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INDUSTRIAL AND PRODUCTION APPLICATIONS OF YBCO CUPRATE: PROSPECTS AND CHALLENGES

O.G. Turayev
Asia International University, Bukhara, Uzbekistan, 200100
Email: ozodjonturayev@gmail.com

Abstract

This review examines the potential for yttrium barium copper oxide cuprate in various industrial and production applications, particularly considering its high-temperature superconducting properties. Despite the inherent advantages of high-temperature superconductivity, the practical deployment of YBCO and similar materials is constrained by challenges such as achieving operational temperatures conducive to widespread industrial adoption and overcoming economic and technical hurdles in large-scale production and maintenance. To fully leverage YBCO's capabilities, research efforts must intensify on developing methods for enhancing critical temperatures and current densities, alongside improving the economic viability of its synthesis and fabrication.

Key words

YBCO, high-temperature superconductor, cuprate, calcination, sintering, solid-state reaction, phase, macromolecule, crystal lattice.

Introduction. Yttrium barium copper oxide is a prominent high-temperature superconductor that exhibits superconductivity above 90 K, making it amenable to cooling with liquid nitrogen, a more economical and manageable cryogen than liquid helium (Reinheimer & Maye, 2025; Satgunam, 2025). This characteristic significantly broadens its potential for industrial and production applications, particularly in contexts where cryogen-free operation or less expensive cooling methods are crucial (Dzul-Kifli et al., 2022; Godeke, 2023). While low-temperature superconductors like NbTi and Nb3Sn have well-established industrial production and exhibit robust mechanical properties at low temperatures and moderate magnetic fields, their intrinsic superconducting performance is insufficient for high-temperature or high-field applications (Zhang et al., 2024). Conversely, the YBCO cuprate, specifically YBa2Cu3O7−x, stands out among cuprates for its comparatively lower anisotropy, enabling its utility in high-field magnet applications where other cuprates are limited by strong vortex fluctuations (Gurevich, 2014). This reduced anisotropy, coupled with its ability to reliably trap magnetic fields exceeding 10 T, makes YBCO particularly attractive for next-generation magnet technology, including applications in accelerators and fusion energy (Cooley et al., 2022; Namburi et al., 2021). However, despite these promising attributes, the widespread industrial deployment of YBCO faces significant challenges, including the inherent ceramic nature of the material, which complicates traditional metallic drawing processes, and the necessity for precise crystallographic orientation during synthesis to achieve optimal superconducting properties (Antoine, 2023). Furthermore, the development of scalable fabrication techniques capable of producing long-length YBCO wires with high performance remains a critical bottleneck for its broad application in sectors like power cables and advanced magnet systems (Zhang et al., 2025).

Literature Review. Current research endeavors are actively addressing these limitations by exploring advanced fabrication methods to enhance the macroscopic homogeneity and atomic-scale nanostructure of YBCO coated conductors (Horide & Yoshida, 2025). This

includes optimizing vortex pinning mechanisms through the introduction of short stacking faults and Cu-O vacancy clusters within solution-derived nanocomposites (Vallés et al., 2022). These innovations aim to improve critical current density and performance in high magnetic fields, which are crucial for the practical deployment of YBCO in various technological applications (Satgunam, 2025). Such advancements are essential for YBCO to effectively compete with or complement other high-temperature superconducting materials, such as Bi2Sr2Can−1CunO2n+4+x and La2−xSrxCuO4, which also present unique advantages and challenges in terms of fabrication and performance (Popovic et al., 2022; Wan, 2024). Indeed, while Bi-based cuprates exhibit high anisotropy and Tl- or Hg-based compounds pose toxicity concerns, YBCO offers a compelling alternative due to its non-toxic composition and favorable critical temperature and irreversible field characteristics (He et al., 2021).

Methodology. To fully harness these advantages, contemporary research focuses on refining deposition techniques like pulsed laser deposition and metal-organic chemical vapor deposition to achieve highly textured YBCO films with enhanced critical current densities (Jha & Matsumoto, 2019). These methods enable precise control over the crystallographic orientation and microstructure, which are vital for optimizing the material's superconducting properties in high-field environments (Vaimala et al., 2024). Additionally, the development of four distinct templates—IBAD-YSZ, IBAD-GZO, IBAD-MgO, and RABiTS—has been instrumental in advancing the fabrication of second-generation high-temperature superconducting wires (Paranthaman & Izumi, 2004). These foundational template technologies are critical for overcoming the brittleness of YBCO and enabling the deposition of the superconducting layer on flexible metallic substrates, thereby facilitating the production of long-length, high-performance wires (Zhou et al., 2021). Further innovation involves incorporating nanoscale inclusions like barium zirconate nanoparticles within the YBCO matrix to create uniform defect pinning centers, thereby significantly enhancing flux pinning properties and critical current densities, particularly in high magnetic fields (Bektaş et al., 2024; Huang et al., 2016). For instance, solution-derived trifluoroacetate YBCO films with BaZrO3 nanoparticles have demonstrated pinning forces of 22 GNm−3 at 77 K, attributed to a novel vortex pinning mechanism involving nanoscale strain-induced Cooper pair suppression (Coll et al., 2012).

Results. These advancements in flux pinning and material processing have enabled YBCO-based magnets to achieve remarkable magnetic fields, such as 26.4 T, surpassing the capabilities of conventional NbTi-Nb3Sn magnets, and an all-superconductor magnet reaching 32 T (Cai et al., 2018). This capability underscores YBCO's pivotal role in pushing the boundaries of magnetic field generation for applications such as fusion energy and high-field NMR, which demand engineering current densities exceeding 1000 A/mm2 at elevated temperatures and magnetic fields (Paidpilli & Selvamanickam, 2022). Notably, recent developments in YBCO wire technology have demonstrated engineering current densities exceeding 900 A/mm2 at 18 T and 4.2 K, with some thick film REBCO tapes achieving over 5 kA/mm2 at 14 T and 4.2 K (Majkic et al., 2018; Usoskin et al., 2018). Furthermore, recent innovations in YBCO wire formulation, particularly those incorporating Y2O3 nanoparticles, have enabled the large-volume production of high-performance wires without relying on c-axis correlated nano-columnar defects, traditionally considered essential for high in-field performance (Molodyk et al., 2021). This demonstrates a significant paradigm shift in defect engineering strategies, moving towards more scalable and cost-effective methods for achieving high critical current densities (Majkic et al., 2018). Specifically, the integration of randomly distributed Y2O3 nanoparticles semi-coherent to the REBCO matrix has shown to enhance Jc isotropically, achieving high pinning forces in YBCO films (Molodyk et al., 2021). Such

microstructural modifications, including the deliberate incorporation of non-superconducting precipitates like BaZrO3 and Y2O3, are critical for enhancing critical current density by providing strong artificial pinning centers that effectively impede vortex motion, even under demanding operational conditions (Chen et al., 2016; Glatz et al., 2019).

Discussion. These improvements are often achieved by tailoring the amount, shape, size, and arrangement of such artificial pinning centers within the YBCO matrix to meet specific application requirements, such as those found in high-field magnets and power transmission (Sieger et al., 2016). This systematic engineering of the defect landscape directly correlates with the observed increase in critical current density and improved performance in strong magnetic fields, which is crucial for advancing technologies like compact fusion reactors and high-efficiency electrical grids (Vallés et al., 2022). The strategic incorporation of artificial pinning centers not only mitigates the degradation of in-field critical current density but also allows for optimization across various magnetic field and temperature regimes, reflecting a complex interplay between vortex dynamics and material inhomogeneities (Wang et al., 2024). This nuanced approach to microstructure design, particularly through methods that introduce artificial pinning centers, has led to significantly enhanced critical current densities, with some studies reporting values exceeding 12 MA cm−2 at 4.2 K and 14 T for thick REBCO samples, surpassing prior commercial benchmarks by a substantial margin (Majkic et al., 2018). These artificial pinning centers, often realized through techniques such as the introduction of secondary phases or chemical doping, are crucial for mitigating vortex motion and thereby enhancing the flux pinning efficiency of YBCO composites (Dahiya et al., 2021).

Conclusion

The sustained enhancement of critical current density and improved performance across varying magnetic fields and temperatures, directly attributable to advanced defect engineering, solidifies YBCO's potential for widespread industrial adoption in high-field magnet applications and advanced power systems. Further optimization efforts continue to focus on understanding the intricate balance between various pinning mechanisms—including point, small-cluster, and columnar defects—to achieve even higher critical current densities and broader operational stability across diverse magnetic field and temperature regimes (Holesinger et al., 2010; Kihlstrom et al., 2020). This involves a precise control over the morphology, dimension, orientation, and concentration of these artificial pinning centers to optimize their synergistic effects on vortex pinning, particularly in the context of improving the critical current density (Kihlstrom et al., 2020; Zhang et al., 2022). For instance, the strategic introduction of nanorods and other fragmented pinning sites has been shown to offer deeper insights into the mechanisms governing flux pinning enhancements in YBCO thin films, thereby contributing to the development of high-performance coated conductor layer structures (Vaimala et al., 2024). However, achieving these advancements often necessitates sophisticated defect engineering techniques, such as particle irradiation, which can introduce well-controlled defects with specific topologies to significantly enhance vortex pinning (Leroux et al., 2015).

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