Critical current and cryogenic stability modelling of filamentary MgB$_2$ conductors

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Abstract. The modelling of a single filament, 6 filaments and 19 filaments MgB$_2$ conductors was performed for two limiting cases: a) isothermal conditions considering $J_c(B)$ dependence, b) considering heating effects but with $J_c$ magnetic field independent. As a starting point of the modelling in case a) we used experimental dependence of $J_c(B, 4.2$ K) for the best wire. Then Poisson equation for magnetic vector potential was solved by finite element method and self-field critical current densities of the wires with different diameter were calculated. There is no significant dependence of $J_c$ in range of electric fields $E = 1 \times 10^3 \mu$V/cm. The isothermal modelling with $J_c$ independent on magnetic field, case b), gave the results more close to the experimental ones. From the modelling of the heating effects we conclude that the cryogenic stability of the used Cu/SUS316/MgB$_2$, Fe/MgB$_2$ and Cu/MgCu$_2$/MgB$_2$ wires is adequate. The stabilizing copper layer can take all the current up to the onset of film boiling of LHe where the current starts to decrease with increasing electric field, i.e. at this point the differential resistivity of the Cu/SUS316/MgB$_2$ wire starts to become negative (indicating the onset of instability). Analysis of mechanically induced defects limiting the $J_c$ in 6 filaments conductor is presented.

1. Cryogenic stability modelling

The problem of a voltage–current relation in a Type II superconductors such as YBa$_2$Cu$_3$O$_7$ and MgB$_2$ carrying a transport current is one the most important for applications [1]. The purpose of the paper is to analyse the influence of non-isothermal conditions on voltage–current relations of MgB$_2$ conductors Cu/SUS316/MgB$_2$, Fe/MgB$_2$ and Cu/MgCu$_2$/MgB$_2$ [2-4]. All the simulations were made under an assumption that when a dc electric field is applied on the cross-section of a composite conductor, the
A conductor carries a dc transport current parallel to its longitudinal axis in a self magnetic field. No transverse currents were modeled. This makes the problem 2D. In practice it means that a part of the composite conductor far away from the current leads was modeled. No inhomogeneities or other defects in materials were considered. The critical current density \( J_c \) of the superconducting parts of the composite conductors was considered to be independent of magnetic field \( [1] \).

**Fig 1.** Calculated voltage–current characteristics (points) of the MgB\(_2\) superconducting composite conductors immersed in liquid He: a) Fe/MgB\(_2\) composite wires. Bare MgB\(_2\) wire has diameter \( d = 0.6 \text{ mm} \) where the Fe/MgB\(_2\) composite wires (insert) have different Fe thickness \( t \). The straight vertical line is the isothermal power-law voltage–current characteristic of the bare MgB\(_2\) wire at 4.2 K. (● - bare MgB\(_2\), ○ - MgB\(_2\) covered with Fe of thickness \( t = 0.25d \), □ - MgB\(_2\) covered with Fe of thickness \( t = 0.5d \) and △ - MgB\(_2\) covered with Fe of thickness \( t = d \)); b) MgB\(_2\)/SS316/Cu composite wire OD 2.9 mm. MgB\(_2\) filament diameter 0.418 mm, overall SS316 matrix diameter 2.6 mm, Cu stabilizer thickness 0.126 mm that provides adequate stabilization for the conductor.

The effect of stabilising iron layers of different thickness on \( E - I \) curves of MgB\(_2\) wire is shown in Fig. 1b. If we define the onset of instability, at a typical critical current measurement, as the onset of negative differential resistance of the sample, then we can conclude, that the presence of the iron coating improves the overall stability of Fe/MgB\(_2\) composites with respect to bare MgB\(_2\) wires. A thickness of the iron layer of about 0.25 of the wire diameter is quite sufficient. However, the instability occurs at the onset of film boiling, which appears at electric fields of about 200 \( \mu \text{Vcm}^{-1} \). At

**Fig 2.** Spatial distribution of the critical current density in a 6-filament MgB\(_2\) wire cross-section in the self-field, for two electric criteria a) 1 \( \mu \text{Vcm}^{-1} \); b) 10 \( \mu \text{Vcm}^{-1} \). There is an evidence that above \( E = 10 \mu \text{Vcm}^{-1} \) there is a current transfer from MgB\(_2\) filaments to copper stabilizer. At this point the differential resistance starts to be negative and after that most of the current starts to flow.
through the iron stabilising layer accompanied by substantial heating. From the point of view of the current limiting effect, the presence of the Fe stabilising layer decreases the effect by about one order of magnitude. Thermal gradients in the bare MgB$_2$ wire are typically 1.35 K/0.3 mm just below the onset of film boiling and 0.2 K/0.3 mm just above the onset of film boiling, which occurs at electric fields between 84 and 84.2 μVcm$^{-1}$ (Fig. 1a).

Calculations conducted for the MgB$_2$/SS316/Cu composite wire prove that the thin copper stabilizer is sufficient to protect the superconductor, Fig 1b, but at low electric fields of the order of $E = 10$ μVcm$^{-1}$ there is a current transfer from MgB$_2$ filaments to copper stabilizer which is also visible in Fig. 2. It is also evident from Fig. 1b, that single core Cu/Cu$_2$Mg/MgB$_2$ conductor [3] is fully stabilized. Calculations of the temperature profiles in the Cu/SUS316/MgB$_2$ conductor at corresponding electric filed criteria given in Fig 3a, causing temperature increase from LHe temperature, are presented in Fig 1.

2. Causes of Mechanical Failure in Multifilament Wires

The drawing process introduces large tensile stresses, which the matrix material needs to be able to carry, since the powder can carry virtually no tensile stress. Ideally, the part of the wire that has already passed through the die has been strain hardened substantially more than the part entering the die. This strengthens the part of the wire subjected to tensile stress and aids the process. As the matrix material nears a point where little more strain hardening can be achieved, the risk of failure increases, since the difference in strength becomes less between material entering and exiting the die. The sudden drop in critical current at 6-filament Cu/SUS316/MgB$_2$ conductor diameter of approximately 0.95 mm is related to the onset of mechanical failure. Since this failure occurs during the drawing process, the density of the powder is still relatively low and it is thus unlikely that the failure is due to cracks forming in the powder. As such, the cause of the failure, first seen at a diameter of 0.90 mm, is most likely due to excessive straining of the matrix material during the drawing process as presented in Fig 4. In Fig 4b, it is seen that initial fracture occurs at the point where the stress strain curve for SUS316 starts reaches plateau. This low gradient of the curve indicates that the matrix material has reached its limit for strain hardening, inducing the problems during the drawing process as mentioned above.

Fig 4. Diameter dependence of $J_c$ for 6-filament MgB$_2$ wire.
An example of this type of failure can be seen in Fig. 5. It was observed that after an area reduction of 94%, the 19 filament Fe/MgB$_2$ conductor showed no sign of external fracture, while internally the filaments are broken and dislocated [5].

![Fig 5. Longitudinal cross section of the ex situ 19 filament Fe/MgB$_2$ conductor at different stages of mechanical deformation. a) OD = 4.48mm, b) OD = 2.52mm. No external sign of fracture were observed, while internally the filaments are broken and dislocated.](image)

### 2.1. Avoiding Failure and Improving Critical Current

Normally failure of the matrix material can be avoided by introducing annealing between drawing steps. However, in the given case where densification of the powder is required in the drawing process, softening the matrix material is not desirable. A possible alternative to drawing is swaging, where no tensile stresses are introduced, Fig 6. As such this would eliminate many of the problems due to strain hardening of the matrix and due to the high hydrostatic pressure generated by this process [6], substantial densification of the ex situ and in situ MgB$_2$ powder is also expected which can improve critical current characteristic [7]. One drawback of the swaging is that the deformation has to be well controlled to avoid inhomogeneous deformation of the superconducting core.

![Fig 6. Simulation of the densification process of the MgB$_2$ powder in 6-filament Cu/SUS316/MgB$_2$ conductor: a) swaging; b) drawing. Initial relative density of MgB$_2$ powder was preset to 70%. Pictures represent an axis-symmetrical cross model.](image)

References

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