Critical current anisotropy of MgB$_2$ tapes

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Abstract. Flattened MgB$_2$ superconductors have an advantage of increased filament density and consequently high transport current density. On the other side, flat rolling is introducing the texture into MgB$_2$, which leads to critical current anisotropy. Therefore, MgB$_2$ tapes prepared from different precursor powders (ex-situ, in-situ and mechanical alloying) deformed in several metallic sheaths were measured in the external magnetic field of variable orientations. Critical current anisotropy of these composite tapes are compared and discussed.

1. Introduction
It was shown that flattening of low temperature superconductors (e.g. NbTi and Nb$_3$Sn) introduces the pinning anisotropy and consequently different $I_c$ values are measured for parallel and perpendicular external field with respect to the flat tape surface [1-2]. In the case of MgB$_2$ manufactured by powder-in-tube (PIT) technique, the filament (powder) density is strongly influenced by the applied deformation. Could rolling produces higher core density in comparison to drawing, which allows reaching considerably higher transport current densities. Therefore, flat rolling is preferred deformation for high current MgB$_2$ [3-4]. On the other side, flat rolling leads to critical current anisotropy: higher $I_c$’s are measured in the parallel orientation of external field with the tape surface. $I_c$ anisotropy of MgB$_2$ tapes made by ex-situ process was presented by several authors [5-7]. Kumakura et al. have published critical current anisotropy for Cu-Ni and stainless steel sheathed tapes and explained it by some c-axis grain alignment of the MgB$_2$ layer [5]. Lezza et al. have shown a strong $I_c$ anisotropy dependence on the grain size [6]. X-ray analysis of the degree of texturing indicated that samples are weakly textured, which correlates with the relative hardness of MgB$_2$ and the used metallic sheath. Flattened four-core ex-situ MgB$_2$-W/Fe wire with small aspect ratio $b/a = 2.19$ has shown also anisotropy above $\mu_0H = 3$ T [7]. $I_c$ anisotropy of in-situ MgB$_2$ tapes [8-9] and the tapes made of mechanically alloyed powders were also measured [10-11]. Recently, the anisotropic property of highly textured thin MgB$_2$ layers formed by molecular beam epitaxy was examined by Yamamoto et al. [12]. Surprisingly, the measured $I_c$ anisotropy of well-textured MgB$_2$ thin layers is smaller than those observed for MgB$_2$ tapes made by PIT. The reason of high $I_c$ anisotropy in PIT MgB$_2$ tapes is not yet fully understood. The aim of the work reported here is to show the scale of $I_c$ anisotropy for differently made MgB$_2$ tapes (ex-situ, in-situ, mechanical alloying) using variable metallic sheaths, additions and also at increased conductor temperatures ($\approx$ 20K) interesting for future applications.

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2. Experimental

Single- and multi-core flat composite superconductors containing MgB$_2$ filaments of variable aspect ratio $b/a$ (width/thickness) and size have been made by powder-in-tube technique (PIT) [7-11]. Different precursor powders (in-situ, mechanical alloying) and metallic sheath materials (Fe, Nb, Ta, Ti) were used [8,10]. Mechanical alloying (MA) is a special variant of the in-situ technique [3]. During the high energy milling a partial reaction to MgB$_2$ ($\approx 30\%$) takes place. Particle size of MA powder is much smaller ($5 – 20$ nm) than for typical ex-situ ($0.1-100$ μm) and/or in-situ ($1-20$ μm) routes. The aspect ratio $b/a$ of rolled tapes is ranging from 3.5 to 11, which influences the degree of grain alignment. MgB$_2$ tapes were measured at different external field orientation in the split-coil 9T magnet at 4.2K or in the superconducting solenoid with variable temperature insert up to 10T and temperatures 4.2 – 22 K. Criterion of $1\mu$V/cm was used for the $I_c$ estimation. The angular dependences $I_c(\alpha)$ and anisotropy factor $k_a = I_{c\text{-par}} / I_{c\text{-perp}}$ (the ratio of critical currents in parallel and perpendicular field direction) as a function of external field were plotted from the measured data. The $\alpha = 90^\circ$ corresponds to parallel field orientation to the tape surface and $\alpha = 0^\circ$ to perpendicular one.

3. Results and discussions

3.1. Angular dependences

All MgB$_2$/metal PIT tapes have a typical angular dependence of critical current with the $I_c$ maximum at parallel external field ($\alpha = 90^\circ$) and $I_c$ minimum at perpendicular one ($\alpha = 0^\circ$), see the curve of circles in figure 1. Although only moderate texture is observed by X-ray for PIT tapes ($c$-axes with crystallite size $\approx 25.0$ nm align perpendicularly to the core/metal interface) [10], the comparable ratio between the $I_c$ maximum to $I_c$ minimum is measured for well textured layer and PIT tape at external field $5 – 5.5$ T, see figure 1. The $I_c$ maximum for the external field oriented perpendicularly to the layer surface (parallel to as-grown columnar grains) was measured due to the strongest pinning when the field is aligned parallel to grain boundaries [12]. High texture leads to a narrow peak of critical current for thin MgB$_2$ layer in comparison to a wide one measured for much less textured MgB$_2$ tape.

![Figure 1. Angular dependences of critical current measured for PIT MgB$_2$ tape (circles) [8] and thin MgB$_2$ layer prepared by MBE (squares) [12].](image-url)
Thin MgB$_2$ layer shows also second (much smaller) peak at 90°, which is explained by the surface pinning [12]. It is interesting but not yet understood why so differently textured MgB$_2$ materials show comparable ratio of critical currents in two basic external field directions.

3.2. Anisotropy factor

The anisotropy factor $k_a$ for MgB$_2$ tapes made by ex-situ, in-situ and MA is plotted in figure 2. The shape of $k_a(\mu_0H)$ characteristics is similar for all tapes, but the absolute values of $k_a$ are different. The highest $k_a$ is measured for the tapes with MA powder and the smallest for ex-situ one having the powder particle size of 10 $\mu$m [6]. Though the resistive measurements of the MA filaments in different field directions show an intrinsic anisotropy value of about 1.5 [13], the transport current anisotropy is much higher and exponentially increasing with field. It can be only partially explained by the texture introduced by rolling. Two $k_a$ dependences in figure 2 plotted for MA/Ti tapes (circles) demonstrate clearly the strong effect of rolling. While $k_a \approx 10$ is measured for the tape deformed by two-axial rolling (TAR, filled circles) at 8.5 T, apparently increased anisotropy ($k_a = 70$) is observed for the same tape composition and aspect ratio subjected to flat rolling deformation. In the case of MA powder, flat rolling is introducing the texture for already existing MgB$_2$ grains and also for not reacted Mg particles, both having the hexagonal cell structure. The effect of heat treatment (HT) temperature was also examined. Figure 3 shows not changed $k_a(\mu_0H)$ characteristics for three identical MA/Fe tapes annealed at different temperatures below and above the melting point of magnesium. The same result was obtained for MA/Ti tapes annealed in the temperature scale 650-800°C. It confirms that the texture of MgB$_2$ core is controlled only by deformation. But, as already mentioned this texture is really moderate and cannot be alone as a reason of so high $k_a$ values. Another pinning anisotropy influenced by texture (e.g. oriented defects – dislocations) should contribute to the total $I_c$ anisotropy, which has to be verified by a deep structural analysis by TEM. It was already shown that $k_a$ is influenced also by doping (SiC, C) [8, 14], which reduces the grain size and increases the upper critical field through the carbon substitution into boron positions in MgB$_2$. Changed grain size and/or grain shape is influencing the grain-boundary pinning and also higher $H_{c2}$ is lowering $k_a(\mu_0H)$. Consequently, both effects are effective ways to reduce high anisotropy factor of PIT MgB$_2$ tapes.

![Figure 2. Anisotropy factors measured for ex-situ (squares) [6], in-situ (triangles) [8] and MA (circles) [10] PIT tapes.](image-url)
3.3. The effect of conductor temperature

Anisotropy factors of in-situ MgB$_2$ tapes sheathed by Fe and Nb were measured at temperature range 4.2 – 22 K. Figure 4 shows the $k_a(\mu_0 H)$ characteristics extrapolated into higher external fields (dashed or dotted lines). One can see the strong effect of conductor temperature on the anisotropy factor $k_a$. The temperature dependence of $k_a$ at 4T is plotted by figure 5. Though of relatively small tape’s aspect ratio $b/a = 4.25$, the $k_a$ values of Fe sheathed tape are very high especially close to 20 K, which is interesting temperature for a future cryogen-free applications of MgB$_2$ conductors.

Figure 3. Anisotropy factors measured for MA/Fe tapes annealed at different temperatures.

Figure 4. Anisotropy factors measured for two in-situ tapes having Fe and Nb sheath at temperatures 4.2, 7, 14 and 22 K.
Figure 5. Temperature dependences of $k_a$ for Fe and Nb sheathed in-situ MgB$_2$ tapes at constant external field 4 T.

Figure 6 compares $I_c$ anisotropy of MgB$_2$ PIT tape and thin MgB$_2$ layer with high temperature Bi-2223/Ag tape at liquid helium temperature. Anisotropy factor $k_a > 1$ is advantage for the central part of the coil winding, where the external field is parallel with the flat side of conductor, but the coil current density can be reduced substantially due to the effect of radial field component at the coil edges. In the case of thin layer MgB$_2$ conductor, $k_a < 1$ will decrease the coil current due to the axial field in the central part. The similar behaviour was observed for flat Nb$_3$Sn superconductor having columnar grain.
structure oriented perpendicularly to the tape surface [15]. Though the $I_c$ anisotropy of high temperature superconductor (HTS) Bi-2223/Ag is very high at liquid nitrogen temperature ($k_a > 100$ at 1 T), it is reduced to $k_a \approx 2$ at 4.2 K. Critical current anisotropy of MgB$_2$ has to be minimized by the conductor design (shape) and/or by a proper doping to avoid the coil current decrease by the radial component of magnetic field.

4. Conclusions

The $I_c$ anisotropy of differently made MgB$_2$ tapes has been studied experimentally and compared with the results of thin film made by molecular beam epitaxy [12]. It was shown that observed anisotropy is connected with the texture introduced by rolling deformation and it is increasing with conductor temperature going to 20 K. The reason of high current anisotropy factors for the tapes made by PIT technique is not yet fully understood and very high $k_a$ values cannot be explained only by moderate texture of MgB$_2$. Most probably some another pinning anisotropy influenced by texture (e.g. oriented defects – dislocations) should contribute to so high anisotropy, which has to be verified by TEM analysis. From the point of practical application of MgB$_2$ it is important to reduce $I_c$ anisotropy especially at temperature close to 20 K by the conductor design (shape) or by a proper doping to avoid the undesired coil current decrease by radial magnetic field.

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