Flexibility and contact resistance of CORC® cables and wires: Experiments and modeling

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***Abstract*— HTS Conductor on Round Core (CORC®) cabling concept allows cables to be manufactured with round formers as small as two to five millimeters in diameter. CORC® consist of several layers of helical tapes wound around a central metallic core in an alternating fashion. Various parameters like winding angle, tape width, substrate thickness, number of layers, and lubrication, significantly influence the CORC® cables and wires' performance. A set of bending experiments is conducted on single-layer CORC® cables and wires with different cabling parameters to check the flexibility and determine the critical bending radius. The current conduction through the CORC®'s core is also studied by insulating the core. Results are analyzed and compared with the help of a detailed finite element (FE) model. The FE modeling consists of three steps – tape production process, tape winding, and bending of CORC® cables or wires. The local potential distributions on a scale smaller than the width of the superconductor tape are tested experimentally. An electrical network model is created to study the effects of degraded spots in the tape and visualize the strained tape's current flow. The experiment consists of measurements at local spots on the REBCO tape with a specially designed multipoint probe, which are then compared with the full length CORC® performance. The inter-tape contact resistance of simplified CORC® wires is also investigated at 77 K. The influence of lubrication, multiple cooldown cycles, and the bending diameter were investigated. In addition, an electrical resistance network model is also build to predict the contact resistance distribution along the wire when the bending load is applied.**

Keywords—CORC®, Finite Element Modeling, Contact resistance, Electrical network model, REBCO tape, HTS cables

I. INTRODUCTION

The work on CORC® cable and wires is categorized into three sections.

A. *Bending of CORC® cables and wires*

A detailed finite element model is created in ABAQUS software and validated with multilayer CORC® cable experiments. The CORC® FE model consists of the production process, tape winding, and cable bending. The tape's production process involves the MOCVD process in which a thin REBCO layer is deposited on a Hastelloy substrate at 1020 K, then cooled to 350 K for depositing copper layers on top and bottom of the tape. After that, the tape is cooled to room temperature. The tape is modeled with multilayered shell elements due to the thin layer nature. The tape layers experience thermal strain due to the difference in coefficient of thermal expansion between matrix materials. The final shape of the tape is spherical. The tape is then wound over a cylindrical core, usually copper or steel. Then the whole CORC® cable or wire is cooled down to liquid nitrogen temperature. At 77 K, the cable/wire is bent to 30 mm diameter in steps. The strain in the REBCO layer is monitored during the bending process. The permanent damage or the irreversibility point is reached when the intrinsic strain in the REBCO layer exceeds locally a critical strain value of 0.45%, significantly decreasing the performance of the CORC® cable. Locally and globally, it will affect the REBCO tape's performance, i.e., the critical current I_c and n-value will drop drastically. Figure 1 shows the strain profile in the REBCO layer on a bent CORC® cable.

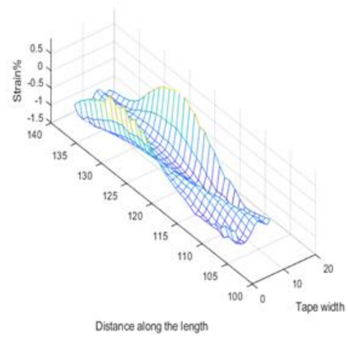

Fig 1: Strain on one twist pitch length of the REBCO layer after bending.

An open cryostat is used to create a liquid nitrogen bath at 77 K. A bent CORC® cable is then inserted into the cryostat with a series of voltage taps placed on the helical tape of the CORC® cable. Bending formers of different diameters ranging from 400 to 30 mm are used to bend the cable to a suitable radius manually. At first, a straight cable is measured for the critical current and then warmed up to room temperature. The cable is then bent to 400 mm diameter, and the cycle is repeated in sequence up to 30 mm diameter. The voltage readings are recorded for each bending diameter. Different cables are selected to study the influence of core diameter, winding angle, winding tension, tape width, Hastelloy thickness, and lubrication. Due to the large fraction of core in cable and single layer nature of tested cable, the current conduction through the copper core can influence the damage analysis of the tape. A series of CORC® wires with insulated core is also studied experimentally and compared with modeling results.

The experimental results for some CORC® wires and cables showed some irregularity in critical current degradation with the decrease in bending curvature. The irregularities disappeared for cables with insulated former, pointing to the observation that the current conduction through the copper cope influences the result of these typical single layer CORC® cables, especially at small bending diameters. The finite element model showed good agreement with experimental results, and thus the FE model can qualitatively predict the flexibility of CORC® cable/wire.

B. *Local potential distribution in REBCO tapes*

For a CORC® cable in bending configuration, there are areas on the tape where the critical strain is exceeded. These zones will permanently degrade the CORC® cable performance. It should be expected that it matters where the voltage taps are placed within one revolution and the tape's width. The mechanical strain-data from the Abaqus® model is translated to the critical current data of the REBCO tape using Ekin's strain formula. Since Abaqus is modeling software for the mechanical domain, the electrical domain modeling is done in a discrete simulation program in Multisim® using SPICE commands. This model showed potential distribution variation in both longitudinal and transverse directions in cases where the critical strain of the REBCO tape is exceeded.

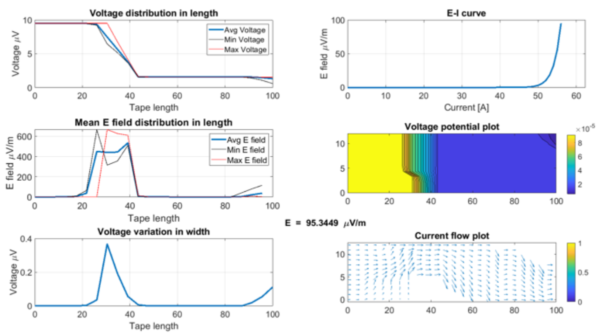

Fig 2: Electrical behavior of a REBCO tape on a bent CORC® cable – 50 mm bend diameter.

To validate the electrical network model, an experimental setup is designed to scan the variation in voltage distribution. Spring probes are assembled as voltage taps in a holder to place accurately on the tape of a bent CORC® cable. The entire assembly was manufactured using a composite material Nylon PA 2200. The manufacturing is done with a 3D-printer; the material showed no significant shrinkage in LN2. Figure 3 shows the assembled system after manufacturing.

The network model was experimentally verified for the variation in the longitudinal direction of the REBCO tape in CORC® configuration. Consequently, it has been proven that the placement of voltage taps along the longitudinal direction of a CORC® cable in bending configuration matters for bending diameters where the critical strain of the REBCO tape is exceeded. An increase of approximately 10% in I_c can be measured if the voltage taps are placed approximately 50 cm away from the local damage. The transverse direction experiments remained inconclusive since only noise was measured. This is because of the limitation of the used nano-voltmeters, which introduce large errors in the transverse electric field due to very small values of measured voltage from voltage taps placed at small distances.

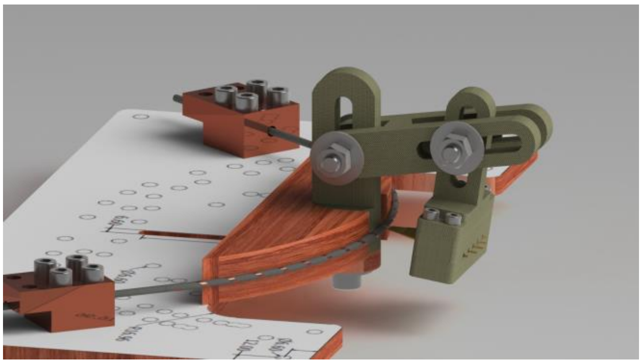

Fig 3: A total overview of the multipoint voltage tap probe mounted on the CORC® cable bending setup.

C. *Contact resistance*

Two different experiments were carried out on four CORC® samples with different types of lubrication. The first experiment's goal is to measure the contact resistance of the four samples and find the influence of multiple cooldown cycles on the contact resistance. The second experiment's goal is to measure the influence of the bending load on the contact resistance. An electrical network model is made to predict the local contact resistance along the sample's length.

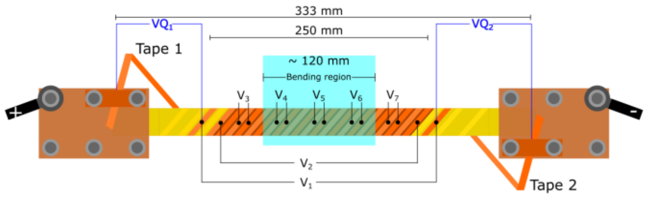

Figure 4: Voltage tap placement on the samples for the bending load experiment.

The lubrication increases the contact resistance of the sample. For instance, some lubrication type increases the contact resistance twice the magnitude compared to certain other types. The influence of the cooldown cycle in contact resistance is not observed. The contact resistance of all samples decreased when the samples were bent around the formers. The reduction in contact resistance saturated around 80 mm bending diameter for all measured samples. The magnitude of reduction in contact resistance was different for different lubrication types. A simple electrical network model is made to predict the change in local contact resistance when the sample is bent. The network model consists of two parallel circuits of series resistance connected by a set of contact resistances and both ends of the parallel circuits connected to the terminal resistance.