Effects of impurities addition in MgB$_2$/Nb tapes on flux jumps instability and critical current density

M Polichetti*1, D Zola1, I Husěk2 P Kovác2 and S Pace1

1 CNR-INFM, Laboratorio Regionale "SuperMat", Salerno, and Dipartimento di Fisica, Università di Salerno, via S. Allende 84081 Baronissi (SA), Italy
2 Electrical Engineering Institute SAS, Dubravska cesta 9, 84239 Bratislava, Slovakia
E-mail: polimax@sa.infn.it

Abstract. In order to understand the effect of impurities inclusions on the transport properties of MgB$_2$ tapes, by means of magnetization measurements we have analysed non-commercial monofilamentary tapes in which titanium (Ti), tungsten (W) and silicon carbide (SiC) normal particles were included. All the samples under analysis have the same cross section and their MgB$_2$ filament is embedded in a superconducting niobium matrix. For all the tapes a magnetic field ($H_a$) up to 65 kOe has been applied parallel to the filament, and we have compared their magnetization loops $M(H_a)$ measured in the temperature range from 2 K up to 30 K. The results show that the process of adding normal particles in the material, in order to increase the transport properties, produces at low field opposite effects to those at higher field. Moreover, all the particles included produce the common result of an enhancement in the thermomagnetic instability, and consequently a decrease of the transport properties, at low temperature and magnetic fields.

1. Introduction

MgB$_2$ tapes with a critical current density ($J_C$) of about $10^6$ A/cm$^2$ can give a promising chance to use this material for the manufacturing of cryogen-free small magnets, superconducting dipole and fault current limiter [1]. Nevertheless, at temperatures lower than 10 K, a thermomagnetic instability has been observed which limits the critical current density especially at low field [2, 3, 4, 5]. This instability appears as flux jumps or in dendritic form, and they are observed as a large reduction or give a noisy behaviour in the magnetization. The thermomagnetic instability can be generally explained starting from the critical state of type II superconductors which, in a simple form, is given by the relation $\nabla \times \vec{B} = \mu_0 \vec{J}$, where $B$ and $J$ are respectively the magnetic induction field and the current density limited in the superconductor to the $J_C$ value. If $J_C$ decreases with temperature ($T$)(as usually happens), the critical state may become unstable because the flux motion is an exothermic process triggered by a thermal fluctuation which locally rises the temperature of the superconductor because of its very low specific heat ($C$). This temperature enhancement reduces the $J_C$, and the flux motion starts, adding new heat to the system. This positive feedback may realize an thermal avalanche of the magnetic flux [6].

However the production of higher performance superconducting tapes is devoted to increase the $J_C$ of the wires. This goal is usually obtained by means of normal particles, enhancing the pinning force, added to the superconducting material without any decrease in the critical
temperature \((T_C)\). The addition of approximately 10\% by volume of nanoscale ceramic particles or reactive metal powders effectively improves the electrical transport properties of MgB\(_2\), and this occurs even if the dimensions of the normal particles are much larger than the coherence length \(\xi\) \([7]\). Recently a detailed study about the chemistry of the Ti addition revealed the role of the reactive metals as absorber of oxygen and hydrogen from MgB\(_2\) resulting in a more pure superconducting phase \([8]\). Nevertheless, the effects of particles addition on the thermomagnetic properties of the MgB\(_2\) wires are not fully investigated.

In this work, we have studied the thermomagnetic instability in MgB\(_2\) monofilamentary tapes embedded in a Niobium matrix. In particular, magnetic measurements have been performed on four kinds of MgB\(_2\) monofilamentary tapes, namely a pure MgB\(_2\) tape (Tape A) and three additional tapes respectively with the same amount (10wt\%) of titanium (Tape Ti), tungsten (Tape W), and silicon carbide (Tape SiC) inclusions.

2. Experimental Results and Discussion

All the tapes used in the present work have similar width \((w)\) and thickness \((t)\) (see Tab. 1) and the superconducting filament has width \(w_F = 0.87\) mm and thickness \(d_F = 0.44\) mm. The critical temperature of the common niobium matrix is 9.2 K independently of the impurity added in the tapes. On the other hand, both the onset \((T_{C-\text{ons}})\) and the critical temperature \((T_C)\) of the MgB\(_2\) fraction changes with impurities, as summarized in the table 1 together with the other main features of the superconducting filament. In all the magnetic measurements, carried out by a Quantum Design PPMS Model 6000 equipped with a VSM, the external magnetic field has been applied parallel to the filament length, thus reproducing the slab geometry. From magnetic measurements, the critical current density \((J_C)\) of each tape has been evaluated using the Bean expression for a superconducting parallelepiped in longitudinal field:

\[
J_C = \frac{120 w_F}{t_F (3 w_F - t_F)} M
\]

where \(J_C\) is measured in A/cm\(^2\) and the irreversible magnetization \(M\) is in emu/cm\(^3\). The \(J_C\) behaviour as function of the applied magnetic field \((H_a)\) has been reported in Fig. 1a for \(T = 20\) K. We can observe that at low \(H_a\) the tape with the highest critical current density is the one without any particle included in MgB\(_2\). Very similar values at low field are measured in the tape with Ti and W, whereas the Tape SiC has the lowest \(J_C\). The effect of impurities on the improvement of \(J_C\) is observed at fields larger than 35 kOe where the tape with SiC shows a lower depression with field. However similar effects are visible in the tape with Ti particles, although the field dependence appears very similar to the Tape A. Finally, a worsening is produced by adding tungsten particles in MgB\(_2\). Similar behaviour is repeated in the \(J_C(H_a)\) measured at other temperatures, as reported in Fig. 1b which shows the temperature behaviour of \(J_C\) estimated at \(H_a = 0\) kOe and 40 kOe.

| Name  | \(T_{C-\text{ons}}\) (K) | \(T_C\) (K) | \(w\) (mm) | \(t\) (mm) |
|-------|-----------------|--------|--------|--------|
| Tape A | 36.3            | 34.9   | 1.51   | 0.72   |
| Tape Ti| 35.4            | 34.3   | 1.50   | 0.70   |
| Tape W | 36.3            | 34.0   | 1.55   | 0.73   |
| Tape SiC | 33.8          | 31.8   | 1.55   | 0.71   |
effect of the particles inclusion is mainly the improvement of the $J_C$ at high field and this is accomplished by just a little reduction of $T_C$ in all the tapes. The lowest $T_C$ of Tape SiC (31.8K) is attributed to partial carbon substitution of boron in the MgB2 lattice. Nevertheless, since the MgB2 shows flux jumps at temperatures below 10 K [2] we investigate the effect produced by the inclusions on the thermomagnetic properties of the tapes. The fact that all the tapes have the same cross section and the same metallic matrix embedding the superconducting filament represents a good opportunity to study the effect of particles addition on the stability of the cables. Unfortunately, the flux jumps in MgB2 appear in the temperature range where the niobium matrix is also superconductive. Moreover, flux jumps could also occur in the niobium foil surrounding the MgB2. For this reason, we have evaluated the threshold criterion for the thermomagnetic stability of the matrix and focused the attention on the $M(H_a)$ loops measured at $T = 6$ K and $H_a > 1$ kOe, where the flux jumps are not observed even in 1 mm thick Nb samples carrying a critical current density of $10^6$ A/cm$^2$ [9].

In Fig. 2, the first magnetization curves measured at 6 K in all the tapes are shown. As the $H_a$ ramps, two peaks are observed: the first one at 1.6 kOe, is due to the flux penetration in niobium sheet, followed by a decrease in the absolute value of $M$, due to the magnetic field effect on $J_C$ of the niobium. By increasing the magnetic field from $H_a = 2.3$ kOe, the $|M|$ grows again, because the magnetic flux starts to penetrate into the MgB2 filament, up to a second maximum at 5.2 kOe related to the full penetration of the MgB2. This behaviour is ascribed to the low $J_C$ value in niobium at $H_a > 2$ kOe. By using the Bean model, and in particular the case in which $H_a$ is lower than the full penetration field, we estimated that the $J_C$ carried by the niobium matrix at 6 K is $2 \times 10^4$ A/cm$^2$. The threshold parameter for the thermomagnetic stability is given by $\beta = J_C^2(t/2)^2/[3\gamma C(T_C - T)]$ where $\gamma = 8570$ kg/m$^3$ is the niobium density, $C = 1.03$ J/kg-K is the specific heat (measured at 6 K) [10] and $t$ is the tape thickness. With these values $\beta = 0.06 < 1$ at 6 K, thus ensuring that the niobium sheet is thermomagnetically stable at this temperature.

The analysis reported above allows us to discuss the behaviour of the magnetization of our samples analyzing the magnetization of the second and the third branch in the $M(H_a)$ loops, reported in Fig. 2b for all the tapes. We can observe that no jump occurs in the undoped sample, whereas the instability increases in the samples in which the particles were added. The tape with SiC show noisy magnetization extending up to $H_a = 5$ kOe whereas the tapes with W and Ti particles have one and two large jumps respectively in the same field range. This
Figure 2. $M$ versus $H_a$ measured at 6 K in the tapes: a) Virgin magnetization curves b) Second and third branch of the magnetization loops.

indicates that another effect due to the particles addition is the increase of the instability in the MgB$_2$ filament. Moreover, the less stable sample, Tape SiC, has the lowest $J_C$ at low fields at all the temperatures. These results suggest a link between the thermomagnetic instability and the current transport performance of the tapes. In particular, we can consider two scenarios. First, if the particles addition increases the pinning force, this does not lead to a gain in $J_C$ because of the larger thermomagnetic instability generated. The instability extends itself also to higher temperature even where there are not observable jumps in the magnetization. The pinning results effective at high field where the thermomagnetic instability is commonly suppressed because the specific heat has larger values. Nevertheless, improvements of the tapes performances are reported even if the dimensions of the added particles is much larger than $\xi$, so excluding any good effect on the pinning force. In this case, the second scenario could be that the observed enhancement of $J_C$ at low field, is probably obtained because the thermal properties of the MgB$_2$ are improved by more efficient thermal links among the MgB$_2$ grains. For this reason, in our case a worsening of the thermal efficiency can explain the behaviour at low field of the Tape SiC which has the largest $J_C$ at large field when the thermomagnetic instability is suppressed. In conclusion, our analysis suggests that an improvement of the $J_C$ performance of MgB$_2$ tapes, by adding normal particles, has to be accomplished by a control of their effect on the thermal properties of the superconducting fraction.

3. References
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