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Perspective

Commercial compact fusion triggered REBCO tape industry: Pulsed laser deposition technology opportunities and challenges

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ABSTRACT

The rapid rise of commercial compact fusion devices has triggered fast-growing demand for high-temperature superconducting tapes, creating a major opportunity for the high-temperature superconducting (HTS) tape industry. Pulsed laser deposition (PLD) has been extensively applied for fabrication of heteroepitaxial HTS wires or tapes based on REBCO-type superconductor, also referred to as, coated conductors (CCs). A combination of multi-plume, multi-turn deposition technique and use of high-power excimer lasers has enabled and accelerated the industrialization of REBCO coated conductors. Currently, the annual production of top-tier PLD-based, HTS-wire manufacturers exceeds 3,000 km-12 mm, contributing to over half of the total global HTS wire production. PLD-REBCO tapes have demonstrated excellent in-field performance (I_c > 200 A-4 mm @20K, 20T, B//c) and competitive pricing (~$20/m). PLD technology continues to evolve, demonstrating strong competitive advantages. However, challenges remain in further cost reduction, process stability, and increasing efficiency of raw material utilization. AI-based data mining and tackling emerging fundamental issues are seen as potential solutions to further improve stability and performance.

1. Background

Among practical superconductor candidates, $REBa_2Cu_3O_{7-\delta}$ (REBCO, RE = rare earth or Y) CCs have superior physical and mechanical properties for power and magnet applications. REBCO CCs are also considered as the most promising for ultrahigh-field magnets (>20 T), in particular, for compact fusion reactors. Compared to low-temperature superconductors, REBCO CCs permit generation of higher magnetic fields well above 15 T, thus significantly reducing the reactor size and making commercialization via compact fusion reactors possible. YBCO was discovered in 1987, and the first attempts to use pulsed laser deposition (PLD) for epitaxial growth of REBCO film on single crystal substrates followed within a year. Taking advantages of rapid progress of industrial excimer lasers with maximum power reaching 1,200 W (308 nm, 2 J/pulse, 600 Hz), engineering of the PLD for REBCO CCs has greatly accelerated. The fundamental process of PLD is well understood, i.e., the high energy density laser ablates the target surface, generating plasma (so called "plume"). The plume expands directionally, depositing on the substrate to form a film. Compared with other deposition techniques (i.e., Metal-Organic Chemical Vapor Deposition or Chemical Solution Deposition), the key advantage of PLD-REBCO is to modulate the microstructure from bottom-up, and to grow multi-component films with the same composition as the target. Such proportional stoichiometry transfer is crucial for REBCO compounds with multiple cations, especially in REBCO films with intentionally introduced artificial pinning centers (APCs). Although all the physical mechanisms involved in PLD are not yet fully clarified, the technology has significantly evolved and has made great strides in scaling REBCO CCs from the laboratory-scale to industrial-scale.

PLD REBCO films have been extensively studied in laboratory-based, static deposition processes. These studies have uncovered key fundamental issues such as weak-link behavior, fundamentals of heteroepitaxial growth, maintaining good epitaxy in thicker films, and incorporation of nanoscale APC's [1]. To deposit large-area films, scientists at the International Superconductivity Technology Center in Japan proposed a multi-plume and multi-turn PLD (MPMT-PLD) technique for lab-scale fabrication of REBCO tapes in a reel-to-reel manner. Its success hinges on, (i) the use of a precise raster scanning system enables rapid sequential generation of multiple plumes across a large-size target within an extremely short time, and (ii) a helical traveling of tape that passes different positions within the deposition zone. This configuration increases the deposition time and also suppresses the potential nonuniformities in the deposited films as a function of length.

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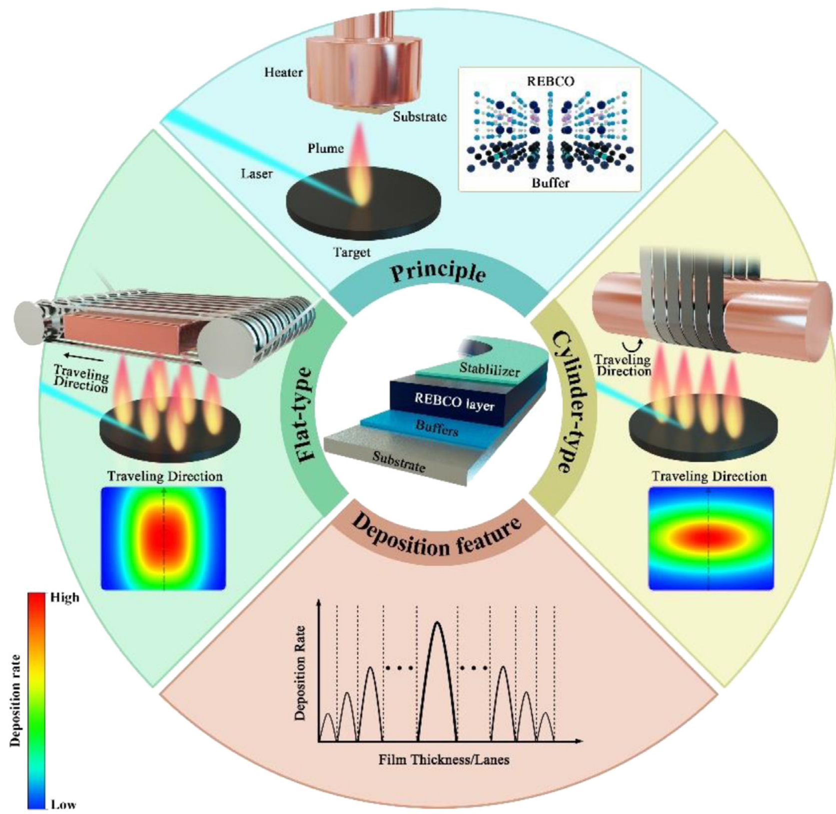

Fig. 1. Schematic of conventional lab-scale, static PLD facility and epitaxial growth of REBCO (upper panel), schematics of flat-plate and cylinder-type PLD and corresponding growth rate distribution over the deposition zone (left panel and right panel, respectively), the common deposition feature of MPMT-PLD process (below panel), and the typical configuration of REBCO CCs is shown in the center panel.

2. State-of-the-art of industrial PLD-REBCO

Triggered by huge and urgent demands of compact fusion reactors (i.e., approximately 10,000 km-4 mm wide tapes for CFS SPARC device), commercialization of REBCO CCs has advanced rapidly. Presently, there are about 15 HTS wire vendors worldwide, with a total annual capacity of over 5000 km of 12 mm-wide tape. Four of the top-tier companies are based on the PLD manufacturing route. These include Faraday Factory Japan LLC (FFJ, previous SuperOx, Japan), Shanghai Superconductors (SST, China), Fujikura Ltd (Japan) and S-innovation (Russia). These four manufacturers, alone contribute over half of the overall world-wide production. In addition, new companies, i.e., High Temperature Superconductor Inc. (HTSI, U.S.), SuperMag Technology (China), Suprema (Italy) and traditional vendors like SuNAM (Republic of Korea) and SuperPower Inc. (U.S.), have chosen or are also considering the PLD route.

To realize mass production, each company has its own technology preferences. Primary differences between companies lie in the heating and drive systems of the vacuum chamber, mainly divided into flat-plate and cylinder types (as shown in Fig. 1). Fig. 1 illustrates the projected deposition zones of the two types. From the growth rate distribution, it is evident that long tapes inevitably experience different temperature profiles and growth-rate at different points in the deposition zone. Fortunately, both geometries have demonstrated the feasibility of fabricating long tapes with high-uniformity. For the flat-plate type, FFJ has made numerous technical upgrades relying on their long-time experience with lab-scaled PLD facilities. Recently, they have adopted a novel yttrium-rich YBCO formulation, and successfully demonstrated very-high and reproducible J_e in large volume production (over 1000 A/mm^2 at 20 K, 20 T) [2]. Similar facilities are also being employed by SuperMag and HTSI. For the cylinder type, Fujikura Ltd has developed a hot-wall heating system, allowing near isothermal deposition conditions. Kilometer-class long tapes with very high I_c uniformity has been demonstrated by Fujikura [3]. SST has also developed a radiation assisted conductive heating system for enlarging the deposition zone at high tape traveling speeds [4]. In general, PLD-REBCO tapes have already demonstrated excellent in-field performance and competitive pricing, i.e., I_c > 200 A-4 mm @20K, 20T, B//c, at prices of $15 – 30/meter. However, it is difficult to make direct comparisons of manufacturing technologies in terms of cost and yield, due to the limited public information.

3. Opportunities

The rapid manufacturing progress of industrial-scale HTS tapes using PLD has much surpassed expectations. Extensive use of PLD-REBCO in the large-scale demonstration projects allows customers and HTS wire vendors to accumulate large amounts of data and conduct iterations and drive continuous improvement of tape performance. This improves industrial-scale HTS wire performance, homogeneity and yield, and significantly enhances industry confidence. Commercial compact nuclear fusion is a niche application for REBCO, and the commercial availability of very large-volumes of cost-effective and high-performance REBCO is essential. From an industrial perspective, further scalability and improved reproducibility is needed. Unlike MOCVD and CSD, PLD does not need to modulate complex chemical reactions, simplifying the process control and offering the unique technology advantages. Financially, it also makes easy decision for facility replication and attracts startups to adopt this technology, accelerating positive feedback of demand and technical advancement.

4. Challenges

To further enable commercial applications, the cost of REBCO CCs has to be substantially reduced further to $ 50/ kA m in the near-term, with a target price of $ 10–20/kA m [5]. A major scale-up of production is needed. FFJ and SST have demonstrated the feasibility of scale-up through the replication and expansion of their existing production lines. Yet, there are still several other technical challenges. First, from the consumption perspective, high-power excimer lasers and raw materials (i.e., large-size REBCO target) deserve proper attention and further optimization since both account for the main cost and directly affect the tape performance. It is also crucial to further improve laser efficiency, i.e., I_c generated by per unit of energy (A/Joule). Low utilization rate of REBCO targets (<50%) and a long delivery for implementing new recipes also adds additional challenges to mass-production R&D. Furthermore, user-friendly maintenance of key facility components, e.g., optical system (windows, mirrors, etc.) and heating plate/cylinder, may also need to be re-designed. Secondly, how the optimal deposition process window can be widened remains an open scientific question. During continuous deposition (sometimes exceeding 10 h), process parameter fluctuations (e.g., temperature, PO_2, target-substrate distance) should be within the optimal deposition process window so as to not affect performance. Achieving high consistency in batch-to-batch performance is vital. Operation stability of facilities/components is needed over many years. In addition, development of effective on-line monitoring, feedback and control is needed. For mass-production oriented R&D, it is believed that each vendor has accumulated a large amount of production-data, including process parameter fluctuations, microstructure, superconductivity, etc. Although some patterns are highly dependent on composition-process-equipment and may not be universal, AI-based data mining and correlation establishment can offer inspiration for further improving stability. Moreover, the emerging fundamental issues, e.g., phase evolution at high-rate deposition, effect of REBCO stoichiometry and flux pinning characteristics related to mixed nano-microstructure also needs further investigation via collaborations between academia and commercial manufacturing facilities and vendors.

In summary, PLD has demonstrated strong potential for the large-scale production of high-performance REBCO coated conductors, particularly in response to emerging demands from compact fusion applications. Further advancements in process stability, cost reduction, and data-driven optimization will be essential for broad applications. Collaborative efforts between industry and academia will play a key role in addressing these remaining challenges.

CRediT authorship contribution statement

Yue Zhao: Writing – original draft, Validation, Investigation, Funding acquisition, Conceptualization. **Yue Wu:** Writing – review & editing, Visualization, Investigation, Funding acquisition. **Amit Goyal:** Writing – review & editing, Funding acquisition. **Hannu Huhtinen:** Writing – review & editing, Funding acquisition. **Petriina Paturi:** Writing – review & editing. **Yuji Tsuchiya:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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