Evaluation of Shear Strength in Soldered and Mechanical Lap Joints of High-Temperature Superconducting Tapes Intended for a Remountable Magnet*)

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This study describes the electro-mechanical response under tensile and shear stresses of the mechanical and soldered lap-joint methods proposed for joining Rare-Earth Barium Copper Oxide (*RE*BCO) high-temperature superconducting (HTS) coated conductors (CCs) in designs of a "remountable" (demountable) HTS magnet and joint-winding of an HTS magnet intended for the helical fusion reactor FFHR-d1. Proper joint of *RE*BCO CCs for the HTS magnets not only requires sufficiently low joint resistance to avoid quench phenomena, but also involves mechanical stability against large electromagnetic forces. Results obtained from tensile test to apply shear stress namely tensile shear tests performed on mechanically jointed *RE*BCO CCs showed that the linear proportionality between shear strength and contact conductivity of the joint is conserved for larger joint section area. An attempt to describe the failure mechanism of mechanical lap-joint revealed that a bending moment is originated at the joint section. Furthermore, results from tensile shear test on soldered joint between *RE*BCO CCs with copper stabilizer showed failure of the *RE*BCO CCs with small axial loads while joint remained intact.

Keywords: segment-fabrication, demountable magnet, remountable magnet, high-temperature superconductor, *RE*BCO coated conductors, mechanical lap-joint, soldered lap-joint

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1. Introduction

The concept of a superconducting magnet being assembled from several segments has been proposed for Tokamak and Heliotron fusion reactors since 1980 [1, 2]. Since the development of Rare-earth Barium Copper Oxide (*RE*BCO) high-temperature superconducting (HTS) coated conductors (CCs) with critical parameters far exceeding that of low-temperature superconductors (LTS), research and development activities related with the design and fabrication of superconducting magnets for nuclear fusion reactors have gained more interest from research institutes around the globe. HTS coils can be operated at relatively high temperatures (>20 K) in which range their robustness against heat generation is high (larger specific heat), and the refrigeration energy is lower than LTS coils. Under these considerations, resistive joints on the coils can be acceptable, allowing the design of demountable HTS magnets [3, 4]. Now, demountable HTS toroidal field magnets are considered to be applied to conceptual designs of small tokamaks at fusion nuclear science facilities such as the Vulcan [5] and the ARC [6] in the United States. In Japan, the Large Helical Device type helical fusion reactor, FFHR-d1 [7], featuring HTS technology is being designed by the National Institute for Fusion Science. The design takes the advantageous option of the segment-fabrication [8, 9] to solve the engineering issue of its huge and complex helical coils. There are two options: the joint-winding method [8, 10, 11] in which the helical HTS coils are wound by joining half-pitch or one-pitch of the conductor segments with permanent joints, and the remountable (demountable) segmented coil method [4, 9]. The latter one is currently considered as the advanced option.

The main issue resides in choosing the proper joint method applicable for *RE*BCO CCs in order to satisfy the desired operational parameters [8, 11, 12] (lower joint resistance and high mechanical stability) while maintaining practicality during joint fabrication process. Lap-joint between *RE*BCO CCs is one of the candidates for the segment-fabrication: the mechanical lap-joint where the CCs are pressed together with an indium foil between joint surfaces [10–14] or the soldered lap-joint [8]. The former has been subject of exhaustive research due to its advantages regarding easy fabrication and proficient joint resistance. In a recent study [12], fundamental investigation on tensile characteristics of the mechanical lap-joint between Gadolinium Barium Copper Oxide (GdBCO) CCs having silver and copper stabilizers with a joint surface area of 25 mm^2 showed a linear tendency between contact conduc-

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tance (the reciprocal of contact resistance) and achieved maximum tensile load (shear strength of the joint). It was discussed that as the number of contact asperities increases, so does the contact conductance along with an increase with the shear strength. Moreover, improvement on the shear strength of the joint was achieved when increasing the joint pressure. However, the consistency of these results when joint area becomes larger has yet to be confirmed.

In other previous studies, tensile characteristics of soldered lap-joint between two Yttrium Barium Copper Oxide (YBCO) CCs with only silver stabilizer [15] showed that for higher loads it was observed that delamination between YBCO and buffer layers due to crack formation at the edge of the joint occurred before any visible damage to the integrity of the joint. However, tensile characteristics of soldered joint between *RE*BCO CCs with silver and copper stabilizers, which has higher strength than the YBCO CC with only silver stabilizer have yet to be reported.

Therefore in this study we focused first on the description of the tensile characteristics of mechanical lap-joint between GdBCO CCs having silver and copper stabilizers with a joint area of 50 mm^2 in order to define properly the proportionality between contact conductance and shear strength of the joint. Next, we performed tensile test to apply shear stress at the joint, namely tensile shear test of soldered lap-joint using the same GdBCO CCs with silver and copper stabilizer. A brief analysis of the joint fracture mechanism for the mechanical lap joint was attempted based on structural adhesive joint theory [16]. The procedures and results for tensile shear test of the mechanical and soldered lap-joint are discussed in section 2.

2. Tensile Shear Tests of Mechanical and Soldered Lap-Joints

2.1 Sample fabrication

The copper stabilized GdBCO CC (FYSC-SC05, Fujikura Ltd.) was chosen for this study. The GdBCO CC is 5 mm wide and has a layered structure composed by a Hastelloy substrate (100 µm and 75 µm for previous [12] and present study, respectively)/Al_2O_3 (100 nm)/Y_2O_3 (30 nm)/MgO (5 nm)/CeO_2 (0.5 µm)/$GdBa_2Cu_3O_x$ (1.8 µm)/silver (6.4 µm)/tin (2 - 4 µm) and copper (100 µm and 75 µm for previous [12] and present study, respectively). The GdBCO has critical current of ~265 A at 77 K, self-magnetic field.

For the mechanical lap-joint samples used in this study, the copper stabilizer was chosen as the joint surface. The surface was polished using a #400 grit size sandpaper (particle diameter: 40 µm) and then cleaned using ethanol. The selected joint area was 50 mm^2 (5 mm × 10 mm). An indium foil with a thickness of 100 µm and a size corresponding to the selected joint area was used as interlayer material located between the GdBCO CCs. Figure 1 (a) shows the jig used to apply a joint pressure of 100 MPa

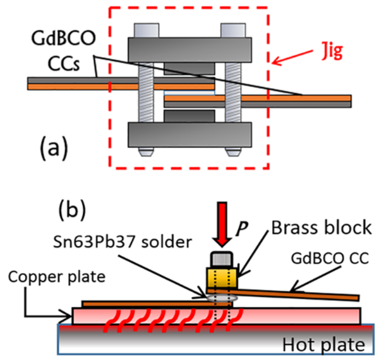

Fig. 1 (a) Mechanical lap-joint fabrication set-up, (b) Soldered lap-joint fabrication set-up.

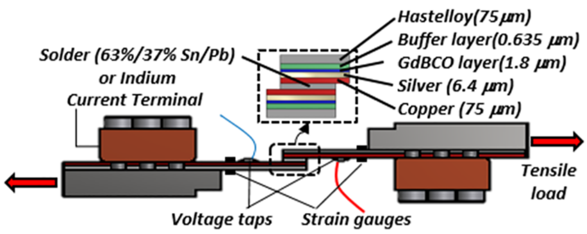

Fig. 2 Experimental set-up of the tensile shear test.

during the fabrication of the mechanical lap-joint. Finally, the joint pressure was released by removing the jig.

For the soldered lap-joint samples, surface preparation was the same as with the mechanical lap-joint samples. After cleaning the surfaces, they were coated with Tin-Lead (Sn63Pb37) solder with a melting point of 183 °C. The joint area for all soldered lap-joint samples was 25 mm^2 (5 mm × 5 mm). Figure 1 (b) shows soldered lap-joint samples fabrication set-up. Both GdBCO CC were placed over a copper plate. Then, the copper plate was heated up to ~230 °C using a hot plate. After the solder became soft enough, small joint pressure (<10 MPa) was applied to the joint section using a brass block bolted to the copper plate during the heat treatment. After cooling down, the joint pressure was released.

2.2 Experimental set-up and procedure

Figure 2 shows the experimental set-up used for the tensile shear test. The samples were placed in a customized tensile shear test machine designed for low temperature experiments. The whole test section is submerged in liquid nitrogen (77 K) and a current of 50 A is supplied. Tensile load is provided by a stepper motor with fixed rotational speed and its amplitude was monitored through a load cell. The potential difference across the joint section was also monitored to evaluate the joint resistance (dividing the voltage by the current). In addition, strain gauges were attached to each GdBCO CC in order to determine irreversible strain [17] and to verify that the specimens were indeed being pulled.

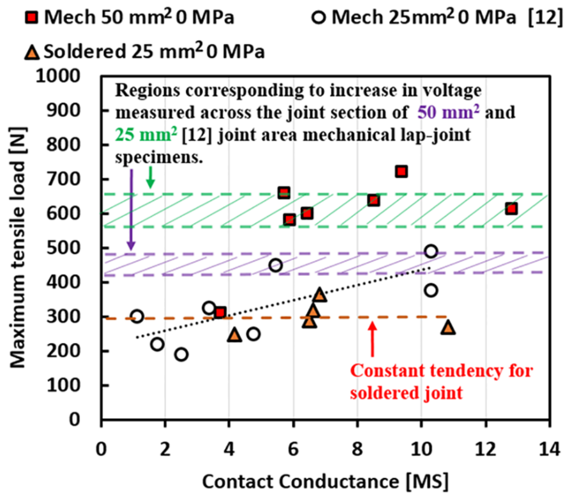

Fig. 3 Maximum tensile load as a function of contact conductance characteristics for mechanical and soldered lap-joint of GdBCO CCs at 77 K.

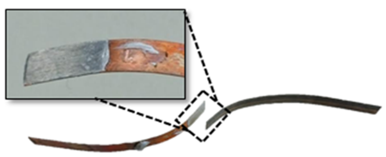

Fig. 4 Mechanical lap-joint sample with a joint area of 50 mm^2 after being pulled apart.

2.3 Results and discussion

Figure 3 shows a graph of the maximum tensile load as a function of contact conductance for mechanical lap-joints without joint pressure and joint areas of 25 mm^2 and 50 mm^2, and soldered lap-joint with a joint area of 25 mm^2 and also without applied joint pressure during the tensile shear test. The contact resistance is obtained by subtracting the layer material's resistance at the joint section from the joint resistance [18].

Results obtained from the tensile shear test of mechanical lap-joint of GdBCO CCs with a joint area of 50 mm^2 showed an increase in maximum applied tensile load. As the tensile load increases during the test, the CCs reach strain values above irreversible strain when load reaches the purple region. The same is true for the green region corresponding to past results [12] where thickness of the CC is 4/3 times larger than that of CCs used in the present study. At these regions, the critical current of the GdBCO CCs has decreased below 50 A, and this was observed as a sudden increase in the voltage measured across the joint. Figure 4 shows a picture of one of the mechanical lap-joint samples after being pulled apart. The failure mechanism of the mechanical joint is related to the shear strength of the interface between the indium and copper stabilizer which is closely related to the real contact area; on a microscale, when two metal surfaces are brought together, the real load bearing area is distributed along contact between

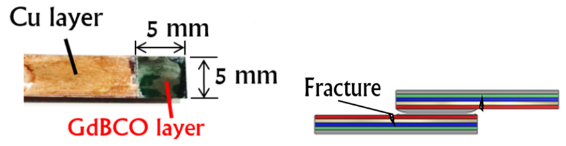

Fig. 5 Picture of one of the soldered lap-joint samples after tensile shear test was performed.

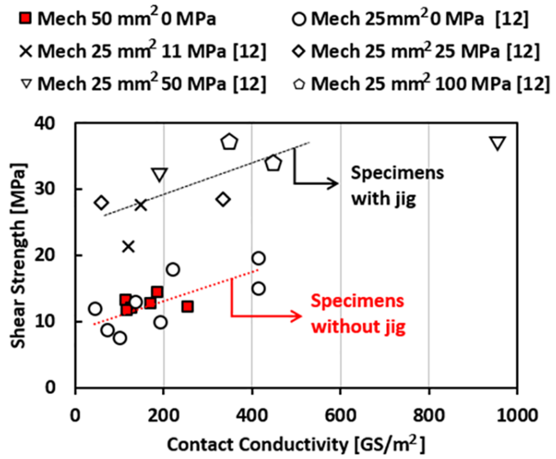

Fig. 6 Shear strength as a function of contact conductivity for mechanical lap-joint of GdBCO CCs at 77 K.

sharp, rough or rugged projections called asperities which deform through elastic and plastic regimes when subjected to compression. Addition of all the contributions from the asperity contacts gives the real contact area between two smooth surfaces [20]. However, it is often difficult to determine this value experimentally.

On the other hand, the failure mechanism for the case of the soldered lap-joint specimens was not due to the joint breaking apart but rather that of the GdBCO CCs deforming until delamination of the CC and further rupture occur. Joint condition of the soldered lap-joint samples after tensile shear test coincided with the one described in [15] as can be seen in Fig. 5 where the joint remained undamaged for all specimen. Failure may be attributed to fracture at the interface between silver layer and GdBCO due to stress concentration induced during tensile shear test. It is also believed that the solder stiffness has also some influence on the joint failure mechanism.

A more specific view of the joint electro-mechanical performance of mechanical lap-joint samples can be obtained through dividing the maximum tensile load and the contact conductance by the joint apparent area which will give the shear strength and contact conductivity. Figure 6 shows these results for all mechanical lap-joint samples with different values of joint pressure. The samples with joint pressures of >0 MPa during the tensile shear test [12] were installed to the tensile machine having the jig shown in Fig. 1 (a) and those with a joint pressure of 0 MPa did not have the jig as is described in Section 2.1. It can

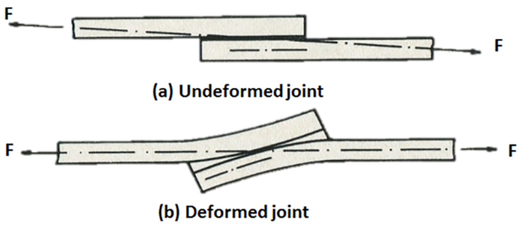

Fig. 7 The Goland and Reissner bending moment factor (geometric illustration) [16].

be confirmed that the linear proportionality between shear strength and contact conductivity of the joint region can be applied for a different joint area. Moreover, joint shear strength for the case of 50 mm^2 fitted with past results linear tendency line for 0 MPa joint pressure [12], meaning that the number of real contact spots per unit area is almost constant regardless of joint length. The reason why the red-dashed and black-dashed linear trending lines differ for the samples with joint pressures of > 0 MPa and for those with 0 MPa is discussed in the next sub-section.

2.4 Failure mechanism of the joints

Following an increase in the applied axial load, a bending moment will appear at the edge of the joint that will make the overlap section rotate until the line of action of the load coincides with the center line of each GdBCO CC as can be seen in Fig. 7. This effect is called the Goland and Reissner bending moment factor [16]. It can be further concluded that the indium layer will no longer be solely in shear, but will have peeling force at the ends of the joint. Moreover, this effect may also have some influence on the crack propagation at the edge of the joint in the case of soldered lap-joint samples. In addition, the upward shifting of the linear tendency (increase in joint shear strength) observed in Fig. 5 when joint pressure is being applied to mechanical lap-joint samples during the tensile shear test is because the use of the jig will not allow the peeling force to develop at the edge of the joint.

Another explanation for the upward shifting may be due to a phenomena called junction growth [19, 20]. According to Tabor [19], when a tangential load is applied simultaneously with a normal load, plastic flow will occur at a lower applied normal pressure. Even if it is a small tangential stress, it produces a small but finite displacement and causes an increase in the real contact area [19,20]. This phenomena is called "junction growth" and it gives rise to the shear strength of the interface layer between the indium and the copper stabilizer. However, the tribological effects on metallic adhesion are beyond the scope of this paper, so they will be treated in future works.

Nevertheless, the current design for the HTS conductors proposed for the FFHR-d1 [11] will include joint pressure being applied by copper and stainless steel jackets around a HTS CCs region. In such a case, the Goland and Reissner bending moment can be neglected and the junction growth is also expected.

3. Conclusion

In this study we described the electro-mechanical behavior of both mechanical and soldered lap-joint between GdBCO CCs with copper stabilizer under uniaxial tensile load at 77 K. Results indicated that the linear tendency between joint shear strength and contact conductivity can also be applied for the case of mechanical lap-joint with different joint areas. On the other hand, the results for the soldered lap-joint showed that even with different mechanical stabilizer like copper in the case of the *RE*BCO CCs used in this study, the joint section remained undamaged while the *RE*BCO CCs broke in the process at a constant load value. In addition, a brief consideration of the fracture mechanism for both types of joints revealed that for the case of lap-joints with no joint pressure, a bending moment that makes the joint section rotate is generated due to non-collinear loading.

Acknowledgments

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