On the scaling of pinning force in ceramic MgB$_2$

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Abstract. We present an investigation of the field dependence of the pinning force of dense MgB$_2$-based superconducting composites as obtained by spark plasma sintering with different ingredients which are designated to enhance the pinning force $F$. Generally, the latter quantity, scaled to the maximum pinning force $F_{\text{max}}$, obeys a scaling law as a function of the scaled field $h$ when the irreversibility field $B_{\text{irr}}$ is considered as scaling field. The scaled function is described in terms of a generalized scaled function $h^p(1-h)^q$. However, in our samples the scaling is absent. In addition, the peak of the scaled function shifts to higher reduced fields $h$ when the temperature increases. Depending on the level of doping and the nature of the nanosized particles used to build the superconducting composites, we found that the scaled force can be depicted either with a combination of generalized scaled functions with different exponents or with a single function but multiplied with an envelope, usually an exponential factor. The former dependence is present in the samples with a high amount of nanoparticles and mirrors two types of pinning of close weights. The presence of the exponential factor in the latter dependence is attributed to the combined effect of the intrinsic anisotropy of MgB$_2$ and the random orientation of the grains relative to the magnetic field.

1. Introduction

Critical current density is a crucial parameter for superconducting materials. It reveals the capacity of the superconductor to carry current in a dissipationless way in different condition of applied field and mechanical stress. Actually, this property is directly related to the strength the vortices are pinned against the Lorentz force. The pinning force $F_p$, or more precisely, the core pinning is the result of the interaction between the vortex matter and the underlying crystal structure. Any type of defect, impurity, dislocation, grain boundaries, etc., which breaks the superconducting symmetry is susceptible to act as pinning center, hence, to generate a pinning force on the vortex system. The modelling of the dependence of the pinning force on the magnetic field and other possible parameters that are important during the operation requires a simple and, if possible, a universal relationship. The main activity was focused on the scaling of the pinning force measured in different conditions (temperature, strain, etc) on a universal curve as a function on the scaled magnetic field. Actually, the existence of scaling requires the factorization of the pinning force into two parts as $F_p(t(T), h(B), x, y) = K(t(T), x, y) f(h(B))$, where $t$ is a function of temperature $T$, $h$ is the scaled field as a function of the applied field $B = \mu_0 H$ and $x, y$ other variables. $K(t(T), x, y)$ must be proportional to the maximum pinning force $F_{p,\text{max}}$. Fitz and Webb [1] have proposed a general relationship for the scaled function $f(h) = h^p(1-h)^q$ with $h = B/B_{\text{scal}}$ whereas $K$ was related to the upper critical field $B_{c2}$. In the original model, $B_{\text{scal}} \equiv B_{c2}$, but later, when high temperature superconductors were investigated, it was replaced by the irreversibility field $B_{\text{irr}}$ for obvious reasons. As Ekin [2] have mentioned the first condition for scaling is the existence of similar shapes of the field $B$ dependence of the $F_p$ curves where $F_p = J_B$, with $J$ the...
critical current density. However, this similarity does not guarantee the existence of the scaling. The main problem arises when there are several mechanisms of pinning and their relative weight is temperature dependent or when the superconductor is anisotropic in the case of polycrystalline samples. Anisotropy is mirrored in the dependence of the critical fields on the orientation $\theta$ of the $c$-axis of the superconducting crystal relative to the applied field. It leads to an angular dependence of the critical fields $B_{c2}(\theta) = B_{c2}(0)(\cos^2 \theta + \gamma^2 \sin^2 \theta)^{1/2}$ [3] where $\gamma$ is the upper critical field anisotropy $\gamma = B_{c2,B}/B_{c2,c}$. Consequently, in a polycrystalline sample with randomly oriented grains, all the grain with orientation $\theta$ for which $B_{c2}(\theta) < B$ are in normal state [4]. When this happens, the superconducting material starts to behave like Swiss cheese and the problem becomes percolative in nature [5].

The main problem which arises is related to the scaling field. As Eisterer has noticed [4] the intrinsic field $B_{c2,i}$ is useless because, for practical applications, a superconductor is useful beyond the percolation threshold. Therefore, the most indicated field for scaling should be the irreversibility field $B_{irr}$. For MgB$_2$ single crystals, the difference between superconductivity $B_{irr}$ and $B_{c2,i}$ is not too but it can be considerable in the case of a polycrystalline sample. In the absence of other reasonable choice, the irreversible field should be the most appropriate field for scaling. It remains to find a way to define it. Actually, there are at least three ways to measure $B_{irr}$. The first one is based on the resistance vs. temperature $R(B)$-$T$ curve, specifically the field for which the resistance has 5% of its onset value. However, this method is strongly affected by the possible low temperature shoulders which might be field dependent. A second method is based on the Kramer relationship [6] which proposes $f(h) = h^{1/2}(1-h)^2$, hence, $(J_cB^{1/2})^{1/2} \sim 1-B/B_{irr}$ must be linear in $B$. However, the plot of $(J_cB^{1/2})^{1/2}$ vs $B$ is far from being linear and the result depends on what part of the curve is approximated by a straight line. In some cases it can be made linear on almost the whole field range by playing with the exponents $p$ and $q$ but they will strongly depend on temperature. Finally, a direct measurement from $J_c$ vs $B$ data with a certain criterion, e.g., $500$ A/cm$^2$ seems to be the most reasonable solution.

In this contribution, we show that experimental data taken on spark plasma sintered samples do not display scaling behaviour of the pinning force. In addition, the reduced force $f(h) = h^{p}(1-h)^q$ must be associated with an exponential decay as a function of the scaled field $h$.

2. Experimental

Two series of high density MgB$_2$-based ceramic superconducting composites samples (95-98 % of the crystal density) were fabricated by spark plasma sintering. A series of three samples were fabricated by mixing MgB$_2$ powder with nanosized particles consisting of a Fe core encapsulated in a graphite shell. A second series was fabricated mixing the MgB$_2$ powder with polysiloxane-based copolymer dissolved in chloroform. The samples of the first series contains different amount of metallic Fe: 0.35 wt % (sample MFC-03), 0.6 wt % (sample MFC-06) and 1.0 wt % (sample MFC-10), respectively. The second series consists of samples with the addition of different copolymers calculated so that the content in carbon lead to the nominal composition Mg(B$_{0.95}$C$_{0.05}$)$_2$. Specifically, we used cyclic polysiloxane-co-styrene (sample PSS-C) and linear polysiloxane-co-(styroly-vinyl ferrocene) (sample PSF). Details on the fabrication of the sample, their structure and superconducting properties are given elsewhere [7, 8]. A bare sample was prepared in the same conditions for comparison. In order to evaluate the pinning force we used the critical current density as obtained from irreversible magnetization $\Delta M$ vs field $B$ data by Bean relationship $J_c = 2\Delta M a^{-1}(1-a/3b)^{-1}$, where $a$ and $b$ are the sample size perpendicular to the magnetic field. In each case the reduced pinning force $f_p$ was obtained from the pinning force $F_p = J_cB$ normalized to its peak value $F_{p,max}$.

3. Results and discussion

The reduced pinning force $f_p$, as a function of the reduced field $h$ obtained from magnetization data are presented in the figures 1a to 1d for the pristine MgB$_2$ and MFC-03, MFC-06, PSF and PSS-C samples. It is obvious that in all cases the scaling is absent. In addition, there is a shift of the peak of $f_p$ toward higher fields with increasing temperature. The position of the peak at low temperatures is at a
reduced field $h_{\text{max}}$ higher than the value predicted by Kramer model for the pinning on grain boundaries, i.e., $h_{\text{max}} > 0.2$. Any attempt to fit $f_p(h)$ with the general form $f(h) = h^p(1-h)^q$ fails to fit correctly both the peak and the high field region. After a careful examination we found that the best fit requires the multiplication with an exponential decay as $f_p(h) = \text{const} \times h^p(1-h)^2 \exp(-h/h^*)$ the temperature dependence of the $p$ and $h^*$ (see fig. 2) blows up the scaling of the pinning force. For fit we kept the $q = 2$ as in original models because $(1-h)^2$ is associated with the shear modulus of the flux lattice in any model. It is also interesting that the variation of $h^*$ is slow with the temperature (except the sample MFC-06) with values close to $h^* = 0.2$ which is the $h_{\text{max}}$ in the Kramer model. Consequently, we attribute the shift of the peak to higher fields to the formation of point pinning centers as a result of the normalization of the bad oriented grains at higher temperature, hence, to the development of a new mechanism for pinning. However, the origin of the exponential decay is not clear yet but it appears in almost all dense samples prepared by SPS technique. Most likely, it is related to the distribution of the grain orientation as resulted from this special sintering process.

![Graphs of reduced pinning force vs reduced field](image)

Figure 1. Reduced pinning force $f_p$ vs reduced field $h$: a) MgB$_2$; b) MFC-03; c) PSS-C; d) PSF. The continuous lines are fit with the function $f_p(h) = \text{const} \times h^p(1-h)^2 \exp(-h/h^*)$.

In the composite samples with more additives, hence, less dense, the fit had to be replaced with a combination of Kramer type functions. For example, for the sample MFC-10 the best fit was obtained...
with \( f(h) = w_1 h^{1/2} f(h) + w_2 h(1-h)^2 \) in which the two weights are temperature dependent (fig. 3). Again, the peak shifts toward higher fields with increasing temperature.

Figure 3. Temperature dependence of the fit exponent \( p \). Inset: temperature dependence of the field \( h^* \) as obtained from the fit with the form \( f_p(h) = \text{const} \times h^p(1-h)^2 \exp(-h/h^*) \).

Figure 4. Reduced pinning force \( f_p \) vs reduced field \( h \) for the sample MFC-10. The continuous lines are fit with the function \( f(h) = w_1 h^{1/2}(1-h)^2 f(h) + w_2 h(1-h)^2 \).

In conclusion, we have shown that even for very dense ceramic samples, as obtained by spark plasma sintering, there is no scaling of the pinning force. The reduced pinning force can be depicted by the general expression used in isotropic superconductors but only if it is associated with an exponential decay factor of field which is temperature dependent.

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