Effect of High Doses Gamma Irradiation on Texturing of Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi-2212) Superconductor

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Abstract. The effect of high doses gamma irradiation on the texture and microstructure of Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi-2212) superconductor is studied in order to observe the sustainability of the material in radiation environment such as gamma radiation. The prepared samples have been irradiated with 100 kGray (kGy) of gamma irradiation and investigated by powder X-ray diffraction (XRD) and scanning electron microscopy (SEM). The Texture Coefficient (TC) for both the non-irradiated and irradiated samples has been calculated. The XRD patterns of the samples showed the Bi-2212 phase as the dominant phase. However, reduction in the intensity of Bi-2212 phase is observed in the gamma irradiated sample. Furthermore the calculated TC percentage of the irradiated sample have lower values when compared to the non-irradiated sample. The SEM micrograph of the irradiated sample showed random grains orientation with poorly connected inter and intra-grain microstructure that are in agreement with the calculated TC percentage.

1. Introduction
For practical applications of high-temperature superconductor materials in power engineering, where thermo-mechanical, electromagnetic and radiation induced stresses are expected to occur, the high-temperature superconductor materials need to possess excellent superconducting properties and higher mechanical strength. Radiation effects including gamma irradiation could cause alteration in the structure of the lattice, and the study of radiation effects have been mainly focused on the attempt to resolve these alterations into a moderate number of lattice defects, and to elucidate the properties of these defects [1]. Moreover, the large difference between the critical current achieved in textured materials and random polycrystalline of high-temperature superconducting materials indicates that the grain boundaries are responsible for reducing critical current density ($J_c$) [2]. This was first demonstrated directly by Chaudhari et al. [3], where the critical current inside a grain and across a grain boundary in yttrium-based superconductor (YBCO) film was studied and they found that the inter-grain critical current to be more than an order of magnitude lower.

Bismuth-based high-temperature superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_4$ (Bi-2212) is one of the most promising materials due to its high critical current density, rapid phase formation and phase stability [4]. Gamma irradiation on Bi-based superconductor has ionization and displacement effects. The oxygen displacements from the CuO$_2$ planes of the crystal structures create defects that induced degradation of transition temperature, $T_C$ [5]. CuO$_2$ planes are important in stabilizing the crystal structure and act as the charge reservoir that is responsible to supply charge carriers to the copper
oxide [6]. This will eventually initiate the formation of Cooper’s pairs network to sustain superconductivity in the material.

The purpose of this research work is to investigate the impact of gamma irradiations on Bi-2212 phase superconductor. Characterization of samples was carried out through x-ray diffraction (XRD) patterns and scanning electron microscopy (SEM). The structural integrity was evaluated based on Texture Coefficient (TC) calculations. The results indicate that high dosage of gamma irradiation deteriorates the mechanical and superconducting properties of Bi-2212 superconductor ceramics.

2. Methodology

Bi-2212 superconductor samples with nominal composition Bi$_2$Sr$_2$CaCu$_2$O$_8$ were prepared via the conventional solid-state method. High purity of Bi$_2$O$_3$, Sr$_2$CO$_3$, CaCO$_3$ and CuO powders were homogenously mixed according to the required stoichiometric molar ratio. The precursor’s oxide powder was thoroughly mixed and grounded in agate mortar. The samples were pelletized and then sintered to achieve Bi-2212 phase. After the initial grounding process, the compound went through annealing process at temperature of 800°C for 12 hours. The blackish powder was grounded for about 30 minutes and pelletized under 7 tons of pressure. The pellets were sintered by partial-melt temperature where the samples were heated at maximum heat of 865°C for 6 minutes, annealed at 840 °C for 48 hours and then furnace-cooled to room temperature. Partial-melt process of Bi-2212 is known to significantly improve the microstructure of Bi-2212 phase superconductor since it produces the required texture of the Bi-2212 superconductor compounds [7].

The samples were then irradiated by gamma ray using JS10000 (IR-219) irradiator with dose level of relatively high 100 kGray (kGy). The irradiation was conducted at the SINAGAMA Plant, Malaysian Nuclear Agency. Structural investigations of non-irradiated and irradiated samples were conducted using a Bruker D8 Advanced X-Ray Diffractometer (XRD) to confirm their phase formation. Microstructure investigation was carried out using a Hitachi S3400N Scanning Electron Microscope (SEM).

The texture coefficient (TC) was calculated by using the equation:

$$TC_{(hkl)} = \frac{100 \times I_{hkl}}{\sum_{i=0}^{n} I_{hkl}}$$

where TC$_{(hkl)}$ = texture coefficient, and $I_{hkl}$ = intensity of the Miller index (hkl) reflection [8]. Significant (hkl) planes (008) and (0010) were used to determine TC since it directly contributes to the structural integrity of the Bi-2212 phase samples.

3. Results and discussion

The structure of samples were investigated by x-ray diffraction patterns and the non-irradiated sample drawn sharper and well-defined (008) and (0010) peaks. Figure 1 shows the full XRD patterns generated for both the non-irradiated and irradiated Bi-2212 superconductor samples. Small amount of impurities may resided within the Bi-2212 phase superconducting grains and appeared as unrecognized peaks The position of diffraction peaks of Bi-2212 phase in the patterns is identical for both non-irradiated and irradiated samples, which suggests that no change in lattice parameters occurred within the resolution of the XRD. Nevertheless the intensities are reduced in the gamma irradiated sample that was subjected to 100 kGray dose. This indicates that gamma irradiation reduced the volume fraction of Bi-2212 superconducting phase.
Figure 1. XRD patterns of Bi-2212 phase superconductor for both the non-irradiated and gamma irradiated samples.

The SEM micrographs in figure 2(a) and figure 2(b) show the microstructure of Bi-2212 phase of both the non-irradiated and gamma irradiated samples. The micrograph of gamma irradiated sample in figure 2(b) shows the appearance of misalignments along the c-axis with less dense microstructure. The microstructure is highly porous when compared to that of the non-irradiated sample. The high porosity microstructure of the irradiated samples resulted in weaker interface bonding between the Bi-2212 superconducting grains. In addition the porous microstructure formed between adjacent grains resulted in grain conductivity losses. As such, both the mechanical and superconducting properties of the gamma irradiated sample are significantly reduced [9].

Figure 2. SEM micrographs of (a) non-irradiated sample, and (b) gamma irradiated sample.
Gamma irradiation on Bi-based superconductor prompted ionization and caused displacements on the position of positron-electron pairs and holes in the materials [10]. Higher intensity of gamma irradiation caused ionization that is instantaneous and violent in nature and consequently will deter the production of new superconductive pairs. This will ultimately lead to degradation of the superconducting behavior of the materials. Nevertheless if the electrons and holes interact with phonon, it will result in the formation of new superconductive carriers with larger energy gap and hence producing higher zero transition temperature, $T_c$ [11]. In our gamma irradiated sample, the high intensity irradiation is likely disrupt the production of new superconductive pairs and degrades its superconducting properties.

Table 1 shows the Bi-2212 phase TC values of $(hkl) = (008)$ and $(0010)$, for both the non-irradiated and gamma irradiated samples. A higher value of TC as demonstrated by the non-irradiated sample indicates that the microstructure has a higher degree of orientation along the $c$-axis. TC values also provide indication on the existence of kinetic and thermodynamic processes that are involved in the texture development of the microstructure. Increasing in TC value shows better state of mechanical strength in ceramics materials such as superconductors [8]. In their study on relationship between TC and fracture limit of MgO added Bi-2212 superconductor, Hamid et al. [12] showed that sample with higher TC exhibited better mechanical strength, and the strength deteriorated with decreasing TC value.

| Miller index (hkl) | Texture Coefficient, TC (%) |
|-------------------|-----------------------------|
|                   | Non-irradiated | Gamma irradiated |
| 008               | 18.93          | 14.00            |
| 0010              | 18.11          | 17.29            |

From the results of XRD, SEM and TC, the ionizing gamma particles have caused degrading effects on the structural integrity of the intra-grains and inter-grains in the microstructure of Bi-2212 phase superconductor. In addition, high dose of gamma irradiation caused severe damage on the bonds in the Cu-O planes of the superconducting region and decreases the volume fraction of Bi-2212 phase [9,13].

4. Conclusion

In this investigation, part of the samples were subjected to gamma irradiation with dosage of 100 kGray. The XRD patterns of irradiated sample exhibited reduction in intensities of the Bi-2212 phase peaks. The SEM microstructure of the irradiated sample showed randomly textured morphology with higher porosity. Furthermore, the TC percentage of the irradiated sample showed lesser values when compared to the non-irradiated sample. Based on the morphology and microstructure of the samples, gamma irradiation reduced both the mechanical and superconducting properties of the Bi-2212 superconductor ceramics. Thus the sustainability of Bi-2212 superconductor in high radiation environment is suspect, and its applications as electrical and electromagnetic devices in such environment need to be scrutinized meticulously.

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