Critical current measurement method of high temperature superconducting wires – from international RRT (VAMAS TWA 16) to international standard (IEC TC 90) –

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To develop superconducting materials into industrial materials, NIMS has been developing not only superconducting materials but also superconducting magnets and standardization since the era of NRIM. This article presents an outline of the international standard published in June 2020, from the international RRT in VAMAS TWA 16 to the international standard publication in IEC TC 90.

1. Introduction

The most popular property of superconductivity is zero electrical resistance. Since $R = 0$, Ohm's law, $V = RI$, indicates that no voltage is generated in the superconducting state even a large current is flowing. It indicates that the heat generation $Q = IV$ is also zero. In reality, there is a maximum value of current that can maintain the superconducting state, which is called critical current (I_c). For practical purposes, it is important to decide how to measure this value, because different measurement methods may give different values.

IEC TC 90 issued international standards of I_c measurement method of NbTi superconducting wires (IEC 61788-1) in 1998, I_c measurement method of Nb_3Sn superconducting wires (IEC 61788-2) in 1999, and I_c measurement method of Ag-sheathed Bi-2212 and Bi-2223 oxide superconducting wires (IEC 61788-3) in 2000. Among them, standards of Nb_3Sn and oxides superconductors were based on results of international round robin tests (RRTs) promoted by VAMAS TWA 16[1)-3)].

Currently, six (6) kinds of superconducting wires are commercially available, i.e., NbTi, Nb_3Sn, $Bi_2Sr_2CaCu_2O_8$ (Bi-2212), $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223), $(RE)Ba_2Cu_3O_7$ (REBCO, RE=rare earth), and MgB_2. However, before 2020, only three (3) international standards for I_c measurement method were issued, i.e., for NbTi, Nb_3Sn, and Bi-system, as mentioned in the previous section. The international standard for I_c measurement method of REBCO was published in 2020. In this article, we introduce the international RRT that was a source of IEC 61788-26:2020 Superconductivity - Part 26: Critical current measurement - DC critical current of RE-Ba-Cu-O composite superconductors[4)] published in June 2020. We also introduce the procedure of the international standardization.

TABLE 1. REBCO CONDUCTORS FOR RRT

Manufacturer	A	B	C	D
Rare earth	Y	Gd	Y and Gd	Gd
Deposition method	RABiTS /MOD	IBAD /RCE-DR	IBAD /MOCVD	IBAD /PLD
Conductor width [mm]	4.4	4.1	4	5
Conductor thickness [mm]	0.4	0.1	0.095	0.16
Substrate	Ni-5W	Hastelloy C-276	Hastelloy C-276	Hastelloy C-276
Substrate thickness [μm]	50-75	60	50	75
Lamination	Brass	–	–	–
Lamination thickness [μm]	150	–	–	–
Copper stabilizer	–	Both sides	Both sides	Superconductor side
Copper thickness [μm]	–	No info	20×2	75
I_c [A] in inspection report	102	198	89	>250

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2. History of superconductivity standardization

2.1 International round robin test

The international RRT for I_c measurement of REBCO superconductors was planned in 2014. We prepared a draft guideline and discussed it with the IEC TC 90 Japanese National Committee, which is a domestic committee. We, VAMAS TWA 16 secured a budget to procure superconducting wire for measurement samples that are to be distributed to participants of the RRT. We procured commercially available wires from four manufacturers considering a diversity of countries. The manufacturers were American Superconductor (USA), SuNAM (Korea), SuperPower (USA, the parent company is Furukawa Electric Co., Ltd. of Japan), and Fujikura (Japan). The manufacturers in Table 1 are, from left to right, American Superconductor, SuNAM, SuperPower, and Fujikura. Since the names of the manufacturers were not disclosed to the participating organizations and in test results, the names are A, B, C, and D in the table.

Normally, in a round robin test, the same specimen is turned over, is tested at each participating institution, and the results are compared. However, in the case of I_c measurement, since the wire might be burned or degraded by the test, we decided to distribute specimens cut from the same lot respectively.

Ten (10) institutions participated in this international RRT: six (6) from Japan (including NIMS), and one (1) each from Korea, U.S., Italy, and France. Later, since an additional request was made to a domestic institution, the final number of participants was 11.

In I_c measurement, the sample voltage is measured by a high-sensitivity voltmeter while the current is supplied from a current source in a circuit as shown in Fig. 1. Normally, the current supplied to the sample is increased linearly, and I_c is determined as the current value when the sample voltage reaches a certain threshold (Fig. 2). In the international standards that were already published, I_c is determined as the current value when the sample voltage reaches 1 μV/cm electric field. This definition is also adopted in this RRT.

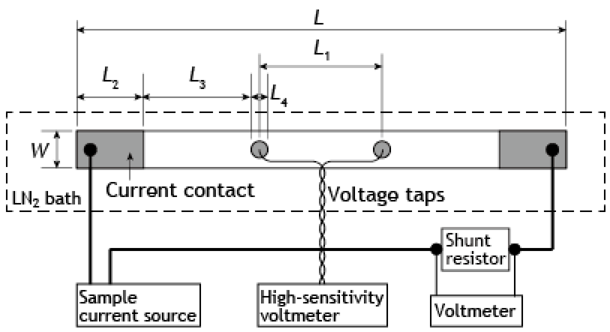

Figure 1. Schematic of I_c measurement setup.

2.1 International round robin test results

Each institution measured five (5) specimens for each wire, which coresponds to five-times measurement, and reported the results. The results are summarized in Table 2. From this table, it can be said that I_c can be measured with a relative standard deviation of around 3%. The subsequent uncertainty analysis shows that most of this standard deviation is due to the non-uniformity of the wire itself, which implies that this level of "variation" is inevitable when the currently commercially available wire is cut into small pieces and tested.

2.2 Uncertainty analysis

At the IEC TC 90 meeting held in 2006, it was decided to introduce *uncertainty* into international standards from the viewpoint of improving the reliability of statistical quantities in standards. Since then, the introduction of uncertainty into

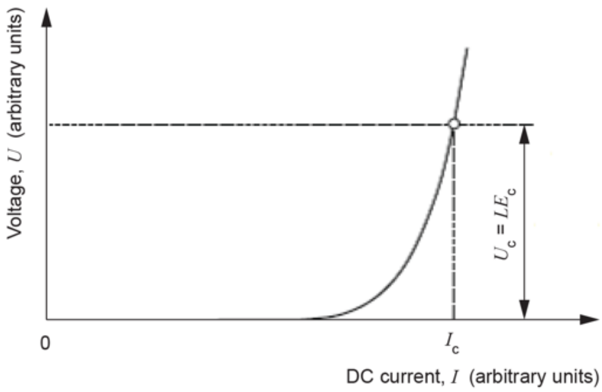

Figure 2. Typical voltage-current characteristics during I_c measurement

TABLE 2. NUMBER OF TESTS, AVERAGE I_C, STANDARD DEVIATION, AND RELATIVE STANDARD DEVIATION FOR EACH CONDUCTOR

Conductor ID	A	B	C	D
Number of tests (*N*)	50	45	50	45
$I_{c,avg}$ [A]	103.42	192.40	90.192	300.08
X_{SD} [A]	3.176	4.447	2.189	5.746
X_{RSD} [%]	3.071	2.311	2.427	1.915

standards has been promoted in the preparation of new or revised standards. The author personally has a negative view of it. The introduction of uncertainty depends on TC in IEC or ISO. However, the decision had already been made before the author was assigned to the position, and the introduction of uncertainty in the standards to be prepared based on this RRT was the prescribed course.

The details of the uncertainty analysis are omitted. To analyze the results of the RRT, various factors were considered, e.g., the distance between the voltage taps, the uncertainty of the voltmeter, the temperature of the liquid nitrogen, etc. However, the result indicates that the inhomogeneity of the wire itself has a significant effect for the uncertainty of I_c measurement[4].

3. Standardization procedure

While the results of the RRT were being compiled, the draft was being prepared and discussed in the domestic committee, the author was loaned to the Ministry of Education, Culture, Sports, Science and Technology. It caused delays, but a new proposal was submitted on January 26, 2017. Although the voting result for this was 100% in favor, 10 pages of comments were submitted from China, France, and US.

If the author had responded to the comments quickly and submitted a CD (Committee Draft) quickly, the work would have progressed much faster. However, since the author was on loaned to MEXT and could not focus on that, it was after returning to NIMS that the author responded, and the CD was not submitted until June 2018. Many comments were submitted again at this stage. In particular, comments from China were very detailed. After this, it was not until 2020 that CDV (Committee Draft for Vote) was followed by FDIS (Final Draft International Standard). At this stage, the main focus was on minor amendments from the IEC Central Secretariat.

The final publication of the standard was on June 11, 2020. It took about three and a half years from the time of the new proposal to the standard. It might have been a little shorter if the author had not been loaned to MEXT. However, we believe that this was largely due to the technical support of the international RRT conducted by VAMAS TWA 16. Most of the standards published by IEC TC 90 so far have been based on RRTs conducted by VAMAS TWA 16, and most of the RRT results have been published in scientific journals. Although the scope of cooperation as VAMAS TWA 16 is indeed narrowing year by year due to tightening budgetary constraints, we will continue to cooperate to the extent possible.

4. Summary

Since the start of its activities, VAMAS TWA 16 (Superconducting Materials) has conducted international RRTs as a pre-standardization and has contributed to most of the international standards issued by IEC TC 90 from a technical point of view. We will continue to cooperate to the extent possible.

References

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