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Application of reflow soldering method for laminated high temperature superconductor tapes

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***Abstract*—A lamination system using reflow soldering was developed to enhance the mechanical properties of high temperature superconductor (HTS) tape. The laminated coated conductor tape was fabricated using the continuous lamination process. The mean, maximum, and minimum tensile loads in a T-peel test of the laminated coated conductor were 9.9 N, 12.5 N, and 7.6 N, respectively. The critical current (I_c) distributions of the non-laminated and laminated coated conductor were compared using a non-contact Hall probe method. The transport I_c nearly matched the non-contact I_c; however, some degraded Ic regions were found on the length of 800 cm of laminated coated conductor. We confirmed that the cause of the partially degraded I_c was due to an increase in line tension by (1) solidification induced by a change of composition that usually occurs in molten brass (Cu, Zn) in solder, or (2) non-homogeneity of the thickness of the coated conductor or metal tapes. We suggest that reflow soldering is a promising method for reinforced HTS tape if the controlling solder thickness and lamination guide are modified.**

1. INTRODUCTION

High temperature superconductor (HTS) tapes have been commercialized with enhanced superconducting properties and enhanced length by several companies [1-4]. However, for most electrical applications (e.g., motor magnets), HTS tape is manufactured in a coil shape. Therefore, non-laminated HTS tape is inherently weak in terms of handling, winding at room temperature, bending, and Lorentz forces at low temperature-induced strain (below 77 K) [5-9]. The mechanical strength and resilience of HTS tapes are important for applications such as motors and electric cables. Generally, HTS tapes are reinforced by lamination with metal tape on one or both sides using solder [4, 10].

Wave soldering using molten solder and reflow soldering using solder cream are manufacturing processes used in the electronics industry to join components to printed circuit boards. The wave soldering method has been adopted by the American Superconductor Corporation (AMSC) for the lamination of HTS tape [10]. Here, the eutectic temperature of solder can be changed if the components of Cu or Zn in the metal tape are dissolved by flux during the long processing time in the wave soldering method. However, we assume that reflow soldering can maintain the compositional ratio of the solder by continuously adding fresh solder cream to the surface of the metal tape. HTS tape lamination using the reflow soldering method has been used only recently. Therefore, we investigated the possibility of using reflow soldering at the lamination of the coated conductor. We developed a lamination system using reflow soldering, and brass tape was laminated on the coated conductor. In addition, we evaluated the critical current (I_c) distribution of the non-laminated and laminated coated conductors using a non-contact Hall probe measurement system.

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2. EXPERIMENTAL PROCEDURES

We prepared coated conductors with a template fabricated using ion beam-assisted deposition (IBAD) method. The structure of the specimen was Cu/Ag/REBCO/$LaMnO_3$/MgO/Y_2O_3/Al_2O_3/Hastelloy C276/Ag/Cu in which the Cu was fabricated by electroplating. Brass metal tapes with a thickness of 150 μm and a width of about 4 mm were used to laminate the coated conductor. We used 62Sn/36Pb/2Ag solder material whose particle size, melting point, and viscosity are 20~45 μm, 183 ^oC, and 200 Pa·s, respectively.

The solder cream was coated on the coated conductor and the brass tape using the doctor blade technique. The coated conductor was laminated on both sides with two brass tapes in a reflow oven. At the end of the production line, the laminated coated conductor tape was coiled. The thermal profile is a key determinant of production yield. In this study, the production yield was not considered. Figure 1 shows the thermal profile at a 300 ^oC setting temperature for reflow soldering. The peak temperature of the lamination guide at the 300 ^oC setting temperature was about 240 ^oC, which is higher than melting point of the solder by 60 ^oC.

In general, there are three heating modes involved in most surface mount technology (SMT) reflow processes: conduction, convection, and infrared radiation (IR). As a preliminary experiment, we used the conduction process in a tube furnace to confirm the possibility of the reflow soldering method for lamination of a coated conductor. In our reflow oven, the pre-heating time is very short compared to the general reflow thermal profile [11].

We compared the I_c distribution of non-laminated and laminated coated conductors through a non-contact I_c measurement using a Hall sensor at 77 K. A detailed description of the non-contact I_c measurement method is given in [12].

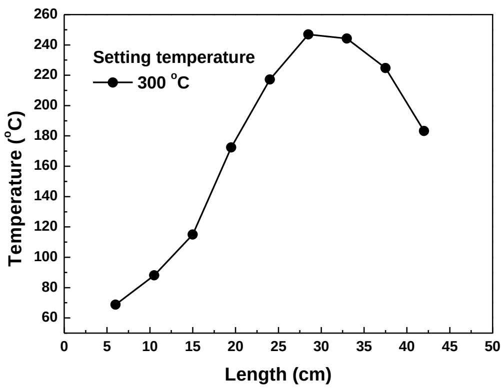


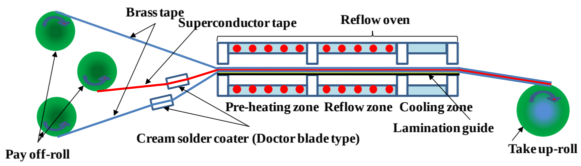
Fig. 1. Thermal profile at 300 °C setting temperature for soldering.

3. RESULTS AND DISCUSSION

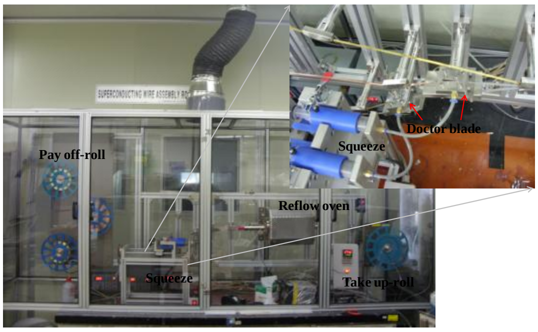
A schematic illustration and photographs of the lamination system with reflow soldering are shown in Fig. 2. Our reflow soldering system uses solder cream mixed with flux, and consists of a doctor blade solder coater, a reflow oven, and a roll to roll system, as shown in Fig. 2(a). The reflow oven is divided into a pre-heating zone, reflow zone, cooling zone, tape guide, and lamination guides.

The solder cream was extruded by squeezing the cream with constant pressure, and the thickness of the coated solder was controlled by adjusting the gap. The thickness of the coated solder was set to 250 µm. Whenever possible, we tried to reduce the thickness of the coated solder. However, we could not obtain a solder thickness of less than 250 µm with a particle size as large as 20~45 µm and a tape width of 4 mm. We assume that the solder thickness could be reduced by using solder with a smaller particle size.

The lamination guides were located in the reflow oven. The guides consist of a thickness control mechanism using a thickness gauge, and a spring press mechanism to prevent de-lamination. High quality soldering with a low number of defects requires optimization of the thermal profile in the system. The heating and cooling rates must be determined by considering the state of the cream solder on the metal tapes. The main reflow conditions are



(a) Schematic of reflow soldering system.



(b) Prototype lamination system.

Fig. 2. (a) Schematic illustration, and (b) photographs of lamination system using the reflow soldering method.

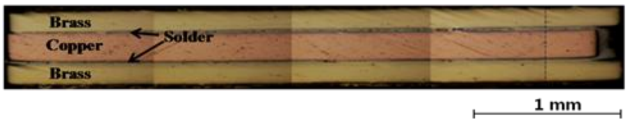


Fig. 3. Optical images of the laminated Cu tape.

pre-heating, reflow heating, and cooling. In the pre-heating step, the flux is activated to remove oxide scale for proper soldering. In the reflow heating step, the solder is heated above its melting point. In the cooling step, the melted solder is solidified to join the metal tape and coated conductor tape.

As a preliminary experiment, we fabricated laminated Cu tape instead of the coated conductor. The thicknesses of the brass metal and Cu tapes were 150 µm and 200 µm, respectively. The sample length was 600 cm, and the thickness of the laminated region was set to 540 µm to maintain a solder thickness of 20 µm. Figure 3 shows cross-sectional optical images of the laminated Cu tape. Although the setting thickness of the solder was 20 µm, the thickness of the solder varied from 12 to 30 µm, which was confirmed through analysis of the cross section using optical microscopy. From this analysis, we found that the variation in solder thickness was caused by an inhomogeneous thickness of the Cu and brass tape. From these results, we suggest that line tension is increased if the total thickness of Cu and brass is thicker than the setting thickness.

Figure 4 shows the thickness distribution of the laminated Cu tape. After lamination, the thickness was measured at intervals of 100 cm. The resulting thickness distribution is shown in Fig. 4. The standard deviation, maximum, and minimum values of the laminated conductor's thickness were 7.4 µm, 552 µm, and 527 µm, respectively.

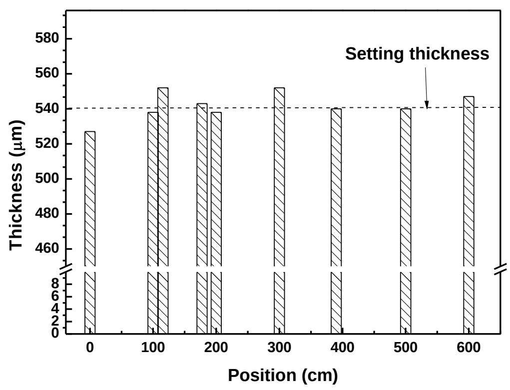


Fig. 4. Thickness distribution of the laminated Cu tape.

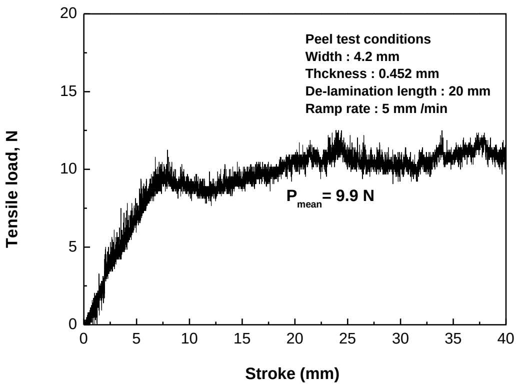
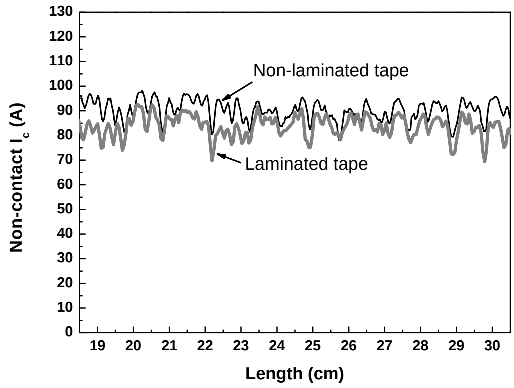
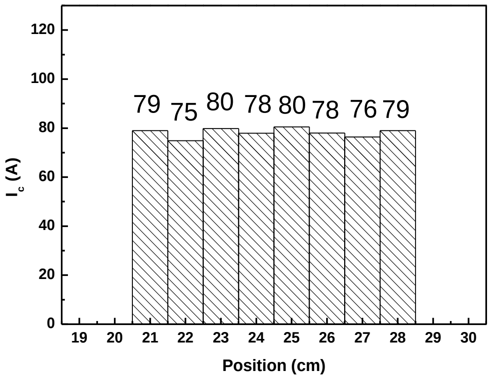


Fig. 5. Results of the T-peel test in a brass-laminated coated conductor.



(a)



(b)

Fig. 6. Profiles of (a) I_{c-H} for non-laminated and laminated coated conductors, and (b) I_{c-T} for a laminated coated conductor measured at 1 cm intervals for a length of 12 cm.

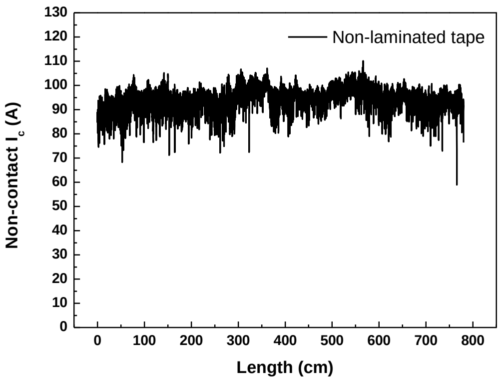
Figure 5 shows the results of a T-peel test in a brass laminated coated conductor. Next, we performed a test based on the KS M ISO 11339 standard entitled "Adhesives-T-peel for Flexible-to-Flexible Bonded Assemblies [13]." The measurement conditions were a cross-head speed of 5 mm/min, a width of 4.2 mm, and a de-lamination length of 20 mm. The mean, maximum, and minimum tensile loads were 9.9 N, 12.5 N, and 7.6 N, respectively, in a stroke range of 10 mm to 30 mm.

We compared the non-contact I_c distribution of non-laminated and laminated coated conductors to check for any defects induced during the lamination process. First, we measured the ΔB distribution of non-laminated and laminated coated conductors (ΔB is the difference between maximum and minimum magnetic fields across the width of a coated conductor). For conversion to transport-critical current, we measured the value of critical current I_{c-T} using the four probe direct current (dc) transport method and obtained the k value, which is a conversion factor calculated from ΔB_{min} and I_{c-T} (for additional details, see [12]).

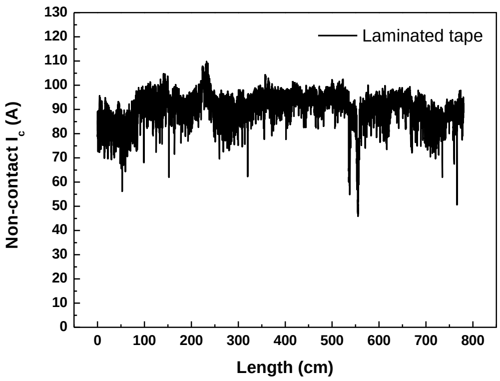
Figure 6(a) shows the I_{c-H} profiles of the non-laminated and laminated coated conductor. Fig. 6(b) shows the I_{c-T} values for a laminated coated conductor measured at 1 cm intervals over a length of 12 cm. The value of I_{c-T} at 8 cm was 76.8 A. The ΔB_{min} and I_{c-T} values for a reference section (1 cm) of the non-laminated and laminated coated conductors were 42.8 G, 51.1 G, and 78 A, 78 A, respectively. The values of coefficient k of the non-laminated and laminated coated conductors were 1.82 and 1.53, respectively. The non-contact I_c distribution of both samples shows a similar distribution in a 12 cm section and the transport I_c nearly matched the non-contact I_c.

To extend the length of the lamination process, we fabricated a laminated-coated conductor with a length of 800 cm and investigated the I_c distribution over the entire length. Figure 7 shows the profiles of I_{c-H} for non-laminated and laminated tape in the 800 cm section. The non-contact I_{c-H} of the laminated coated conductor was partially degraded compared to the non-laminated coated conductor.

From the tension measurement results from the lamination process and a composition analysis of the remnant solder after lamination, we confirmed that the partially-degraded I_c was due to a change in the line tension by (1) solidification induced by a change that usually occurs in the molten brass composition (Cu, Zn) of solder, or (2) non-homogeneity in the thickness of the coated conductor or metal tapes.



(a)



(b)

Fig. 7. Profiles of $I_{c\text{-}H}$ of (a) non-laminated, and (b) laminated coated conductor in the 800 cm section.

4. SUMMARY

We considered a reflow soldering method for the lamination of coated conductors. We compared the non-contact I_c distribution of non-laminated and laminated coated conductors to check for defects induced during the proposed lamination process. We confirmed that lamination damage did not occur in the reflow soldering lamination, and that the transport current I_c nearly matched the non-contact I_c over a short length. However, additional process modifications such as controlling the solder thickness, changing the structure of lamination guide, and draining extra solder are needed to make the proposed process fully compatible with industrial applications. But we expect that the reflow soldering is superior to the wave soldering in terms of the uniformity of adhesive intensity and resistance of solder.

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