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Evaluation of mechanical and thermal properties of insulation materials for HTS power devices at liquid nitrogen temperature

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Abstract

In superconducting power devices including power cables in which high temperature superconducting (HTS) tapes are utilized, a reliable electrical insulation should be achieved for its maximum performance. For an efficient design of HTS superconducting devices, a comparative evaluation of the mechanical and thermal propperties for various insulation materials at cryogenic temperatures is required. Especially, in the process of the property evaluation of the sheet-shaped insulation materials, anisotropy according to the machining direction should be considered because the mechanical and thermal properties are significantly influenced by the sample orientation. In this study, the cryogenic thermal and mechanical properties of various insulation material sheets such as PPLP, Cryoflex, Teflon, and Kapton were determined considering sample orientation. All samples tested at cryogenic temperature showed significantly higher tensile strength as compared with that of room temperature. The ultimate tensile strength at both temperature conditions significantly depended upon the sample orientation. The thermal properties of the insulation materials exhibited a slight difference among samples depending on the orientation: for the PPLP and Cryoflex, the CD orientation showed larger thermal contraction up to 77 K as compared to the MD one. MD samples in PPLP and Cryoflex showed a lower CTE and thermal contraction which made it more promising as an insulation material due to its comparable CTE with HTS CC tapes.

Keywords: Insulation materials, Tensile failure load, Thermal contraction, Cryogenic temperature, Sample orientation

1. INTRODUCTION

High temperature superconducting (HTS) 2G coated conductor (CC) tapes have been achieved many improvement in its current transport properties and acquired more demands in the field due to their significantly high power density [1, 2]. The major applications of CC tapes are the HTS power devices such as electrical power transmission cables, fault current limiters (SFCL), motors, and generators. Superconducting transmission lines with the used of large power cables are an innovative option to transfer large amount of energy, which are now being utilized as a part of the electric distribution grid and now constructed and enhanced up to its highest potential to transfer such energy [3]. The HTS cable system was intrinsically composed of HTS tapes including its constituent components, cooling system and electrical insulation [4, 5].

Due to the development of HTS tapes and its high demand for HTS device applications, insulation materials should also improve its characteristics suitable for different cryogenic applications so that can survive multiple thermal cycles between the room temperature (RT) and the cryogenic operating temperatures. And the dielectric designs have to minimize the mechanical stresses experiencing by the superconducting material [6,7]. Many studies on the evaluation of the mechanical and thermal properties of some insulation materials used in superconducting applications have recently been reported [6-9]. Coefficient of thermal expansion (CTE) compatiblitiy of insulation materials with CC tapes is also necessary and it should be reliable so not to degrade the superconducting properties of the CC tapes under thermal contraction. In this manner, the compatibility of the thermal properties of each layer of the CC tapes enables the cable system to cool efficiently [10]. Thus, verification of the thermal compatibility of CC tapes to insulation materials adopted is important. On the other hand, the mechanical properties at cryogenic temperature are also necessary to determine its limitations, especially when designing a HTS cable system.

Understanding the different behavior of the insulation materials due to the anisotropy may lead in creating a new insulation system that can enhance the performance of the whole cable system. Therefore, in this study, both mechanical and thermal properties of insulation materials such as PPLP, Kapton, Cryoflex, and Teflon were characterized at RT and at liquid nitrogen temperature (77 K). They have different orientations of the machine direction (MD) and cross-machine direction (CD), respectively. The influences of the anisotropy of the samples on the properties were investigated.

2. EXPERIMENTAL PROCEDURES

2.1 Samples

Four different kinds of cryogenic insulation materials such as PPLP, Cryoflex, Kaption and Teflon were supplied for this study. PPLP is the polypropylene laminated paper

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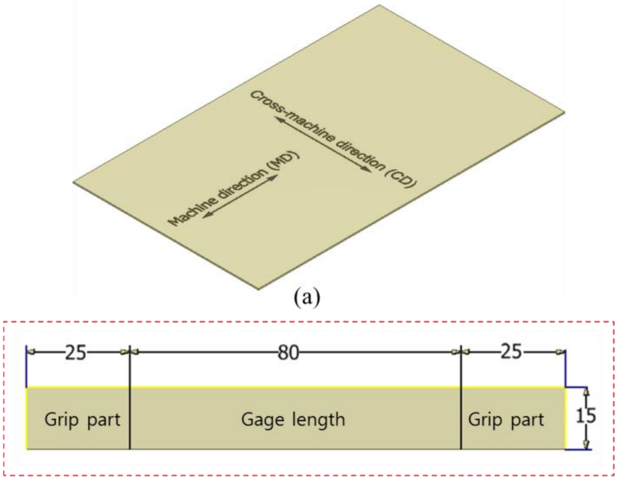
which is a composite insulator comprised of polypropylene ,PP laminated by Kraft papers. A polyethylene (PE) tape (Cryoflex™), which was developed by Ultera and used as a dielectric material in LN$_2$ cooled HTS cables [6]. A Polyimide HN-type sheet (Kapton™) is a general-purpose insulation material which was used over a wider temperature range. Finally, a polytetrafluoroethylene (PTFE) sheet (Teflon™) is widely used materials for various purposes. The material thickness of the single sheet was 100 μm and 90 μm (for PPLP and Cryoflex), and 120 μm and 160 μm (for Kapton and Teflon), respectively. Fig. 1 (a) shows a schematic for the designation of two orientations; the one having a length parallel to machine-direction (MD) and the other having a length parallel to cross-machine direction (CD). The specimen for testing was cut from commercially available insulation sheets with the dimensions of 130 mm and 15 mm for the length and width, respectively, using a razor sharp cutter, as shown in Fig. 1 (b). In the cases of PPLP, Cryoflex and Teflon samples, specimens are prepared with different orientation of MD and CD, respectively.

2.2 Mechanical properties measurement

The setup for mechanical property evaluation of insulation material samples is shown in Fig. 2. The specimen was fixed by gripping blocks at both ends. The upper grip was connected to the loadcell of the material testing machine used and the lower grip was set fixed on the loading frame. To prevent the slippage of the specimen during tensile loading, a sand paper (#800) was inserted on both sides at the gripping parts. Tensile load was applied to the specimen until fracture by a universal material testing machine (Shimadzu AG-IS, load cell capacitiy: 5 kN) [11]. A 25 mm Nyilas-type double extensometer was placed at the middle part of the specimen to measure the deformation induced in the insulation material during tension test [12]. It was connected to the signal conditioner (Kyowa, CDV-700, sampling rate: 500 kHz). The output voltage from the signal conditioner was used to measure the elongation occurred in the specimen. In order to prevent the damage caused at the edge part when the double extensometer is mounted on the flexible test piece, the mounting place of the specimen was wrapped with an aluminum foil, then the double extensometers were attached. For testing at cryogenic temperature, the specimen was submerged on a bath of liquid nitrogen (LN$_2$) and held for 10 min before applying the tensile load to keep thermal equilibrium within the specimen. The tension test was carried out at a constant ram rate of 5 mm/min.

In this study, the displacement from extensometer was used to derive both the elastic modulus, E and the yield strength, σ_y of each sample. The extensometer was removed after it reached the yield point. After removing the extensometer, the specimen was tested continuously until failure occured. Details on the derivation of mechanical properties of the specimen like percent strain, ε_f and the breaking stress, σ_f are described in reference [7].

2.3 Thermal properties measurement at 77 K



(a)

(b)

Fig.1(a) Orientation designation in insulation materials and (b) dimensions of specimen.

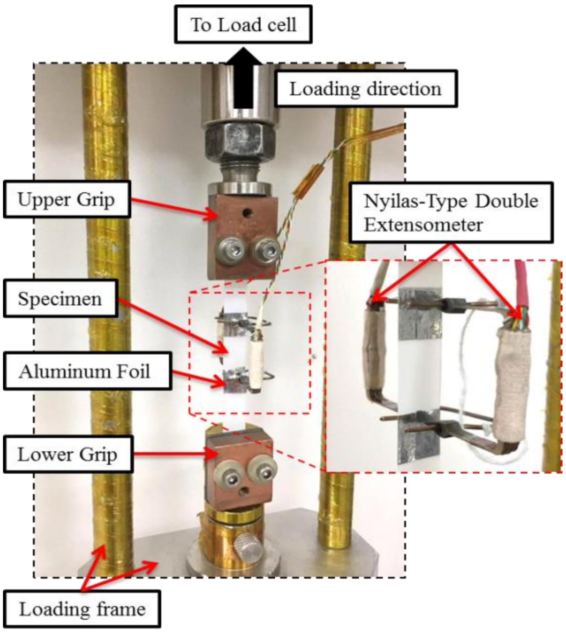


Fig. 2 Photograph of setup for tension testing of insulation material sheet at 77 K with attachment of double extensometers.

A similar setup was used to measure the coefficient of thermal expansion (CTE) and the thermal contraction of the insulation materials induced during cool down to 77 K [9]. The upper end of the specimen was held by the upper grip, and a deadweight was added to the lower part of specimen to ensure vertical flatness of the specimen while measuring thermal contraction. The measurement was done by submerging the setup including the specimen into liquid nitrogen bath. The contraction of the specimen was measured using the same 25 mm Nyilas double extensometers described on the previous section. The output voltage from the signal conditioner was used to calculate the CTE, as well as the thermal contraction of the specimen.

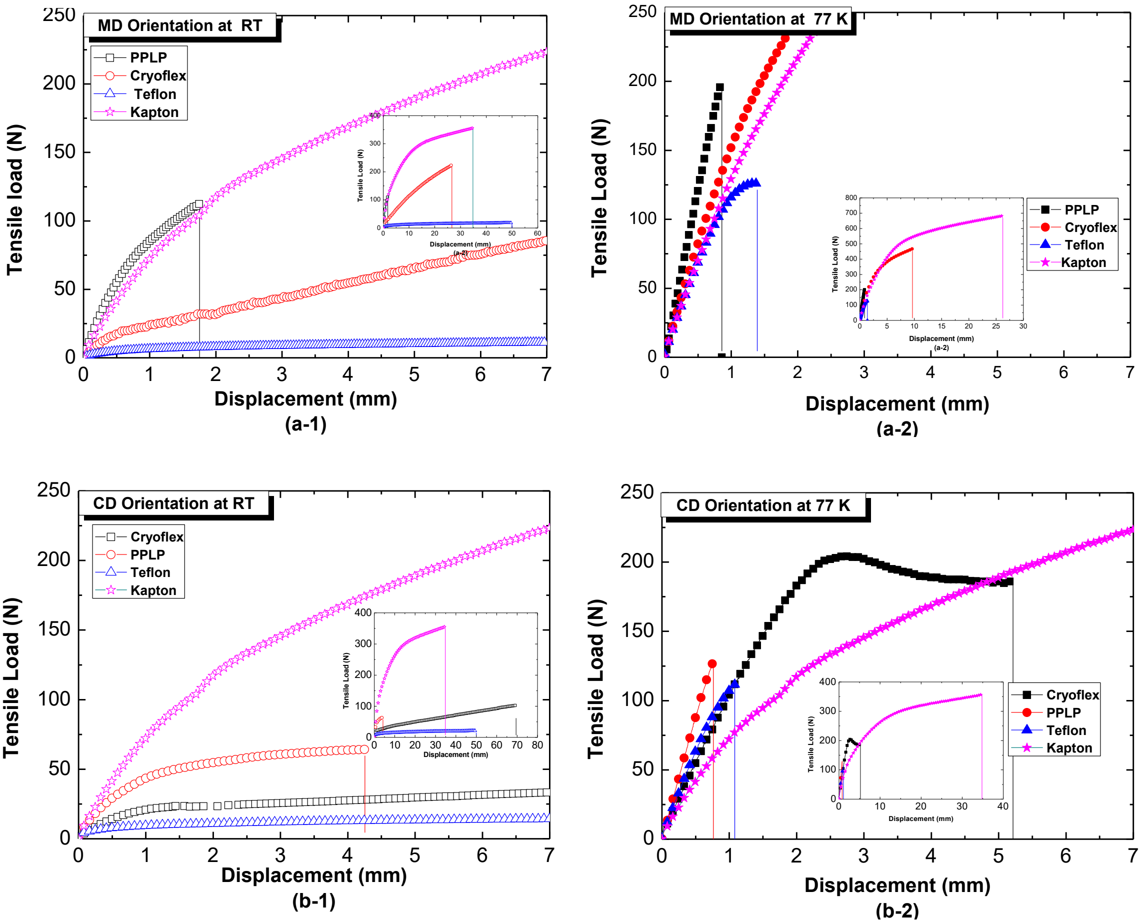


Fig. 3. Load-displacement curves along (a-1) MD of Cryoflex and Kapton at RT, (a-2) MD of PPLP and Teflon at 77K, (b-1) and (b-2) CD of Cryoflex, PPLP and Teflon orientation at RT and 77 K.

The CTE and the thermal contraction of the specimen during cool down from RT to 77 K were calculated using the following formulas [9, 13]:

$$\alpha = \frac{\Delta V}{CF_{@T}(L_{@RT})(\Delta T)} = \frac{\Delta L}{L_{@RT}}\frac{1}{\Delta T} \quad . \qquad (1)$$

$$\varepsilon_{thermal} = \alpha\Delta T = \frac{\Delta L}{L_{@RT}} = \frac{L_{@RT}-L_{T}}{L_{@RT}} \qquad (2)$$

where α is the CTE, ΔV is the output voltage change due to thermal contraction, $CF_{@T}$ is the calibration factor of the double extensometers at a specified temperature which is 77 K with a value of 0.1721 in this study, $L_{@RT}$ is the initial length at RT which corresponds to the gauge length of the extensometer, and ΔT represents the temperature difference during cool down from RT to 77 K. ΔL is the change in specimen length during cool down which corresponds to $\Delta V/CF_{@T}$, and $L_{@T}$ is the length measured at a specified temperature.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties at RT and 77 K

For the evaluation of mechanical properties of various insulation materials, the tension tests were performed for each orientation of samples at RT and 77 K, repectively. Fig. 3(a) and (b) show the load-displacement curves measured along MD and CD orientation for each insulation materials at RT and 77 K, respectively. Practically, all the samples at cryogenic temperature (77 K) exhibited higher tensile load in both MD and CD orientation, but showed smaller displacement compared to RT. The displacement breakage at RT in MD orientation decreased in the order Kapton→Cryoflex→Teflon→PPLP, on the other hand, in the CD orientation the sequence begins at Cryoflex →Teflon→PPLP. In this study, Kapton considered to have only one orientation which is MD among the experiments. At cryogenic temperature, the displacement breakage of specimens showed a significant reduction as compared with the ones at RT. The data gathered in this study agreed with the result in [6] that especially Teflon has significant reduction in the breakage displacement at 77 K.

The failure load at RT decreased in the order of Kapton →Cryoflex→PPLP→Teflon both in CD and MD orientations. In the tensile failure load, the samples tested at cryogenic temperature also showed similar decreasing sequence both in MD and CD orientation. Kapton exhibited the highest failure load among the samples, Cryoflex being the second while Teflon and PPLP have the lower tensile failure load.

Considering the displacement at breakage and tensile

TABLE I
MECHANICAL PROPERTIES OF INSULATION MATERIALS AT RT AND 77 K.

Material orienatition		**Thickness/width (mm)**	**Young's modulus (GPa)**	**Yield strength (MPa)**	**Failure stress (MPa)**	**Failure Load (N)**	**Elongation at break (mm)**	**Elongation at break (%)**
Room temperature (at RT)								
PPLP	**MD**	0.10/15.0	4.95	32.8	50.8	114.3	2.00	2.6
	CD	0.10/15.0	2.40	19.0	22.7	62.3	3.50	4.4
Cryoflex	**MD**	0.09/15.0	3.65	10.3	132.1	237.7	29.4	36.8
	CD	0.09/15.0	0.97	6.50	37.9	102.5	102.7	128.4
Teflon	**MD**	0.12/15.0	-	-	8.40	17.5	29.4	No break
	CD	0.12/15.0	-	-	9.20	19.2	102.7	No break
Kapton	**MD/CD**	0.16/15.0	3.00	34.5	145.1	348.2	33.9	42.4
Cryogenic temperature (at 77K)								
PPLP	**MD**	0.10/10.0	10.8	-	88.6	199.3	0.90	1.1
	CD	0.10/15.0	7.15	-	56.0	121.9	0.70	0.9
Cryoflex	**MD**	0.09/15.0	8.35	134.4	247.0	445.3	8.40	10.5
	CD	0.09/15.0	3.30	55.9	68.6	185.4	6.80	8.5
Teflon	**MD**	0.12/15.0	-	-	59.7	125.4	1.50	1.9
	CD	0.12/15.0	-	-	53.3	112.0	1.10	1.4
Kapton	**MD/CD**	0.16/15.0	5.40	87.1	253	608.0	16.80	21.0

strength, Kapton and Cryoflex are superior to PPLP and Teflon for both testing conditions. Therefore, the comparison of these materials at both RT and cryogenic temperature should be carefully evaluated. Because these insulation materials are being utilized in a superconducting cable operating at cryogenic temperature after installed at RT condition. In Table 1, mechanical properties such as Young's modulus and yield strength at RT and 77 K are listed. It can be found from the table that testing at 77 K both the failure stress and the Young's modulus increased significantly in MD and CD orientation, compared to the samples carried out at RT. The yield strength of the samples was significantly influenced by its orientation since most of the fibers of each samples were alighned to the MD, which explains why mechanical properties along the MD orientation are superior as compared to the CD orientation. This was observed on all samples tested at RT and 77 K.

3.2 Thermal properties at RT and 77 K

Before evaluating CTE and thermal contraction of the insulation sheets using the double extensometers with a 25 mm gauge length, the measurement procedure was checked its validity by using a 50 μm thick brass sheet at 77 K and by comparing obtained values to the reference data [14]. Upon the agreement with the reference data, it can be utilized in measuring thermal properties of insulation sheets at 77 K.

The thermal properties of various insulation materials measured are summarized in Table 2. The value per each sample represents the average of two tests. It then found out that the obtained result on PPLP MD orientation was slighty lower compared to the result obtained in Ref. [9], whichs could be a possible influence of the thickness of the PPLP sheet and different manufacturer. Similarly as the behaviors of mechanical properties exhibited by MD orientation, the thermal properties also indicated that MD orientation showed less CTE and thermal contraction as compared to CD one. MD samples of PPLP (15.50x 10^{-6} /K), Cryoflex (15.61 x 10^{-6} /K) and Kapton (18.88 x10^{-6} /K) showed a low CTE and thermal contraction which making them more promising one as an insulation material due to its comparable CTE with the HTS 2G CC tapes reported elsewhere [15].

TABLE II
THERMAL PROPERTIES OF INSULATION MATERIALS AT 77 K.

Material	**Orientation**	**CTE** ($\times10^{-6}$/K)	**Thermal Contraction** $\Delta L/L_0$ (%)
PPLP	MD	15.5	-0.34
	CD	28.9	-0.64
Cryoflex	MD	15.6	-0.35
	CD	34.2	-0.75
Teflon	MD	48.9	-1.04
	CD	76.2	-1.67
Kapton	MD/CD	18.8	-0.41
Cu-Stabilized CC tape [15]	-	*13.1*	*-0.29*
Brass Laminated CC tape [15]	-	*13.4*	*-0.30*

On the other hand, Teflon exhibited a significantly large thermal contraction during cool down at 77 K, comparing with other insulation sheets. Its CTE and thermal contraction were 48.9x10^{-6} /K and -1.04% in MD orientation, but 76.2x10^{-6} /K and -1.67% in CD orientation, respectively. In superconducting device applications, a large difference in the thermal contraction/expansion between the insulation material and the superconducting wires adopted during cool down can be a possible cause of delamination which might cause the I_c degradation in CC tapes [16]. Therefore, it can be said that the measured CTE in the insulation materials of PPLP, Cryoflex and Kapton along MD direction makes an effective and reliable design of the HTS superconducting devices such as cables and fault current limiters.

Generally, in designing superconducting devices, the understanding of full capabilities of the electrical insulation sheets along its orientation is remarkably important since they are usually fabricated as composite insulators with directional anisotropy. This will possibly improve the electrical insulation and the capability of creating more balanced, superior mechanical and thermal performance by applying multilayered insulation materials along a specific orientation.

4. CONCLUSION

The mechanical and thermal properties of various commercially available insulation materials were evaluated at cryogenic temperature. Mechanical properties of the insulation materials varied and are greatly depended on the testing temperature and the orientation against the applied load. All the samples tested at cryogenic temperature (77 K) exhibited higher tesile failure load both in MD and CD orientation, but showed smaller breakage displacement compared to those at room temperature. And MD samples represented superior mechanical and thermal properties compared to CD ones.

The thermal properties of the superconducting insulation materials exhibited a slight difference among the samples depending on the orientation: for the PPLP and Cryoflex, MD orientation showed a smaller thermal properties compared to CD one. MD samples of PPLP (15.5 x 10^{-6} /K), Cryoflex (15.61 x 10^{-6} /K) and Kapton (18.88x10^{-6} /K) showed a low CTE during cool down to 77 K. Due to the superior mechanical properties of the samples with MD orientation especially in the case of Kapton and Cryoflex and thermal properties of PPLP and Cryoflex made them more promising insulation materials when utilized in the HTS device applications.

This study can be extended to the evaluation of thermal and mechanical properties of composite insulation materials such as particle or fiber-filled epoxy for their application to superconducting device.

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