Microstructural, Phase Formation, and Superconducting Properties of Bulk YBa$_2$Cu$_3$O$_y$ Superconductors Grown by Infiltration Growth Process Utilizing the YBa$_2$Cu$_3$O$_y$ + ErBa$_2$Cu$_3$O$_y$ + Ba$_3$Cu$_5$O$_8$ as a Liquid Source

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Abstract: The infiltration growth (IG) process is well-known as the most established technique consisting of Y$_2$BaCuO$_5$ (Y121) precursor powders and liquid phases toward the fabrication of bulk YBa$_2$Cu$_3$O$_y$ (Y123) superconductor for high field industrial applications. We have reported the fabrication of Y123 bulks using this technique at various ratios of liquid phase source. In this study, the use of liquid phase source toward the infiltration growth of bulk Y123 superconductors at different ratios of Y123 and ErBa$_2$Cu$_3$O$_y$ (Er123) mixed with Ba$_3$Cu$_5$O$_8$ (Y035) was investigated to control the Y121 secondary phase content in bulk Y123 samples. The liquid phase content was optimized by varying the mass. The sample fabricated using Y123 liquid phase (Y$_1$Er$_0$) showed the onset of critical temperature $T_{c-onset} = 91.85$ K. $T_{c-onset}$ slightly decreased with the addition of Er123. Microstructure analysis revealed a uniform distribution of Y211 secondary phase particles in the Y123 matrix. The Y$_1$Er$_0$ sample had the smallest of Y211 particle size among the samples with average size of 0.992 μm. The formation of this smaller-sized Y211 particles with uniform distributions that act as an effective pinning center, had improved the critical current density, $J_c$ of the sample Y$_1$Er$_0$ at 77 K with H//c-axis having the highest $J_c = 54.15$ kA/cm$^2$ and 11.45 kA/cm$^2$ in self-field and 2 T, respectively. The binary mixed of rare earth superconductors (Y123 + Er123) used in the liquid phase could be used to further improve the superconducting properties of Y123 single grains.

Keywords: liquid phase; Y123 superconductor; infiltration growth process; critical current density

1. Introduction

Recently, the revolutionary developments toward REBa$_2$Cu$_3$O$_{7-\delta}$ (RE: Nd, Sm, Gd, (Nd, Eu, Gd) etc.) “RE123” including yttrium barium copper oxide, YBa$_2$Cu$_3$O$_{7-\delta}$ (Y123) have improved in several applications and industrial technologies [1–4]. The excellent performance of the type-II high temperature superconductor (HTS) is gaining a lot of attention due to their potential for practical applications in future technologies. Recently, it was reported that the development of HTS magnet had been introduced into electric machine applications [5]. To achieve much higher critical current density, $J_c$ a lot of
effort was made by many researchers to better develop the superconducting materials. Nonetheless, it is found that the weak links at the grain boundaries of the Y123 system are limiting their critical current density, \( J_c \), performance. Impurity phases and structural inhomogeneities at the grain boundaries of Y123 are some reasons for this weak link behavior to occur [6]. According to previous studies, the introduction of nanoparticles in the YBCO system plays an important role as an effective flux pinning centre [2–8].

The melt-texture growth process has been widely used to produce large Y123 single domain superconductors. Single domain production of bulk Y123 superconductor allows a better performance of their superconducting properties with the presence of RE211 secondary phase particles in the RE123 phase matrix that contribute as an effective pinning centre causing high \( J_c \) values [9,10]. It was reported that introducing RE211 secondary phase particle can improve the strong flux pinning force. However, several disadvantages have been found, such as the inhomogeneity of secondary phase form, significant shrinkage, uneven distribution of Y211 secondary phase particle formation, and large pore generation and cracking on the bulk Y123 superconductor [11]. In order to solve the problems, infiltration growth (IG) technique was developed by Reddy et al. to produce bulk Y123 single grain superconductor [12]. The IG technique involves the infiltration of liquid phases into the RE-211 preforming solid precursor for formation of Y123 in a slow cooling process below the peritectic temperature, \( T_p \) [12,13]. This technique attracts much attention from researchers and the industries due to its best performance that offers near net-shaped final bulk with precisely dispersed Y211 particles. This technique also improves the pinning centres of bulk Y123 superconductors causing the enhancement of high critical current density, \( J_c \) values [9,11].

NdBCO single crystal or melt textured material is used as a seed because of its high melting point and straightforward preparation among the RE-123 groups [14,15]. For this process, liquid phase source plays an important role for the infiltration of the liquid phase (BaCuO\(_2\) + CuO) into the porous RE211 preform bulk. The melted liquid phase permeated into the Y211 phase and reacts to form Y123 single grain under slow cooling conditions. It was reported by Fang et al. that the infiltration of the liquid phase by IG technique produced smaller particle sizes and uniform distribution of Y211 in the Y123 single grain than the melt growth technique [16]. During the infiltration process, the maximum temperature, \( T_{\text{max}} \), must be higher than the peritectic temperature, \( T_p \), of the Y123 samples. This is to ensure the samples are decomposed completely and homogenously during the infiltration process [17]. The best performance of Y121 particles with homogeneous distribution and uniform size in Y123 phase matrix is observed at a temperature of 1050 °C [18]. The highest value of \( J_c \) at 77 K and the self-field is reported to achieve 233 kAcm\(^{-2}\) [11]. The high growth performance of Y123 single domain can be optimized by proper control of the Y211 particle dispersion microstructure and sufficient amount of liquid phase source to infiltrate the Y211 preform source [17–21].

In order to improve high-quality bulk, the liquid phase should be supplied optimally with an appropriate amount of Y211 in the liquid phase source pellet. It is found that the mixture of Er123 into the Y035 liquid phase source has a significant contribution to pump the liquid phases into the Y211 preform pellet. It is noted that the Er123 decomposes at around 960 °C into the Er211 phase and are generated at the bottom of the pellets to support them from collapsing without travelling to the upper Y211 preform pellet. Therefore, in this study, a series of bulk Y123 single domain were prepared using the top seeded IG technique by varying the ratios of liquid phase sources, Y123 + Er123 + liquid phase (Y035). The use of liquid phase content in the Y123 superconductors was investigated in this study. The growth, microstructure, superconducting critical temperature (\( T_c \)), and critical current density (\( J_c \)) were investigated in detail with different amounts of Y123 and ErBa\(_2\)Cu\(_3\)O\(_y\) (Er123) with the mixture of Ba\(_3\)Cu\(_3\)O\(_8\) (Y035) as a liquid phase source. This utilization in the liquid phase is expected to surpass the problem of heavy loss of liquid during the melting and infiltration steps in the IG process.
2. Materials and Methods

Y123 bulk superconductors were prepared using high purity commercial powders of Y211 (Toshima, Higashimatsuyama, Japan, 99.99%), 0.1% platinum, Pt powders (Toshima, Higashimatsuyama, Japan, 99.99%), Er123 powders (Toshima, Higashimatsuyama, Japan, 99.99%), and Y123 powders (Toshima, Higashimatsuyama, Japan, 99.99%). The Y211 powders were mixed with Pt that acted as a grain refiner using an alumina mortar and pestle and then pressed uniaxially into 20-mm diameter pellets. The samples were sintered at the optimum sintering temperature of 925 °C in a furnace [20]. Concurrently, powders of BaO2 (High Purity Chemicals, Saitama, Japan, 99%) and CuO (High Purity Chemicals, Saitama, Japan, 99%) were mixed thoroughly to produce Ba3Cu5O8 (Y035) and was calcined between 820 and 860 °C for 24 h to achieve a target composition of Y035. To investigate the effects on the infiltration of liquid phases and the growth rate in the synthesis of Y123 bulk superconductors, different ratios of liquid phases of Y123 and Er123 were mixed with Y035 in the ratio of 1:1. The ratios of Y123:Er123 were labelled as Y1Er0, Y0.75Er0.25, Y0.5Er0.5, Y0.25Er0.75, and Y0Er1 corresponding to 1:0, 0.75:0.25, 0.5:0.5, 0.25:0.75, and 0:1, respectively. The use of Er123 together with Y123 and Y035 helped enhance the liquid phase to be a more effective source to pump the liquid phase to the Y211 preform pellet as it could help in increasing the growth rate of the bulk Y123 [21].

A schematic illustration of the assembly to fabricate the bulk Y123 single grain superconductor using IG technique is shown in Figure 1. The Y211 preform pellet was placed on the liquid phase pellet and then a Nd123 melt textured seed was positioned in the middle of the top surface of Y211 preform pellet for the growth of single Y123 grains. A Yb2O3 powder plate and an MgO single crystal plate were placed beneath the liquid phase pellet to suppress the liquid loss and subsidiary Y123 nucleation while the Al2O3 plate at the bottom of the arrangement was used as a support. Samples with 20 mm diameter and 5 mm thickness were produced for the fabrication of bulk Y123 single grain samples by IG process using the time–temperature profile displayed in Figure 2. The samples were heated at the rate of 110 °C/h to 880 °C and held at that temperature for 15 min in a furnace. The temperature was then raised to 1050 °C and was maintained for 1.5 h to allow sufficient melt infiltration of liquid phase into Y211 preforms. The temperature was then lowered at a constant rate to 1005 °C in 60 min and then allowed to cool slowly at a rate of 0.1 °C/h for 200 h until the temperature reached 985 °C. The samples were furnace cooled to room temperature at the rate of 100 °C/h to 100 °C. Finally, the samples were annealed at 450 °C in oxygen atmosphere for 250 h.

![Figure 1](image-url)  
**Figure 1.** A schematic arrangement of the precursor sample used in the infiltration growth (IG) experiment.
Figure 2. Time–temperature profile for Y123 bulk fabricated by TSIG process.

Phase formation and crystal lattice properties of the samples were obtained using Phillip X-ray diffractometer (XRD, Phillip, Eindhoven, Netherlands) with Cu-K$_\alpha$ radiation source. Microstructure of the samples was observed using field-emission scanning electron microscope (FESEM) JSM-7100F (JEOL, Tokyo, Japan) EDS & EBSD. The $T_c$ and $I_c$ values were measured using SQUID magnetometer (Quantum Design, model MPMS5, Saitam, Japan). The plots of temperature dependence of magnetic susceptibility for the samples were collected in the presence of magnetic field of 1 mT from 50 to 100 K. Magnetization hysteresis (M-H) loops were measured by applying magnetic fields from 0 to 5 T at 77 K. All samples were cut into a rectangular shape with a dimension of 1.5 mm × 1.5 mm × 0.5 mm to estimate the $I_c$ calculated from the M-H loops based on the extended Bean’s critical state model with the following formula:

$$I_c = 20 \times \frac{\Delta M}{a^2 c \times (b - a/3)}$$

where $\Delta M$ is the difference of magnetic moments during increase and decrease in the M-H loop, $a < b$ is cross sectional dimension and $c$ is the sample thickness [22].

3. Results and Discussion

3.1. X-ray Diffraction Analysis

Figure 3a shows the top surface of the processed bulk Y123 material produced by IG process using the Y123 + Er123 with Y035 as a liquid source. The growth of four faceted lines were visible on the top view which is 20 mm in diameter of all Y123 samples indicating that the Y123 crystals perfectly turned into single grains. For further investigation, Figure 3b shows the X-ray diffraction (XRD) patterns of the bulk Y123 samples with varying contents of Y123 and Er123 with Y035 as a liquid phase source after being annealed at 450 °C for 250 h. The XRD patterns were found to match Y123 with orthorhombic crystal structure and Pmmm space group (ICSD NO. 98-004-1823). All samples show 013 and 103 peaks which indicate the orthorhombic structure were preserved. Besides that, Y211 peaks marked with 0 and indexed by the ICSD NO. 98-002-9780 which commonly coexists with that of Y123 phase were present in all samples. The presence of these peaks may have occurred during the slow cooling through the peritectic temperature in solid form in the Y123 matrix.
Figure 3. (a) The top view of bulk Y123 samples shows that faceted lines were observed indicating the perfect growth of Y123 single grain. (b) X-ray diffraction patterns in the range of 2θ: 20°–80° for the samples.

The lattice parameters and unit cell volume of the samples are summarized in Table 1. The increment of unit cell volume was observed due to change of lattice parameters caused by the decreasing of Y123 contents in the liquid phase. Orthorhombicity of samples which is defined as (b-a)/(a+b) is tabulated in Table 1. The crystallite size of the samples was calculated from peak 103 using the Scherrer equation as given below [23],

\[ \rho = \frac{k \lambda}{B_{\text{size}} \cos \theta} \]  

where \( \rho \) is the crystallite size, \( k \) is the Scherrer constant (~0.9), \( \lambda \) is the X-ray radiation wavelength for Cu-K\( \alpha \) (1.5406 Å), and \( B_{\text{size}} \) is related to the line broadening of peak width at the maximum intensity (FWHM). No definite trend on the variation of the crystallite size can be observed as the composition of Y123 in the liquid phase is reduced.

Table 1. Lattice parameters of \( a \), \( b \), and \( c \) axes and unit cell volume of YBCO with different ratios of Y123:Er123.

| Samples     | \( a \) (Å)       | \( b \) (Å)       | \( c \) (Å)       | \( V^3 \) (Å\(^3\)) | Crystallite Size (nm) | Orthorhombicity Factor |
|-------------|-------------------|-------------------|-------------------|----------------------|-----------------------|------------------------|
| \( Y_1Er_0 \) | 3.8191 ± 0.0004   | 3.8827 ± 0.0004   | 11.6838 ± 0.0007  | 173.2556             | 73.70                 | 0.0082                 |
| \( Y_{0.75}Er_{0.25} \) | 3.8182 ± 0.0004   | 3.8856 ± 0.0006   | 11.6856 ± 0.0013  | 173.3689             | 47.70                 | 0.0087                 |
| \( Y_{0.5}Er_{0.5} \) | 3.8201 ± 0.0008   | 3.8941 ± 0.0013   | 11.6718 ± 0.0020  | 173.6111             | 73.60                 | 0.0096                 |
| \( Y_{0.25}Er_{0.75} \) | 3.8212 ± 0.0009   | 3.8903 ± 0.0015   | 11.6921 ± 0.0048  | 173.8036             | 174.63                | 0.0090                 |
| \( Y_0Er_1 \) | 3.8226 ± 0.0009   | 3.8959 ± 0.0016   | 11.6942 ± 0.0026  | 174.1549             | 103.57                | 0.0095                 |

3.2. Microstructural Analysis of Y211 Secondary Phase Morphology in the Y123 Matrix

Figure 4 presents the microstructure of the bulk Y123 superconductor samples produced by utilizing Y123 + Er123 with Y035 as a liquid phase source and examined by FESEM at magnification of 1000×. The existence of Y211 secondary phase particles distributed in the Y123 matrix can be clearly observed in the figure. The lighter shade surfaces in the micrograph correspond to the Y211 secondary phase particles while the darker shade surfaces belong to the Y123 particles. On closer inspection of the fabricated samples at a higher magnification of 5000×, the FESEM images shown in Figure 5 revealed that the Y211 secondary phase particles were found in circular rounded shape while the larger fairly irregular ones were those that had fused together. Large Y211 secondary phase particles are commonly observed in the matrix of Y123 samples prepared using IG technique [24]. This might be caused by the incongruent decomposition of Y123 materials resulting in large
Y211 secondary phase particles. In addition, small amounts of porosity also appeared in the samples due to the loss of liquid phase during the melt texturing process. This may have suppressed the growth of Y211 secondary phase particles and created the pores. However, the amount of porosity developed in this process can be considered negligible as compared to using the melt growth technique [1,25]. The fine particle sizes of Y211 secondary phase must be in good condition to contribute to the enhancement of flux pinning and $I_c$ [26]. The results above demonstrated that fine particles which have been synthesized will assist in the enhancement of flux pinning and $I_c$.

![Micrographs](image-url)

**Figure 4.** Micrographs at a magnification of 1000× for the YBCO single grain observed at equivalent positions.

The average sizes of the Y211 particles were also determined from the micrograph in Figure 5 using the Image-J software (Java 1.8.0_172, NIH, Bethesda, MD, USA) and the results are listed in Table 2. The average sizes of the particles were calculated from 100 selected grains randomly by measuring both dimensions of the elongated grains based on the diagram illustrated in Figure 6 [27]. The outcome of the analysis shows that the average sizes of Y211 secondary phase particles were between 0.9 and 3 μm. It can also be seen in Table 2 that the smallest Y211 secondary phase particles were found in sample $Y_1Er_0$, followed by $Y_{0.75}Er_{0.25}$, $Y_{0.5}Er_{0.5}$, $Y_{0.25}Er_{0.75}$ with values of 0.99, 1.00, 1.22, 1.64, and 1.54 μm, respectively. The fine and spherical shape in the morphology of Y211 secondary phase particles are attributed to the enhancement of $I_c$ due to interfacial defects of Y123/Y211 that generates and introduced as effective flux pinning sites [1,26].

**Table 2.** Summary of $T_{c-onset}$, $T_{c-zero}$, average particle sizes of the Y211, and $I_c$ values at self-field, 0.5, 1.0, and 2 T of IG processed Y123 produced with different ratio of liquid phase.

| Samples | $T_{c-onset}$ (K) | $T_{c-offset}$ (K) | Average Grain Sizes, D of the Y211 Particles (μm) | $I_c$ at Self-Field (kA/cm²) | $I_c$ at 0.5 T (kA/cm²) | $I_c$ at 1 T (kA/cm²) | $I_c$ at 2 T (kA/cm²) |
|---------|------------------|------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| $Y_1Er_0$ | 91.85            | 90.25            | 0.99 ± 0.24                     | 54.15           | 25.19           | 18.27           | 11.45           |
| $Y_{0.75}Er_{0.25}$ | 91.33            | 89.24            | 1.22 ± 1.28                     | 46.54           | 17.66           | 13.29           | 8.17            |
| $Y_{0.5}Er_{0.5}$ | 91.52            | 90.44            | 1.00 ± 0.36                     | 49.10           | 17.64           | 13.35           | 6.75            |
| $Y_{0.25}Er_{0.75}$ | 91.82            | 90.04            | 1.64 ± 0.49                     | 33.75           | 10.87           | 7.58            | 4.61            |
| $Y_0Er_1$ | 89.34            | 88.25            | 1.54 ± 0.43                     | 34.16           | 12.34           | 8.03            | 0.69            |
Figure 5. (a–e) FESEM images under ×5000 magnifications and distribution of Y211 particle grain size in Y123 matrix. The Y211 particles observed are in spherical shape and fused.

Besides that, the particle sizes of Y211 secondary phase systematically increased as observed on Y_{0.25}Er_{0.75} and Y_{0}Er_{1} at high magnification micrograph. It was reported that the addition of Er123 together with Y123 and Y035 helped enhance the liquid phase to be a more effective source to pump the liquid phase to the Y211 preform pellet as it could help in increasing the growth rate of the bulk Y123 samples [21]. On the other hand, the behaviour of the Y211 secondary phase particles in the Y123 microstructure was clearly observed with inhomogeneous distribution in our study. By increasing the Er123 content in the liquid phase, the Y211 secondary phase particles had increased in size up to 1.64 μm. Hence, sample Y_{0.25}Er_{0.75} and Y_{0}Er_{1} had resulted in larger distribution of Y211 particles due to a lower growth rate of Er123. This might possibly be due to the shorter slow cooling time duration causing the incomplete formation of Y211 particles and utilized in the final sample [28]. For sample Y_{0.5}Er_{0.5}, the reduction of the Y211 secondary phase particle size...
could be attributed to the enhancement of the flux pinning; thus, \( J_c \) increased slightly higher as shown in Table 2. It was reported previously that sufficient liquid phase supplied into the Y211 secondary phase preform pellet leads to the increment of growth rate of Y123; thus, improving the \( J_c \). This indicates that the initial composition used in the IG process is very important to obtain the good growth rate of Y123 single grains.

In the IG process, the sintering temperature during the process is important to the growth of Y211 secondary phase particles in the Y123 single grain matrix [29]. The large particle size of Y211 secondary phase leads to the inappropriate distribution of \( J_c \). This can be observed and explained more in the critical current density, \( J_c \) analysis. From the microstructure analysis, it is clearly shown that the smaller particle size of Y211 secondary phase distribution can be explained with the critical current density, \( J_c \) values of the samples. Therefore, the influence of the microstructure on the critical current density, \( J_c \) is observed from M-H curves using Bean’s critical state model in the M-H loop with \( a < b \) as the cross sectional dimensions and \( c \) is the sample thickness [22].

### 3.3. Critical Temperature and Critical Current Densities Analysis of Bulk Y123 Superconductors

Figure 7 shows the temperature dependence of the dc susceptibility results of IG processed bulk Y123 superconductors produced utilizing the Y123 + Er123 with \( \mathrm{Ba}_2\mathrm{Cu}_3\mathrm{O}_6 \) as a liquid source. All the samples exhibited sharp superconducting transition with high \( T_c\) onset near to 91.85 K for \( \mathrm{Y}_1\mathrm{Er}_0 \) even though there were slight decrements on \( T_c \) in sample \( \mathrm{Y}_0\mathrm{Er}_1 \). From Table 2, transition temperature, \( T_c \), for samples \( \mathrm{Y}_1\mathrm{Er}_0 \), \( \mathrm{Y}_{0.75}\mathrm{Er}_{0.25} \), \( \mathrm{Y}_{0.5}\mathrm{Er}_{0.5} \), \( \mathrm{Y}_{0.25}\mathrm{Er}_{0.75} \), and \( \mathrm{Y}_0\mathrm{Er}_1 \) were 91.85, 91.33, 91.52, 91.82, and 89.3 K, respectively. Sample \( \mathrm{Y}_1\mathrm{Er}_0 \) has the highest \( T_c \) of 91.85 K. However, it can be observed that sample \( \mathrm{Y}_{0.5}\mathrm{Er}_{0.5} \) had lower transition width, with \( \Delta T \) of around \( \sim 1 \) K. Broadening in \( \Delta T \) is correlated with the increasing of Y211 secondary phase particle size due to the inhomogeneous growth of Y211 secondary phase particles resulting from the insufficient supply of liquid phase that infiltrated into the Y123 [21].

![Figure 7. Temperature dependence of normalized magnetization.](image)

The transition width is defined by the difference between \( T_{c\text{-onset}} \) and \( T_{c\text{-zero}} \), which indicates better homogeneity of oxygen distribution in the sample [30]. Sample \( \mathrm{Y}_{0.5}\mathrm{Er}_{0.5} \) shows smaller \( \Delta T \), indicating that the sample had better homogeneity of Y211 secondary phase particle distribution in the Y123 matrix. The remaining samples show different \( \Delta T \), although sharp transition was still observed in each sample. These results show that all samples had good quality, similar to those reported from previous studies [12,31]. Furthermore, \( \mathrm{Y}_0\mathrm{Er}_1 \) sample exhibited the lowest \( T_c \) at 89.34 K. Furthermore, the \( \mathrm{Y}_0\mathrm{Er}_1 \) sample exhibited the lowest \( T_c \) at 89.34 K. During the melting process, Y123 phase may
not be completely formed because of oxygen deficiency and fluctuations of compositional regions that may cause broadening in transition width [28–31]. Previous studies using IG technique to prepare the Y123 material by a ball milling technique showed the highest superconducting temperature obtained was 93.2 K with transition width below 1 K [11].

The critical current density ($J_c$) curves measured using the extended Bean’s critical state model at 77 K, H//c-axis at self-field for all samples are shown in Figure 8. $J_c$ for $Y_1Er_0$, $Y_{0.75}Er_{0.25}$, $Y_{0.5}Er_{0.5}$, $Y_{0.25}Er_{0.75}$, and $Y_0Er_1$ were 54.15, 46.54, 49.10, 33.75 and 34.16 kA/cm², respectively. The $J_c$ values obtained for all samples were higher compared to previous studies involving addition of Er123 in the liquid phase [21]. It shows that samples with $Y_1Er_0$ had the highest $J_c$ values among the other samples. The increment of Er123 in the liquid phase of Y035 decreased the $J_c$ values. The highest $J_c$ was for sample $Y_1Er_0$, followed by $Y_{0.5}Er_{0.5}$. It is mainly due to the formation of smaller sized Y211 secondary phase particles and uniform distributions that introduce higher pinning forces [16].

![Figure 8. Measured $J_c$–H characteristics at 77 K at self-field of samples with various amount of LP ratios (Y123:Er123).](image)

In addition, the $J_c$ enhancement can be caused by the refinement of Y211 secondary phase and pore elimination during the process [27]. The results lead to remarkable improvement of a better performance as Y123 bulk had optimized the growth condition with uniform distribution of the secondary phase particles in the Y123 matrix. Previous studies found that the optimum amount of Er123 in liquid phase with optimum mass ratios could help to improve the growth rate and $J_c$ value performance [21]. In this study, the growth was significantly different where samples with $Y_1Er_0$ contained the smallest Y211 particle average grain sizes. This proves that the fabrication process is very crucial to control the dispersion of Y211 secondary phase particles within the Y123 matrix to obtain critical current density, $J_c$ value in fabrication of Y123 superconductors with the IG technique.

According to a previous study by Chen et al., higher number of small particle Y211 could attribute to the enhancement of $J_c$ in low fields [32]. To achieve these smaller particle sizes, similar studies also reported that the presence of larger diameter of liquid phase pellets than solid source pellets could better help to supply sufficient amounts of liquid to infiltrate the preform Y211 secondary phase [33]. Similar results had been reported by Zhao et al., where the refinement of Y211 particle sizes could be controlled with the addition of dopants like CeO₂ and Pt in the liquid phase that could enhance the Y211 particle distribution grain sizes [34].
4. Conclusions

The IG process was successfully used to fabricate single grain bulk Y123 superconductors by infiltrating the liquid source of Y123:Er123 and Y035 into the Y211 preform to form Y123. From XRD, it was found that Y123 were well indexed with orthorhombic crystal structure and Pmmm space group with sample Y0.5Er0.5 having the highest orthorhombic factor among other samples. The crystallite size for all samples varied with the ratios of Y123:Er123 in liquid phase. From the microstructure, transition temperatures, and critical current density, $J_c$ analysis, it can be concluded that the distribution of Y211 secondary phase particles were uniformly distributed in the Y123 matrix. However, the average particle size of Y211 secondary phase particles were found to increase with the increasing ratios of Er123 content in the liquid phase pellet concluding that the binary system mixture between Y123 and Er123 used in liquid source pellet should be studied more. The improvement of higher $J_c$ or higher density of Y211 secondary phase particles as effective pinning centres can be attained by adjusting the ratio of rare earth elements. A variation in $T_c$ and $J_c$ values have been observed due to the inclusion of Er123 content in liquid phase. A significant $J_c$ value of 54.15 kA/cm$^2$ proved that the samples of Y1 Er0 showed the highest $J_c$ among the others, followed by 49.10 kA/cm$^2$ for Y0.5Er0.5. It was found that the optimum amount of liquid source (Y123:Er123 = 1:0) showed a much better formation of single grain bulk Y123 superconductors due to the sufficient infiltration of the liquid phase in bulk Y123 compared with other samples. Nevertheless, appropriate amounts of Er123 used in the liquid source pellet could be proven through the $J_c$ analysis where the $J_c$ values using the Y0 Er1 had deduced the $J_c$ value of the samples. Based on these results, we can optimize the addition of Er123 in the liquid phase resulting in the improvement of the microstructure and high $J_c$ values of the bulk Y123 single grains.

Author Contributions: Conceptualization, A.N.K., M.M.A.K. and M.M. (Masato Murakami); methodology, A.N.K., S.P.; formal analysis, A.N.K.; investigation, A.N.K., M.M.A.K., M.M. (Muralidhar Miryala) and S.P.; resources, A.N.K., S.P. and M.M. (Muralidhar Miryala); writing—original draft preparation, A.N.K.; writing—review and editing, M.M.A.K., M.M. (Muralidhar Miryala), S.K.C. and H.B.; supervision, A.H.S., A.R. and K.P.L.; project administration, M.M.A.K. and M.M. (Muralidhar Miryala); funding acquisition, M.M.A.K. and M.M. (Masato Murakami). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universiti Putra Malaysia under FRGS grant FRGS/1/2017/STG02/UPM/02/4 and Shibaura Institute of Technology, Japan for research exchange program.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical restrictions.

Acknowledgments: The author would like to thank valuable support and financial assistant by Shibaura Institute of Technology and WAZAN Universiti Putra Malaysia during her research exchange program.

Conflicts of Interest: The authors declare no conflict of interest.

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