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Stress, strain and mechanical analyses of REBCO superconducting tapes using finite element method.

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Abstract—High-temperature superconducting (HTS) tapes, represented by Rare Earth-Barium-Copper-Oxide (REBCO) conductors, are promising for high energy and high field superconducting applications. However, practical applications subject HTS conductors to various stresses and strains, including residual stresses due to thermal mismatch and tensile stresses from Lorentz forces. This can result in reduced load-carrying capacity and the risk of electromechanical properties degradation. Investigating the mechanical behavior of REBCO tapes under different tension loads is necessary to properly understand the stress-strain distribution inside the layered structure. However, assessing the mechanical properties of each HTS component presents unique challenges due to their brittle nature, sensitivity to environmental conditions, and complex layered structure. This study demonstrates how Finite Element Method (FEM) simulations, combined with experimental tests, can effectively describe the mechanical behavior of each component in a laminated superconductor tape.
Keywords—HTS, FEM, COMSOL, mechanical properties

I. INTRODUCTION

High temperature superconducting Rare Earth-Barium-Copper-Oxide (REBCO) conductors hold significant promise for a range of energy and high magnetic field applications like power cables, generators, fusion, accelerators, medical devices. This is primarily due to their high critical temperature and critical current density even in the presence of a high background magnetic field [1]. REBCO coated conductors (CC) are composed of layered materials, featuring multiple laminated high-aspect-ratio (HAR) layers with distinct material properties [2]. This layered structure includes a substrate, a stack of buffer layers, the REBCO layer, and stabilizing layer(s). Notably, in CC, the substrate and stabilizer(s) are substantially thicker than other functional layers, significantly influencing the mechanical and electromechanical properties of the superconducting wire under tension. In addition, a CC is composed of very different types of materials including soft metals, brittle ceramics and hard metal alloys. Serving as the backbone of the tape, the substrate acts as the mechanical foundation for the other layers. Different manufacturers employ various substrate materials such as Hastelloy and stainless steels, each with unique mechanical properties. Stabilizing layers, typically a layer of copper on top of a thin silver layer, are applied using techniques like electroplating for the first and sputtering for the second. These layers not only offer protection during the transition from superconducting to normal state but also reinforce the mechanical integrity of the superconductor tape. While the mechanical behavior of commonly used substrate and stabilizing layer materials is well-understood, analyzing the mechanical properties of thinner layers like the REBCO layer and stacked buffer layers poses a more complex challenge. These layers, characterized by extreme HAR and brittle behavior, are challenging to isolate and study. Their mechanical behavior within the complete CC structure is hindered by their reduced thickness compared to the primary layers. This study illustrates how Finite Element Method (FEM) simulations accurately represent stress-strain distribution in each individual layer, starting from experimental analysis of coated conductor superconducting tapes under uniaxial tension.

II. EXPERIMENTAL SETUP

The REBCO tape considered were made by Fujikura. The tape has a width of 12 mm while the layered structure is divided in a Hastelloy substrate of 50 µm thickness, a buffer layer of 0.2 µm thickness, a REBCO layer of 2 µm thickness and finally a copper layer of 20 µm surrounding the whole tape. Typically, a silver protective layer of 2 µm thickness is placed at the interface between REBCO and copper, in this work the protective layer has been omitted due to its negligible mechanical influence [3].

Tensile tests are performed at room temperature using a servo-hydraulic testing machine, an end of the tape is locked into a fixed clamp while the other end is locked into a clamp free to move vertically. A load cell constantly records the applied load, while the strain is studied using Digital Image Correlation (DIC). DIC is an optical method that employs image registration and tracking techniques to analyze and compare the variation of the position of different points on the sample surface and from those derive the displacement field during the deformations [4]. A scheme of the experimental setup is shown in Fig. 1.

III. NUMERICAL MODEL

To evaluate the stress-strain distribution generated in each one of the tape component FEM simulation software COMSOL Multiphysics was employed.

The main challenge related to simulate the superconductor layered structure is the great difference in the thickness of each component. The typical meshing considered for simulations, the tetrahedral meshing, would require a high density of domain elements at the interface between REBCO/buffer layer and other components to properly compute the interaction of finer elements with the thicker one. This method would lead in general to more complex and more expensive simulations in terms of computational time. Therefore, we considered a mapped mesh of squared elements that does not require the clustering of domain elements in specific areas. This process allows to better control the refinement of the mesh, leading to more accurate results in less computational time.

The first set of simulations considered compare the stress-strain distribution generated in two tapes, the first one composed only of substrate and the copper stabilizer while in the second one also the REBCO and buffer layers were considered.

The second set of simulations instead compares the mechanical response of a full tape and a tape where the buffer layers are absent.

The geometry considered for both simulations have a width of 6 mm and a length of 2 mm. Due to the spatial symmetry of the structure and boundary conditions, the bottom edge and the axis of the tape are represented as symmetry plane, allowing to simulate only a quarter of the interested region.

IV. RESULTS

As is possible to observe in Fig.2, the comparison between the first set of simulations confirms that the REBCO layer does not affect the stress-strain distribution generated in the main layers of the tape. This result allows to further simplify the numerical model considered. It is indeed possible to neglect the effect of the REBCO layer when interested in the overall mechanical properties of the whole tape, while it is possible to employ a unidirectional coupling by applying the strain distribution calculated in the substrate and the stabilizer to the REBCO layer when interested in a more locally focused mechanical behavior.

Similar results are obtained from the second set of simulations. In both case the REBCO layer shows the same stress-strain distribution, meaning that the buffer effect on the superconducting layer is negligible and they can be computed as a single layer with uniform mechanical properties, allowing for a further simplification of the numerical model.

V. CONCLUSIONS

In this work we employed finite element simulations to represent the mechanical response generated in the layered structure of a superconductor tape under uniaxial tension.

We compared the stress-strain distribution inside each component considering different layers combinations to understand their relative influence. The preliminary results show that the main structural component of the tape, the substrate and the stabilizer are unaffected by the thinnest layers, and in a similar way the buffer layer has a negligible impact on the REBCO layer. Both results allow to decrease the complexity of the simulations considered, decreasing the general computational cost while maintaining accurate results.

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Topic

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