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EVALUATION OF A STRENGTHENING AND INSULATION SYSTEM FOR HIGH TEMPERATURE BSCCO-2223 SUPERCONDUCTING TAPE

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ABSTRACT

Recent advances in BSCCO-2223 superconducting tape quality and length have led to demonstration programs for coil performance. The conductors in these coils need to be insulated without damage to the superconducting properties. A paper insulation process developed at the General Electric Company (GE) for low temperature superconducting Nb_3Sn tape has been modified to provide the same insulation system to high temperature (HTS) superconducting tapes, such as BSCCO-2223. In this paper, we report on the insulation process and its effect on the tape performance. Several long lengths of conductor have been tested, unwound, insulated and retested to examine any degradation issues. Additionally, it is known that HTS materials are inherently weak in relation to the winding and handling stresses in a manufacturing environment. A system to provide mechanical stabilization to Nb_3Sn tape through a lamination process has been successfully applied to high temperature superconductors as a method to build a strong, windable composite. The system is described and mechanical and electrical properties of the strengthened tapes are discussed.

INTRODUCTION

As the critical current (I_c) and the available lengths of silver-based BSCCO tapes advance to the point of commercial viability, two important conductor characteristics must also be addressed: tape mechanical strength and turn-to-turn insulation. The development of methods to strengthen and insulate the tapes enables the fabrication of layer-wound coils with solenoidal and racetrack geometries. Insulation and lamination processes developed at GE for Nb_3Sn tapes have been modified to be compatible with BSCCO tapes.

The silver matrix in powder-in-tube BSCCO tapes are fully annealed during the heat treatment of the tapes. This dead-soft silver adds very little strength to the brittle BSCCO conductor and irreversible strain damage can easily occur during the tensioning and handling of the tapes. As first demonstrated by Benz[1], high strength laminations can be added to superconducting tapes to improve their tolerance to tensile and bending stresses. This paper describes the in-line process developed to laminate copper and steel to long lengths of BSCCO tapes. Results of the mechanical testing and critical current measurements of several samples of BSCCO-2223 conductor are reported.

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Commercially available superconductors, such as NbTi, utilize either an enamel type insulation coating, such as formvar, or a serving of glass or nylon. The disadvantage of enamel type coatings on tapes is the tendency towards inadequate edge coverage. Serving processes are typically slow and tend to apply excessive forces to the conductor. An alternative process, using a folded paper insulation, is described in this paper. Test results for BSCCO tapes are included.

CONDUCTOR STRENGTHENING

The mechanical and electromagnetic forces experienced by superconducting coil windings must not overstress the superconductor. It is known that BSCCO tape superconductors are highly strain sensitive as compared to conventional NbTi conductors. The highly annealed state of the silver stabilizer used in powder-in-tube BSCCO tapes provides very little strength to the conductor. As a result, the winding tension for the bare conductor must be limited to approximately 0.5 kg. This low level of tension is barely practical for the manufacture of solenoidal windings, and is insufficient for racetrack geometries due to the sagging of the straight sections and the risk of conductor buckling in the lower layers as the winding progresses.

It has been observed in the lamination of stabilizing copper foils in the manufacture of Nb_3Sn tape[2], that the reacted Nb_3Sn foil entering the lamination process is supported and protected from mechanical damage by the stabilizer during further processing. Even though the silver acts as the stabilizer for the HTS material, it was thought that copper could be laminated to the superconductor for the purpose of strengthening. The lamination process has been applied to the silver-base BSCCO tapes, with excellent results.

Laminator Description

The laminator consists of three dancer arm controlled payoff drives, one for the superconductor and two for the laminated foils. Payoff tensions can be set independently. All three foils are transported over rollers to the lamination tooling closure point. The tooling set can be raised for "stringing up" the machine, but is immersed in a lead-tin solder bath during the lamination process. The immersed foils are wetted by the molten solder and bond to each other in the closure point, as shown in Figure 1. The closure point rollers counter-rotate to the direction of the laminated foil to maintain cleanliness in the exiting product over long lengths. As the strengthened superconductor exits the closure, a compressed air quench is used to solidify the solder. The laminated tape is then transported over more rollers and pancake wound onto a takeup spool.

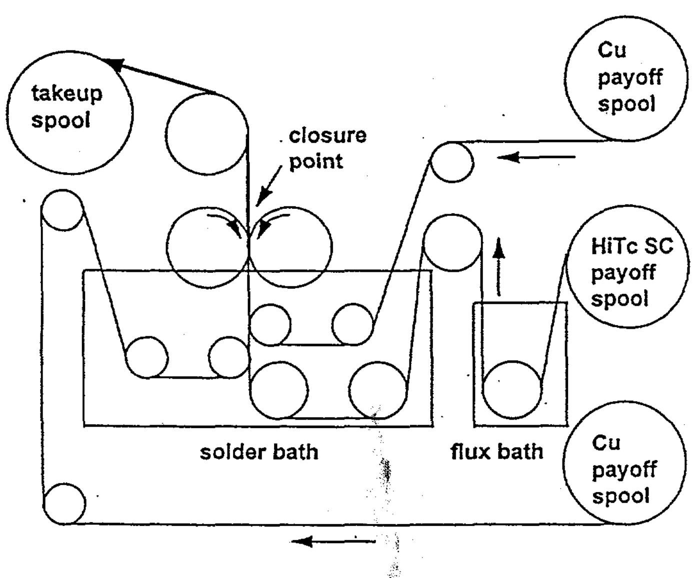

Figure 1. Lamination system for superconducting tapes.

The Lamination Experiment

Spring-hard, pre-tinned copper foil, 0.081 mm thick by 25.4 mm wide, has been procured in lengths up to 3500 meters. These lengths have been slit to 3 mm widths and wound onto pancake spools. Tensile tests show the tinned copper foil to have an ultimate tensile strength (UTS) of 400 MN/m2. Two lengths of this copper were placed in the copper payoff drives of the laminator. The copper payoff tension was set to 0.45 kg. A length of copper foil 0.203 mm thick by 3 mm wide was first placed in the superconductor payoff drive to simulate the process. The strengthening copper foils were strung up through the preheated tooling and onto the takeup spool. The tooling, modified for the HTS tape widths, was then immersed in the 250 C solder bath and the drives were started, beginning the lamination process with the exterior foils only. No issues with foil guidance or the modified roller set were noted. A line speed of 2.4 m/min, corresponding to an immersion time of 7.5 seconds was set and maintained for the balance of the experiment.

Figure 2. - Lamination photomicrographs. Copper for process simulation, left (a), IGC HTS tape, center (b), ASC HTS tape, right (c). Scale with the laminated copper dimensions, 0.081 mm thick by 3 mm wide.

The drives were then stopped and the thicker copper foil, simulating the superconductor, was strung up over the tooling and inserted into the closure point. This bare copper length was wiped with a flux containing the active ingredients of HCl and ZnCl prior to entering the solder bath. The tooling was immersed in the solder bath and the drives were restarted. A 50 meter trial length was run. The drives were then stopped and the tooling lifted from the solder bath. Bond testing at the end of length showed a very well bonded lamination with no voids. A slight lateral misregistry can be seen in Figure 2a.

Next, a sample of BSCCO-2223 multicore tape conductor from Intermagnetics General Corporation (IGC) was placed on the payoff spindle, strung up through the flux wipe, over the tooling and inserted at the closure point. The payoff tension was set to 0.23 kg for this and the next length of HTS material described. The tape measured 0.164 mm thick by 3.25 mm wide. A 60 meter length was laminated without incident. Bond testing appeared good. Some misregistration was noted and the slight difference in conductor and foil lamination widths can be seen in Figure 2b.

A second sample of BSCCO-2223 multicore tape conductor with a high strength matrix from American Superconductor Corporation (ASC) was also laminated. The sample measured 0.263 mm thick by 4.11 mm wide. The lamination tooling pulleys for the superconductor were changed to accomodate this wider material. The tooling was preheated, the superconductor was strung up, and the material was inserted into the closure point. Bond between the superconductor and the copper was good. Again, a misregistry problem can be observed in the cross section shown in Figure 2c. The misregistration can be corrected by refinement of the exit rollers as well as by obtaining lamination material equal in width to the HTS tapes.

Lamination Mechanical and Electrical Results

All samples were respooled and tensile tests were performed on the as-received and the laminated materials. Data for the tensile tests, shown in Table 1, shows that for the copper, a small amount of degradation occurs in the lamination process, probably as a result of the heat of the solder bath beginning to recrystallize the cold worked structure of the copper. For the IGC material, the copper adds a fourfold increase in UTS. In the case of the ASC material, already prestrengthened by the high strength matrix, the copper laminations add a forty percent increase in UTS. Although the UTS of both conductors after the lamination process is nearly the same, it took 30 kg to fracture the ASC conductor, compared to only 20 kg to fracture the IGC conductor, due to the different cross sectional areas of the starting tapes. Elongation prior to fracture in the ASC tape rose from 6 percent in the "as received" tape to nearly 8 percent in the laminated tape. In the IGC tape elongation prior to fracture rose from less than 1 percent in the "as received" tape to greater than 3 percent in the laminated tape.

When returned to the suppliers for full length I_c testing to determine degradation, it was found that the IGC tape had lost 80 percent of the total I_c availible prior to the lamination process when tested at 0 Tesla (T) and 77 Kelvin (K). It is possible that this conductor is losing I_c as a result of strain sensitivity. The wheels immersed in the solder only had a 5 cm diameter which has been shown by Yau[3] to be at the minimum diameter for zero loss due to strain sensitivity in a multifilamentary BSCCO tape. On future experiments, the lamination wheel diameter for the superconductor will be increased to 8 cm. Another possible explaination is that the takeup tension, at 2.27 kg, was too high and is beginning to exceed the axial strain limits of the conductor. Takeup tension will be reduced on future experiments by reducing the closure pressure on the laminator and by reducing the number of rollers in the conductor path.

The ASC conductor, with its significantly higher "as received" strength due to the high strength matrix, was found to have lost none of its starting Ic due to the lamination process. This material, upon return to the supplier, was progressively strained and Ic tested to determine strain sensitivity of the laminated conductor. The results, see figure 3, show the lamination process significantly improves the strain sensitivity of this conductor. Samples of both the "as received" and the laminated tapes were loaded in 10 to 20 MN/m^2 increments for 2 minutes, the load removed and an I_c test performed. Whereas the "as received" tape show a dropoff in Ic at strains greater than 70 MN/m^2, the laminated tape is able to maintain Ic up to strains of 120 MN/m^2, a 70 percent increase. This potential benefit will have to be weighed against the decrease in coil critical current density due to the additional cross sectional area occupied by the copper laminate in a winding.

Table 1. Ultimate tensile strength in MN/m^2 for the as received and laminated materials

Conductor	Copper	IGC	ASC
As Received	449	41	116
As Laminated	427	162	159

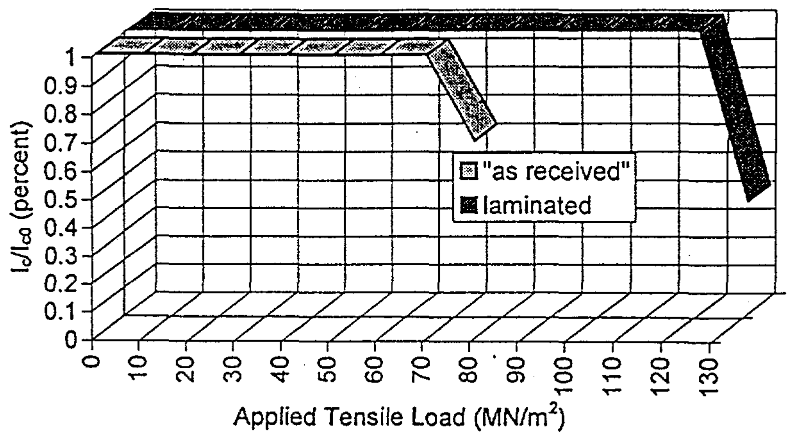

Figure 3. ASC strain sensitivity measurements.

JOINING

The lamination process may prove to have another advantage in the manufacture of products from HTS materials. Since the copper laminate can be procured in up to 3500 meter lengths and the lamination tooling can be lifted from the solder bath, a method to join the shorter HTS lengths can be envisioned. At the end of each HTS length, the tooling can be lifted from the solder bath and the start end of a new HTS length can be overlapped with the end of the previous length and inserted into the closure point. The tooling would then be reimmersed and the drives restarted. The end result would be multiple HTS lengths with lap solder joints laminated between continuous, long lengths of copper. This would allow very long lengths of conductor to be supplied to the insulator and to magnet winding. The lap solder joint and the surrounding copper would both serve to resistively transfer current at the HTS ends, not an issue in a nonpersistent mode of device operation. This method is being examined further for manufacturing practicality and reproducability as well as for joint effectiveness.

CONDUCTOR INSULATION

A paper insulation system was previously developed at GE for Nb_3Sn tape.[4] More recently, this system has been used to insulate BSCCO-2223 tapes. Conventional insulation of superconducting wire normally uses an enamel-type coating, such as formvar, that is applied to the conductor surface and then baked in an oven in a continuous, reel-to-reel process. In addition to problems with inadequate enamel coverage on the edges of tapes, this method presents a problem for solder laminated tapes because the enameling oven temperature can cause debonding of the soldered laminates. Also, the HTS materials are extremely strain sensitive and would be damaged if transported reel-to-reel at elevated temperature.

An alternative insulation commonly used in superconductors involves serving on a thin glass or woven nylon tape at a 45 degree angle around the circumference and along the length of the conductor. On thin, brittle intermetallic tape superconductors, however, the force applied to the conductor as a result of the serving can be sufficient to damage the superconductor. Additionally, the serving process runs extremely slow. The paper insulation method developed at GE involves a continuous folding and wrapping of a thin paper insulation around the circumference of the superconducting tape, all at relatively high speeds, with little or no load on the conductor. I_c testing of Nb_3Sn tape, both before and after insulation, indicate zero degradation with the insulation process. Testing of BSCCO tapes before and after insulation show degradation in the range of 0 to 15 percent, depending on the material tested, however, this is believed to be caused by line tension on the payoff and takeup sides of the process. The process can be modified to eliminate strain degradation effects by tension minimization. The higher strength, laminated tapes will also help make this operation more forgiving.

Insulator Description

The insulation system consists of several components shown in figure 4. A dancer arm controlled payoff drive is used to minimize the strain on the superconductor by feeding the insulator with tape at a minimum tension. An eddy current defect detection unit is in place between the payoff and the insulator folding tooling. This unit will stop the process for examination of defects by the operator if the threshhold limit of the unit is exceeded. The paper payoff, insulation folding tooling and glue applicator wheel make up the bulk of the insulator. Finally, the insulated material is spooled up by the takeup drive.

In figure 5, the paper folding sequence is shown. In the first step of this continuous process, the paper with glue applied to the right edge, glue upward, arrives at the start of the die, under the superconducting tape. In the second step, a die on the left curls the left edge of the paper over the top of the tape. The next die creases the left edge to complete the left fold. In the third step, the material enters the second half of the die set where a die component curls the right edge of the paper over the top of the superconducting tape, already covered with the left side paper. The last die component creases the right edge to complete the right fold. This final die also serves to press the right edge onto the left edge, causing the glue on the right side to stick to the left side paper. A final closure roller also presses the glue to bond. This process is capable of line speeds of up to 75 meters per minute, compared to 3 to 5 meters per minute for serving-type insulation machines.

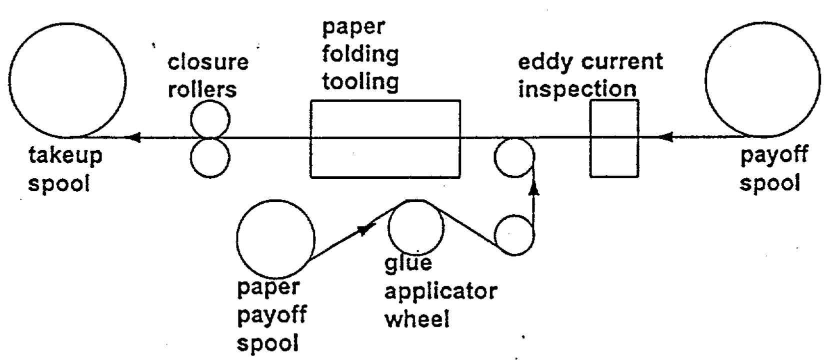

Figure 4. Insulation machine diagram, overall system.

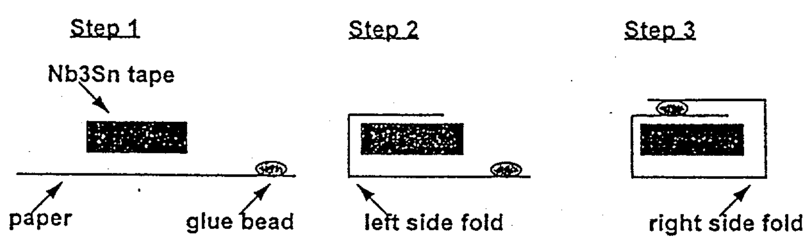

Figure 5. Insulation folding tooling concept.

Insulator Experiments and Results

Three lengths of HTS material were run on the insulator. The first length was a monofilament BSCCO tape, 0.152 mm thick by 5.0 mm wide, from IGC. The tape, on a pancake spool, was placed in the payoff. Payoff tension was set to 0.45 kg. The material was strung up through the insulation tooling and the start end was attached to a pancake takeup spool. Takeup spooling tension was set to 0.54 kg. The 70 meter length was run off at a speed of 10 meters per minute due to the relatively short length provided. This length, tested prior to leaving IGC, was returned after insulation for additional testing to determine the level of I_c degradation that occurred as a result of insulation. This length was resistive when measured at 0 T and 77 K after the insulation process.

This result, although disappointing, was thought to be due to the high line tensions used and the high strain sensitivity of the monofilament tape. The second length was a multifilament BSCCO tape, 0.205 mm wide by 3.3 mm wide, from IGC. This length was allowed to "free wheel" in the payoff, experiencing less than 0.01 kg of payoff line tension. On the takeup side of the process the line tension was reduced to 0.25 kg. The 90 meter length was insulated and sent for retested. It was found that the I_c of this length degraded by less than 13 percent as a result of the insulation process. Four more lengths of this type of conductor were insulated and are waiting to be wound into a test coil.

The final length tested was a multifilament BSCCO tape, 0.276 mm thick by 4.3 mm wide, from ASC. This length also had a high strength matrix as did the ASC laminated sample. The length was run at less than 0.01 kg of payoff tension and takeup tension was held to less than 0.18 kg over the entire 95 meter length. At this time, this length has not been tested for I_c degradation, but is expected to lose little or no I_c. This result is expected because of the larger cross sectional area of the conductor, the very low process tensions used and the low strain sensitivity of the high strength matrix tape.

CONCLUSIONS

A process used in the lamination of Nb_3Sn tapes has been successfully modified to strengthen HTS tapes. More process modification is needed to make this process fully compatible with conventional silver matrix HTS materials. As is, however, the lamination works quite well with high strength matrix HTS tapes. Efforts need to continue to reduce the strain the process imparts to the HTS tape. Line tensions will be reduced and roller diameters will be increased. For production runs, copper that is the same width as the HTS tape will be procured. Work needs to continue to correct lateral misregistration of the laminated tapes. Future work on strengthening materials will explore minimizing the cross sectional area of the laminate while maximizing strength. Towards this end, 0.05 mm and 0.025mm thick copper and stainless steel foils are being procured.

The insulation process, developed for Nb_3Sn tape, has successfully covered HTS tapes with insulating paper, but, again, in the case of tapes with conventional silver matrix, not without some degradation in I_c. Work will continue to minimize the strain imparted to the tapes by the insulation process. Although very long lengths of HTS materials are still not commercially available, the methods used in the manufacture of Nb_3Sn tapes are applicable and useful in making HTS materials easier to use and more robust in the manufacture of devices.

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