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# Investigation of Pinning Force Density $F_p$ and Critical Current Density $J_c$ of $Nd_{0.33}Eu_{0.33}Gd_{0.33}$ $Ba_2Cu_3O_y$(NEG-123) Superconductors with Addition of 211 Phase Particles and Analysis with a Theoretical Evaluation Based on Flux Creep-Flow Model

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## Abstract

The pinning force density $F_\mathrm{p}$ and the critical current density $J_\mathrm{c}$ were investigated in $Nd_{0.33}Eu_{0.33}Gd_{0.33}Ba_2Cu_3O$(NEG-123) superconductors with addition of NEG-211 and EG-211 secondary phase particles of the volume fractions up to 10 mol% by analyzing experimental data of DC magnetization and compared with theoretical calculation based on flux creep-flow model taking the pinning parameter into account. The pinning parameters such that the number of flux lines in the flux bundle ($g^2$), the most probable value of pinning strength ($A_\mathrm{m}$), distribution width ($\sigma^2$), upper critical field ($B_{c2}$) were determined so that a good fit was obtained between theoretical and experimental results.

***Keywords:*** *The pinning force density $F_p$ and the critical current density $J_c$ , NEG-123 superconductors, 211 secondary phase particles, Flux-creep-flow model.*

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NEG- 211 and EG- 211 দ্বিতীয়ক দশা কণা সমূহের ১০ মোল% পর্যন্ত সংযোজন করা $Nd_{0.33}Eu_{0.33}Gd_{0.33}$ $Ba_2Cu_3O_y$ (NEG -123) অতি পরিবাহীর ধরে রাখা বলের ঘনত্ব $F_p$ এবং সংকটপূর্ণ প্রবাহ ঘনত্ব $J_c$ একমুখী চুম্বকনের পরীক্ষণীয় ডাটা হতে বিশ্লেষণ করা হয়েছে এবং ফ্লাক্স ক্লিপ ফ্লো-মডেল ব্যবহার করে ধরে রাখা স্থিতিমাপ গণনার মাধ্যমে তাত্ত্বিক হিসাবের সাথে তুলনা করা হয়েছে। ধরে রাখা স্থিতিমাপগুলো যেমন ফ্লাক্স বান্ডিলের ফ্লাক্স রেখার সংখ্যা ($g^2$), ধরে রাখা শক্তির সবচেয়ে বেশী সম্ভাব্য মান ($A_m$), বন্টন প্রশস্ততা ($\sigma^2$) এবং উচ্চতর সংকটপূর্ণ ক্ষেত্র ($B_{c2}$) মানগুলো এমনভাবে নির্ণয় করা হয়েছে যাতে তত্ত্বীয় এবং পরীক্ষণীয় ফলাফল ভালভাবে সামঞ্জস্যপূর্ণ হয়।

## 1. Introduction

It is considered a portion of a superconducting wire wound in the form of a magnet. This part carries a transport current and is exposed to a magnetic field when the magnet is energized. In most field ranges, practical superconductors with high k values are in the mixed state and the magnetic flux penetrating them is quantized. Usually, the current and the resultant magnetic field are perpendicular to each other and a driving force of a similar form to the Lorentz force acts on the fluxoids. When the fluxoids are driven by this force, a macroscopic electric field is induced:

$$\boldsymbol{E} = \boldsymbol{B} \times \boldsymbol{v}$$

Where $\boldsymbol{v}$ is the velocity of the fluxoids. The local electric field around the normal core is shown schematically in Fig.1. Normal electrons are driven by this electric field, resulting in an energy dissipation. Thus a corresponding electrical resistance appears.

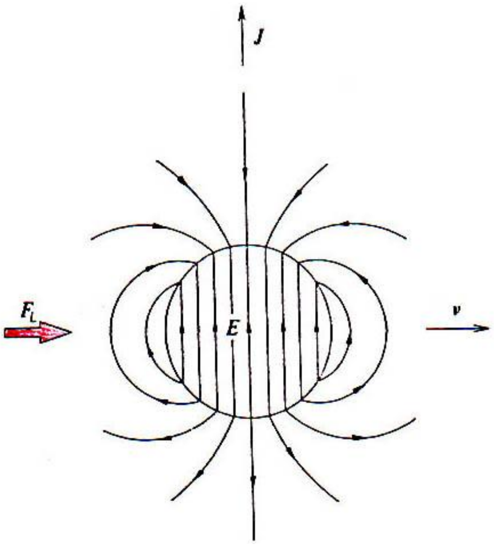


**Figure 1.** Non-uniform component of the induced electric field around a moving fluxoid core.

It is necessary to stop fluxoid motion in order to use superconductors in the nonresistive state. The interaction against the Lorentz force to stop the fluxoid motion is called flux pinning. Inhomogeneities in superconductors, such as dislocations, grain boundaries, voids and precipitates, contribute to this interaction. These inhomogeneities are called pinning centers. The transport current can be applied to the superconductor without energy dissipation up to a certain value, the critical current. The corresponding current density $J_c$, the maximum density of the nondissipative current, is the critical current density. At this current density, the Lorentz force that the fluxoids in a unit volume experience is $J_c B$. This means that the pinning centers in a unit volume exert the same force as this on the fluxoids, since those do not flow. The macroscopic force density of the pinning centers $F_p$, is called the pinning force density. Hence

$$J_c = \frac{F_p}{B}$$

To increase critical current density $J_c$, pinning force density $F_\mathrm{p}$ is required to be increased.

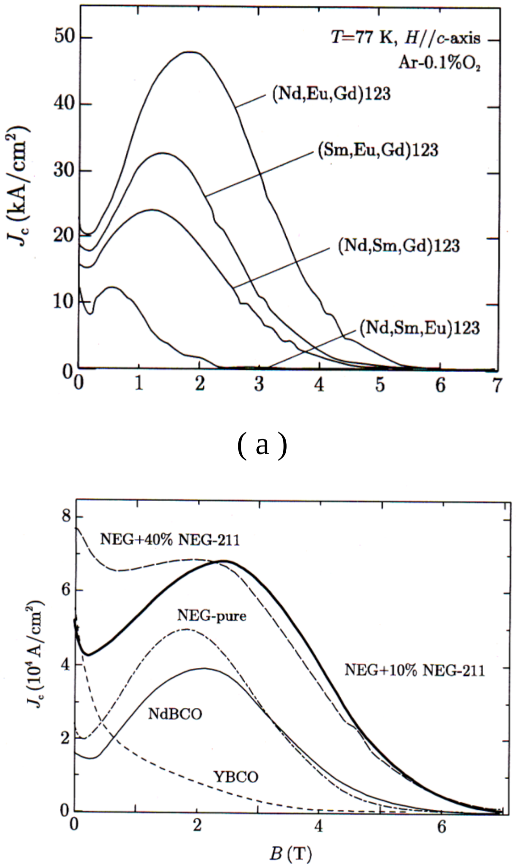
The high $T_c$ value in high-temperature superconductors is an attractive feature in realizing industrial applications. Also large critical current density ($J_c$), high irreversibility field ($B_i$) and small magnetic relaxation are required for power applications of high temperature superconductors. Up to now, RE-Ba-Cu-O bulk superconductors are the most promising candidates for high field applications [1].

Melt-processed RE-Ba-Cu-O bulks contain various defects such as non-superconducting second-phase precipitates, twin boundaries, point defects (oxygen vacancies), stacking faults and dislocations which all may serve as pinning centers. For bulk RE-Ba-Cu-O fine dispersion of RE 211 particles into RE-123 matrix is effective in enhancing pinning, which led to $J_c$ enhancement to the level of $10^9$ $A/m^2$ at 77 K [2]. For the development of facilities of applications, it is still necessary to increase $J_c$ and hence pinning force density $F_p$ of superconductors. Among RE-123, NEG-123 is now pinning candidates for application due to large $J_c$ than other RE-123 superconductors.

Recently Muralidhar *et al* has developed new $Nd_{0.33}Eu_{0.33}Gd_{0.33}$ $Ba_2Cu_3O_y$ called NEG-123 system and it has been systematically demonstrated that the flux pinning properties of the new material are superior to those of Y-123 or Nd-123 [3].

The critical current density $J_c$ in the bulk superconductors of the type $Nd_{0.33}Eu_{0.33}Gd_{0.33}Ba_2Cu_3O_y$ (NEG), where three rare earth elements (RE) are mixed together at the rare earth site, is considerably improved with addition of 211 phase particles [4]. That is, $J_c$ is improved to the level of $7\times10^8$ $A/m^2$ in NEG-123 with 40 mol% NEG 211 at 77K at 2T, as shown in Fig. 2 [5] together with data of melt-processed YBCO (Y-123) and NdBCO (Nd-123) superconductors.

Hence, in this paper, the measurement of DC magnetization in NEG-123 superconductors with addition of 211 phase particles are analyzed and ($J_c$-$B$) and ($F_p$-$B$) characteristics in NEG-123 have been investigated with addition of various volume fraction of NEG-211 and EG-211 phase particles. To clarify experimental results, a theoretical calculation based on flux creep-flow model determining various pinning parameters such as $A_m$ (average distribution of flux pinning strength), $g^2$ [6] (no. of flux lines in the flux bundle), $\delta$ (distribution width), $\gamma$, etc. are also investigated.



( a )

( b )

**Figure 2**.

(a) $J_c$-$B$ properties (77K , $B \parallel$ c axis) of ( R1 ,R2 , R3 )-123 composites OCMG processed in 0.1% $O_2$ –Ar [ 4 ]

(b) Comparison of the field dependence of the critical current densities at 77K measured by SQUID magnetometry; the field is applied parallel to the *c* – axis [ 5 ] .

## 2. Experimental Work

The experimental work has been done by Hasan *et al* [7] at KIT (Khyshu Institute of Technology) in Japan. The experimental data of DC magnetization has been analyzed and compared with theoretical calculation based on flux creep-flow model taking the pinning parameter into account.

Specimens were prepared by ISTEC (International super-conductivity Technology Center) group. The details of the specimen preparation was described in [8, 9].

Magnetization loops were measured using a DC magnetometer (SQUID). A large negative magnetic field (-7T) was applied to ensure full penetration before starting a measurement. The magnetic field is applied with $\Delta\mu_0 H_a = 0.25T$ and $H \| C$-axis. The field is swept in no overshoot mode and persistent current mode. The magnetization in a magnetic field along the C-axis was measured using the Quantum Design SQUID magnetometer. The onset supercon-ducting transition temperature of all the samples was in the range of 92.5-93.3K.

The critical current density $J_c$ is estimated from the measured magnetization hysteresis using the Bean model as

$$J_c = \frac{6a}{b(3a-b)}\Delta M$$

where $\Delta M$ is the magnetization width, $a$ and $b$ are the length and the width of the specimen, respectively.

### 2.1. Theoretical calculation

The experimental results are analyzed using the flux creep and flow model [6]. One of the important parameters which determine the flux creep and flow characteristics is the pinning potential, $U_0$. The $U_0$ is a function of the flux pinning strength and flux bundle size. The virtual critical current density in the ideal creep-free case, $J_{c0}$, is used as a parameter which represents the flux pinning strength, and its dependence on temperature and magnetic field is usually expressed as

$$J_{c0} = A(1-\frac{T}{T_c})^m B^{\gamma-1}(1-\frac{B}{B_{c2}})^2$$

where A is a constant representing the magnitude of $J_{c0}$, and m and $\gamma$ are pinning parameters.

The pinning potential in bulk superconductor is given by

$$U_0 = \frac{0.835 g^2 k_B J_{c0}^{1/2}}{\zeta^{3/2} B^{1/4}}$$

where $\zeta$ is a constant depending on the kind of pinning center. $g^2$ is the number of the flux lines in the flux bundle.

It is assumed that A is distributed as

$$f(A) = K_P \exp[-\frac{(\log A - \log A_m)^2}{2\sigma^2}$$

where $A_m$ is the most probable value of A, $\sigma$ is a parameter representing the statistical distribution width and $K_p$ is a normalization constant. Further details of the theoretical analysis is described in [10]. These parameters $A_m$, $\sigma$, $\gamma$ and m are determined so as to obtain good agreement between experimental and theoretical results.

## 3. Results and discussion

In Fig. 4.4 (a) and (b), the magnetic field dependence of $J_c$ with different volume fraction of NEG-211 and EG-211 phases at 80K is shown, respectively.

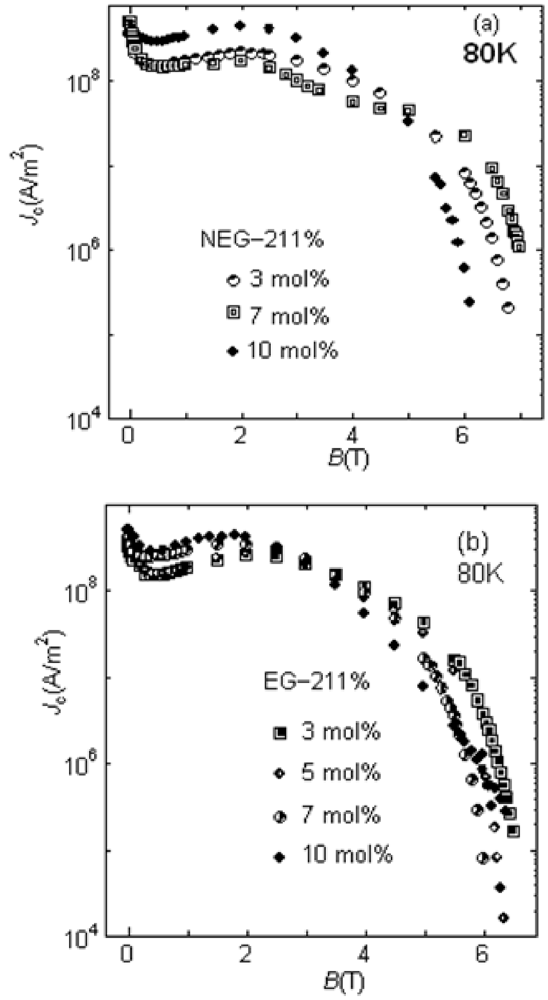


**Figure 3.** Field dependence critical current density $J_c$ in NEG-123 system with different volume fraction of (a) NEG-211 (b) EG-211 particles at 80 K.

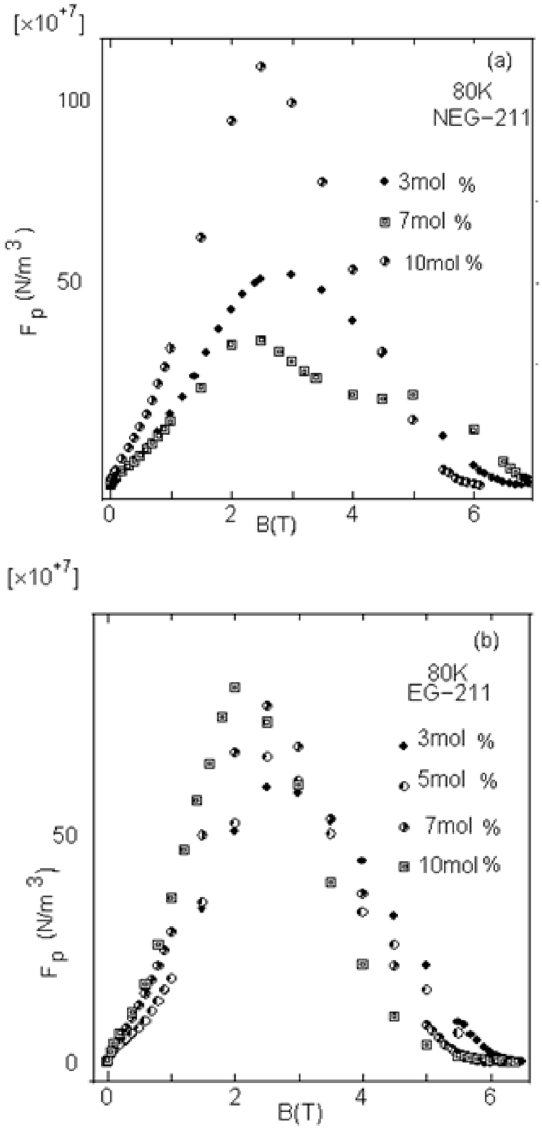


**Figure 4.** Field dependence of pinning force density $F_p$ in NEG-123 system with different volume fraction of (a) NEG-211 and (b) EG-211 particles at 80K.

In Fig. 4: (a) and (b), the magnetic field dependence of $F_p$ with different volume fraction of NEG-211 and EG-211 phases at 80K is shown, respectively.

For experimental calculation we have used the following data of the sample.

**Table 1.** Length, width and thickness of NEG-211 and EG-211 phase particles.

| **Type of material** | **Length *(l)*** | **Width *(w)*** | **Thickness *(d)*** |
|---|---|---|---|
| NEG-211 3mol% | $1.73\times10^{-3}$ m | $1.75\times10^{-3}$ m | $4.3\times10^{-4}$ m |
| NEG-211 7mol% | $1.92\times10^{-3}$ m | $2.18\times10^{-3}$ m | $1.6\times10^{-4}$ m |
| NEG-211 10mol% | $1.38\times10^{-3}$ m | $1.47\times10^{-3}$ m | $3.9\times10^{-4}$ m |
| EG-211 3mol% | $1.73\times10^{-3}$ m | $1.98\times10^{-3}$ m | $4.7\times10^{-4}$ m |
| EG-211 5mol% | $2.14\times10^{-3}$ m | $2.17\times10^{-3}$ m | $5.1\times10^{-4}$ m |
| EG-211 7mol% | $2.08\times10^{-3}$ m | $1.88\times10^{-3}$ m | $3.6\times10^{-4}$ m |
| EG-211 10mol% | $1.89\times10^{-3}$ m | $2.17\times10^{-3}$ m | $5.5\times10^{-4}$ m |

On the other hand, the experimental results of critical current density $J_c$ and pinning force density $F_p$ at 80K are compared with the theoretical prediction of the flux creep-flow model. The theoretical results of $J_c$ and $F_p$ are also shown in Fig 5 and Fig. 6. The parameter which is used in the theoretical calculation is shown in the table 2. The pining parameters $A_m$, $m$, $\gamma, \delta, \sigma^2$ and the number of flux lines in the flux bundle, $g^2$, are determined so that a good fit between theoretical and experimental results can be obtained and it is found that the agreement is good at the low and high field region. The enhancement of $J_c$ and $F_p$ with increasing 211 phase particles at low field region can be explained by the enhancement of $A_m$. But the exceptional 7mol% of NEG-211 specimen has smaller $A_m$ value due to lower $J_c$. On the other hand, the distribution width of pinning strength $\sigma^2$ value are 0.01-0.014.

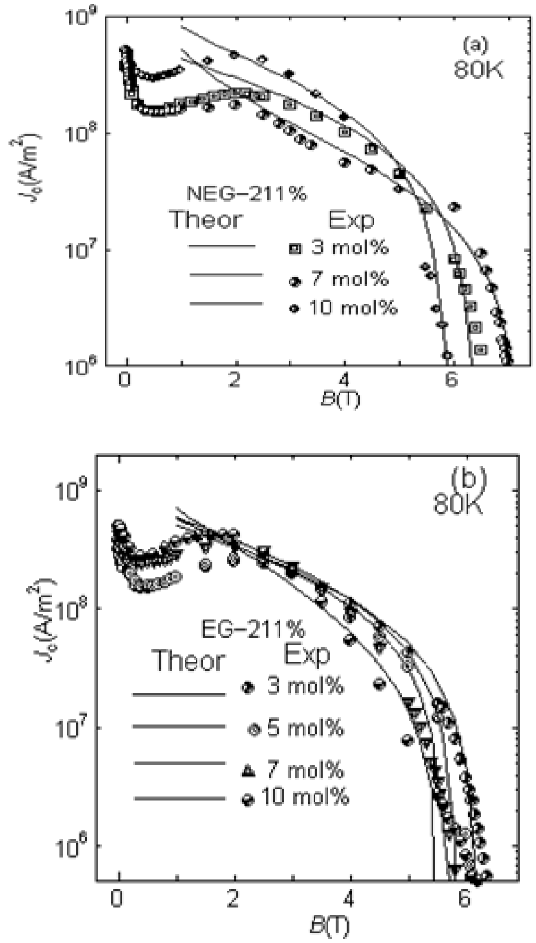


**Figure 5.** Theoretical fitting of $J_c$ -$B$ curve with experimental results by using the flux creep-flow model at 80 K.

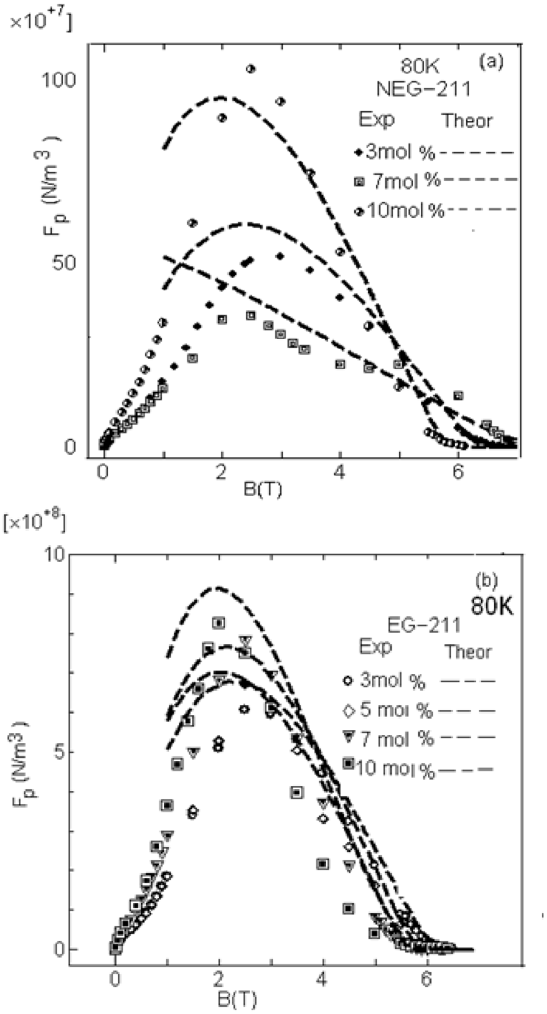


**Figure 6.** Theoretical fitting of $F_p$-$B$ curve with experimental results by using flux creep-flow model at 80K. But the 10 mol% of EG-211 has large $\sigma^2$ as the critical current density $J_c$ of this specimen has exceptional shape in the high field region compared with other specimens.

**Table 2.** Pinning parameters which are used for theoretical calculation.

| Specimen | $T_c$ | $B_{c2}$ (80 K) | $A_m$ | $\sigma^2$ | $\gamma$ | $m$ | $g^2$ |
|---|---|---|---|---|---|---|---|
| NEG-211 (3)mol% | 92.5 | 7.92 | $5.8\times10^{10}$ | 0.014 | 0.98 | 2 | 6.40 |
| NEG-211 (7)mol% | 93.3 | 14.17 | $4.2\times10^{10}$ | 0.010 | 0.10 | 2 | 6.58 |
| NEG-211(10)mol% | 93.2 | 8.83 | $7.8\times10^{10}$ | 0.010 | 0.73 | 2 | 3.70 |
| EG-211 (3)mol% | 92.9 | 7.74 | $5.0\times10^{10}$ | 0.010 | 0.94 | 2 | 6.40 |
| EG-211 (5)mol% | 93.3 | 7.10 | $6.6\times10^{10}$ | 0.012 | 0.95 | 2 | 6.22 |
| EG-211 (7)mol% | 92.6 | 7.73 | $7.0\times10^{10}$ | 0.120 | 0.84 | 2 | 4.60 |
| EG-211 (10)mol% | 93.2 | 6.14 | $5.5\times10^{10}$ | 0.055 | 0.50 | 2 | 9.50 |

The Figures 5 and 6 suggest that the agreement is good between theoretical and experimental results.

## 4. Conclusion

This paper describes pinning force density $F_p$ and the critical current density $J_c$ in NEG-123 superconductors by analyzing experimental data of DC magnetization and comparison with theoretical calculation based on flux creep-flow model taking the pinning parameter into account. Flux pinning properties were investigated with focusing on the origin of the critical current density, $J_c$, for the superconductor with addition of NEG-211 and EG-211 secondary phase particles of the volume fractions up to 10 mol%.

The pinning parameters such that the number of flux lines in the flux bundle ($g^2$), the most probable value of pinning strength ($A_m$), distribution width ($\sigma^2$ ), upper critical field ($B_{c2}$) are determined so that a good fit is obtained between theoretical and experimental results.

Based on the discussion, the following conclusions are obtained:

1. It is concluded that a pronounced increase in $J_c$ at the peak field region occurs by increasing the volume fraction of both the NEG-211 and EG-211 phases. On the other hand , $J_c$ at high fields deteriorates with the addition of 211 phase. From Fig. 5 and Fig. 6, the result also suggest that the agreement is good between experimental and theoretical results.
2. The pinning force density, $F_p$, increases with increasing field at a certain value and then decreases with increasing field. The pinning force density, $F_p$, has a maximum value near 2 Tesla for both NEG-211 and EG-211 phase particles. The results also suggest that the agreement is good between theoretical and experimental results.
3. The enhancement of $J_c$ and $F_p$ with increasing 211 phase particles at low field region can be explained by the enhancement of $A_m$ .It is found that $g^2$ decreased at the peak field, suggesting a softening of the flux line lattice .On the other hand, the value of distribution width of pinning strength $\sigma^2$ are 0.01-0.014.

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