Simulation of Field Dependence of Critical Current Densities of Bulk High \( T_c \) Superconducting Materials regarding Thermally Activated Flux Motion

M Santosh\(^1*\), S Pavan Kumar Naik\(^2\) and M R Koblischka\(^3\)

\(^1\) E300 Huron Street, M5S 3J6, Faculty of Arts and Science, University of Toronto, Canada
\(^2\) Superconducting Materials Laboratory, Department of Materials Science and Engineering, Shibaura Institute of Technology, 3-7-5 Toyosu, Koto-ku, Tokyo 135-8548, Japan
\(^3\)Experimental Physics, Saarland University, Campus C 6 3, 66123 Saarbrücken, Germany

* santoshjuly@msn.com

Abstract. In the upcoming generation, bulk high temperature superconductors (HTS) will play a crucial and a promising role in numerous industrial applications ranging from Maglev trains to magnetic resonance imaging, etc. Especially, the bulk HTS as permanent magnets are suitable due to the fact that they can trap magnetic fields being several orders of magnitude higher than those of the best hard ferromagnets. The bulk HTS \( \text{LREBa}_2\text{Cu}_3\text{O}_{7-\delta} \) (LREBCO or LRE-123, LRE: Y, Gd, etc.,) materials could obtain very powerful compact superconducting super-magnets, which can be operated at the cheaper liquid nitrogen temperature or below due to higher critical temperatures (i.e., \(~90\) K). As a result, the new advanced technology can be utilized in a more attractive manner for a variety of technological and medical applications which have the capacity to revolutionize the field. An understanding of the magnetic field dependence of the critical current density \( (J_c(H)) \) is important to develop better adapted materials. To achieve this goal, a variety of \( J_c(H) \) behaviours of bulk LREBCO samples were modelled regarding thermally activated flux motion. In essence, the \( J_c(H) \) curves follows a certain criterion where an exponential model is applied. However, to fit the complete \( J_c(H) \) curve of the LRE-123 samples an unique model is necessary to explain the behavior at low and high fields. The modelling of the various superconducting materials could be understood in terms of the pinning mechanisms.

1. Introduction

The physical properties of high critical temperature \( (T_c) \) cuprate superconductors are highly susceptible to impurities and crystalline defects present in the final composites [1]. In cuprate superconductors, \( \text{LREBa}_2\text{Cu}_3\text{O}_{7-\delta} \) \( (\text{LREBCO or LRE-123, with light rare earth elements such as Y, Nd, Sm, Gd, etc.}) \) materials were found to be well suited for technological applications due to low flux creep effects as compared to Bi-Sr-Ca-Cu-O compounds. The important applications of the superconducting materials can be realized in many fields such as SQUIDS which is a highly sensitive magnetometer, superconducting electromagnets which are more powerful than ferromagnetic materials. Furthermore, magnetic resonance imaging and nuclear magnetic resonance imaging in the medical
field and fusion reactors based on magnetic confinement, particle accelerators, fault current limiters, electric motors and generators, high sensitivity particle detectors, etc., are possible applications. All these applications clearly demonstrate a necessity to develop high quality superconductors. A high critical current density ($J_c$) is the prime requirement; designing a suitable microstructure of the final composition is elementary to enhance the magnetic properties at the boiling point of liquid nitrogen, i.e., 77 K. However, several reports from the literature show that it is essential to process the LREBCO compounds, except YBCO in reduced oxygen atmospheres or addition of extra Ba to prevent the formation of unwanted LRE$_{1+x}$Ba$_{2+x}$Cu$_3$O$_y$ solid solutions (LRE/Ba–ss) type with lower $T_c$ [1-4]. The LRE$^{3+}$ ions can occupy the Ba$^{2+}$ sites because of similar ionic radii. Increasing replacement of Ba$^{2+}$ sites can cause a reduction of $T_c$ and lead to a deterioration of the superconducting properties [5-8]. The oxygen controlled atmospheres and addition of Ba not only suppresses the formation of solid solutions of the LRE/Ba–ss, but permits local compositional fluctuations of the (LRE$_{1+x}$, LRE$^{1-4}$)Ba$_2$Cu$_3$O$_{y-5}$ type (i.e. LRE/LRE$^1$–ss, where LRE and LRE$^1$ are different light rare earth elements) in the processed samples which leads to enhanced flux pinning [8]. This process has suppressed the rapid fall of the $J_c$ values at higher fields, often reported in MG processed samples.

In the case of melt-grown superconductors, further increase of the $J_c$ values were reported by introducing nano-sized inclusions and mixed rare earth elements into the superconducting matrix phase [9]. Studies in the literature on mixed LREBCO superconductors [10-14] report strong flux pinning due to lattice mismatch defects arising from the presence of different LRE elements in the matrix. Hence, the high $J_c$ is maintained up to high fields due to enhanced pinning which could be related to the following factors: firstly, LRE sites are substituted by LRE$^1$ elements, due to which the lattice mismatch arises among the neighbouring unit cells of LRE-123 and LRE$^1$-123.

The source of flux pinning in different field regions in the LREBCO materials have been investigated widely in recent years. The presence of low-$T_c$ clusters due to the formation of different chemical fluctuations both the LRE/Ba-ss and LRE/LRE$^1$-ss has been confirmed through various methods. Muralidhar et al. [9] have proposed that in LREBCO composites nanometric sized LRE-rich low-$T_c$ clusters act as field-induced pinning centres ($\Delta T_c$ pinning centres) and thus result in the peak effect. It is known that to enhance the $J_c$-$H$ performance of superconductors, both the $T_c$ and the number of effective pinning centres should be increased. The coherence length of the LREBCO superconductors is on the nanoscale; thus the increment of defects or size of compositional fluctuation in the nano-scale is beneficial for flux pinning. Including the interfacial defects generated due to 211/123 interface, twins, dislocations, chemical compositional fluctuations created due to the presence of different 123 unit cells, and stacking faults have been proven to be effective flux pinning centers [13-19].

The microstructural features in the LREBCO superconductors prevent the movements of the fluxioids. Depending on the size and type of the defect, the pinning will be effective at different fields. It is necessary to understand the basic mechanism playing different roles in LREBCO superconductors which are pivotal for enhanced magnetic properties. For this purpose, we have undertaken modelling of the $J_c$ curves of different bulk LREBCO superconductors, which may help to understand the different pinning mechanisms and by which one can produce high quality LREBCO superconductors.

2. Experimental details
The synthesis of all precursor powders and fabrication of all the YBCO bulks are discussed elsewhere [20]. Sample A was fabricated with ball milled Y-211 precursor powders. Sample B was fabricated with as synthesizd Y-211 phase particles. Both samples A and B were processed employing the infiltration growth process. Sample C is also YBCO superconductor, but processed via the melt-growth technique. The field dependence of critical current density ($J_c(H)$) of the processed LREBCO superconductors was calculated using extended Beans critical state model by utilizing the $M$-$H$ loops recorded up to 6 T field at 77 K. To evaluate the different pinning mechanisms, present in the LREBCO bulk high-$T_c$ superconductors and the $J_c(H)$ curves are fitted with an exponential expression.
3. Results and discussion
From the literature [21], it is well known that the size of the defects in the superconductors play a role influencing \( J_c \) at different applied magnetic fields. The presence of such defects can give rise to strong flux pinning or a peak in \( J_c \) at a particular field. This peak field is related to the vortex lattice spacing as shown in equation (1).

\[
H_p = \frac{\phi_0}{\sqrt{3(a_f^2)}} \tag{1}
\]

where \( \phi_0 \) is the flux quantum and \( a_f \) is the vortex lattice spacing. Equation (1) suggests that the flux pinning at fields less than 1 T can be caused by defects of a size more than 50 nm. The interfacial defects due to LRE-211/LRE-123 boundaries would give rise to flux pinning at such low fields. In the literature, correlations were made on the flux pinning at low fields due to LRE-211 content and the defects originating at the LRE-211/LRE-123 interfaces [22-25]. Figure 1 represents the possible dependence of the peak field on the defect spacing at different fields as given by equation (1). From this figure, it is clear that the smaller the defect size, the larger the peak field will be. Therefore, it is crucial to create fine sized defects or to control the size of LRE-211 particles within the LRE-123 matrix to make the interface defect density large in the LRE-123 matrix.

![Figure 1. The relation of the peak field \( (H_p) \) with the size of the defect spacing in cuprate superconductors is illustrated as schematic diagram.](image)

To account for high \( J_c \) observed up to large (1-10 T) fields, the defect spacing should vary from 15 – 50 nm. Researchers believe that the pinning at low field depends on the density of the interfacial defects due to LRE-211/LRE1-123 interfaces present in the matrix. In the present work, three different YBCO superconductors are being discussed which exhibited the enhancement of \( J_c \) up to high fields as compared to the literature [26-29]. From the above discussion, the presence of different \( J_c(H) \) behaviour in LREBCO superconductors could be attributed to different types of pinning centres which are induced by various additives/defects. Therefore, \( J_c(0) \) of sample A is superior to that of sample B and C. The rapid fall in the \( J_c(H) \) curves of the melt textured YBCO with large \( J_c \) values is reported to exhibit an exponential variation with magnetic field [30-33]. Since the present \( J_c(H) \) curves show faster reduction at low fields, but slow decrease at high fields, we assume that there are two different mechanisms operative in describing the \( J_c(H) \) behaviour across the field range up to 5 T. As a result, we consider two terms to fit the measured data to equation (2) given below.

\[
\frac{J_c(H)}{J_c(0)} = A_1 \exp\left(-\frac{\mu_0H}{\tau_1}\right) + A_2 \exp\left(-\frac{\mu_0H}{\tau_2}\right) + A_3 \exp\left(-\frac{\mu_0H}{\tau_3}\right) + y_0 \tag{2}
\]
where $A_1, t_1, A_2, t_2, A_3, t_3,$ and $y_0$ are the fit parameters.

In order to investigate the nature of flux pinning that occurs up to high fields at 77 K, we have normalized the $J_c(H)$ with respect to zero field $J_c$, i.e., $(J_c(H)/J_c(0))$, which is plotted as a function of the applied field in figures 2 (a)-(c) for sample A, B and C, respectively. In each panel, both the experimental $J_c/J_c(0)$ curve and the detailed fitting of the measured field dependence of the normalized $J_c$ to equation (2) is shown.

![Figure 2](image_url)

**Figure 2.** Panel (a) represents the normalized current density $J_c(H)/J_c(0)$ and fitted curves of sample A, similar curves are given in panel (b) for sample B and in panel (c) for sample C.

Due to the two competing mechanisms of flux pinning due to precipitates and interfaces (grain boundaries and cell boundaries), it is difficult to separate the contribution of each mechanism. However, it is now accepted that the pinning is nearly proportional to the volume fraction of precipitates, and is inversely proportional to the cell size or grain size. The proportion of the pinning centers depends on the processing conditions. It is found that at the optimum size, the density of the precipitates is about ten times the density of grain boundaries.

The details of the fit parameters obtained from the $J_c(H)$ curves at 77 K for samples A, B and C superconductors are listed in Table 1. $J_c(H)$ at low fields fits well to the first term. The parameters $t_1$, $t_2$ and $t_3$ represent the decay rate of the $J_c$ curve with $A_i$ ($i=1,2$ and 3) as the amplitude. The parameter $t_1$ is applicable at low fields and its value is smaller for sample C as compared to the other two samples. This explains why the $J_c$ curve of sample C decays more rapidly as compared to the other samples. The peaks in the $J_c$ curves are observed for only sample A and B at intermediate fields, whereas no peak is observed in sample C. Due to this, samples A and B are fitted with 3 exponential terms and
sample C is fitted with only two terms. The large $t_2$ values compared to $t_1$ represents the slow decay of the $J_c$ curves.

Table 1. The fitting parameters for samples A, B and C.

|       | $A_1$  | $t_1$  | $A_2$  | $t_2$  | $A_3$  | $t_3$  | $y_0$ |
|-------|--------|--------|--------|--------|--------|--------|-------|
| Sample A | -239.8778 | 0.9061 | 125.17 | 0.83205 | 115.83 | 0.9965 | -0.09836 |
| Sample B | 0.67855 | 0.2938 | 4.1085 | 0.6277 | -0.41021 | -3.1407 | 0.34889 |
| Sample C | 0.68941 | 0.1300 | 0.34404 | 1.4837 | -- | -- | -0.02183 |

Conclusions

In this paper, the flux pinning nature of different LREBCO superconductors at different applied magnetic fields (zero to high fields) were analyzed with an aid of a model. An exponential equation is utilized for analyzing the $J_c$ curves of different bulk LREBCO superconductors. The exponential term (first term) in the expression fits the lower field region of the $J_c(H)$ curves. This is ascribed to flux pinning at interfacial defects. The $t_1$ parameter is smaller for sample C, due to fast decay of the $J_c/J_c(0)$ curve. The samples B and C show the peak effect at intermediate fields due to strong $\Delta T$, pinning provided by nano-sized defects within the superconducting matrix and this behavior is in agreement with the first term of the expression. Three exponential term equation is employed to explain the lower field, peak field and higher field behavior of $J_c$ curves.

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