Electro-mechanical studies of MgB\textsubscript{2} wires and cables prepared by different processes

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Motivation:
MgB\textsubscript{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\textsubscript{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\textsubscript{2} conductors of variable design and manufacturing process
**MgB<sub>2</sub> 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.

**σ(ε) curve** of MgB<sub>2</sub> wire is not linear and the composite modulus must be determined by:

$$E = f_f E_f + (d\sigma_m / d\varepsilon_m) \cdot f_m$$

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

Generally, MgB<sub>2</sub> 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 $J_c$).
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 ($\sigma_{irr}$) and stress ($\varepsilon_{irr}$)

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

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, MgB₂ superconducting wires, Basics and applications”, World Scientific 2016, 439-454.
Tolerance to tensile strain/stress is affected by the filaments density and also by HT conditions:
- more dense filaments > higher $\sigma_{\text{irr}}$/lower $\varepsilon_{\text{irr}}$,
- the strength of SS is reduced by HT at 800°C.

Reversible behaviour...


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 $\varepsilon < \varepsilon_{\text{irr}}$), the **critical current varies linearly** with applied strain:

$$I_c(T,B,\varepsilon) = I_c(T,B,0) \left[1 + K_1(T,B)\varepsilon\right] \quad (1)$$

where $K_1(T,B)$ is the (normalized) **slope** of the reversible strain response. Using the approach presented by eq. (1), the $K_I$ relation for the **constant temperature** (4.2 K) and **magnetic field** ($\approx 6$ T) will be:

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

where $p$ is **external pressure acting on the** $\text{MgB}_2$ compound.

Kitaguchi et al. have analyzed the **slope of** $I_c$ versus the reduced field $b = B/B_{\text{irr}}$: it falls on an **universal line independently of temperature**, $K_I$ is $\uparrow$ with $B$ close to $B_{\text{irr}}$. 
Effect of W additions into MgB$_2$ filaments

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.

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

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

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 °C – IMD, ∼700°C – in-situ and above 900°C – ex-situ).
**Bending of unsymmetrical MgB$_2$ conductor**

In two directions:
- direct bending $- I_c$
- straightening $- I_c$

**Cu - out**

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

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

Tape straightening - attributed to partial stress release.

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