4MO-03, 21.9.2017

Electro-mechanical studies of MgB_2 wires and cables prepared by different processes

P. Kováč, L. Kopera, T. Melišek, M. Kulich, J. Kováč, and I. Hušek
Institute of Electrical Engineering of SAS, 841 04 Bratislava Slovakia

Motivation:

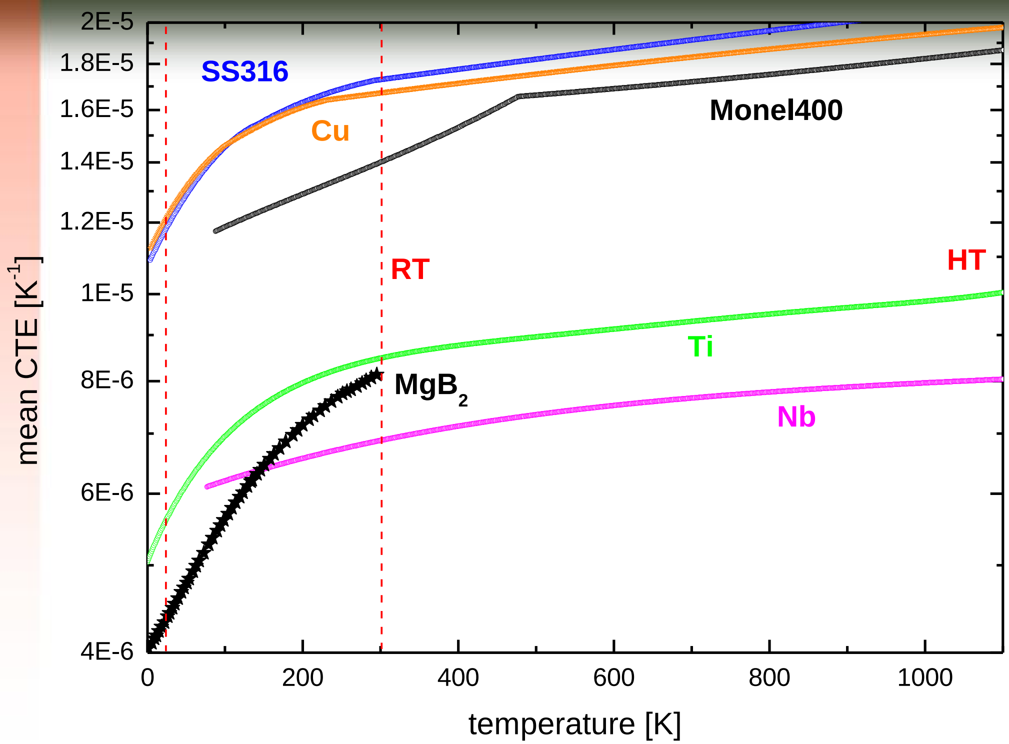
MgB_2 wires are composites consisting of **brittle filaments** inside one or more **ductile metallic sheaths**. Coils winding and magnets performance are not possible without **mechanical stress**.

Final properties of MgB_2 coils are **affected also by mechanical stresses** during the handling and operation.

Therefore, the **effects of mechanical loads** (e.g. **tension, pressure, bending and torsion**) have to be studied.

This presentation**:** effect of **tension at 4.2K**, **bending at RT** and **torsion** after HT applied to MgB_2 conductors of **variable design** and manufacturing **process**

MgB_2 phase in the cooled composite wire



Young modulus of the composite can be described by **the rule of mixtures** if metallic matrix and filaments are **elastic**:

$$E = f_f E_f + f_m E_m$$

where f_f and f_m are the volume fractions of filaments and matrix.

$\sigma(\varepsilon)$ curve of MgB_2 wire **is not linear** and the composite modulus must be determined by:

$$E = f_f E_f + (d\sigma_m / d\varepsilon_m)_{\varepsilon f} \cdot f_m$$

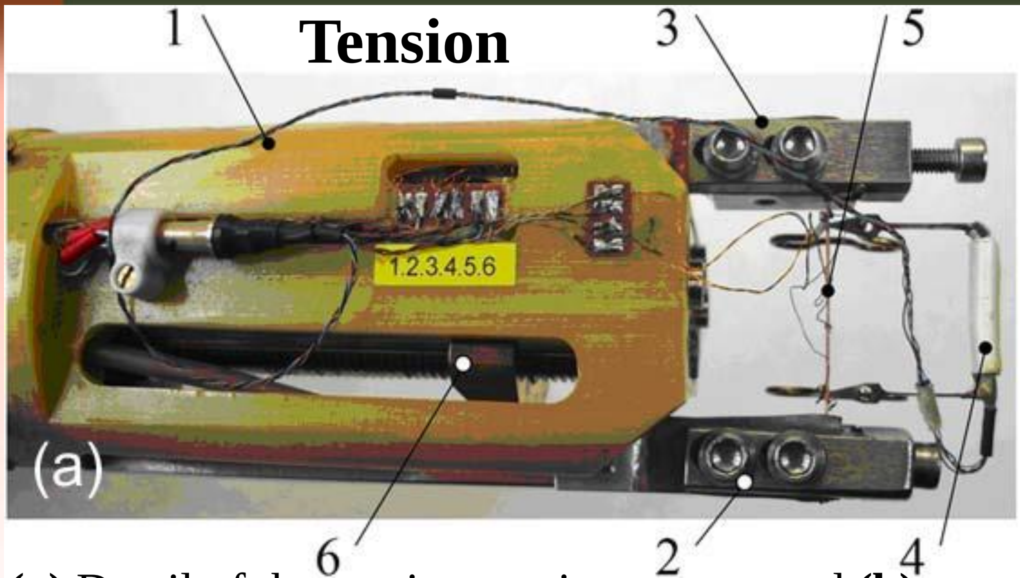
where $(d\sigma_m / d\varepsilon_m)_{\varepsilon f}$ is the slope of the matrix stress-strain curve at filament strain ε_f.

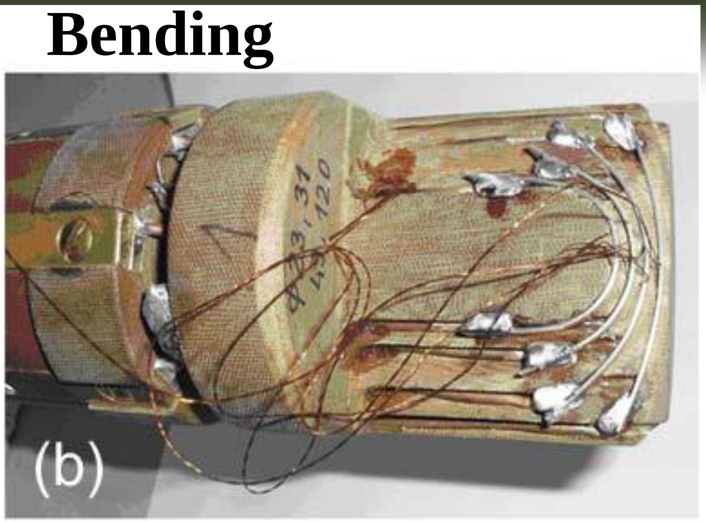
Generally, **MgB_2 filaments** are under **pressure stress** due to higher **CTE of** used **metallic sheaths**.

Additional stress (**tension or bending)** is superposed to residual one, which is **increasing or decreasing** (compensating) the final stress - **affecting sup. properties** (decreased T_c **and** J_c).

Kovac P and Kopera L, *IEEE Trans on Apll Sup* **22** (2012) 8400106

Electro-mechanical characterization of MgB_2 wires

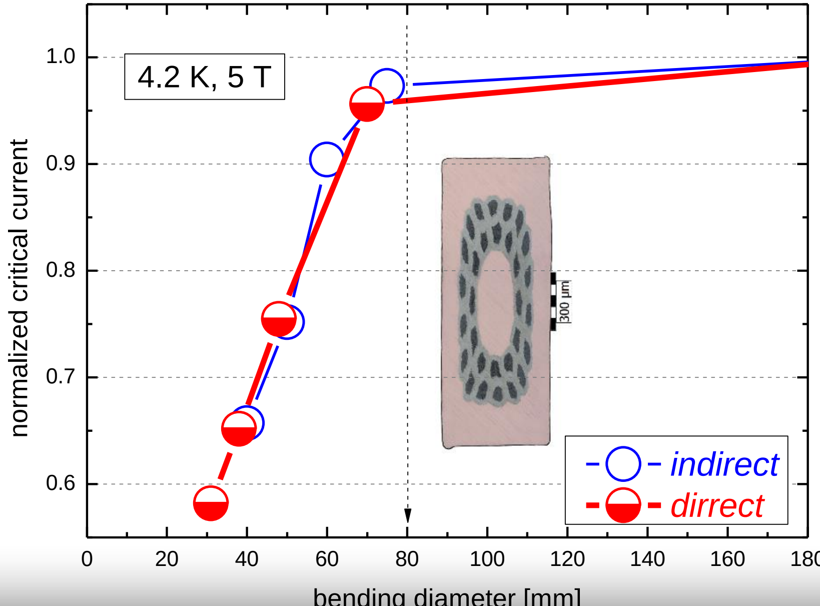




(a) Detail of the tension test instrument and **(b)** sample holder used for the **direct** measurement of critical current degradation by bending stress.

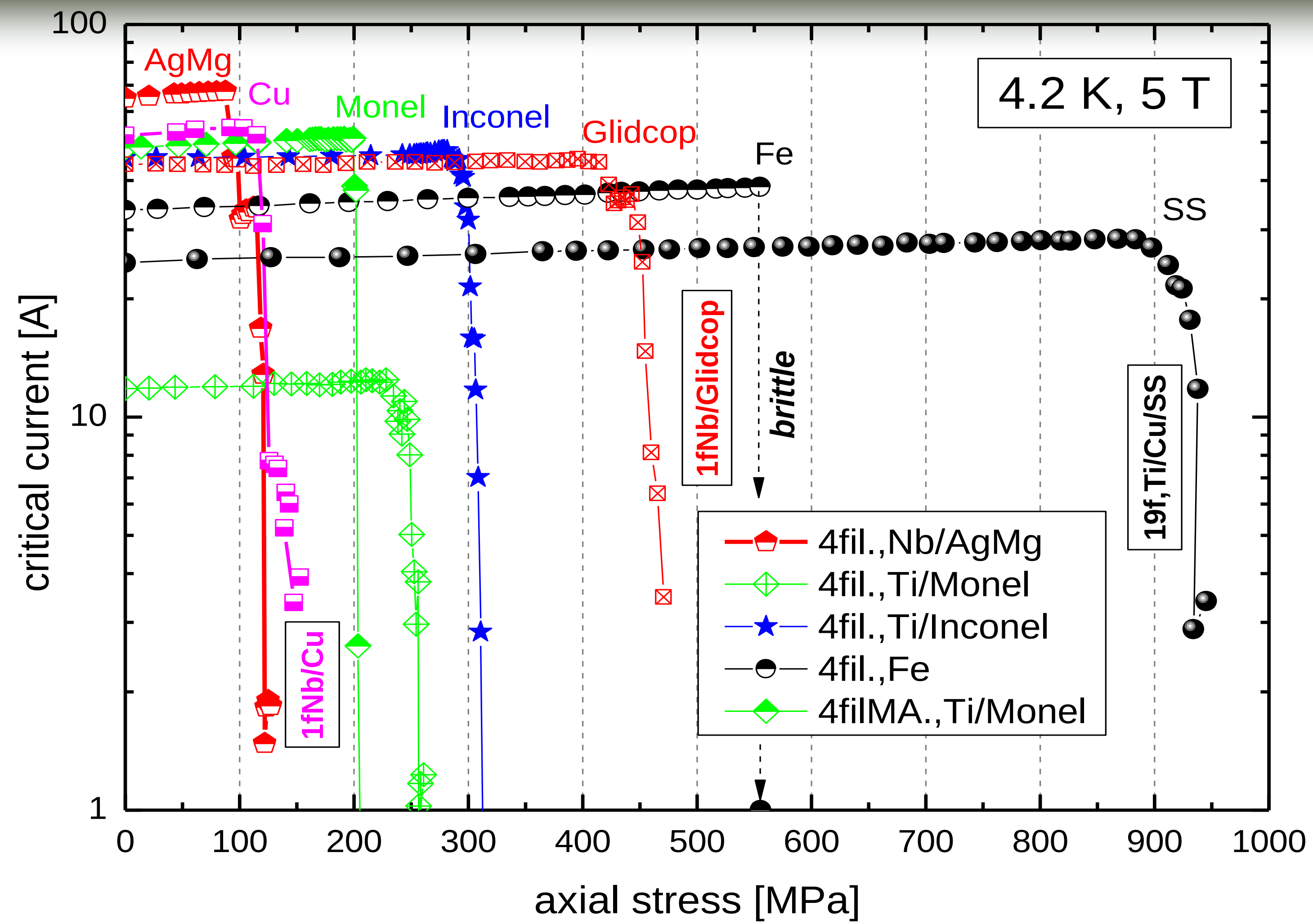
Tension tests: $\sigma(\varepsilon)$, $I_c(\varepsilon)$ and $I_c(\sigma)$, which allow to estimate: **irreversible strain (σ_{irr}) and stress (ε_{irr})**

Bending tests (direct or indirect): $I_c(d_b)$, which allow to estimate: **critical diameter, $I_c(\varepsilon_b)$**



Kopera L, *Sup Sci and Technol* **21** (2008) 115001 // Kovac P et al. *Sup Sci and Technol* **29** (2016) 045002

Tolerance to axial tension of in-situ wires at 4.2 K

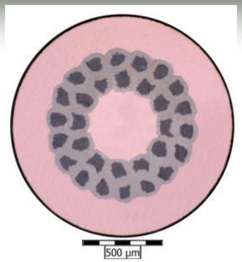


Tolerance to tensile stress is dominantly influenced by **outer sheath**:

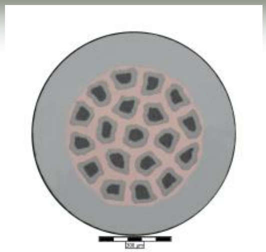
- the **lowest** for AgMg and Cu, Monel-GlidCop, Fe - **extremely brittle**, SS - the **highest**

P. Kováč, MgB_2 superconducting wires, Basics and applications", *World Scientific* 2016, 439-454.

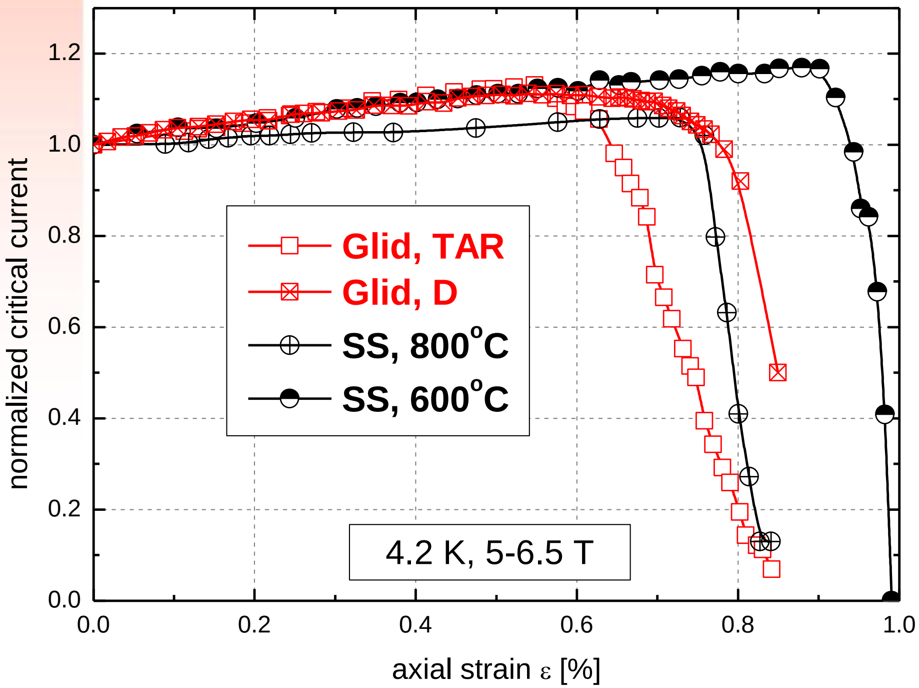
Tolerance of filamentary MgB_2 to tension

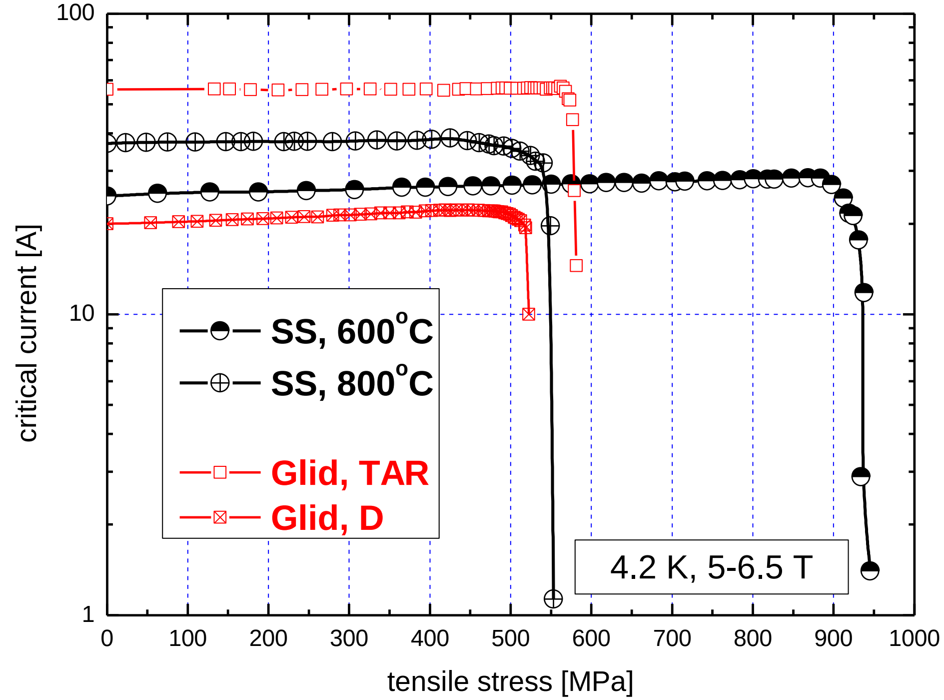


MgB_2/Ti/GlidCop
Drawing (D) and rolling (TAR)



MgB_2/Ti/Cu/SS
HT at:
600 and 800°C





Tolerance to tensile strain/stress is affected by the **filaments density** and also by **HT conditions**:
- more dense filaments > higher σ_{irr}/lower ε_{irr}, - the strength of SS is reduced by HT at 800°C.

P. Kováč et al. *Supercond. Sci. Technol.* **26** (2013) 105028

Reversible behaviour…

M. Dhallé, *Sup Sci and Technology* **18** (2005) S253

Dhallé M et al.: Up to the irreversible tensile strain, behaviour at different temperatures and magnetic fields (i.e. $I_c(T,B,\varepsilon)$ for $\varepsilon < \varepsilon_{irr}$), the **critical current varies linearly** with applied strain:

$$I_c(T,B,\varepsilon) = I_c(T,B,0)\left[1 + K_I(T,B)\varepsilon\right] \qquad (1)$$

where $K_I(T,B)$ is the (normalized) **slope** of the reversible strain response. Using the approach presented by eq. (1), the $\boldsymbol{K_I}$ relation for the **constant temperature** (4.2 K) and **magnetic field** (≈ 6 T) will be:

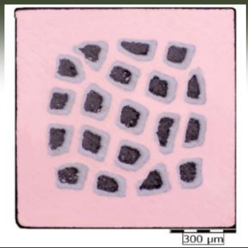
$$K_I = \frac{1}{I_c}\frac{dI_c}{d\varepsilon} = \frac{1}{I_c}\frac{dI_c}{dp}\frac{dp}{d\varepsilon} = \frac{E}{I_c}\frac{dI_c}{dp} \qquad (2)$$

where ***p*** **is external pressure acting on the** $\mathbf{MgB_2}$ compound.

Kitaguchi et al. have analyzed **the slope of** $\boldsymbol{I_c}$ versus the reduced field $b = B/B_{irr}$:
it falls on an universal line independently of temperature, $\boldsymbol{K_I}$ **is ↑ with** ***B*** **close to** $\boldsymbol{B_{irr}}$.

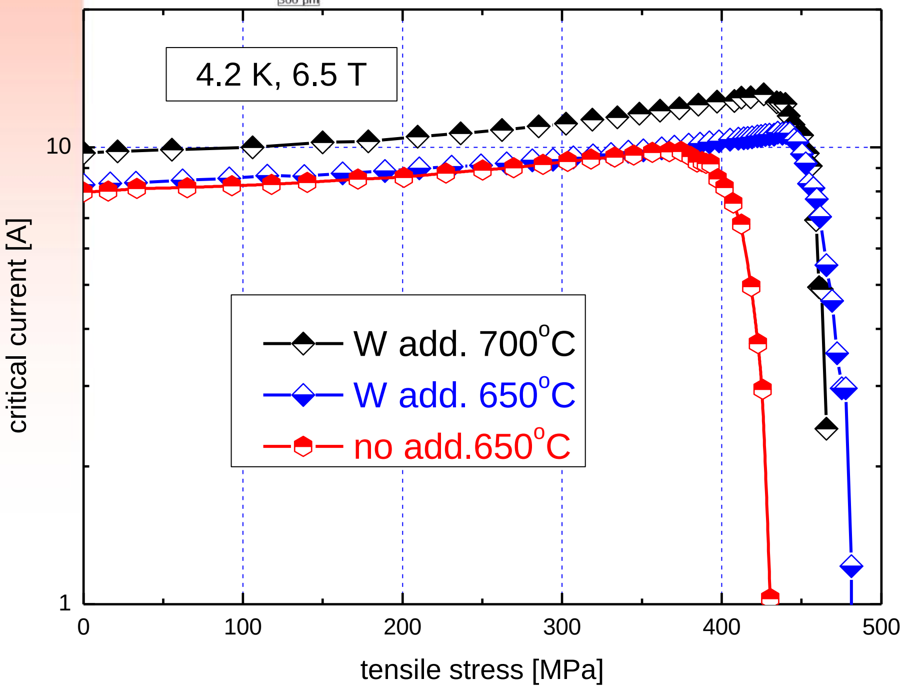
Kitaguchi H and Kumakura H *Supercond Sci Technol*. **18** (2005) S284

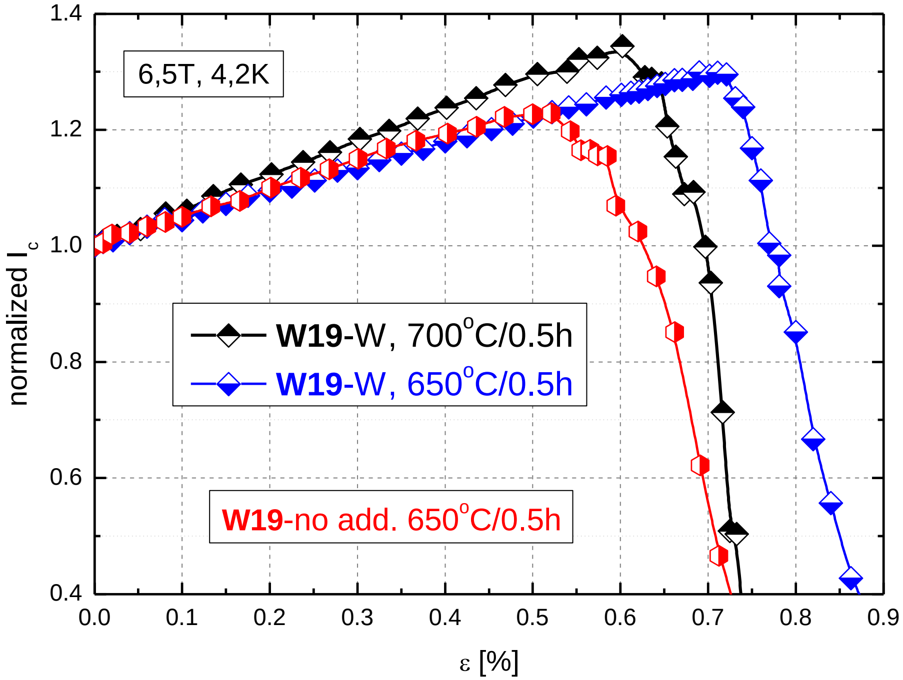
Effect of W aditions into MgB_2 filaments



19 fil. MgB_2/Nb/GlidCop

In-situ wire, Mg + B powder mixture and with 15 wt% of W addition of particle size < 20 µm



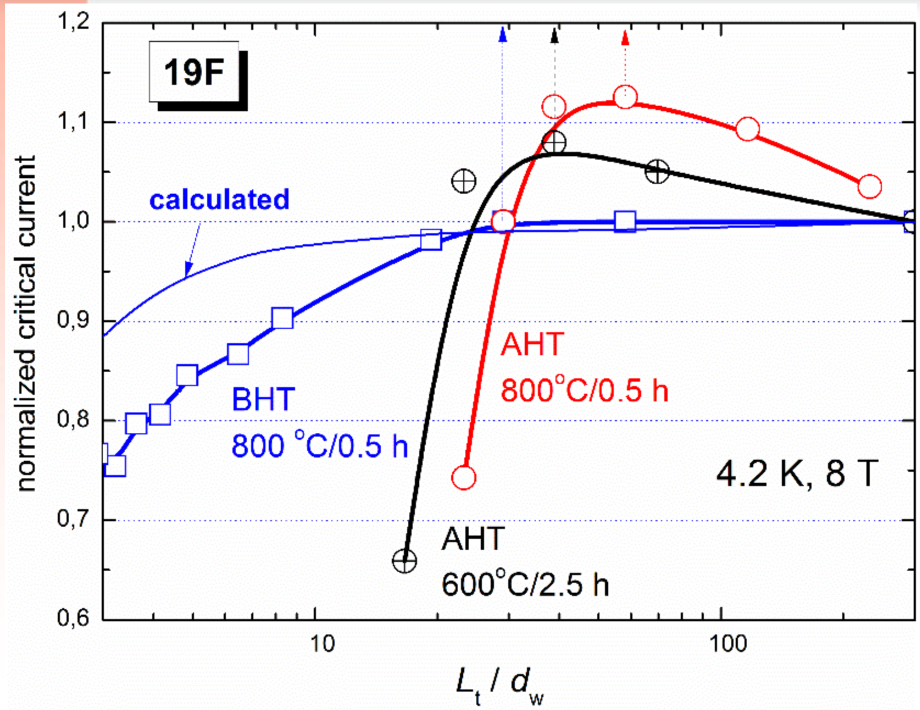


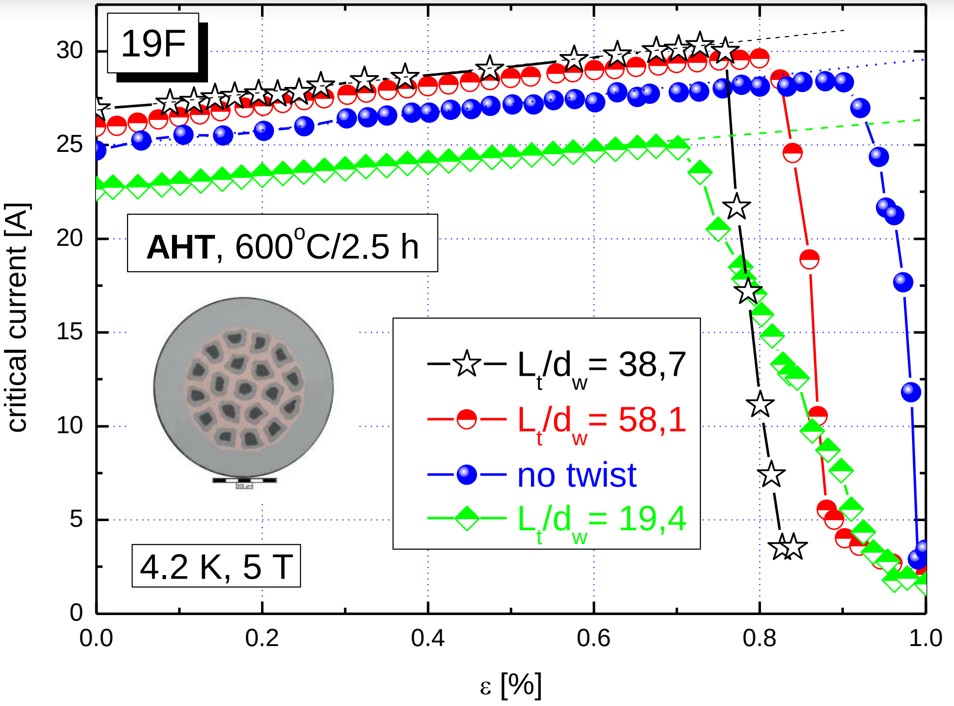
- 15 wt% additions of W particles into filaments **improved** the stress and strain **tolerance**
- W addition allows to **increase I_c** by tension up to 30–35% compared to not stressed one
- Presented improvements are attributed to **mechanical reinforcement** of MgB_2 filaments by distributed and ***elongated W particles*** (grain connectivity).

P. Kováč et al. *Cryogenics* **60** (2014) 5–8

Strain tolerances of twisted MgB_2 wires

Twisting of wire before heat treatment **(BHT)** and after heat treatment **(AHT)**



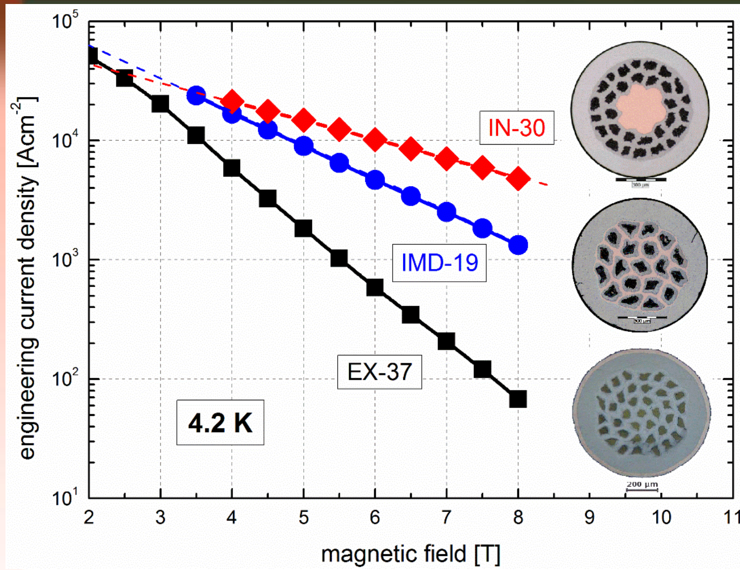


No current improvement has been measured for standard twisting applied before heat treatment (**BHT**).

Twisting applied after heat treatment increases the I_c of filamentary wire by 8–20%. Improvement of I_c by twisting **AHT** is explained by a partial **compensation of residual stress** through the applied torsion.

Kovac P et al. *Sup Sci and Technol* **24** (2011) 115006

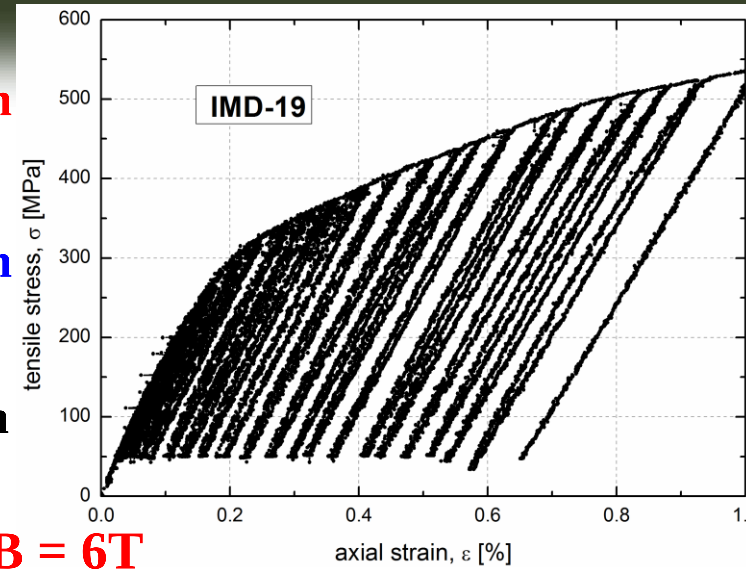
Monel sheathed wires under loading and unloading



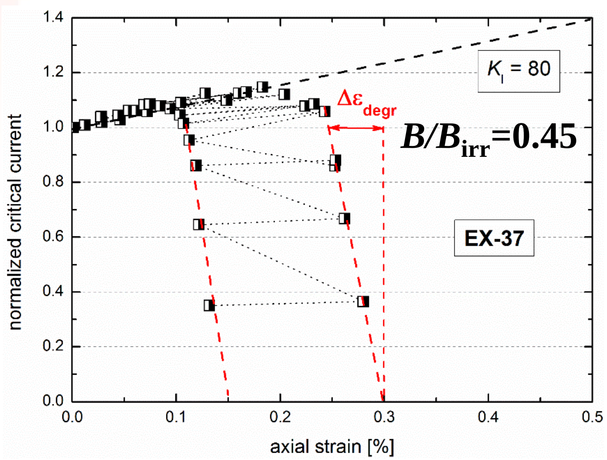
675°C/60min HyperTech

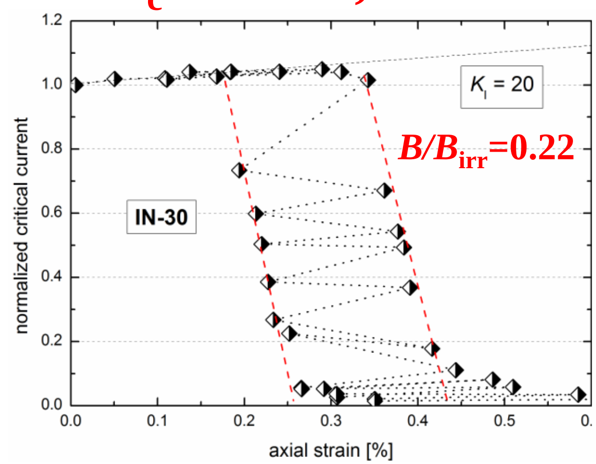
650°C/60min

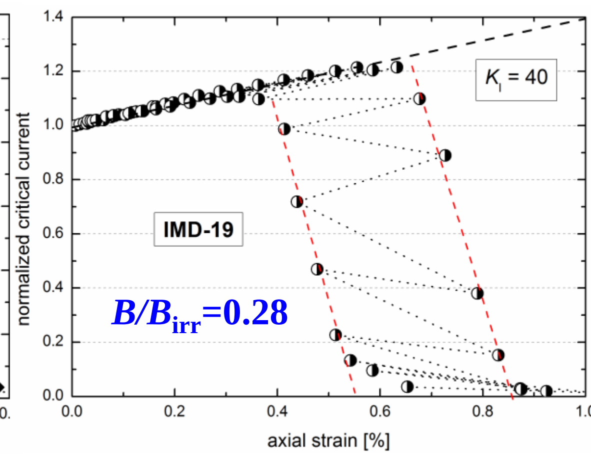
920°C/30min Columbus



I_c at 4.2 K, B = 6T





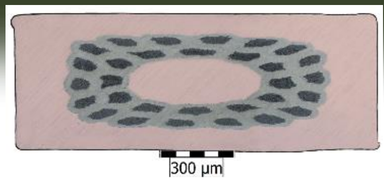


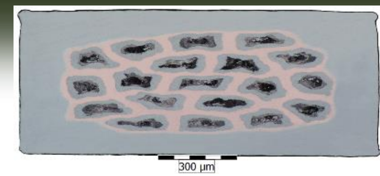
The lowest strain tolerance is measured for **EX-37** wire ε_{irr} **= 0.2%**, ε_{irr} **= 0.31%** for **IN-30** wire, and the best one for **IMD-19** wire having ε_{irr} **= 0.55%.**

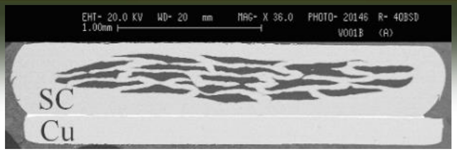
It is due to different HT conditions (**sheath softening**) and **grain connectivity** – best for IMD.

Kovac P et al. *Sup Sci and Technol* **30** (2017) 065006

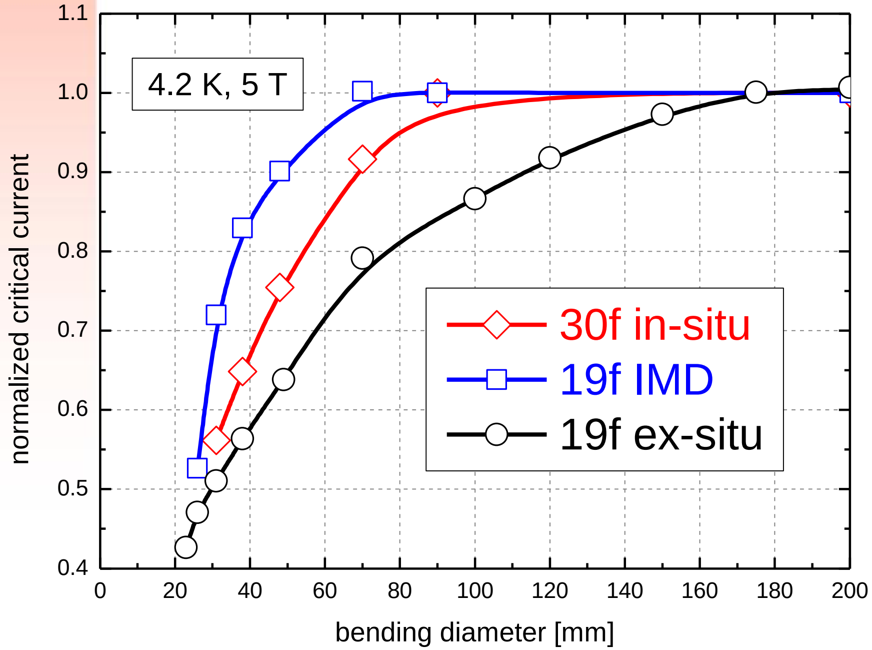
Bending of MgB_2 wires made by EX, IN and IMD

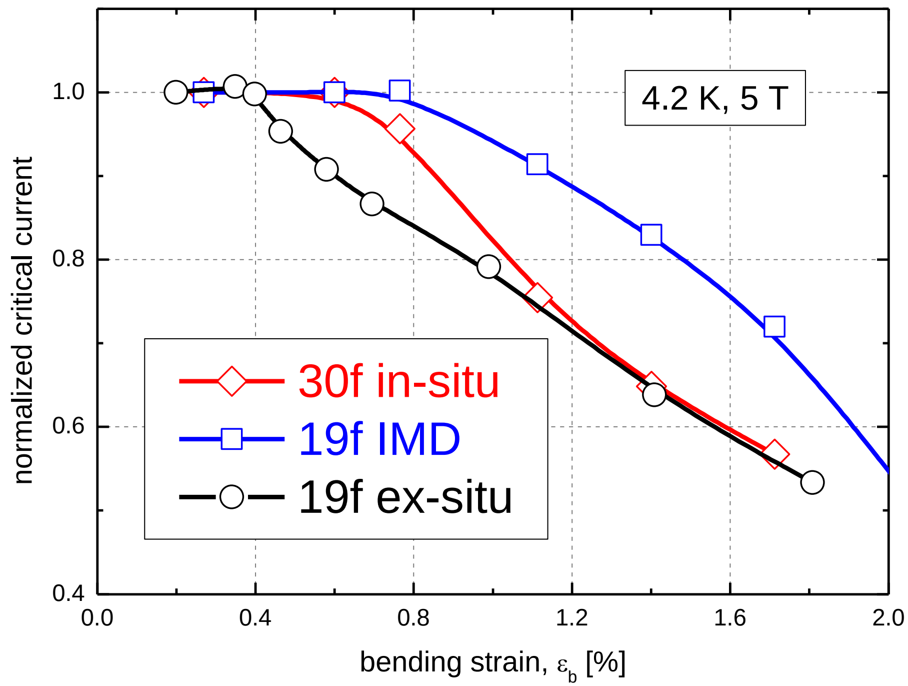






30f **in-situ,** Ti/GlidCop (0.54 x 1.3 mm^2) 19f **IMD,** Nb/Monel (0.5+0.2 x 3 mm^2) 19f **ex-situ,** Ni/Cu





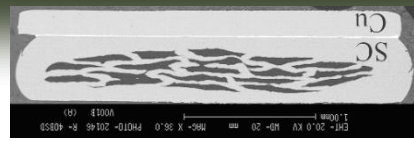
The observed differences in the **strain tolerances** among the **in-situ**, **ex-situ** and **IMD** wires are attributed to different **grain connectivity** and dominantly to mechanical **strengths of sheath materials** affected by the final heat treatment (**~640 ºC** – IMD, **~700ºC** – in-situ and above **900ºC** – ex-situ).

Kovac P et al. *Sup Sci and Technol* **29** (2016) 045002

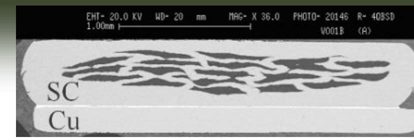
Bending of unsymmetrical MgB_2 conductor

In two directions:

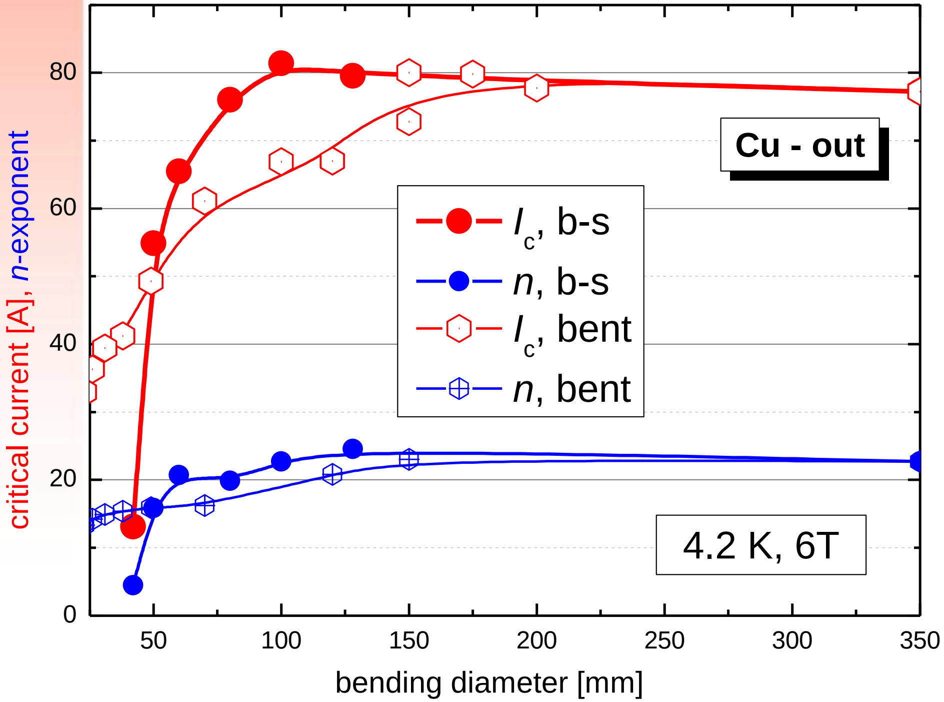
- direct bending – I_c
- **straightening** – I_c

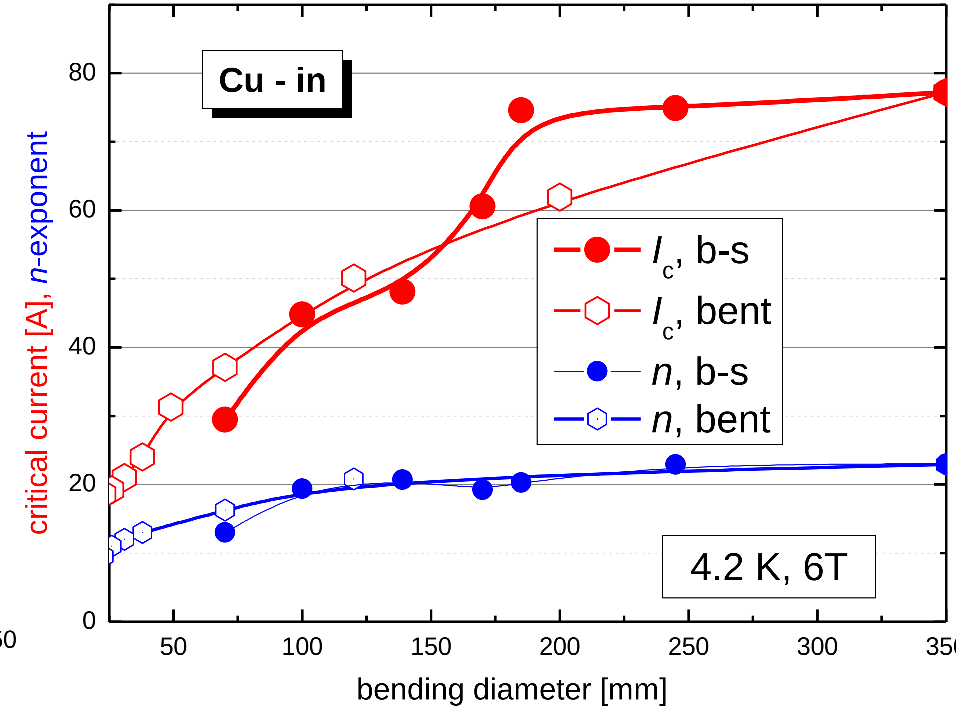


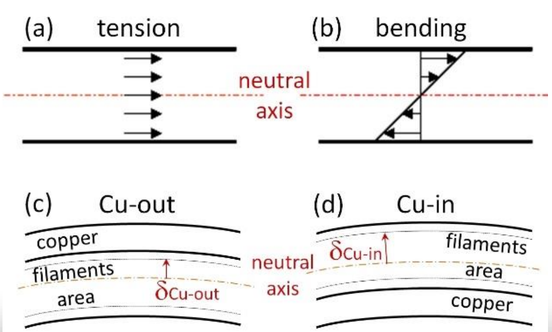
out



in







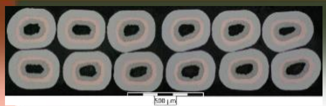
I_c **degradation** is much lower for **Cu-out (~175 mm) Cu-in (> 350 mm) .**

Tape **straightening -** attributed to partial **stress release.**

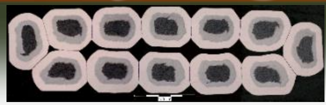
$\varepsilon_b = h_t/(R_b + h_t)$

Kovac P et al. *IEEE Trans on Apll Sup* **25** (2015) 6200607

Tolerances of MgB_2 cables to bending stress

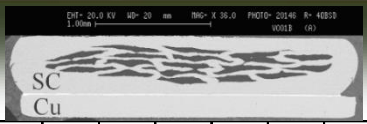


R1



R2

R3



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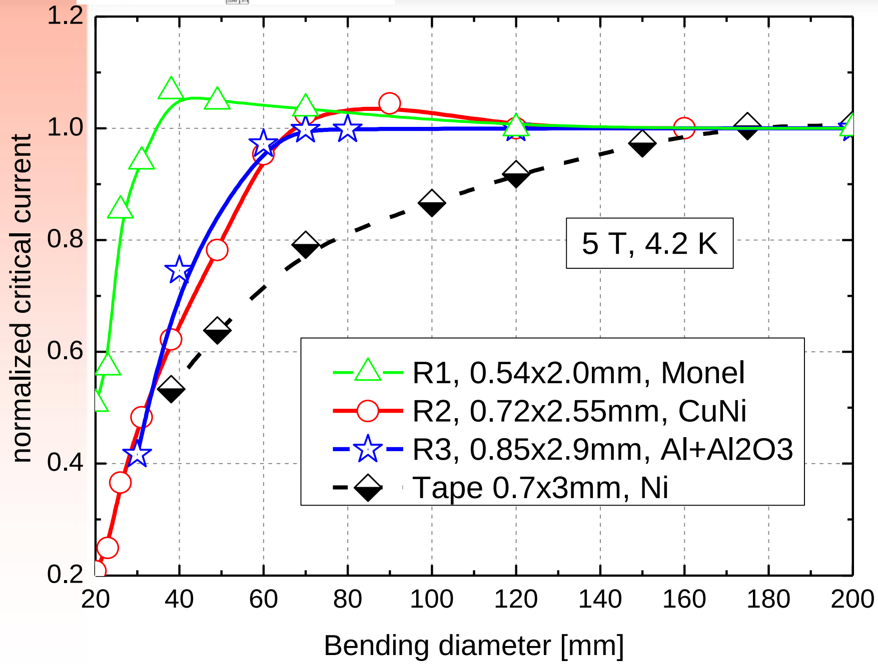

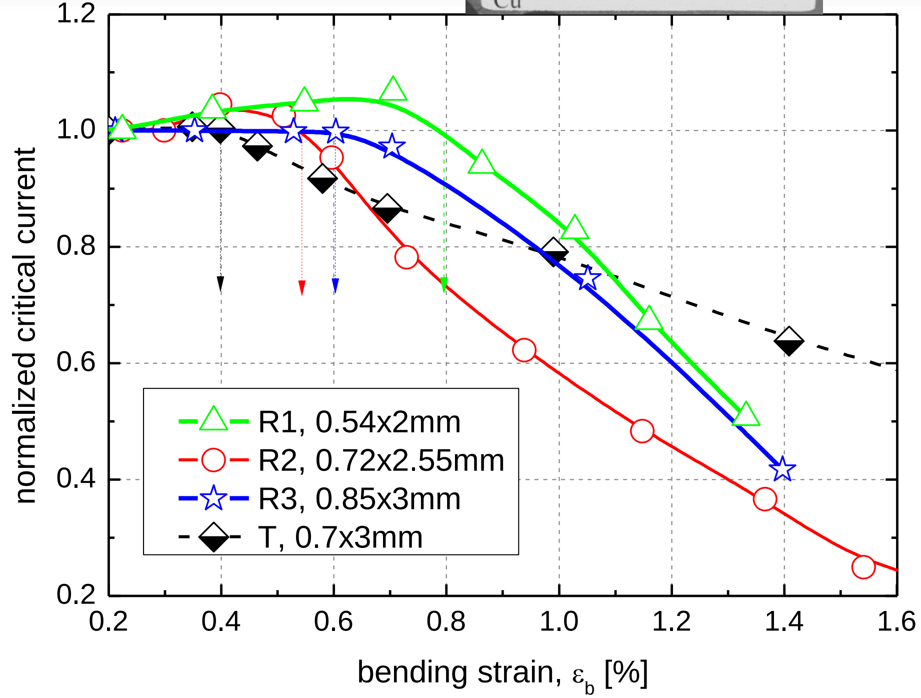

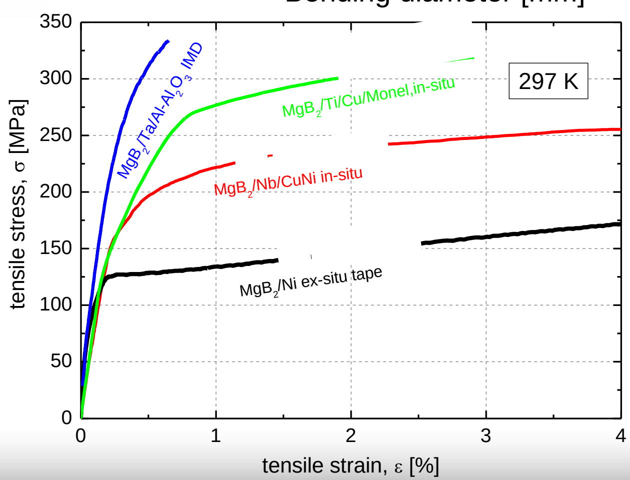

- **low I_c degradation** of Rutherford cable by bending **< 35 – 70 mm.** It correlates well with the strands diameter and σ(ε) of strands at room temperature
- **important for multi-pole generators – low diameter racetrack coil**

Kopera L et al. *Sup Sci and Technol* **30** (2017) 015002

Kovac P et al. *Sup Sci and Technol* under review ...

Conclusions

- Electro-mechanical characterization by **tension and bending** has been performed for MgB_2 conductors of different architecture and sheaths mat.
- It was found that **outer sheath has a dominant effect** on the stress tolerance of MgB_2 composite wire.
- The stress tolerance can be **improved by filament structure** (**W-addition**, **densified filaments** – rolling or swaging and by **IMD process**).
- MgB_2 conductors made by **IMD shows the best strain tolerance** (by **tension and bending**).
- **Twisting** of filaments is changing the **residual stress** inside the wire and consequently the **strain tolerance is decreased**, but I_c **values** are **increased**.
- Rutherford **MgB_2 cables** offers the **lowest bending diameters** after HT, which can be interesting for winding of multi-pole motors/generators.