Correlation of magnetic and magneto-optical properties with microstructure analysis in melt-textured 
\(\text{Nd}_{0.33}\text{Sm}_{0.33}\text{Gd}_{0.33}\text{Ba}_2\text{Cu}_3\text{O}_y\)

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Received 29 March 1999; received in revised form 13 April 1999; accepted 27 April 1999

Abstract

Magnetic properties of the melt-processed ternary superconductor \(\text{Nd}_{0.33}\text{Sm}_{0.33}\text{Gd}_{0.33}\text{Ba}_2\text{Cu}_3\text{O}_y\) (‘‘NSG’’) with non-homogeneously distributed NSG-211 particles were investigated by means of magnetic and magneto-optical measurements. Flux distributions obtained by means of magneto-optic imaging after zero field-cooling and field-cooling were analyzed in order to understand the flux penetration behavior of this compound. The current-carrying length-scale was determined from the reverse leg of the magnetization hysteresis loops and compared to the actual dimensions of the sample. This was done both on the whole sample and on three individual domains to which the sample was subsequently divided. Magnetization hysteresis loops of all samples exhibited a strongly developed secondary peak in the temperature range 30 K \(\leq T \leq 77 \text{ K}\). The critical current and pinning force densities derived from these data were normalized to the values at the peak position, \(J_{\text{max}}\) and \(F_{\text{max}}\), respectively, and analyzed as a function of applied field reduced both to the respective peak field and irreversibility field. © 1999 Published by Elsevier Science B.V. All rights reserved.

PACS: 74.60 Ec; 74.60 Ge; 74.60 Jg

Keywords: Magnetic and magneto-optical properties; \(\text{Nd}_{0.33}\text{Sm}_{0.33}\text{Gd}_{0.33}\text{Ba}_2\text{Cu}_3\text{O}_y\); Melt-textured superconductor

1. Introduction

Light rare earth (LRE)\(\text{Ba}_2\text{Cu}_3\text{O}_y\) (where LRE denotes Nd, Eu, Sm, Gd) superconductors melt-processed in low oxygen partial pressure exhibit a high irreversibility field, \(B_{\text{irr}}\), accompanied by a large critical current density, \(J_c\), in intermediate fields, at the maximum of the secondary (fishtail) peak. At \(T = 77 \text{ K}\), \(B_{\text{irr}} > 7 \text{ T}\) and \(J_c\) usually approaches the order of magnitude of \(10^9 \text{ A m}^{-2}\) at the peak position [1,2]. A characteristic feature of the LRE-123 superconductors is the existence of a solid solution between the LRE atoms and Ba, which leads to the formation of a LRE-rich phase with weaker superconducting properties. Using the oxygen-con-
trolled melt growth (OCMG) process to prepare the samples, the amount of this LRE-rich phase can be controlled so that a high superconducting transition temperature, $T_c$, results [3].

Very recently, it has been reported that OCMG processed (LRE$_1$, LRE$_2$, LRE$_3$)Ba$_2$Cu$_3$O$_y$ superconductors (that is, three different LRR elements mixed together at the rare earth site) show the superconducting transition temperature $T_c$ in the range of 93 K and $J_c$ even higher than in the samples prepared under normal oxygen pressure [4]. The large values of $J_c$ in these materials are again due to a pronounced fishtail peak. The analysis of the fishtail effect in 123 (i.e., Y and Tm) compounds [5–7] led to the conclusion that the random pinning disorder due to oxygen deficient zones is responsible for the formation of the peak. The even better magnetic properties of the ternary compounds are related to the increased disorder on the rare earth site which causes a more uniform distribution of the LRE-rich phases [8]. Furthermore, it was found that this combination of three LRE elements enables the formation of submicron-sized Gd$_2$BaCuO$_x$ (Gd-211) particles, which can effectively increase the critical current density [9,10]. These so-called 211 particles (or 422 in the case of Nd) are randomly distributed throughout the (LRE$_1$, LRE$_2$, LRE$_3$)-123 matrix [11].

A pronounced fishtail effect is commonly found in the ternary compounds; the peak position at 77 K is typically located at around 2–2.5 T, and the peak height usually exceeds that of the central peak in the magnetization loop. The typical fishtail shape is usually modified, especially on the low-field side of the peak. This implies that aside of the random pinning disorder another type of pinning structure is active in the intermediate field range. The corresponding pinning mechanism should have different field and temperature characteristics. The role of the non-superconducting Y-211 and/or Nd-422 particles in the pinning process requires therefore a detailed study. One has to take into account also the inhomogeneity of the distribution of the non-superconducting particles in a given sample. The inhomogeneity is closely related to the variation of growth conditions as documented in Ref. [12] for the case of Y-211 particles trapped in Y-123 crystals. The phenomenon of entrapment of Y-211 particles in melt-textured Y-123 crystals was qualitatively explained by the pushing/trapping model [5]. This model explains the behavior of a foreign particle existing in the front of an advancing solid–liquid interface during solidification and shows that the amount and size of the Y-211 particles varies with distance from the seed. Generally, for characterization studies, small rectangular specimens are cut from the original pellet, rather far from the seed in order to ensure a homogenous particle distribution.

To reach a better insight how the non-superconducting particles influence the pinning properties ($J_c$–$B$ characteristics), we studied in detail a zone where the distribution of 211 particles strongly varies. Microstructure analysis coordinated with both magnetic characterization and magneto-optical (MO) investigation of flux distributions should help to understand the role of the non-superconducting particles in the flux pinning. In the present paper we decided to cut a large sample from the pellet near the seed. After magnetic and MO measurements the sample was further divided into smaller pieces and successive magnetic and MO measurements were performed to investigate how the magnetic properties vary within the sample. The microstructure analysis was carried out using a polarization microscope and a scanning electron microscope (SEM); the local flux distributions were studied at 30 K using MO imaging.

2. Experimental

Powders with the atomic ratio of (Nd$_{0.33}$Sm$_{0.33}$Gd$_{0.33}$)Ba$_2$Cu$_3$O$_y$ (‘‘NSG’’) were sintered and pressed into pellets of about 20 mm in diameter, which were then subjected to the OCMG process in 0.1% O$_2$ in Ar atmosphere. The details of the sample preparation are given elsewhere [1,4]. From the melt-textured NSG pellet a rectangular specimen with dimensions of $(a \times b \times c) = 2.0 \times 1.40 \times 0.38$ mm$^3$ was cut in a distance of about 6 mm away from the seed. The sample was mechanically polished to obtain a surface roughness of 0.5 µm. We used the MO imaging with a ferrimagnetic Bi-doped Y–Fe–garnet thin film with in-plane anisotropy to observe the flux distributions [6,7]. Our MO detection system is equipped with an electromagnet to apply a field up to 0.5 T, a helium gas flow cryostat, and an optical microscope attached to a color CCD video camera.
MO investigations were performed at $T = 30\, \text{K}$; the magnetic field was applied parallel to the $c$-axis of the sample. Integral magnetic properties were studied using a commercial SQUID magnetometer (Quantum Design models MPMS 5 and 7) in the temperature range between $30\, \text{K}$ and $77\, \text{K}$ and in fields up to $7\, \text{T}$.

### 3. Results and discussion

#### 3.1. Microstructure analysis

A polarized light image of the NSG sample is presented in Fig. 1a, revealing the twin plane pattern in the $(a,b)$-plane. The dark spots are due to several holes and $211$ particles. Furthermore, a grain boundary pattern is visible dividing the sample into three domains, labeled D1, D2 and D3, respectively. Along these boundaries $211$ particles clustered so that these areas appear black in the polarization image. One domain was wedge-shaped and stretched across the entire length of the sample. We denoted this domain as D1. Its surface was $1.06\, \text{mm}^2$. In the lower part of the image, two other domains are seen. The smaller square domain, with surface area of $0.75\, \text{mm}^2$, was denoted as D2. The third domain (D3) was the largest one, with a surface measuring $1.13\, \text{mm}^2$. It is important to note that the occurrence of such domains are not typical for the NSG compound.

Fig. 1b presents domains D2 and D3 in an SEM micrograph. Here, we can clearly distinguish between the dark holes and the $211$ particles (white). The size of the $211$ particles varies between 10 and $100\, \mu\text{m}$; also some very small ($\approx 1\, \mu\text{m}$ size) white spots can be detected. Entrapment of $211$ particles is commonly observed in melt-textured RE$\text{Ba}_2\text{Cu}_4\text{O}_{y}$ samples even when the starting composition is stoichiometric as in the present case. Note also that no additions like Pt or CeO$_2$ were used to refine the $211$ particle size. Electron microprobe analysis revealed that the $211$ particles are of the NSG-$211$ type, i.e., Nd, Sm, and Gd is contained in the $211$ particles in the same ratio as in the superconducting matrix. In domain D2, the $211$ particles are relatively uniformly distributed, whereas D3 shows only a small overall concentration of $211$ particles, and a large portion of the domain is free of $211$ particles.

#### 3.2. Magneto-optical studies

All flux patterns presented in this paper are taken at a temperature $T = 30\, \text{K}$ in order to achieve large enough contrasts; the exposure time of the camera is always kept constant during an experimental run in order to allow for a direct comparison of the images to each other. In the color representation, flux of positive sign is imaged as green; well-shielded regions are represented as brown. Vortices of opposite polarity (after a change of field direction) are imaged yellow.

The MO investigations at $30\, \text{K}$ reveal a quite inhomogeneous flux penetration into the sample. In
Fig. 2a–h, we present the initial flux penetration (i.e., along the virgin curve). The sample is completely shielded up to an applied field of 30 mT (a). In (b), 45 mT, flux starts to enter the sample through a grain boundary between domains D2 and D3, whereas the remainder of the sample is still completely shielded. In (c), 75 mT, (d), 120 mT, and (e), 150 mT, flux continues to penetrate along the grain boundary network until the sample is completely decoupled into three magnetically independent domains. From (f), 180 mT, on, vortices begin to enter into these domains as well. The flux penetration starting from the grain boundaries is evidently “easier” than starting from the sample edges, which...
is a clear indication of a surface (entry) barrier. Finally, in (g), 330 mT, and (h) 510 mT, a more or less regular flux penetration into the domains can be observed. Here, it is important to mention that the grain boundaries are not weak links. In such a case, even a very small applied field would be sufficient to destroy the coupling between the domains almost instantaneously. The present grain boundaries are capable of carrying a transport current, which causes a gradual decoupling of the domains. This gradually decoupling is typical for high-$T_c$ samples as discussed in Refs. [13,14].

Fig. 3 presents the reduction of the applied field towards the remnant state ($\mu_0 H_s = 0$ T) after applying the maximum field of 510 mT. In (a), the field is reduced to 150 mT. Vortices are leaving the sample also through the grain boundaries. The series (b)–(e) illustrates the further reduction of the field. In (d), 45 mT, vortices of opposite polarity ("negative vortices"; yellow) become stable inside the grain boundaries. Around these negative vortices, an annihilation zone with $B = 0$ T is formed. On further decreasing the external field, more and more such negative vortices are created until the remnant state is established in (f). The generation of these negative vortices takes place first where the pinning properties are weakest. Therefore, the observation of negative vortices allows to identify weak-pinning areas.

In order to check if the grain boundaries are not only at the sample surface, but indeed separate the sample into three domains through the entire thickness, the sample was further thinned down by another 100 μm. ZFC studies were repeated on the thinned NSG-whole sample and the stepwise flux

![Fig. 3. Reduction of field toward the remnant state at $T = 30$ K (sample ‘‘W’’), after applying a field of 510 mT. (a) 150 mT, (b) 105 mT, (c) 75 mT, (d) 45 mT, (e) 15 mT, and (f) 0 mT (remnant state). The reversal of the stray field is indicated by the color change from green (‘‘positive’’ field) to yellow (‘‘negative’’ field). The marker is 1 mm long.](image)
entry was again observed, thus confirming that the sample is definitely multi-domain in the whole thickness. Fig. 4 shows flux patterns on this thinned down sample; in (a) a field of 270 mT is applied. We notice that the three domains are decoupled magnetically. The ZFC remnant state can show if the sample is fully penetrated or not. It was impossible to fully penetrate the sample even after thinning down as our maximum applied field available was only 0.51 T, while the full penetration field, $H^*$, of the sample was around 2.0 T. In contrast to this, (b) presents a state obtained after field-cooling the sample in a field of 270 mT. After the temperature of 30 K is reached, the external field is removed (FC remnant state). In this case, a fully penetrated sample results. Also in this remnant state, negative vortices are generated and enter the sample through the grain boundaries and other weak-pinning areas. However, as the sample is fully penetrated, the annihilation of vortices of opposite polarity effectively “scans” these weak-pinning areas; even in a bulk superconducting sample. Therefore, we proposed such field-

![Image](image1.png)

**Fig. 4.** (a) The flux penetration through the grain boundaries (sample “W”) in an applied field of 270 mT, $T = 30$ K. (b) Trapping of flux in the remnant state after field-cooling in a field of 270 mT. The field was removed after $T = 30$ K was reached. In both cases, vortices of opposite polarity can be seen along the grain boundaries, but the field-cooled state in (b) is fully penetrated. The marker is 1 mm long.

![Image](image2.png)

**Fig. 5.** MO studies on domain D2 at 30 K. The marker is 100 μm long. (a) Domain D2 in zero-field cooled remnant state after a maximum field of 510 mT and then subjected to a negative field of $-15$ mT. Negative fields facilitate the entry of negative vortices and thus can give information about the weak channels. (b) 90 mT field-cooled remnant state of D2 subjected to a field of $-510$ mT and brought back to the remnant state. The field is removed after reaching 30 K. This clearly shows that a field of 510 mT is not sufficient to penetrate to the center of the sample and annihilate the field-cooled trapped flux.
cooled remnant states as effective means to analyze bulk superconducting samples by means of magneto-optic imaging [15].

After these experimental runs, the domains were separated mechanically and the domain D2, which is rich in 211 phases, was studied individually. The

Fig. 6. (a) FC remnant pattern of domain D2 at $T = 30 \text{ K}$, after FC in a field of 90 mT. The marker is 100 $\mu$m long. The resulting flux pattern is nearly uniform to the eye, but a closer inspection reveals important differences; see (b). (b) 3D contour plot of the field distribution of the state shown in (a). The contour plot of the local field, $B_z$, reflects the morphology of the sample surface. Furthermore, several islands of trapped flux can be seen which are due to the presence of 211 particles.
magneto-optic studies on the domain D2 are represented in Fig. 5. In (a), the sample was zero field cooled, then a maximum field of 510 mT was applied and subsequently switched off. Afterwards a small negative field of 15 mT was applied. The remnant state shows that the flux penetration is not isotropic, even though the sample geometry is not perfectly symmetric. The small negative field has pushed the trapped flux from the border of the sample towards the interior. There are three distinct regions: The center part is flux free (Meissner phase). This region is surrounded by an area of positive flux, which in turn is bordered by negative vortices.

In Fig. 5b, the remnant state is presented after the sample was field-cooled in a field of 90 mT and then a maximum negative field of 510 mT was applied at 30 K and subsequently switched off. Applying a negative field to the remnant state causes vortices with opposite polarity to enter the sample through possible weak channels. The penetration of negative vortices creates annihilation zones when they meet the positive flux. The study of negative vortices enables us to map the regions of weak channels. In Fig. 5b, there is a flux trapped in the central region in contrast to the ZFC remnant state where the central region is in Meissner regime. The annihilation zone is now in the interior of the sample and not at the border as before. This clearly shows that a field of 510 mT is not sufficient to penetrate up to the center of the sample and annihilate the field cooled trapped flux. The non-uniform distribution of the second phase particles is clearly reflected in the asymmetric flux pattern in the remnant state. Nevertheless the shape of the flux pattern in the center of the sample is in both cases similar, indicating that the weak channels are used for flux entry as well as for the flux exit.

To correlate the flux lattice state with the microstructure we plotted the 90 mT field cooled remnant state (Fig. 6a) as a three-dimensional (3D) contour plot (Fig. 6b). The contour plot shows the morphology of the surface. We realize that in only about 20% of the area in the central part high magnetic flux can be found, indicating that flux has escaped from the sides. 211 particles surrounded by a dense structure of contour lines can be clearly observed [15]. The strain around the 211 particles evidently affects and traps vortices, which indicates that the interface of the non-superconducting particles and the normal matrix can act as an efficient pinning medium.

4. Magnetic measurements

4.1. Critical temperature determination

To determine $T_c$ of the samples, zero-field-cooled (ZFC) curves were measured by means of a SQUID magnetometer, in an applied magnetic field of 1 mT. The entire sample had $T_c = 93.1$ K with a superconducting transition width less than 1 K. The sample D1 had the same $T_c$ value but the width of the transition increased to 2.5 K. The domain D2 showed the highest $T_c$ of 94 K with a sharp transition within 1 K. ZFC and field cooled (FC) curves of all the samples are plotted in Fig. 7. The whole sample (denoted by ‘‘W’’) had the smallest Meissner signal indicating better pinning properties than have the individual domains. This indicates that the interfaces substantially contributed to the flux pinning. The domain D2, containing a larger amount of non-superconducting particles, expelled magnetic flux less than D1.

4.2. Hysteresis measurements

Magnetic hysteresis loops (MHLs) were measured by a SQUID magnetometer in the no overshoot

![Fig. 7. $T_c$ measurements on the entire NSG sample ‘‘W’’, domain D1, and domain D2, performed using an applied field of 1 mT.](image-url)
mode in the temperature range of 30–77 K. The magnetic field was always applied parallel to the c-axis. Critical current densities, \( J_c \), were calculated from the MHL height \( \Delta m \) using the extended Bean model for the rectangular specimen \([16,17]\). \( J_c = \Delta m / \rho \) with \( \rho = 1 / 2a^2d(b - a / 3) \), where \( d \) is the thickness of the sample and \( a \) and \( b \) are its lateral dimensions, \( b \geq a \).

Keeping in mind that these samples contain an inhomogeneous distribution of 211 particles, we checked the effective current length-scales within the sample. As suggested by Angadi et al. \([18]\), the \( J_c \) value obtained from Bean model depends on the length scale on \( A \) which the current flows. A non-destructive method for \( \Lambda \) estimation is based on the analysis of the magnetization loop \([18]\). In the disk of the radius \( r \) and thickness \( d \), magnetized along the normal, the initial slope of the reverse leg of the MHL is related to the effective current lengthscale as
\[
\frac{dm}{dH} = - \left( \frac{\pi^2 A}{\ln(8r/d) - 0.5} \right).
\]

Here \( m \) is the magnetic moment (in A m\(^{-2}\)) and \( H \) is the applied field (in A m\(^{-1}\)). We approximated our nearly rectangular samples by a disk with an effective radius giving a surface area equal to the surface of the actual sample. The length-scale of the sample \( W \) was about 64% of the sample "radius". \( \pi A^2 \) was about 45% of the actual surface of the sample. None of the individual domains had such a large surface, the biggest domain extended to only 36% of the total sample surface area. This indicates that the domains were not completely magnetically independent. Similar calculations for the individual domains after their separation revealed that the domains D1 and D2 had length scales of 77% of their "radii". This means that a high \( J_c \) flew at only 60% of the domain area.

The above analysis can be taken as only a qualitative measure as the approximation of the rectangular samples by a disk is rather crude. Nonetheless, we can conclude that before separation the domains were magnetically coupled and only a small portion of the whole sample carried a high critical current. From this analysis also follows that \( J_c \) averaged over the whole sample volume was lower than the values in the individual domains after their separation. Fig. 8 demonstrates that this was the case at all measured temperatures. The domain D1 had always the highest \( J_c \), whereas \( J_c \) of \( W \) was always found to be the lowest of all. All three \( J_c(B) \) curves, for \( W \), D1, and D2, showed a clear peak effect (PE) without any evidence of the twin structure activity \([19]\). The fishtail peak \( B_{ri} \) of all three samples varied with temperature; the fishtail maximum position and irreversibility field scaled with temperature approximately equally: \( B_{ri} \) of \( W \) were always low, in D2, always high; the whole sample always exhibited intermediate values of both quantities. Note a rather strong distortion of the \( J(B) \) curve of \( W \) at 77 K. At higher temperatures the corresponding field range came out of the experimental range of fields.

4.3. Fit of the experimental curves

It is a common feature of PE that the maximum shifts to lower fields and the magnitude decreases
with increasing temperature. It also appears that a shift of the fishtail maximum to higher fields usually brings about also an increase in irreversibility field. To compare the PE of different samples at different temperatures it is useful to normalize the curves with respect to some characteristic value. If the fishtail maximum coordinates, \((B_{pk} J_{max})\), are used as such a characteristic value, the normalized PE shape of the hysteresis loop in RE-123 superconductors can be well approximated by the expression

\[ J_s(b) = J_r \exp\left[\frac{1 - b^n}{n}\right] \]  

(2)

where \(J_s = J_c/J_{max}\), and \(b = B/B_{pk}\). \(n\) is parameter describing field dependence of the characteristic activation energy \([21,22], U_0 \propto B^{-n}\), and the characteristic critical current density is assumed to be a linear function of field \([21-23], J_b \propto B\).

In Fig. 9a we present the \(J_s(B)\) curves of the samples W, D1, and D2, normalized to their fishtail maxima. The data measured at 77 K were chosen as at this temperature nearly all the curves fit into our experimental field window of 5 T. These curves were analyzed by means of Eq. (2). The fits are in the figure represented by lines. Sample W fitted with \(n = 1.85\) but the curve was somewhat distorted, probably due to incomplete electrical inter-connection of the individual domains. Although the \(J_s(B)\) curves of domains D1 and D2 look not much alike (Fig. 8), after normalization they nearly collapsed to one curve and from their fit by Eq. (2) we obtained \(n = 1.57\) and \(n = 1.51\), respectively.

Fig. 9b shows the same data presented in terms of the pinning force density, \(F = B J_s\). For the \(F(B)\) dependence normalized to the fishtail peak coordinates \((B_{pk}, J_{max})\), the relation equivalent to Eq. (2) reads \([23]\),

\[ F_n(b_f) = b_f^2 \exp\left[\frac{(1 - b_f^n)}{n}\right] \]  

(3)

with \(F_n = F/F_{max}\), \(b_f = B/B_{pk}\). The fits of the \(F_n(b_f)\) data by Eq. (3) resulted in similar values of the fitting parameter as in the previous case, \(n = 1.77\), \(n = 1.55\), and \(n = 1.56\) for samples W, D1, and D2, respectively. The slight variation in the \(n\) values is due to different effective weights exerted on individual experimental points in both representations, especially in the low-field range.

Finally, we normalized the field variable to irreversibility field. The resulting curves are presented in Fig. 9c together with fitting curves according to a modified Eq. (3),

\[ F_n(b_{irr}) = (\beta b_{irr})^2 \exp\left[\frac{1 - (\beta b_{irr})^n}{n}\right] \]  

(4)

with \(b_{irr} = B/B_{irr}\) and \(\beta = B_{irr}/B_{pk}\). Note that \(b_f = \beta b_{irr}\), \(1/\beta\) describes the mutual position of the fishtail peak with respect to irreversibility field. In the fits of the data in Fig. 9c both \(n\) and \(\beta\) were taken as free parameters. The introduction of an additional fitting parameter caused a slight change in the \(n\) values. We note that the \(n\) values corresponding to different data representations are close to each other. They are, however, significantly lower than those met sometimes in NdBa\(_2\)Cu\(_3\)O\(_7\) single crys-
The same applies for the parameter $1/r$ that was found in all three cases significantly lower than \( \approx 0.4 \), the value observed in some NdBa$_2$Cu$_3$O$_7$ single crystals [23].

Fig. 9a–c reflect some common features of different data representations. For example, the distortion of the curve measured on the whole sample is apparent in all three plots and the \( n \) value is in all cases significantly different from those of individual domains. Another common feature is the collapse of the normalized data of domains D1 and D2 onto one curve. From this we conclude that the rather massive 211 particles, if active at all, act as a random pinning disorder, pinning on which results in the observed typical fishtail shape of the magnetization curve. The higher concentration of the 211 particles in domain D2 might be consistent with the enhancement of both \( B_{\text{pk}} \) and \( B_{\text{ir}} \) in this domain. Although the critical current densities in domains D1 and D2 significantly differ, shapes of the normalized curves of D1 and D2 are practically identical. For a detailed insight into the role of 211 particles in flux pinning more experimental and theoretical work is needed.

5. Conclusions

A sample of the ternary compound NSG possessing a three-domain structure was studied, first on the sample as a whole, then on separated domains, by means of the microstructure analysis, magnetic and magneto-optical measurements. SEM showed that the sample had a non-uniform distribution of NSG-211 particles, in size from 2 to 100 \( \mu \)m. The MO images proved that magnetic flux enters the whole sample step-wise, first penetrating along grain boundaries, then entering grains. The critical current scale-length analysis showed that the domains were partially coupled before separation. After the separation the domain D1 had a high \( J_c \), while D2, rich in 211 particles, exhibited intermediate \( J_c \) but significantly higher \( B_{\text{pk}} \) and \( B_{\text{ir}} \) than the other two samples. The fishtail shape of the MHLs of individual domains can be well fitted by the exponentially decaying functions following from TAFC model. The values of the free parameters \( n \) and \( \beta \) indicate that magnetic properties of the studied material can be further improved. An effective control of the pinning site distribution and size is necessary to optimize the pinning mechanisms in the melt textured samples.

Acknowledgements

This work was partially supported by NEDO for the Research and Development of Industrial Science and Technology Frontier Program. AD, MJ and MRK thank the Japanese Science and Technology Agency (STA) for the support of this work by the provided fellowships. The work was completed under the partial support of GA ASCR No. A1010919. The authors thank T. Mochida and S.J. Seo for their technical assistance and valuable discussions.

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