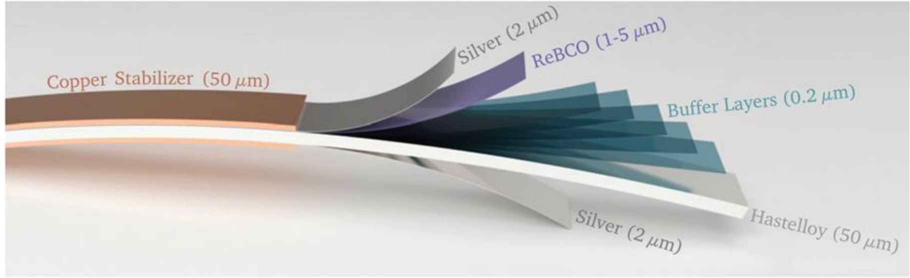




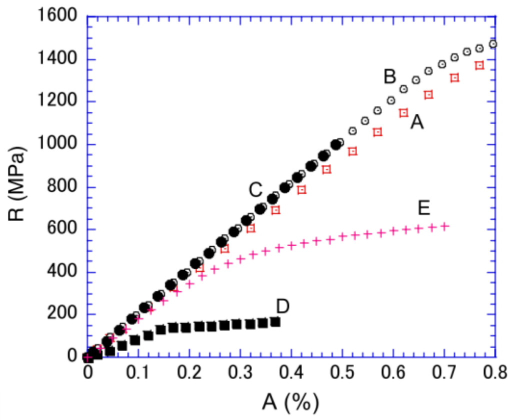
C. Accettura - Magnets R&D for the Muon Collider Study - https://indico.cern.ch/event/1476966/

Characterization: at which scale ?

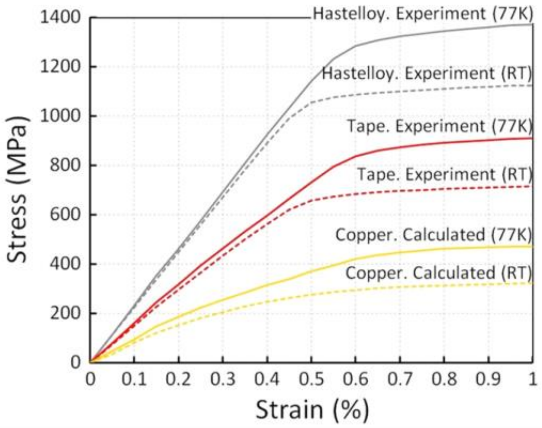
- REBCO CC are made of several thin layers (**0.1 – 100** µm) of materials which behave mechanically very differently.
- The **limiting factors** for our applications (critical current degradation, delamination, etc.) occur at the **micro** scale.
- For a deeper understanding of the degradation mechanisms, we have to rely on properties measured at a coherent scale.



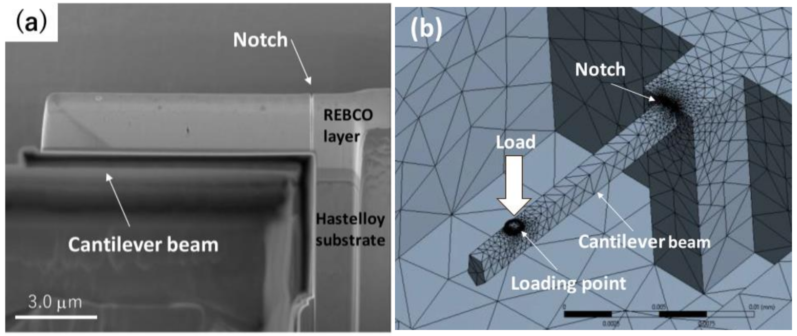
J. Van Nugtereen, 2016



K. Osamura et Al., Supercond. Sci. Technol. 22 (2009)



Ilin et Al., Supercond. Sci. Technol. 28 (2015)



S. Muto et al., IEEE TAS 30, 4, 2020

Methodologies proposed

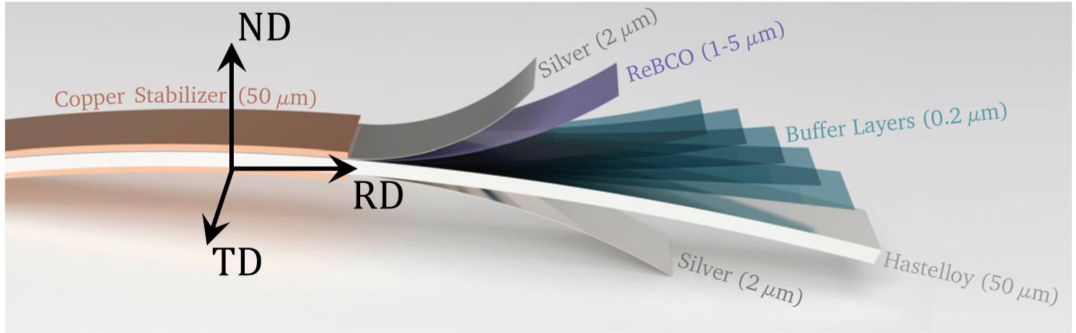
- Background

  1. Nanoindentation → Elastic-plastic behavior
  2. Micropillar compression → Plastic flow
  3. Micropillar splitting → Fracture toughness

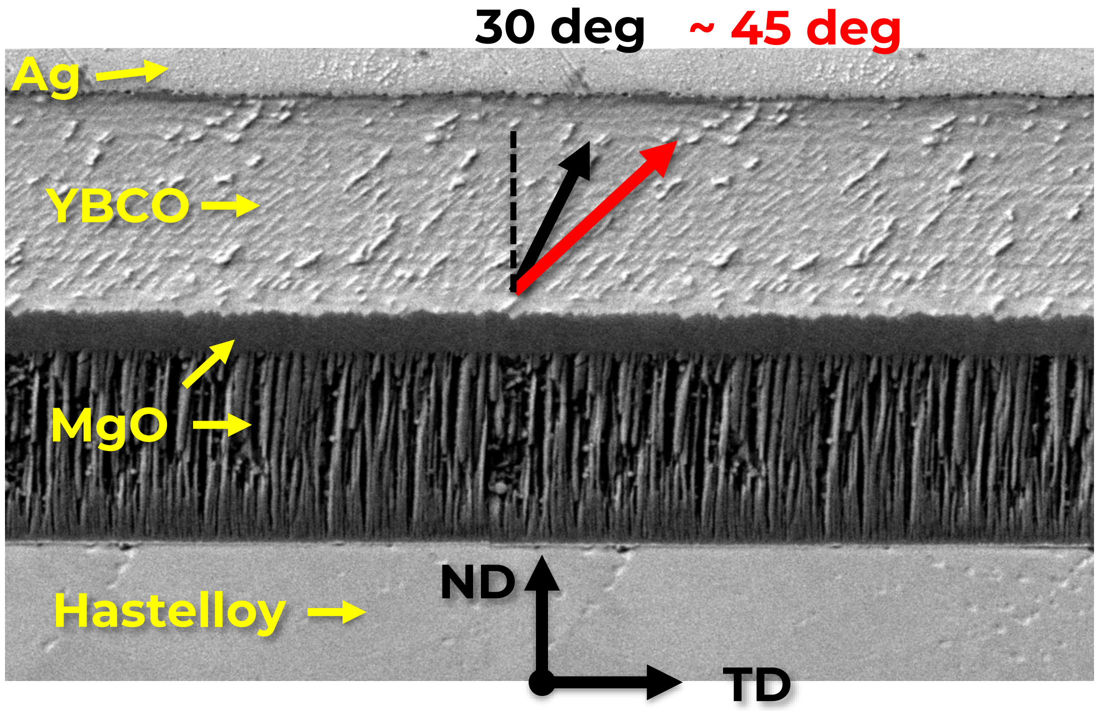
- Conclusions & Next steps
- Discussion

Materials:
YBCO tape from THEVA®

- THEVA® TPL4000-series: Inclined Substrate Deposition (30 deg)

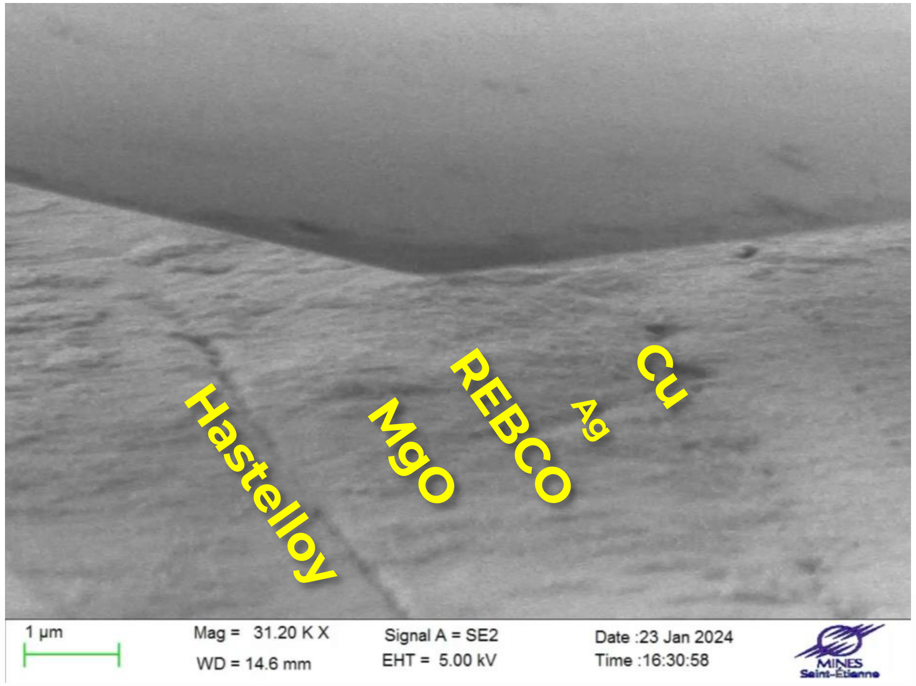


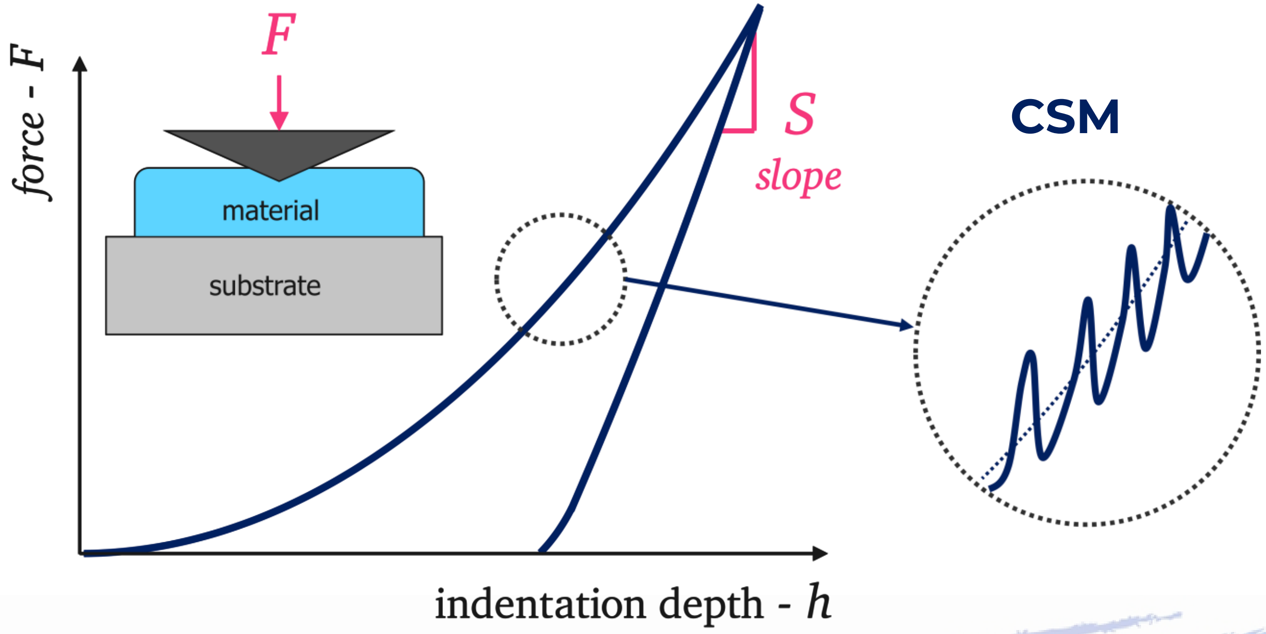
J. Van Nugtereen, 2016



Nanoindentation: Introduction

- Applying a controlled load *F* to a diamond tip and monitoring the penetration depth *h* inside the material.
- We measure the contact stiffness *S* and obtain the elastic modulus *E* and hardness *H* of the material.

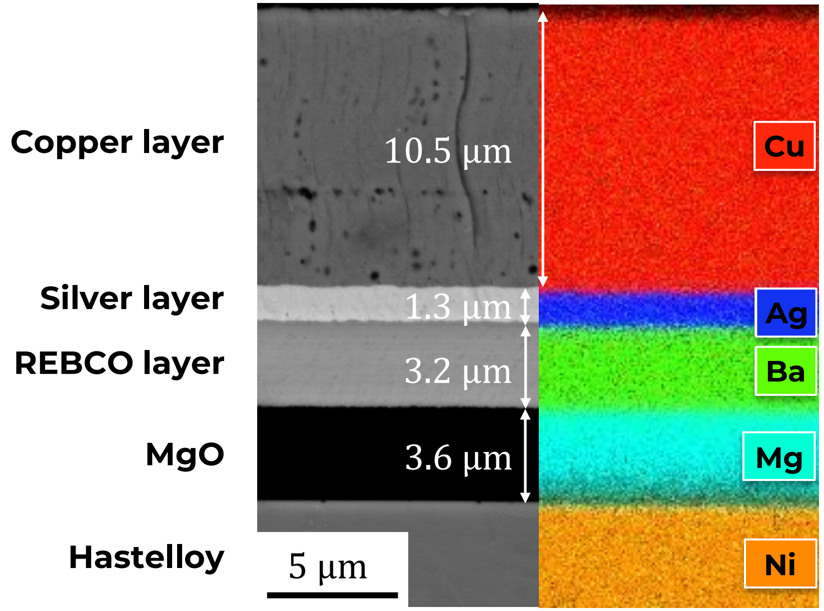


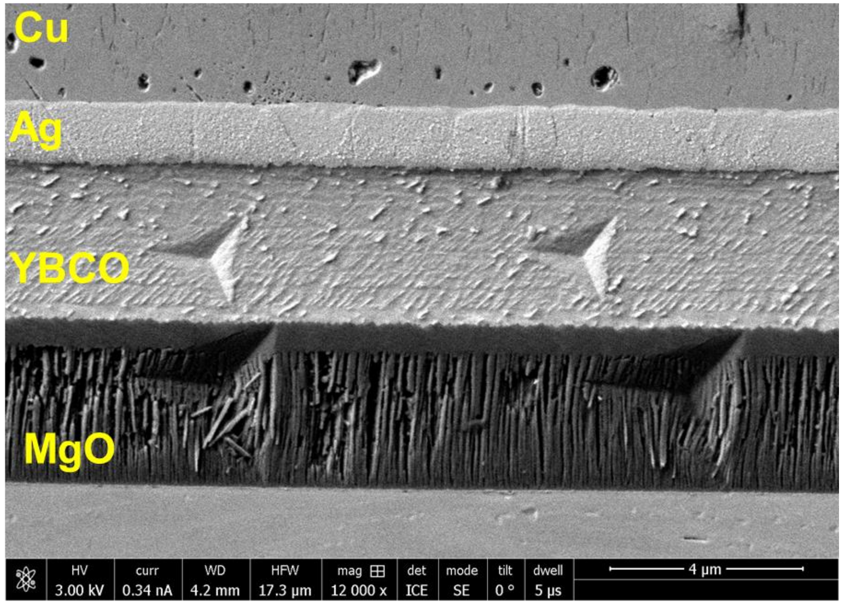


Nanoindentation: Methodology

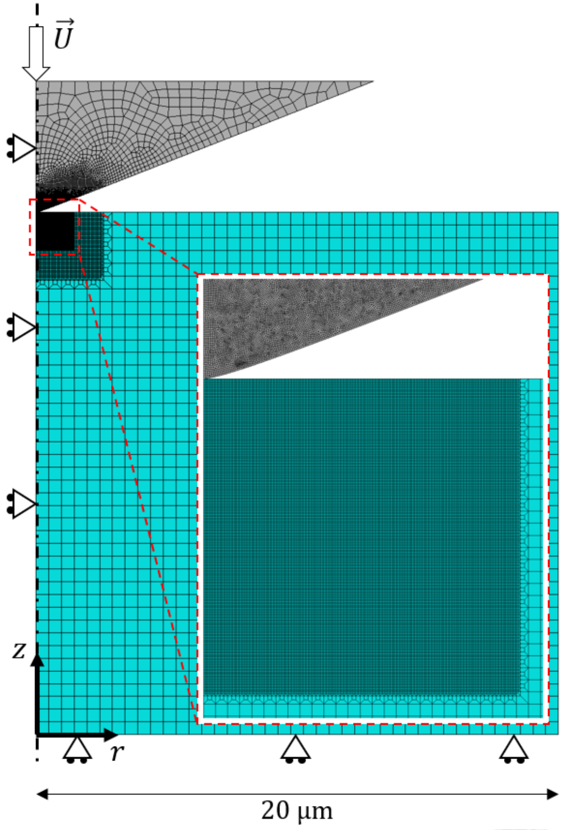
For REBCO & MgO:

- 5-10 indents optically targeted.
- Valid penetration depth < 150 nm.



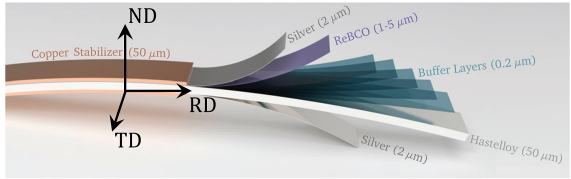


+ Coupled Mechanical FE Model

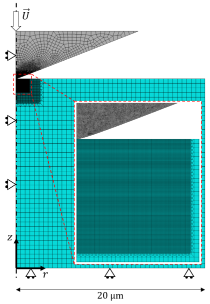


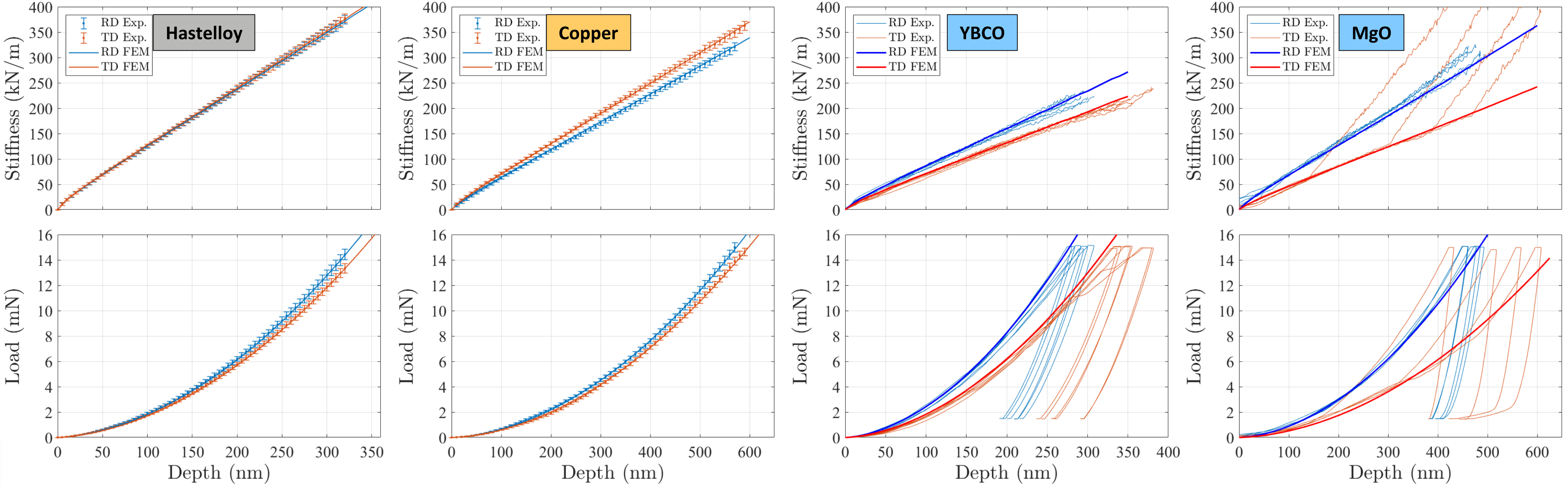
Nanoindentation: Results on THEVA® at Room Temperature

	Hastelloy	Copper	YBCO	MgO
	E (GPa)	E (GPa)	E (GPa)	E (GPa)
RD	197	84	155	95
TD	195	90	120	60



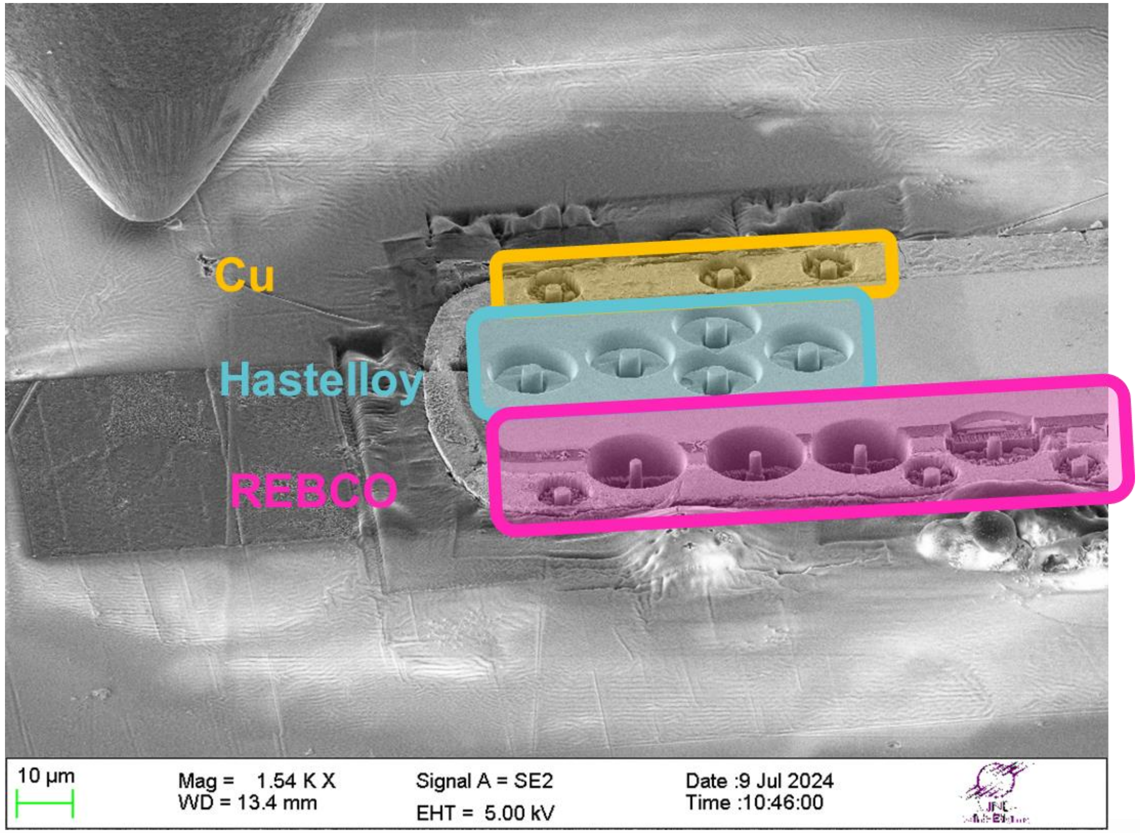
J. Van Nugtereen, 2016

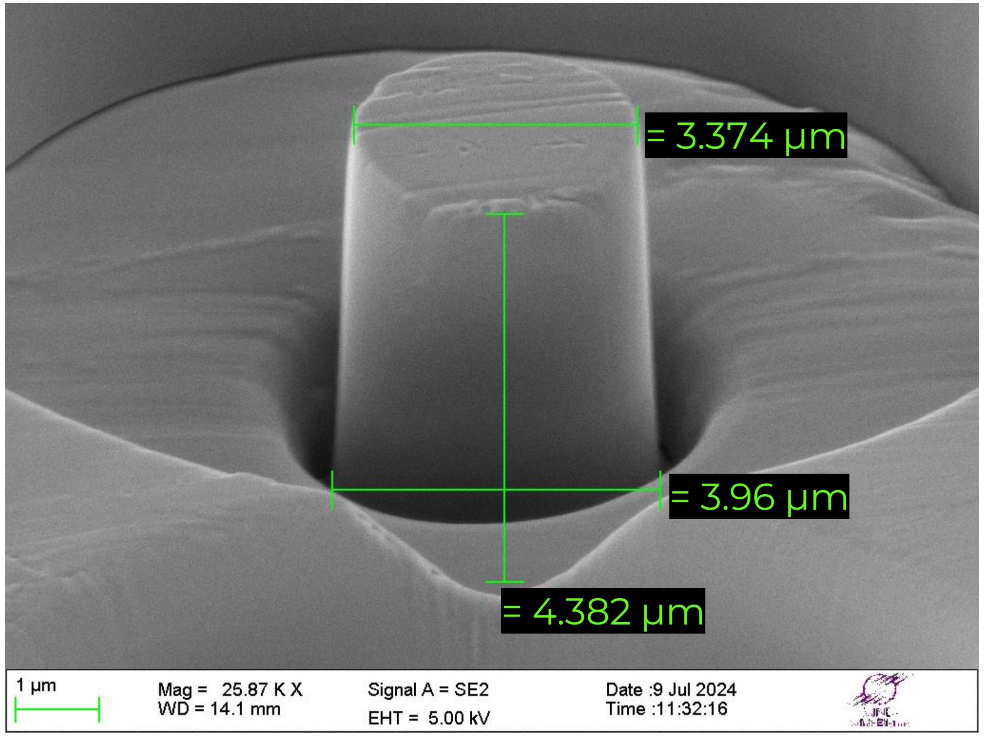




Micropillars: Drilling

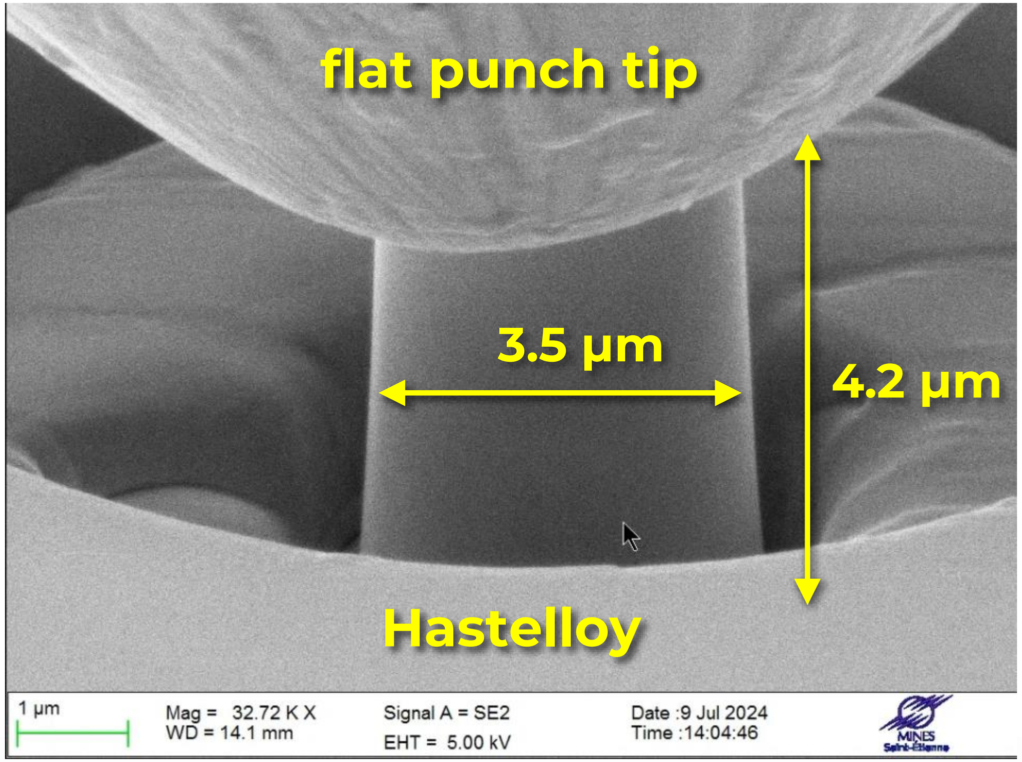
- FIB milling of micropillars

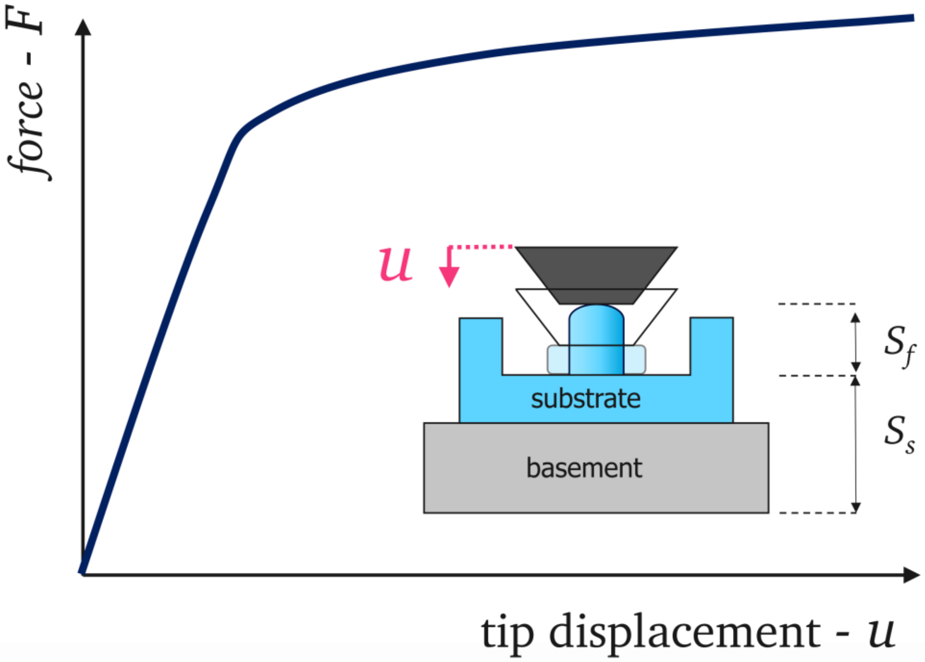




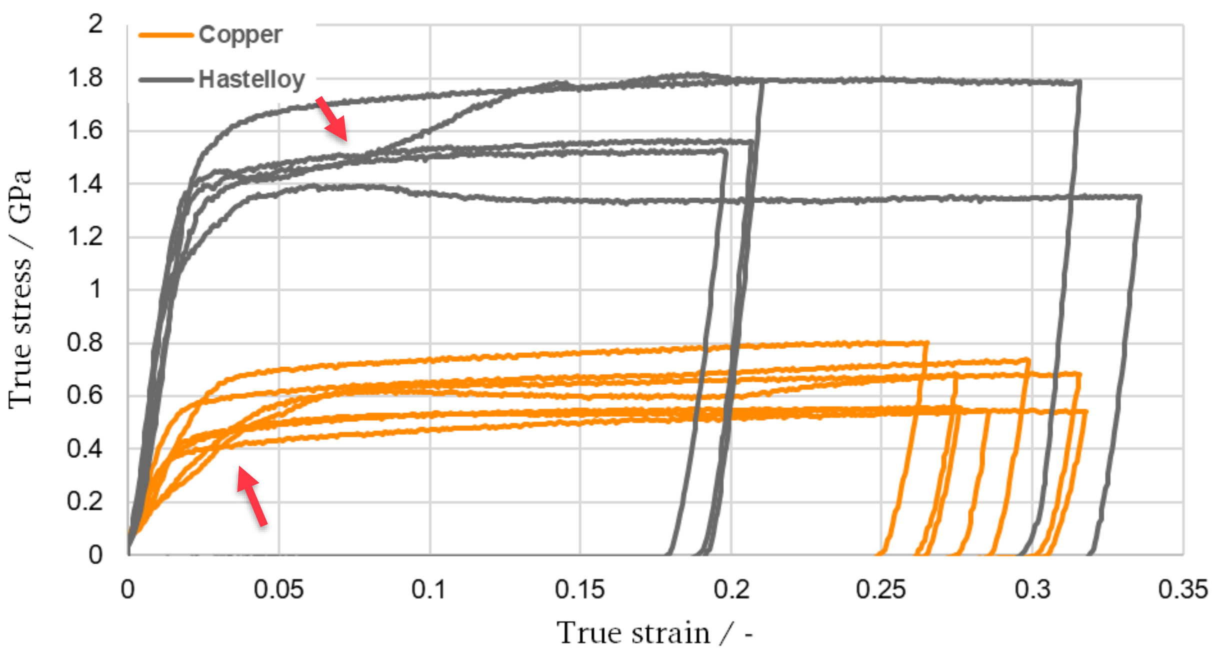
Micropillar compression: Introduction

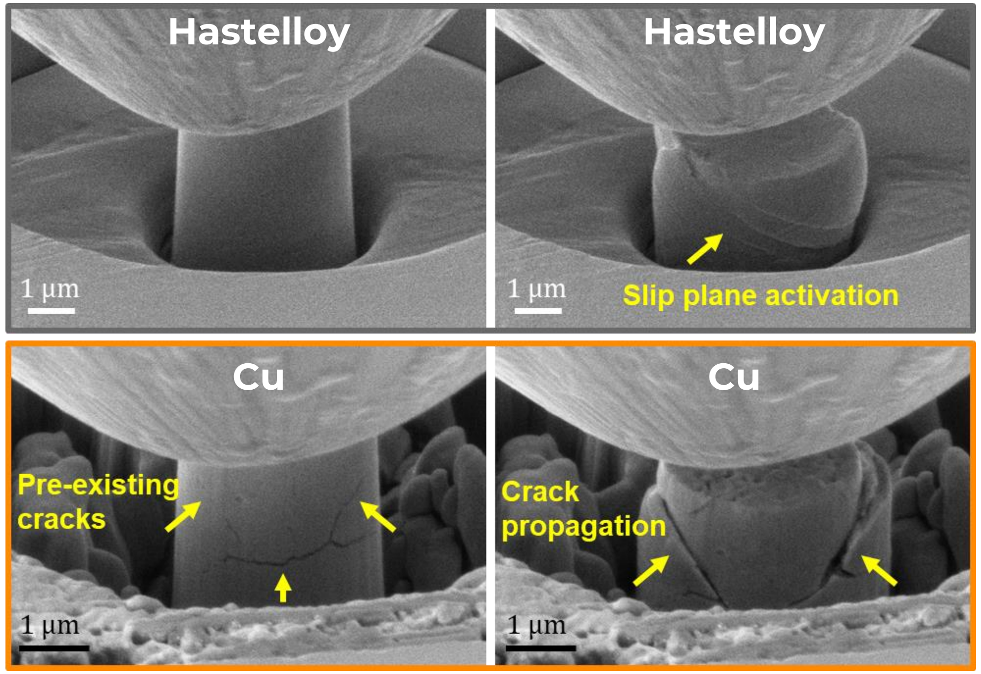
- Applying a displacement *u* to a flat punch tip measuring the load response *F*.





Micropillar compression: Hastelloy & Copper





Hastelloy		Copper	
σ^y / GPa	* ε^y / %	σ^y / GPa	* ε^y / %
1.2 – 1.6	0.61 – 0.82	0.4 – 0.6	0.42 – 0.66

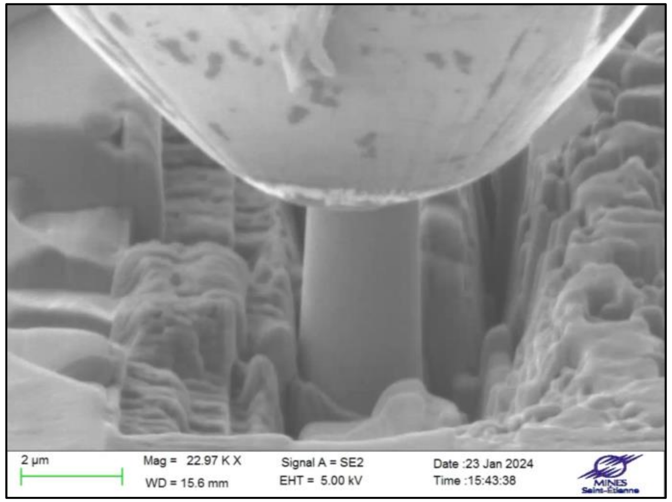
* using elastic moduli from nanoindentation measurements

Scattering between curves:

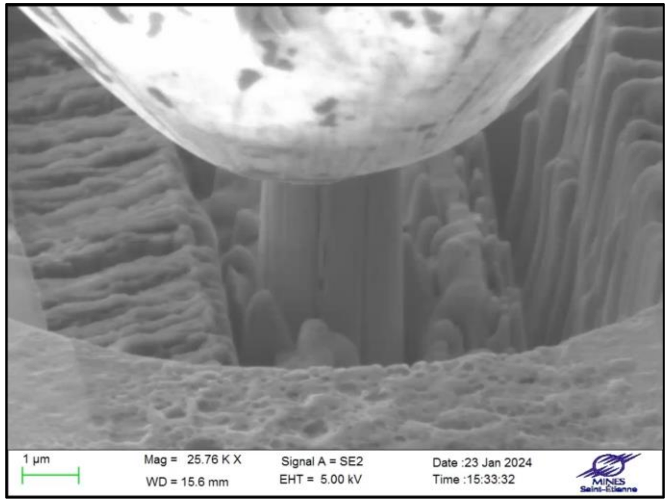
- Hastelloy: single/multiple slip plane activation
- Copper: pre-existing cracks

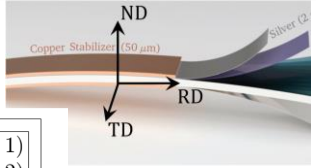
Micropillar compression: the anisotropy of RE(Y)-BCO

Sample 1 – TD

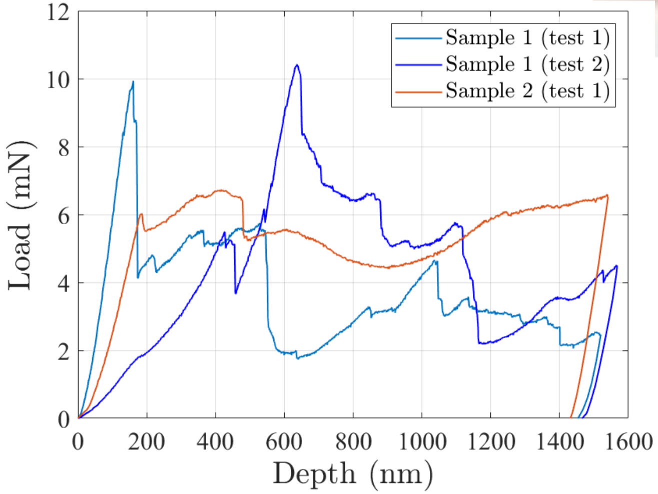


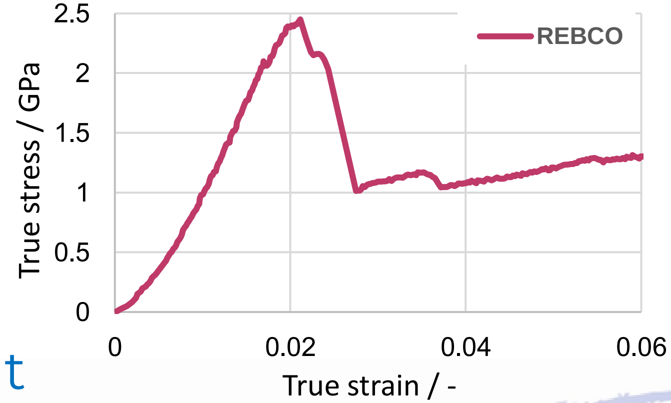
Sample 2 – RD





J. Van Nugtereen, 2016

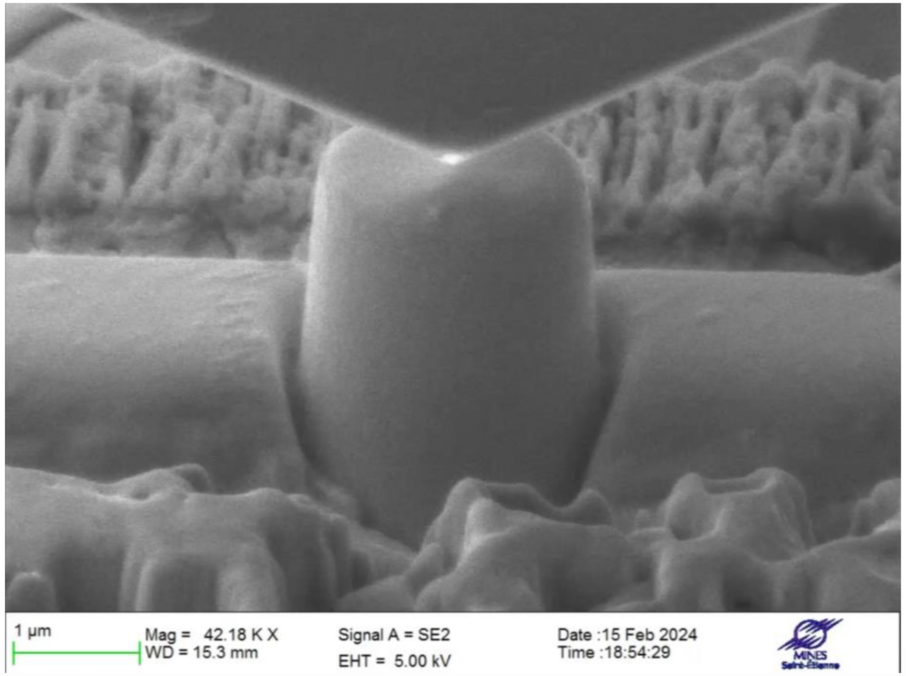


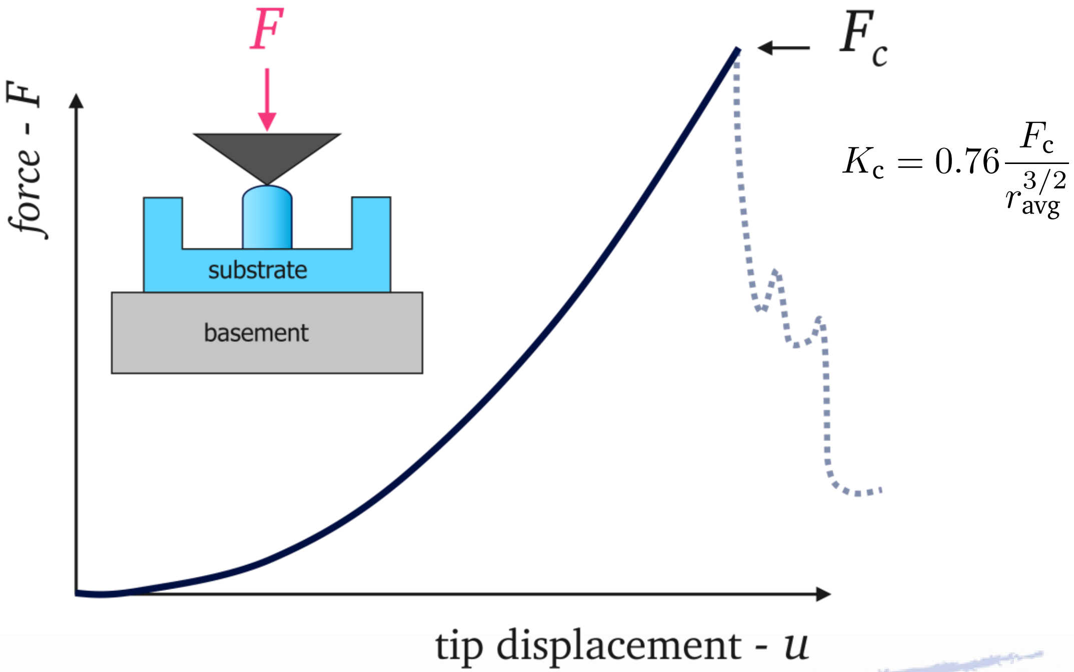


- Sample 1 exhibits brittle failure, as it occurs before any plastic deformation.
- Buckling / plastic failure depending on orientation.
- At the moment it is a non-conclusive measurements.
- Further investigation will be done on tapes of different manufacturers.

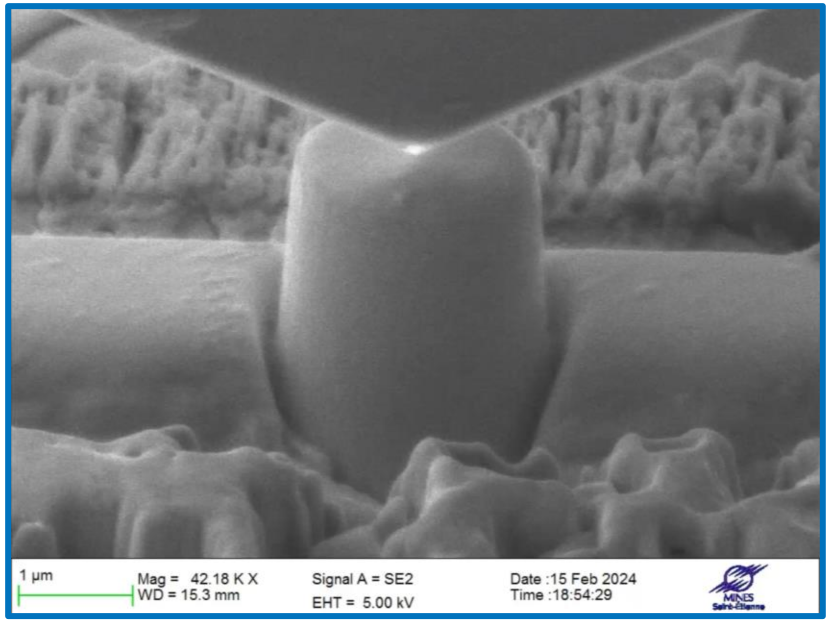
Micropillar splitting: Introduction

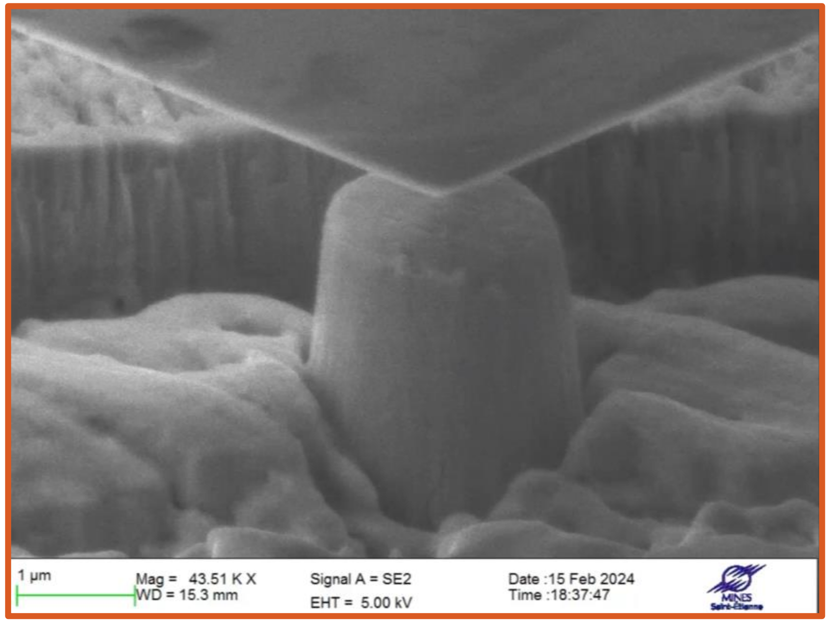
- Driving a sharp tip into a pillar until a fracture occurs. From the critical load F_c, we determine the fracture toughness K_c.

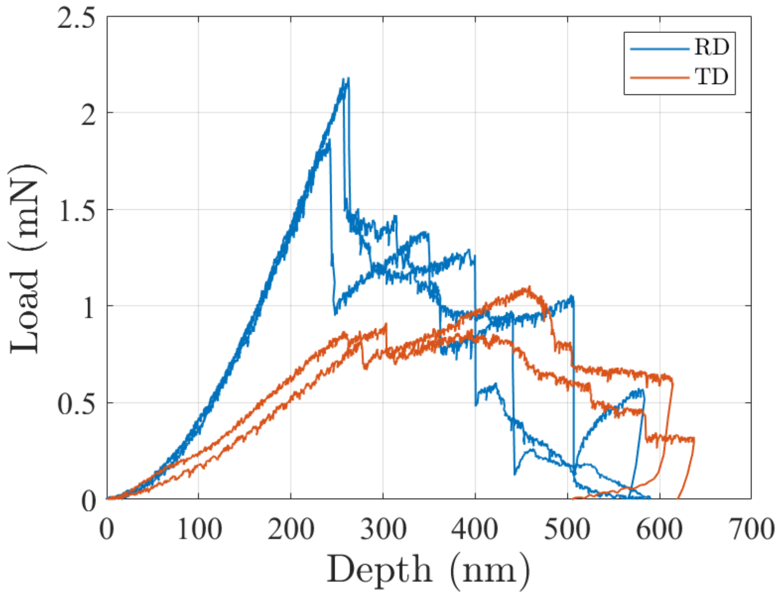




Micropillar splitting: RE(Y)-BCO







- Evident anisotropic behavior.
- Microstructural analyses needed for deeper understanding.
- Values of K_c are low with respect to traditional metals [ref.1] $K_c \sim 20 - 110$ MPa$\cdot\sqrt{\mathrm{m}}$, and ceramics, $K_c \sim 5 - 10$ MPa$\cdot\sqrt{\mathrm{m}}$.
- However, they agree with those found in literature [ref.2]

	REBCO		
	E (GPa)	σ_y (GPa)	K_c (MPa$\sqrt{\mathrm{m}}$)
RD	155	4.00	1.34 ± 0.12
TD	120	2.80	0.56 ± 0.02

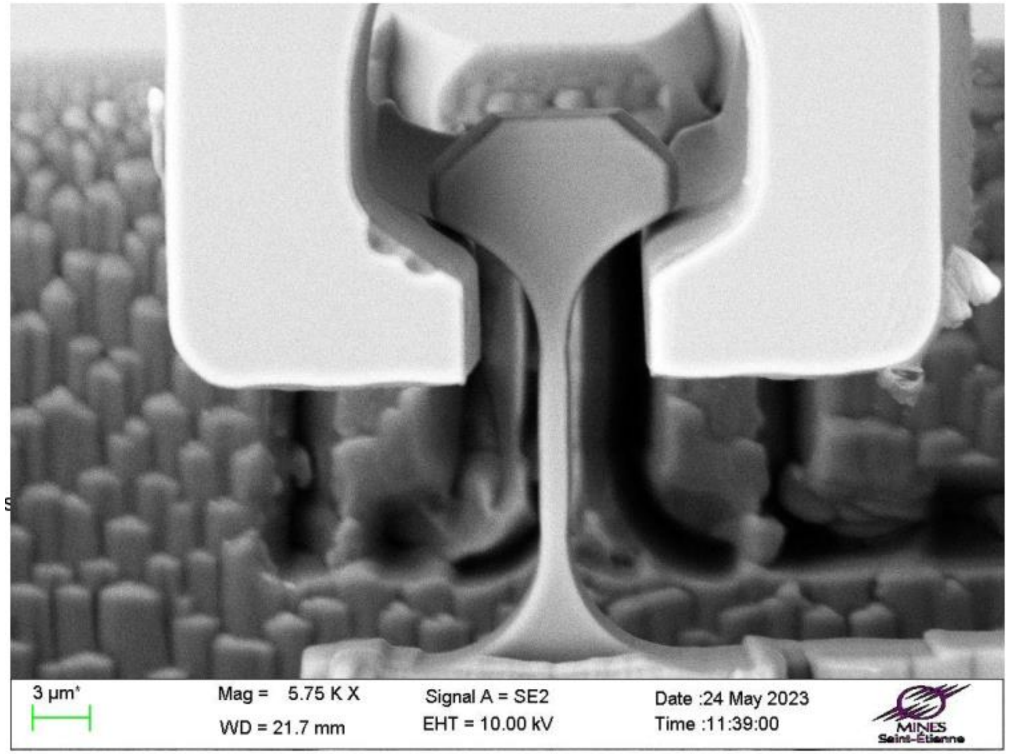
[ref.1]: MatWeb, online, accessible at https://www.matweb.com/index.aspx
[ref.2]: S. Muto et al., IEEE TAS 30, 4, 2020

Conclusions

- Nanoindentation measured reliably the **elastic properties** (of most) of the REBCO tape layer materials.
- Micropillar compression has highlighted the high **yield strength** of Hastelloy and Copper.
- Micropillar compression has shown the low **fracture toughness** of YBCO.

	REBCO		
	E (GPa)	σ_y (GPa)	K_c (MPa$\sqrt{m}$)
RD	155	4.00	1.34 ± 0.12
TD	120	2.80	0.56 ± 0.02

Next steps



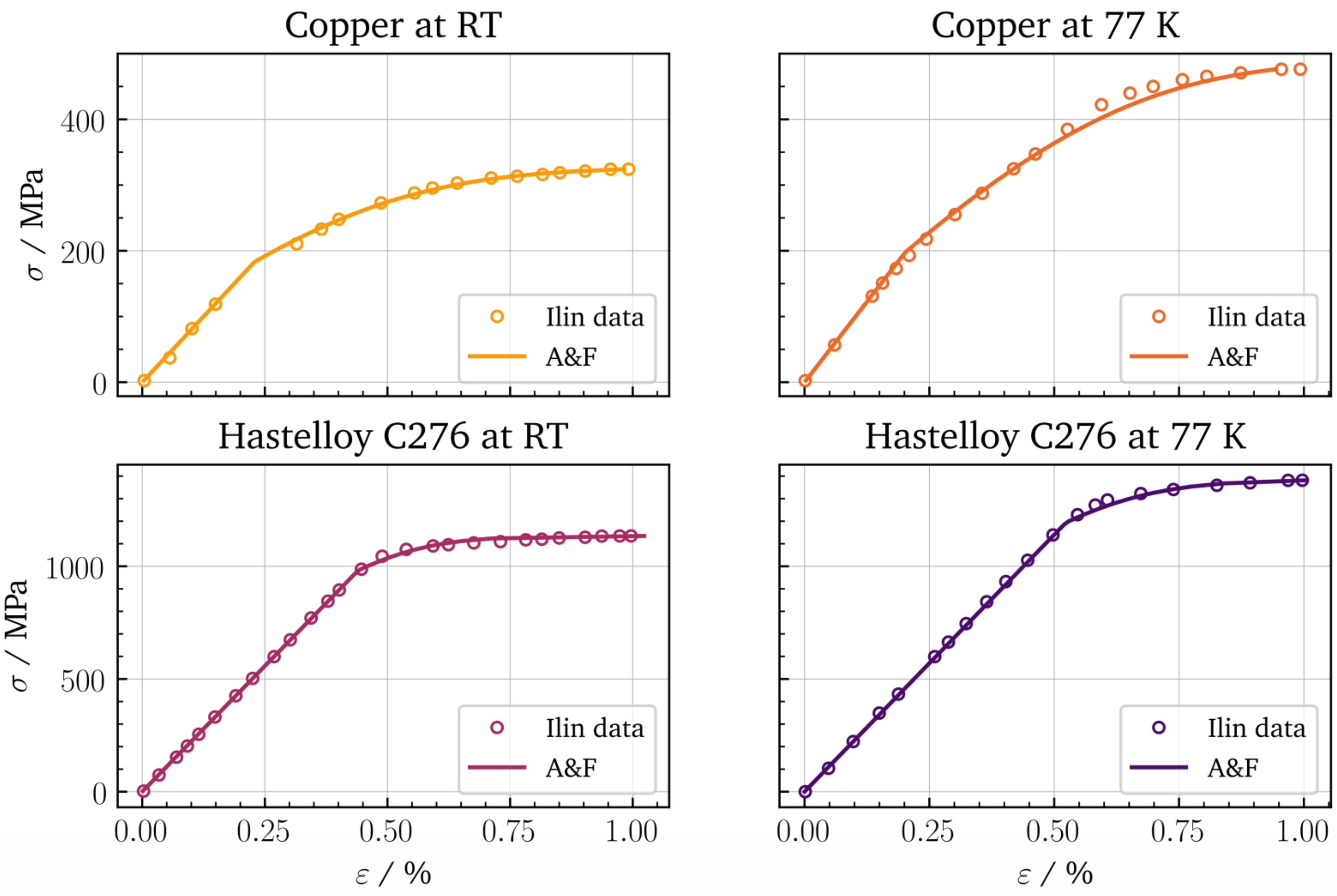
Credit S Kalácska - Mines Saint-Etienne

- We are thinking of trying to characterize the mechanical delamination strength (MDS) at the microscale.

Thank you !

MMWG, 21.11.2024

Discussion:
Properties from Ilin



$$f(\bar{\bar{\sigma}}, R) = |\sigma| - \sigma^y - R$$

$$R = \frac{H}{\gamma}\left[1 - \exp(-\gamma p)\right]$$

$$p = \sqrt{\frac{2}{3}\varepsilon^p : \varepsilon^p}$$

Copper

	E_{Cu} / GPa	$\sigma^y{}_{Cu}$ / MPa	H_{Cu} / GPa	γ_{Cu}
RT	80	183	91	629
77 K	98	197	191	648

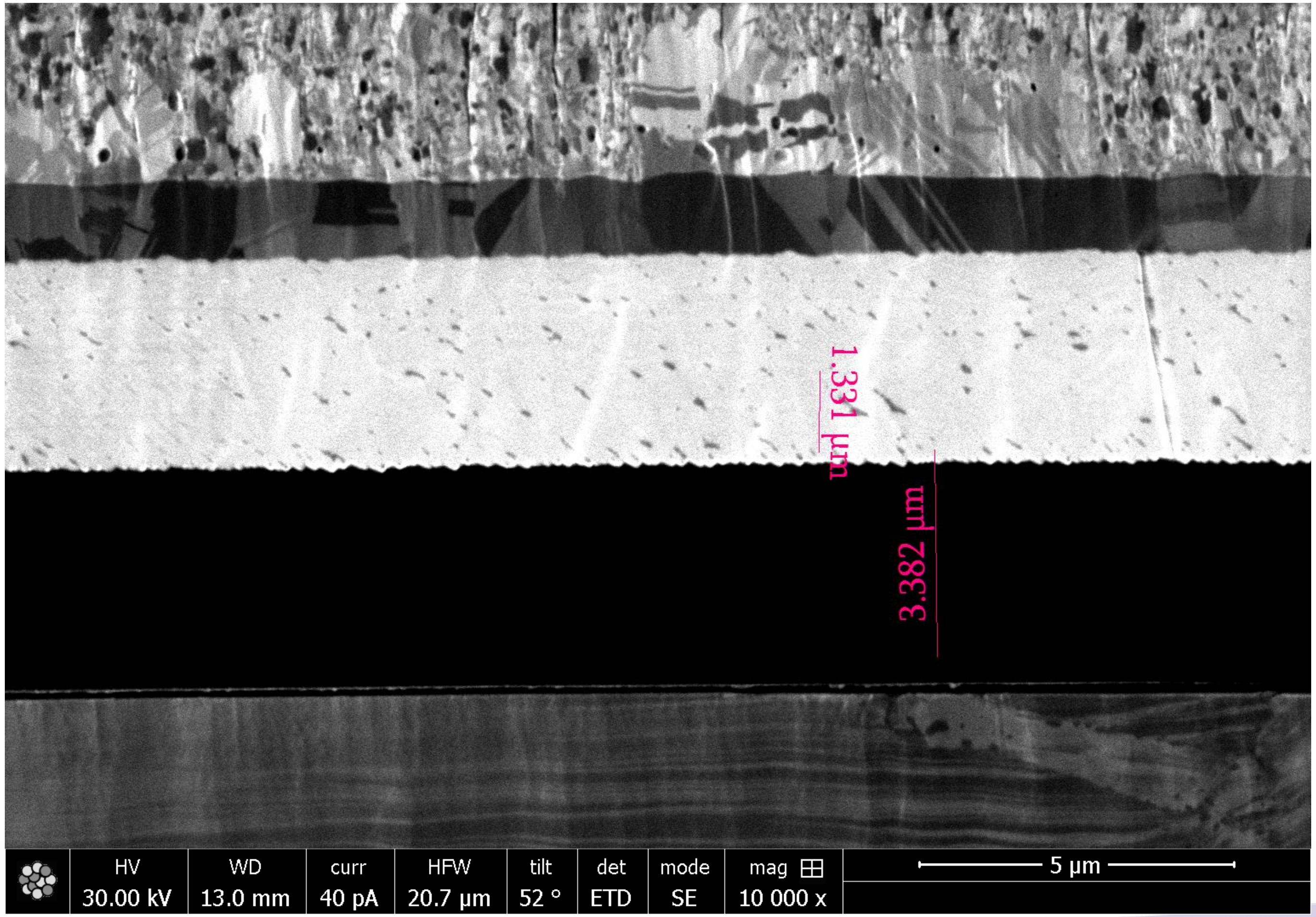
Hastelloy C276

	E_{C276} / GPa	$\sigma^y{}_{C276}$ / MPa	H_{C276} / GPa	γ_{C276}
RT	223	981	191	1241
77 K	228	1194	190	995

tb,chaboche,mat_cu,1
tbdata,1, σ^y, H, γ

Grain sizes

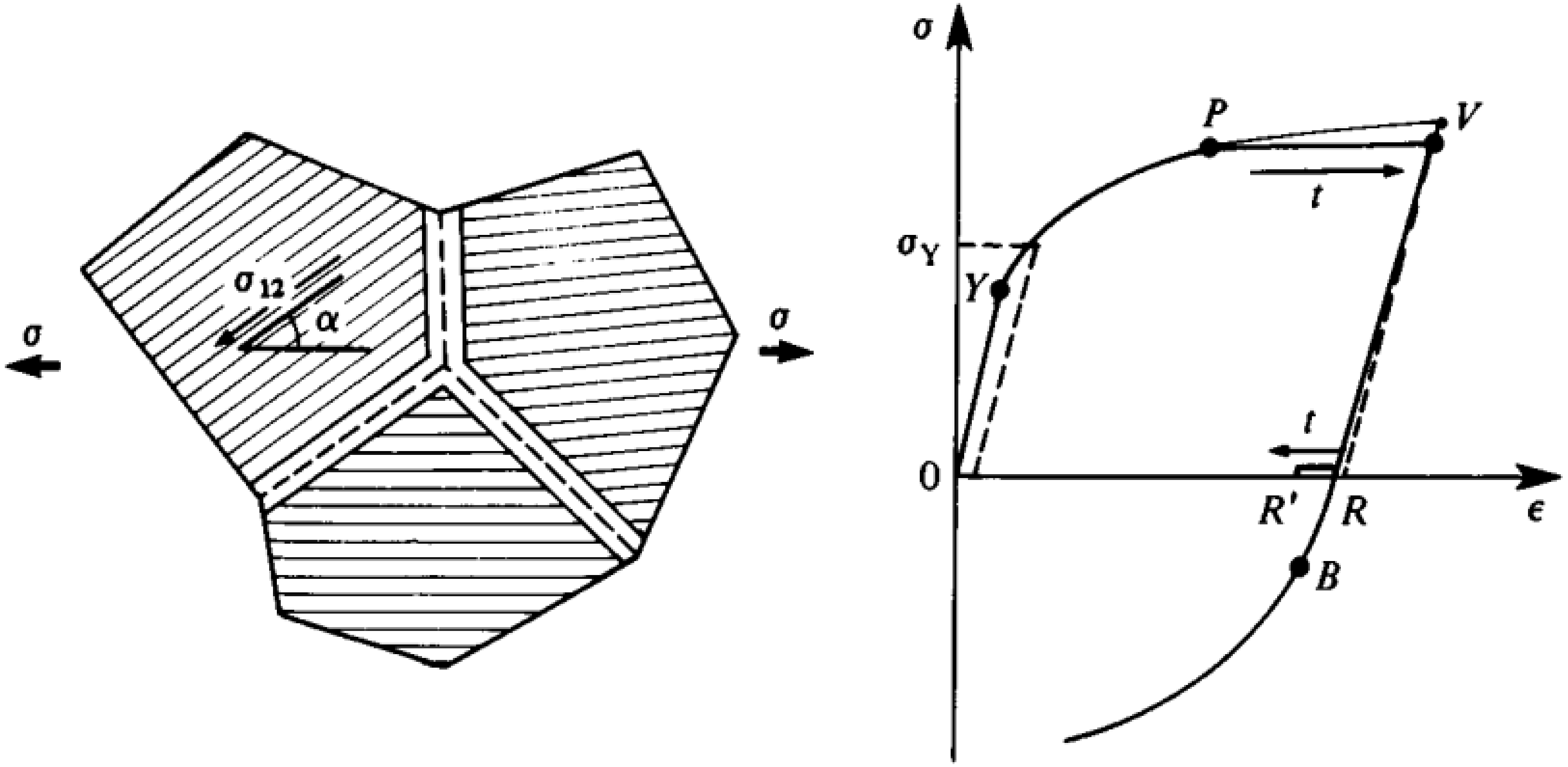
- X-ray Photoelectric Spectroscopy images (XPS) showing the microstructures



Plastic deformation of a polycristal

The first slip occurs in crystals with crystallographic slip planes oriented at $\alpha = \pi/4$ to the direction of external stress.

Fig. 1.17. Deformation of a polycrystal.



from Chaboche – Mechanics of solid materials