Variation of Pinning Force Density Throughout the TSMG Y123 Superconductor with Location

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ABSTRACT
Top seeded melt growth (TSMG) Y123 sample with 35 mm diameter was produced by using Nd123 seed and its superconducting parameters such as transition temperature (Tc), critical current density (Jc) and pinning mechanism were locally examined by taking small specimens which are containing defects in different number, size and distribution from different locations throughout the sample. The Tc of the main sample was determined from the resistivity measurement as 93.4 K. It was observed that the Jc was higher in the region close to the seed, while the Jc decreased towards to the edge or the deeper regions of the sample. Effective pinning mechanisms at different temperatures were determined by plotting the curves of the pinning force density (fp) of the specimens versus reduced magnetic field (h=H/Hmax) and the locational variations of the Jc were examined. It was seen that below the value of h = 0.2, normal point pinning was dominant at 30 and 50 K, while surface pinning was dominant at 77 K, in all specimens. In addition, a transition was observed between two different pinning mechanisms when the Hmax > h > 0.2. The transition was took place between ΔK and normal point pinning at 30 and 50 K while it was seen between ΔK and surface pinning at 77 K.

Keywords: Pinning force density, Critical current density, Local variation of superconductivity, TSMG Y123.

Introduction
Discovery of the high temperature superconductor (HTS) which offer a superconducting transition at the liquid nitrogen temperature have been lead to many studies on the usability of superconductors in both materials science and its engineering applications. It is essential to achieve high superconducting properties such as critical current density (Jc), critical transition temperature (Tc) and field trapping capabilities for the applications [1-3]. On the other hand the magnetic field penetrates in the form of vortices in the HTSs and vortices can move easily when the temperature approaches the Tc or when high fields are applied. At that case, the Jc value is suppressed by thermal fluctuations and the increasing applied magnetic field due to the vortex motion caused by the effect of the Lorentz force [4]. Therefore, the vortices are needed to pin into the crystals to improve the Jc by introducing effective pinning centers in the form of impurities and defects (such as oxygen vacancies, dislocations, aggregation defects, chemical additives and secondary phase particles) [5]. Additionally, the sizes of these defects must be in the nanometer range [6].

The HTSs are generally produced by annealing the samples, which are pressed in the selected composition with appropriate methods and heat treatments. The Y123 single crystals grow basically in a structure with non-superconducting green inclusions called the Y211 phase entrapped and distributed throughout the matrix. The obtained superconducting samples can be single or multi grained. For this reason it is important to determine the optimum conditions for the fabrication of the sample in order to obtain a high current carrying capacity. It is possible to produce large single-grained samples aligned in the c-axis direction with the melting methods and especially top seed melt growth (TSMG) and infiltration growth (IG) methods are promising. Generally, seeds having a higher melting temperature and a similar crystal structure to the main sample are used in these methods [7-12].

On the other hand, since Jc in two-phase alloys is affected by the size and distribution of the second phase particles, the selected region cut from the sample affects the Jc value. Even Jc values can be change throughout the sample. If the small sections selected from multi-grain samples include in grain boundaries, micro cracks or different size and distribution of the pinning centers, it would be also effect the Jc value. So the superconducting properties of the melt growth bulk superconductor generally change with the position in the volume [13, 14]. In this study, the Jc values of the specimens taken from different parts of the TSMG Y123 sample were calculated and the regional variations of the pinning force densities and pinning mechanism were examined at different temperatures.

Material and Method
The powder mixture prepared in Y2O3: BaCO3: CuO = 1:2:3 stoichiometric ratio was calcined in an alumina
crucible at 900°C for 30 hours with an intermediate grinding. The powder mixture was ground again after the calcination process and completely melted at 1450°C in a platinum crucible. The melted powder mixture poured onto a copper plate and cooled quickly by hitting with another copper plate. Thin plates obtained after the melting process was ground again and Y123 starting powder was prepared. 40 g of the starting powder was weighed and pressed into a 35 mm diameter pellet under 11 tons/cm$^2$ pressure. The Nd123 seed was placed in top surface center of the sample pressed into the pellet and the sample was placed on an alumina substrate with Y$_2$O$_3$ powder. The sample was grown by applying the heat treatment given in Figure 1. After all, the grown Y123 sample was annealed for 200 hours at 500°C in oxygen atmosphere.

Resistivity and magnetization measurements were made by taking small specimens from the Y123 sample obtained after crystal growth process. The location of the specimens (a, b, c and d) is schematically given in the Figure 2 and they were labeled as Y-a, Y-b, Y-c and Y-d. Y-a, Y-b and Y-c were used for magnetization measurements and Y-d was used resistivity measurement.

**Results and Discussion**

**Synthesis and Characterization**

X-ray diffraction patterns of the main Y123 sample and small specimens cut from the different portion of the Y123 sample are shown in Figure 3. Main sample Y123 and the Y-a, Y-b and Y-c specimens have predominantly (00ℓ) orientation peaks and small amount of the non-superconducting Y$_2$11 inter phase formed by the heat treatment process was also observed in the structure. This indicates that the sample has almost single-crystal
structure and a preferential orientation in the c-axis
direction. The preferred orientations of HTS result to
higher $J_c$ [19]. In addition, the presence of the he Y211
phases are known to function as pinning centers in Y123
samples produced by melting process. On the other hand,
the specimens Y-b located near the corner and Y-c located
near the bottom of the sample have also extra low
intensity peak of Y211 phase different from the Y-a. This
situation states that non superconducting residual phases
increase with increasing distance from the seed.

**Figure 3.** X-ray diffraction pattern of TSMG Y123
sample and Y-a, Y-b and Y-c specimens cut from the
sample.

**Electrical Investigation**
The resistivity-temperature curve of the Y-d specimen
during heating at 0T magnetic field and the temperature
change curve of $dR/dT$ determined the $T_c$ transition
temperature at which the superconducting state starts
are given in Figure 4. Transition temperature $T_c$ was
determined as 93.4 K from the maximum peak position of
the $dR/dT$ curve and the transition gap ($\Delta T_c$) obtained full
width half maximum of the curve was approximately 1 K.

**Figure 4.** The resistivity-temperature curve of the Y-d
specimen under 0 T magnetic field and the $dR/dT$
curve determined the $T_c$ value.

**Magnetic Investigation**
Figure 5 shows the variation of $J_c$ calculated from the
Bean critical state model against the external magnetic
field for Y-a, Y-b and Y-c specimens at 30, 50 and 77 K. In
the low magnetic field and high temperature region, $J_c$
decreases quickly with the temperature. It is clearly seen
in Figure 5 that $J_c$ changes slightly with the increasing field
at 30 and 50 K. This variation shows that all specimens are
resistant to the external magnetic field and this case
observed in single crystal superconductors. In addition,
there is no explicit difference between all the specimens,
there are only small variations. The specimen Y-a cut from
the near the seed at first layer had clearly higher
$J_c$ rather
than the Y-b cut from far the seed at first layer and Y-c cut
from the second layer. It is well known that the $J_c$
decrease as the distance the seed location on the upper
surface center of the sample increases [14]. The $J_c$
decreases much more when the operated temperature
approaches the $T_c$ because of the flux pinning created by
the linear correlated disorders such as interfaces between
the Y211 particles and Y123 grains [20]. Even so, it is seen
that the $J_c$ value in 77 K does not decrease to zero even
under 4T area. The high $J_c$ value in 77 K shows the quality
of the sample and it’s preferred for technological
applications. Homogeneity of the different phases and
particles into the main matrix can be change with the
position for the melt growth bulk superconductors and so
the superconducting properties can be changed. It was
thought that one of the reasons for this is that the
distribution and the size of the 211 particles that acting as
the pinning center in the structure. Because the applied
magnetic field starts to penetrate into the structure at
constant temperatures with the increasing field, the
superconductivity weakens and $J_c$ decreases due to
mobility of the vortex [21]. The other reason is that the
composition of the melt varies continuously during the
melt process. The local microstructure and the local
properties are defined from the melt composition [13].
In order to study the nature of the pinning mechanism, firstly the volume pinning force were calculated. The volume pinning forces, $F_p$, scaled in a function of the applied magnetic field for all the specimens at 30, 50 and 77 K and were given in Figure 6. In contrast to the $J_c$, $F_p$ always gives a maximum peak at $H_{\text{max}}$ before the $F_p$ reaching zero at the irreversibility field ($H_{\text{irr}}$). Since the $F_p$ value does not drop to zero in the applied field, it is difficult to determine the $H_{\text{irr}}$ value precisely for HTS. Therefore, $H_{\text{max}}$ value was used instead of $H_{\text{irr}}$ [17]. $H_{\text{max}}$ values were determined as 3.74, 4.15 and 4.22 T at 30 K, 4.16, 4.68 and 4.63 T at 50 K and 1.97, 4.16 and 1.08 T at 77 K for the Y-a, Y-b and Y-c, respectively. $F_p(H)$ curves exhibit growing curvatures at low fields and low temperatures and the curve began to fall down after the peak value at high fields as 30 K and 50 K. On the other hand, the shape of the curvatures distorted at 77 K as the transition temperature is approached. Also, Y-a had a much greater pinning force than Y-b and Y-c as expected from the $J_c$ results.

The normalized volume pinning force density $f_p = F_p/F_{p,\text{max}}$ (where $F_{p,\text{max}}$ is the maximum pinning force) are plotted versus the reduced magnetic field $h = H/H_{\text{max}}$ in Figure 7. Equations (2)-(4) are also presented in the Figure 7. Dotted line represents that $\Delta \kappa$ pinning, the dashed line represents normal (Δℓ) point pinning and the solid line represents surface pinning. It is well known that HTSs have large $\kappa$ values and core pinning is dominant rather than magnetic interaction in the superconductors. The core pinning leaves two different sources called $\delta l$ and $\Delta \kappa$ (or $\delta T_c$) pinning [22]. $\delta l$ pinning centers are very effective at low fields and low temperatures and the centers behave like normal conducting particles embedded in the superconducting matrix. On the other hand, $\Delta \kappa$ pinning centers are effective at the intermediate areas and temperatures, as they act as local oxygen deficient regions [23]. As shown in Figure 7, the specimens scaled in agreement below $h = 0.2$ (low field region) with Equation (3), stating that the samples are predominantly affected by the normal point pinning at 30 and 50 K. The major defects in this category are the dislocation and needle...
shape Y211 precipitations. When the magnetic fields increase a value between the $h = 0.2$ and $H_{\text{max}}$, intermediate field region, the results are not scaled on a single theoretical curve. That is the plots are located between $\Delta \kappa$ and normal point pinning. Because $\Delta \kappa$ pinning centers consisting of the large precipitation, it is thought that the specimens have different sizes of the pinning centers in the samples. So, it can be said that large Y211 particles contribute to flux pinning.

The pinning force scaling were analyzed for various specimens cut from the different location of the whole TSMG Y123 which is having different number, size and distribution of defects (Y211 inclusions, dislocation, stacking fault etc.). Observed (00$\ell$) peaks indicate an orientation in c-axis for all the specimens and states that single crystal behavior. The $J_c$ value of the specimen cut from the close region to the seed of the top surface is higher than the specimens taken from the more extreme and lower regions of the sample. This difference in the $J_c$ value change with depending on the number of 211 particles acting as the effective pinning center. The dominant pinning mechanism was normal point pinning (at 30 and 50 K) and surface pinning (at 77 K) below the low field region. The mechanism changed from $\Delta \kappa$ to normal point pinning (at 30 and 50 K) and changed from $\Delta \kappa$ to surface pinning (at 77 K) in $H_{\text{max}} > h > 0.2$ field region. Dominant pinning mechanism changes with increasing the applied field and temperature due to the differences in the pinning centers. Observed transitions between the different pinning mechanisms as the applied field intensity increases originates from the different sizes and shapes of the Y211 particles presented into the structures of the samples. Therefore, the inhomogeneous distribution of different types and shapes of defects into the matrix causes the main superconducting properties such as $J_c$ and flux pinning to vary locally. In this study, the defects that cause the superconducting properties to change are the Y211 particles trapped in the main matrix during the crystal growth process.

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**Conflicts of interest**

The author states that did not have conflict of interests

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