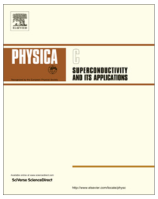
Physica C 490 (2013) 20–25

Contents lists available at SciVerse ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc



Critical current densities of doped MgB_2 strands in low and high applied field ranges: The $J_c(B)$ crossover effect

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ARTICLE INFO

Article history:
Received 22 March 2013
Accepted 9 April 2013
Available online 25 April 2013

Keywords:
MgB_2
Transport J_c
Flux pinning
Irreversibility fields
Upper critical fields
Crossover effect

ABSTRACT

Numerous classes of dopant have been added to MgB_2 in order to raise the upper critical field, B_{c2}, and hence to increase the field range over which the pinned superconductor has the possibility of supporting supercurrent. Thus dopant additions to grain-boundary-pinned MgB_2, for example, have the effect of raising the high field critical current density, $J_c(B)$. However, at low fields, when B is relatively small compared to B_{c2}, $J_c(B)$ decreases as B_{c2} increases. This leads to a low field convergence, or even the intersection, of the $J_c(B)$ curves of a family of variously doped MgB_2 strands. Two important conclusions derive from this "crossover effect": (i) Doping-induced increases of B_{c2} should be applied only if improved high field properties are required. For low field applications of MgB_2 such as: low field nuclear magnetic resonance imaging (MRI), synchrotron insertion devices, and current leads, doping should be avoided since not only would the increased B_{c2} degrade J_c, but the possible chemical byproducts of doping may reduce connectivity; (ii) If an across-the-board increase in $J_c(B)$ is desired there is no substitute for increased connectivity, in regard to which densification of the MgB_2 layer (the subject of a separate report) is recommended.

1. Introduction

1.1. Overview of this work

The paper begins by displaying numerous examples of the frequently encountered, but not specifically recognized, crossover effect in pairs of doped and undoped strands. The crossover effects in sets of (i) five variously doped but otherwise identically processed MgB_2 strands and (ii) identically processed C-doped strands with increasing concentrations of C are then presented. The mechanism of this effect in grain-boundary-pinned MgB_2 is then explained in terms of the corresponding Dew-Hughes equation in which justification is given for the replacement of B_{c2} by the irreversibility field, B_{irr}; the analysis is further extended to the Dew-Hughes equations for volume and point pinning. The paper concludes with a discussion of the general implications of the crossover effect, especially with respect to the effects of doping on the $J_c(B)$ behavior for low-field applications, and emphasizes that increases in connectivity result in across-the-board increases in $J_c(B)$.

1.2. Literature survey

Magnesium diboride has an upper critical field, B_{c2}, which can increase rapidly in response to doping. Values of B_{c2} for MgB_2 have varied from about 8 T (heavily C-substituted high pressure, high temperature synthesized, bulks with randomly oriented polycrystalline grains [1]) to more than 50 T (in the *ab* plane) for hybrid physical–chemical vapor deposited epitaxial thin films doped with high percentages of both C and O [2]. Dopant substitution of C onto the B site [3,4] or of metals such as Na [5], Zr [6–8] , Al [9], Ca [10], Mn [11], or Pb [12]) onto the Mg site have been investigated. In all cases it was found that doping-induced increases in high field B_{c2}, and hence high field J_c, were accompanied by reductions in the J_c at low fields, leading to what we refer to as the "low field crossover effect".

This phenomenon can be observed in the J_c vs. B plots published by Kim et al. [13] for SiC-addition, Lee et al. [14] for C-addition, Lezza et al. [15] for B_4C addition, Li et al. [16] for SiC-addition, Mahmud et al. [17] for SiC-addition, Mudgel et al. [18] for nano-C addition, Ojha et al. [19] for Eu_2O_3 and Pr_6O_{11}, Pan et al. [20] for SiC and SiC + Ti additions, Rahul et al. [21] for SiO_2 additions, Shan et al. [22] for Ti_3SiC_2 addition, Susner et al. [4] for C-addition, Varghese et al. for SiC addition [23] and C + SiO_2 additions [23], Vinod and Syamaprasad [24] for SiC and TiC additions, Ye et al. [25] for SiC and SiC + aromatic hydrocarbon additions, Zeng et al. [26] with $C_6H_8O_7$ additions, and Zhang et al. [27] for Sb_2O_3 additions.

Fig. 1, a compilation of pairs of doped/undoped $J_c(B)$ data from the literature, clearly demonstrates the effect. The crossover field varies with temperature and from sample to sample and may be influenced by variations in powder purity and size, connectivity, and strand processing conditions. Although the crossover is ex-

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http://dx.doi.org/10.1016/j.physc.2013.04.060

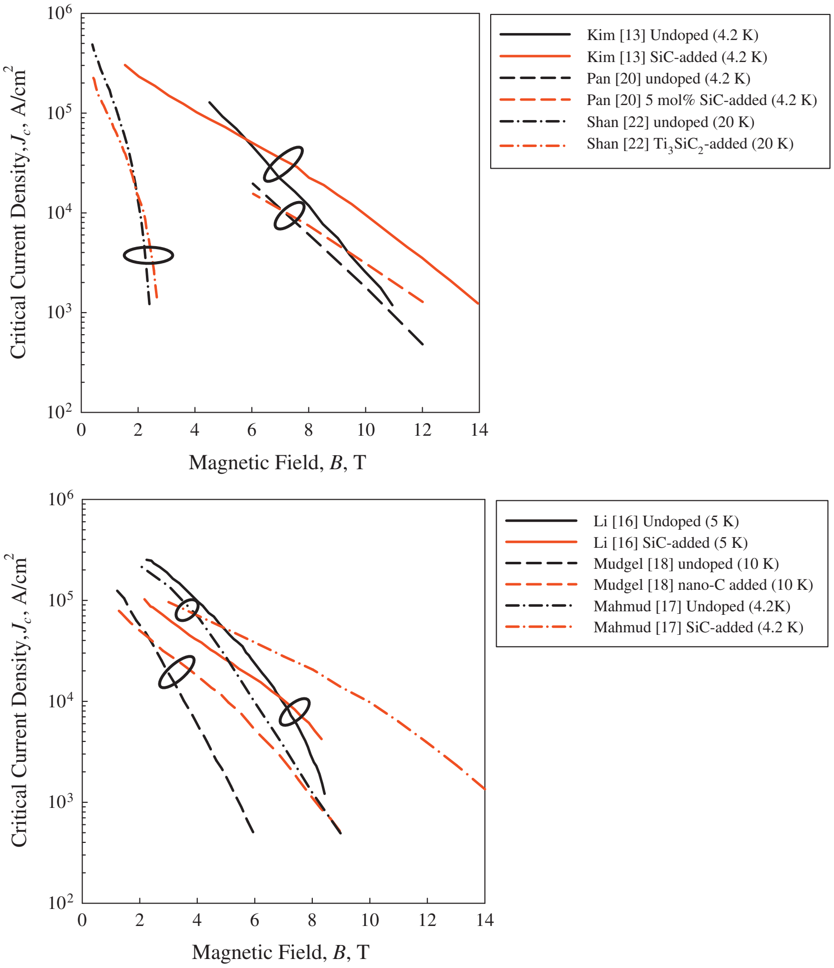

Fig. 1. J_c vs. B data for MgB_2 from the literature showing the crossover effect.

pected to manifest itself at low fields, an increase in the connectivity of one of the strands in a pair (see Section 5.3) may cause the crossover point to shift in field or even disappear. However, if the processing variables can be well controlled, in other words when a series of strands made by a single manufacturer under fixed processing conditions differ only in dopant species or concentration, the $J_c(B)$ crossover takes place over a narrow range of low fields. This is demonstrated in the following case studies.

2. Case studies of the crossover effect

2.1. Case Study 1: MgB_2 doped with various additives

To further investigate the crossover effect in MgB_2, a well-controlled series of strands produced by a single manufacturer under fixed processing conditions and differing only in dopant species or concentration is desired. Such a series of monofilamentary doped powder-in-tube (PIT) MgB_2 strands was prepared by Hyper-Tech Research Inc. [6,17,28–31] using standard Mg powder (99%, ~325 mesh) and B powder from the now-depleted stock of so-called "99 B", Table 1.

2.2. Case Study 2: MgB_2 doped with increasing concentrations of carbon

A second set of samples made with the same Mg powder but with B powder obtained from Specialty Materials, Inc. (SMI) of Lowell, MA, was also fabricated by HyperTech Research, Inc. [4,32]. The B powders were produced via the plasma-induced reduction of BCl_3 gas by H_2 as described in [4,33,34]. Methane (CH_4) was added to the H_2 gas stream in varying quantities so as to intimately add C to the resultant B powders, creating "pre-doped B". This approach has been shown to be very effective in homogeneously substituting C for B in MgB_2, enabling a monotonic increase in B_{c2} with C-content [4,8]. The actual C contents, first measured in [4], are listed in Table 2.

Table 1
List of sample properties for 10 K $J_c(B)$ data using various additives[a] (Case Study 1).

Sample	Sample number[b]	Heat-treatment	Composition	B_{irr}[c] (T)
MgB_2	869	700 °C/20 min	$Mg_{1.09}B_2$	11.0
+SiC	1009	675 °C/40 min	+4 wt.% SiC	16.9
$+ZrB_2$	1535	675 °C/40 min	+1 wt.% ZrB_2	13.1
+Ag	1529	550 °C/360 min	+2.1 wt.% Ag	14.5
+TiC	1272	675 °C/40 min	+3 wt.% TiC	11.9

[a] The strands were manufactured by Hyper Tech Research (HTR) using procedures outlined in [6,17,28–31]. They were powder-in-tube monofilamentary and made using standard Mg powder and boron powder from the now-depleted stock of so-called "99 B.".
[b] Internal HTR tracking number used to facilitate strand data traceability.
[c] Based on $J_c(B)$ at 100 A/cm^2.

2.3. Strand heat treatment in the two case studies

Wire lengths of ~20 cm were heat treated (HT) at 675 °C for 40 min. (unless otherwise listed) in Ar-back-filled quartz ampoules. The initial Ar pressure was such that at the annealing tem-