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Welding — Micro joining of second generation high temperature superconductors —

Part 3:
Test methods for joints

Soudage — Micro-assemblage des supraconducteurs à haute température de deuxième génération —

Partie 3: Méthode d'essai des assemblages

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 44, *Welding and allied processes*, Subcommittee SC 10, *Quality management in the field of welding*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 121, *Welding and allied processes,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

A list of all parts in the ISO 17279 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Official interpretations of ISO/TC 44 documents, where they exist, are available from this page: https://committee.iso.org/sites/tc44/home/interpretation.html.

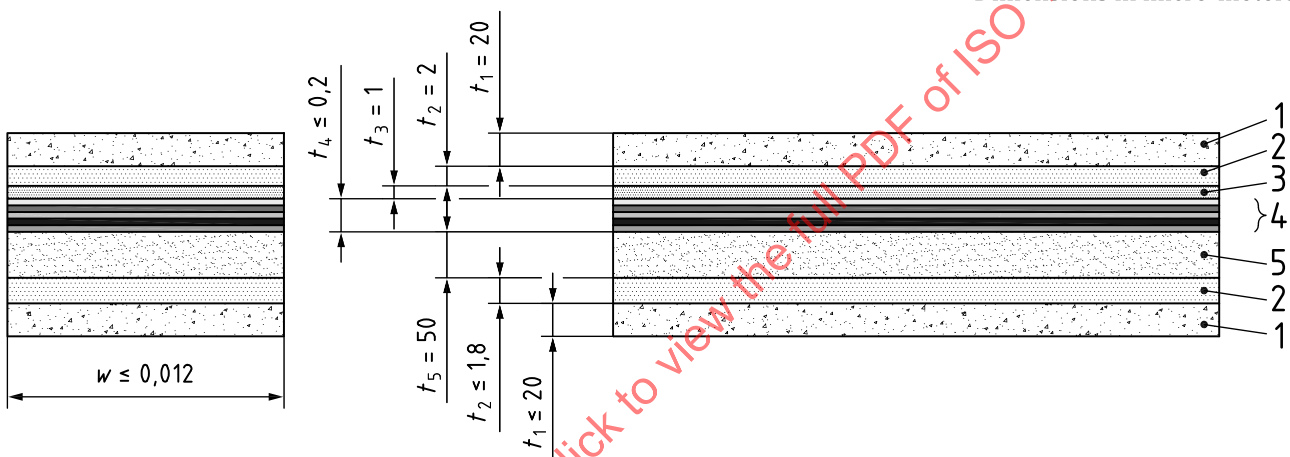
Introduction

The increasing use of second-generation high temperature superconductors (2G HTSs) and invention of resistance-free joining on 2G HTSs have created the need for the ISO 17279 series in order to ensure that joining is carried out in the most effective way and that appropriate control is exercised over all aspects of the operation. ISO standards for micro-joining and joint evaluation procedure are accordingly essential to get the best and uniform quality of 2G HTS joint.

Superconductor is a material that conducts electricity without resistance and has diamagnetism below critical temperature (T_c), critical magnetic field (B_c) and critical current density (J_c). Once set in motion, electrical current flows forever in a closed loop of superconducting material under diamagnetism.

2G HTS constitutes of multi-layers and total thickness is around 60 µm to 90 µm and the superconducting layer made from $REBa_2Cu_3O_{7-x}$ is only 1 µm to 3 µm thick depending on manufacturer's specifications. Figure 1 shows schematic drawing of typical multiple layers, and the constituents and thicknesses of each layer in the 2G HTS.

Dimensions in micro-meters



Key

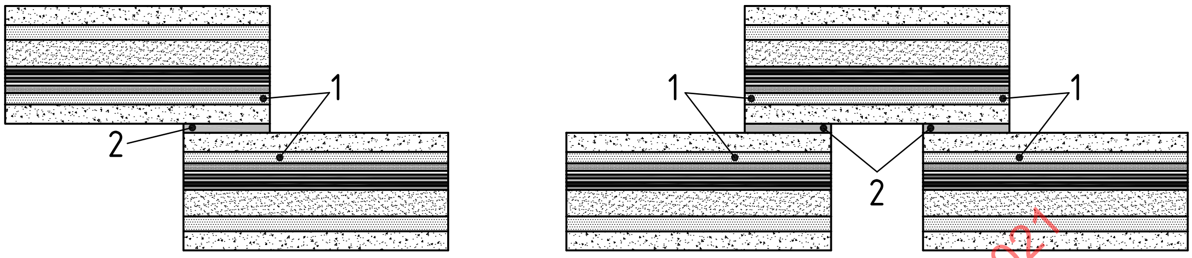
1 Cu stabilizer
2 Ag overlayer
3 REBCO-superconducting layer
4 buffer stack
5 hastelloy®C-276 substrate

t_1 thickness of layer 1
t_2 thickness of layer 2
t_3 thickness of layer 3
t_4 thickness of layer 4
t_5 thickness of layer 5

NOTE Not to scale.

Figure 1 — Typical 2G HTS multi-layers, and the constituents and thicknesses of each layer

Currently soldering, brazing or any filler is applying in superconducting industry as shown in Figure 2, which shows high electrical resistance at the joint providing fatal flaw in the superconductor.



a) **Lap joint** b) **Bridge joint**

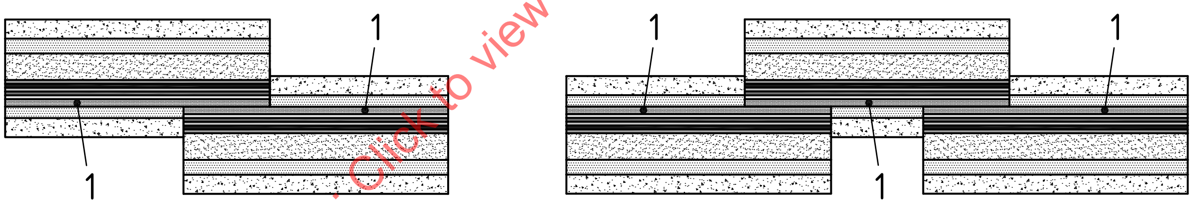
Key

1 REBCO-superconducting layer

2 solder

Figure 2 — Soldering to join 2G HTS

However, the ISO 17279 series focuses on the direct autogenous joining of 1 μm to 3 μm thick superconducting layers of 2G HTSs as shown in Figure 3 without filler metals and recovery of superconducting properties by oxygenation annealing process, which shows almost none electrical resistance at the joint.



a) **Lap joint** b) **Bridge joint**

Key

1 REBCO-superconducting layer

Figure 3 — Direct autogenous joining of 1 μm to 3 μm thick superconducting layers of 2G HTSs for superconducting joint

ISO 17279-1 specifies requirements for the qualification of 2G HTS joining procedure. 2G HTS joints should be capable of performing required electric, magnetic and mechanical properties and free from serious imperfections in production and in service. To achieve that goal, it is necessary to provide controls during design and fabrication.

ISO 17279-2 specifies requirements for the qualification of personnel performing welding and testing.

Welding — Micro joining of second generation high temperature superconductors —

Part 3: Test methods for joints

1 Scope

This document specifies the requirements for the test methods for joint of micro-joining of 2G HTS to fulfil the requirements of ISO 17279-1 and ISO 17279-2.

This document specifies test methods for determining the capability of joints for the production of the specified quality. It defines specific test requirements, but does not assign those requirements to any specific product group.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 17279-1:2018, *Welding — Micro joining of 2nd generation high temperature superconductors — Part 1: General requirements for the procedure*

ISO 15607:2019, *Specification and qualification of welding procedures for metallic materials — General rules*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 17279-1 and ISO 15607 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Test methods for joint

4.1 General

ISO 17279-1:2018, 5.5.4, describes requirements for qualification of test personnel, for test methods, witness during testing and retesting. Especially, ISO 17279-1:2018, Table 1, shows the type of testing, the extent of testing, the confirmation of testing, and required tests for the procedure qualification according to ISO 17279-1. ISO 17279-1:2018, 5.9, requires the acceptance criteria of the tests. The manufacturer can have at their disposal sufficient competent personnel for the testing and operating the test equipment, or can contract the specific tests to the specialized organizations. The manufacturer can witness the tests from specimen preparation to data acquisition and analysis according to manufacturer's quality assurance requirements.

The operating procedures and cautions of the test equipment shall be applied when the equipment is used for testing according to this document. The operator of the specific equipment shall establish the capability to perform the required test, and calibration and qualification of the test equipment shall be maintained up-to-date according to an appropriate quality management program. Qualification records and certificates shall be kept up-to-date.

The tests except visual testing shall be performed at the cryogenic environment and do not purport to address the safety concerns associated with its use. It is the responsibility of whoever uses this method to establish appropriate safety and health practices prior to use.

4.2 Visual testing

4.2.1 General

This subclause defines the method of visual testing of materials and joints used in 2G HTS.

4.2.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program. Personnel conducting visual testing shall annually pass an examination where their vision, with or without correction, meets the Jaeger J2 near vision test at a distance not less than 30,5 cm as well as a colour perception test. The vision examination records shall be maintained for the current year and shall be available for review.

4.2.3 Test equipment

Calibrated instruments shall be used for testing, wherever required, this includes all necessary measuring instruments and gauges.

4.2.4 Surface condition and preparation

The surface for the test shall be uniform and smooth and shall be clean and free of scale, rust, oil, grease, detrimental oxides and other deleterious foreign materials such as Ag or Cu spots of 2G HTS. The surfaces of the finished joints shall be suitable to permit proper testing. All joint preparations shall meet drawing specified dimensions (whether provided via dimensions on the drawing or in a welding specification). If no dimensions are provided as part of the drawing or ordering documents, the dimensions shall meet dimensions specified by approved welding procedure specification (WPS).

4.2.5 Testing

Testing shall be performed in accordance with a written procedure or method applicable under testing. The testing area shall include the joint and the accessible adjacent heat-affected zone (HAZ) for some distance from the joint edge of the base metal. The testing shall be in the after joining and final heat-treated condition (oxygenation annealing), or otherwise required, and be free of all coatings and other surface conditions such as paint, plating, etc. The joints shall be tested in the as-welded condition. Testing will be conducted with specimen suitable dimensions.

Direct visual testing shall be used. If required, mirrors and magnifying lenses are used to improve the angle of vision and to assist. The minimum light intensity at the surface is 1 000 lux (100 foot-candles). The written procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number and date, revision number, identification of joints, complete testing requirements including lighting and method of testing, evaluation of indications, acceptance criteria, disposition of joints after evaluations.

4.2.6 Acceptance criteria

The requirements of ISO 17279-1:2018, Table 4, shall be met. Lack of bonding, lack of fusion, cracks and pin holes are not acceptable.

4.2.7 Test report

After the completion of the testing, the results shall be entered in the test report. A form of a test report is shown in Annex A.

4.3 Four-point-probe testing

4.3.1 General

This subclause defines the method of four-point-probe testing of base materials and joints used in 2G HTS. Critical current (I_c), critical current density (J_c) and *n*-value can be measured from the test.

NOTE Typically, the resistance of the point of contact (contact resistance) is far smaller than the resistance of the test specimen, and can thus be ignored. However, for superconductors under cryogenic conditions, the contact resistance can dominate and completely obscure changes in the resistance of the test specimen itself. The effects of contact resistance are eliminated with the use of four-point-probe testing.

4.3.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program.

4.3.3 Test equipment

Calibrated instruments shall be used for testing.

4.3.4 Surface condition and preparation

Subclause 4.2.4 shall apply.

4.3.5 Testing

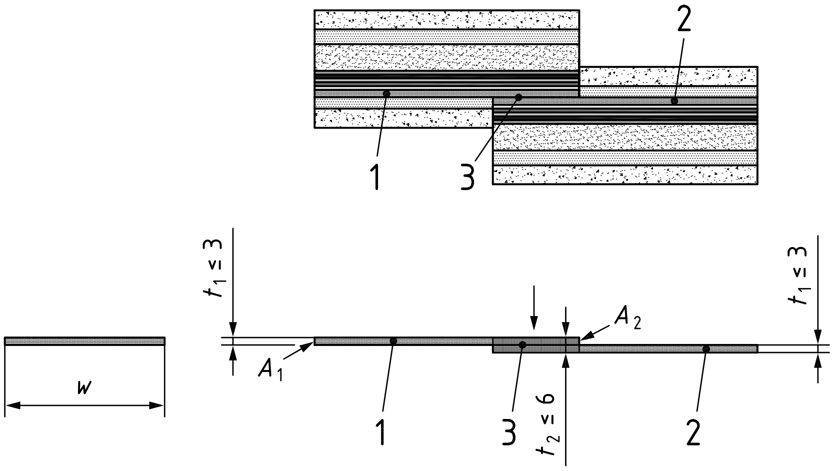
4.3.5.1 General

Testing shall be performed in accordance with a written test procedure or method applicable to the 2G HTS. The written test procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number, date, revision number, identification of joints, complete testing requirements including method of testing, evaluation and reporting after evaluations.

The testing area shall include the joint and the accessible adjacent HAZ of base material for some distance from the joint edge. The total length of specimen shall be at least 60 mm including 20 mm joint. The test shall be done after joining and final heat-treated condition (oxygenation annealing), or otherwise required, and is carried out at the LN2 cryogenic environment or other temperature determined by the manufacturer. The test shall be done at weld reinforced condition with commercially available materials considering thermal shrinkage coefficient so as not for joints to be damaged during the test.

Schematic of two superconducting layers with lap-joint in 2G HTS is shown in Figure 4. When current passes through a superconducting layer (1 µm to 3 µm thick) of 2G HTS from superconducting layer 1 to joint to superconducting layer 2, the current generates a voltage difference between superconducting layer 1 and superconducting layer 2. 2G HTS without joint and HAZ is resistance-free in cryogenic environment, thus the most voltage difference comes from joint and HAZ.

Dimensions in micro-meters

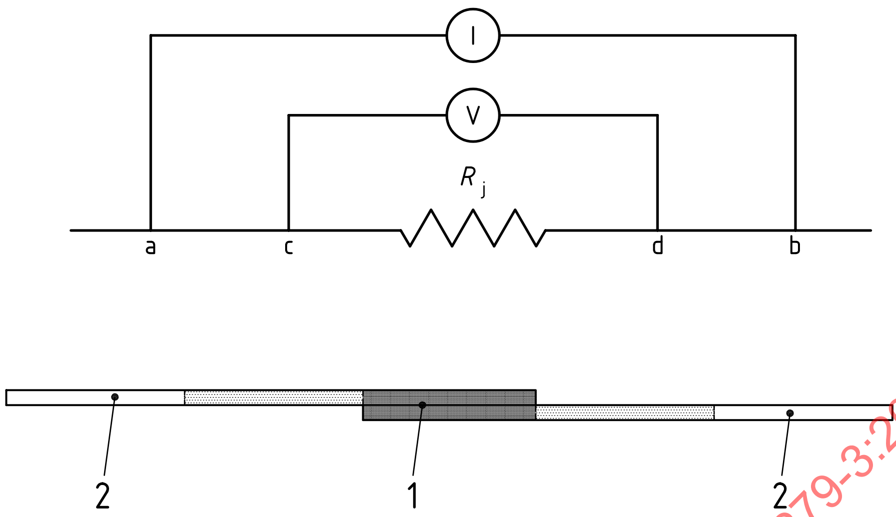


Key

1 upper superconducting layer
2 bottom superconducting layer
3 joining area
w width of superconducting layer
t_1 thickness of superconducting layer (1 µm~3 µm)
t_2 almost 2 t_1 or slightly less than 2 t_1 depending on pressure during joining
A_1 cross-sectional area of superconducting layers 1 and 2 ($A_1 = t_1 \times w$)
A_2 cross-sectional area of lap-joined two superconducting layers ($A_2 = t_2 \times w$)

Figure 4 — Typical 2G HTS multi-layers, and the constituents and thicknesses of each layer

Figure 5 is a schematic of four-point-probe testing in lap-joined 2G HTS. Four probes are attached to the test specimen as shown in the figure. A current is made to flow the length of the test specimen through probes labelled a and b in the Figure 5. This can be done using a current source or a power supply having current output readout. If the test specimen has any resistance to the flow of electrical current, then there is a drop of potential (or voltage) as the current flows along the test specimen, for example between the two probes labelled c and d in the figure. The voltage drop between probes c and d can be measured by a digital voltmeter. The resistance of the test specimen between probes c and d is the ratio of the voltage registering on the digital voltmeter to the value of the output current of the power supply. The high impedance of the digital voltmeter minimizes the current flow through the portion of the circuit comprising the voltmeter. Thus, since there is no potential drop across the contact resistance associated with probes c and d, only the resistance associated with the joint and associated HAZ of superconductor between probes c and d is measured as a function of current. 2 HAZ lengths adjacent to the joint are about twice of joint length. However, the HAZ is dependent on the heat input and dwell time during joining. Manufacturer may determine the HAZ length by four-point-probe testing.



Key

1 joining area

2 heat-affected zone (HAZ)

R_j electrical resistance of the joint

[a] Current lead 1.

[b] Current lead 2.

[c] Voltage tap 1.

[d] Voltage tap 2.

Figure 5 — Schematic of four-point-probe testing in lap-joined 2G HTS CC

The test procedure is as follows.

a) Attach c and d (joint fusion line each) probes to the test specimen and connect to a digital voltmeter and attach a and b (5 mm from the c and d each) probes to an ammeter and a power supply. A strip chart recorder may be connected between probes c and d.

b) Set the thermocouple reader to read the K thermocouple and read the symbol of the thermocouple attached to the thermocouple. Do not bend the thermocouple.

c) Place the container, test specimen with attached probes, and thermocouple. Pour liquid nitrogen or other cryogen into the container. Read the potential across the thermocouple.

d) When the container is completely cooled and the temperature drops to about 70 K or whatever decided, turn the power supply on. When the resistance of the superconductor changes with variable current, the voltage output changes. Read the potential difference on the voltmeter. The ratio of the voltage to the current flowing through the test specimen is the resistance of the superconductor between the two voltage probes (c and d).

In Figure 5, current (I) passes through the two end probes (a and b) and voltage (V) is measured between the two centre probes (c and d) which is for joint and HAZ. The average resistance, R, between the two centre probes (c and d) is calculated from Formula (1).

$$I = V / R \quad (1)$$

where

V is the voltage difference;

I is the current flow between the two centre probes (c and d).

R is also given by Formula (2) because most voltage difference comes from joint and HAZ.

$$R_j = \rho_j \times l_j / A_2 \text{ or } R_{HAZ} = \rho_{HAZ} \times l_{HAZ} / A_1 \quad (2)$$

where is

ρ_j is the resistivity of the joint in Ω-cm;

ρ_{HAZ} is the resistivity of the HAZ in Ω-cm;

l_j is the length of the joint measured in cm;

l_{HAZ} is the length of the HAZ measured in cm;

A_1 and A_2 is the cross-sectional areas of superconducting layer and lap-joined two superconducting layers in cm^2, respectively.

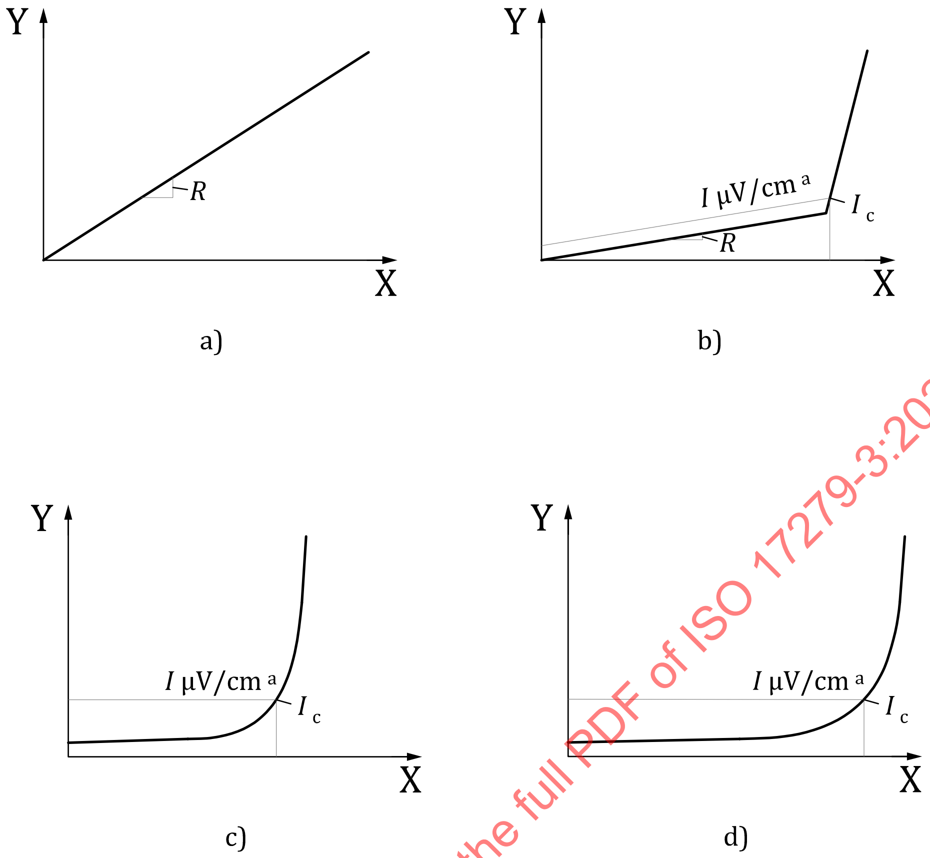
Thus, total resistance of the test specimen with lap-joint is as Formula (3).

$$I = V / (R_j + R_{HAZ}) \quad (3)$$

4.3.5.2 Self-field critical current (I_c)

Critical current value of joint ($I_{c,j}$) is extremely important to confirm joint integrity. The self-field critical current (I_c) values of the joined superconductor shall be measured using a standard four-point-probe testing and in a bath of liquid nitrogen (LN_2) or other pre-determined cryogenic environment. Although this method is not an ultimate method, it is quite effective in the first-round evaluation. If the current is plotted versus the voltage reading in 2G HTS, the result is similar to that shown in Figure 6. The V-I curve is obtained from a commercially available data acquisition system (DAS) and LabVIEW[1]. The DAS and LabVIEW shall be calibrated.

1) LabVIEW is the trademark of a product. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.



Key

X current in A

Y voltage in V

Figure 6 — Examples of *V-I* curve measured in joint of 2G HTS CC

Figure 6 a) and b) show resistance and are not superconducting joints. However, Figure 6 c) and d) shows perfect superconducting joint, of which the slope of *V–I* curve is zero (zero voltage and resistance) till around its critical current (I_c). Figure 6 c) is lower than the virgin (heat-unaffected base metal) and Figure 6 d) is same of the virgin, respectively. The self-field I_c values of the 2G HTS joint shall be measured using a 1 µV/cm criterion from the *V-I* curve obtained by four-point-probe testing. When the distance between voltage taps [Figure 6 c) and d)] is 8 cm, the current value at 8 µV is critical current (I_c).

4.3.5.3 Critical current density (J_C)

J_c characterizes the maximum electrical transport current per cross-sectional unit area that the superconductor is able to maintain without resistance and is expressed in terms of I_c divided by joined cross-sectional area. The cross-sectional areas of virgin (base metal) and joint in Figure 4 are A_1 and A_2 respectively and expressed as Formula (4).

$$J_{c,v} = I_{c,v} / A_1 \text{ or } J_{c,j} = I_{c,j} / A_2 \tag{4}$$

For example, when the thickness and width of superconducting layer in 2G HTS are 1 µm and 4 µm, respectively, and I_c of 84 A in Figure 6 d) is applied, A_1 and A_2 are 4 µm^2 and 8 µm^2. Then, $J_{c,v}$ and $J_{c,j}$ can be calculated as 21 A/µm^2 and 10,5 A/µm^2, respectively, which are extremely high due to 2G HTS.

4.3.5.4 *n*-value

Most V-I characteristics in 2G HTS can be approximately expressed by $V \propto I^n$, which is typically quantified by the parameter, n. The *V-I* transition to the normal state is defined by Formula (5).

$$(\rho / \rho_c) = (I / I_c)^n \text{ or } (V / V_c) = (I / I_c)^n \quad (5)$$

where

ρ_c is the critical resistivity;

V_c is the critical voltage;

I_c is the critical current.

This parameterization has been very useful in the high J_c superconductors, where the *n*-value is regarded as an index of the superconductor quality. The *n*-value can vary significantly in conductors with higher resistivity. The power relation is a practical way to analyse the transition. The *n*-value is a useful tool to evaluate a conductivity (σ) of 2G HTS. A high *n*-value is inversely related to the width of the *V–I* transition. In turn, the width of the distribution is reflected in the *n*-value, where n is proportional to σ. Higher *n*-value indicates substantial improvement in J_c. Likewise, the *n*-value characterizes the sharpness of a resistive transition in the *V–I* curve at I_c measurement. When the *n*-value is higher, the resistivity is lower and the superconductivity is better.

Figure 7 a) illustrates an example of low *n*-value. Figure 7 b) illustrates a high *n*-value in *V–I* curve of four-point-probe testing in 2G HTS. The *n*-value is measured as follows:

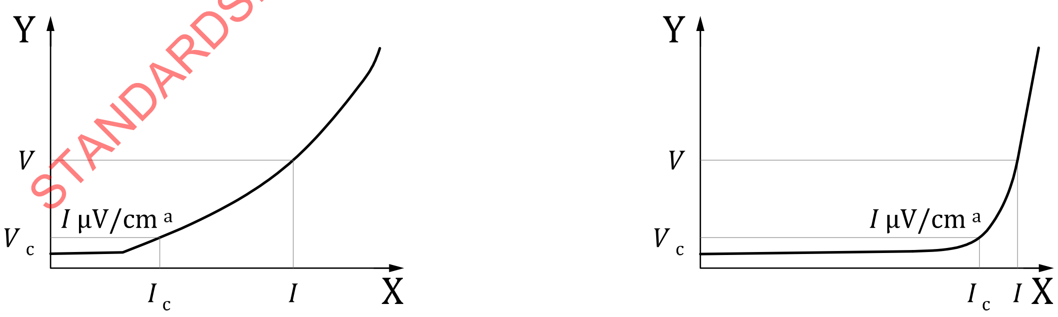
a) apply *l* µV/cm criterion to determine V_c and I_c;

b) select the pre-determined voltage (V) and determine the current (I) in the curve;

c) transfer the numbers (V, V_c, I, I_c) to Formula (6):

$$n = \ln (V / V_c) / \ln (I / I_c) \quad (6)$$

When *n*-values are directly compared from the different *V-I* curves, apply the same pre-determined V in the *V-I* curves. For example, when V_c, V, I_c and I are 1 µV, 50 µV, 10 A and 50 A respectively in Figure 7 a), and V_c, V, I_c and I are 1 µV, 50 µV, 84 A and 89 A respectively in Figure 7 b), n can be calculated as 1 in Figure 7 a) and 67,45 in Figure 7 b) by applying Formula (6).



a) **Low *n*-value**   b) **High *n*-value**

Key

X current in A

Y voltage in µV

a Criterion.

Figure 7 — Examples of *n*-value in *V-I* curve of four-point-probe testing

4.3.5.5 Cyclic thermal shock characteristic

The cyclic thermal shock is to determine the I_c variations or profiles of the joint in cyclic thermal shock in liquid nitrogen bath or other cryogenic environments. The cryogenic environments, cycles for thermal shock, temperatures (high and low) and number of tests are determined by the manufacturer. Table 1 shows recommended parameters for cyclic thermal shock.

Table 1 — Recommended parameters for cyclic thermal shock testing

Cryogenic environments	Cycles for thermal shock	Temperature		Holding time at high and low temperature		Number of tests
		High	Low	High	Low	
Liquid nitrogen or temperature decided by the manufacturer	5	Room temperature	Liquid nitrogen or temperature decided by the manufacturer	30 min	30 min	5

4.3.6 Acceptance criteria

The requirements of ISO 17279-1:2018, Table 5, shall be met.

4.3.7 Test report

After the completion of the testing, the results shall be entered in the test report. A form of a test report is shown in Annex B.

4.4 Field-decay testing

4.4.1 General

This subclause defines the method of field-decay testing of joints used in 2G HTS. A field-decay technique is used to determine the resistance of a 2G HTS closed loop with a 2G HTS joint to a level below 10^{-12} Ω and magnetic field strength variation over time.

4.4.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program.

4.4.3 Test equipment

Calibrated instruments shall be used for testing.

4.4.4 Surface condition and preparation

Subclause 4.2.4 shall apply.

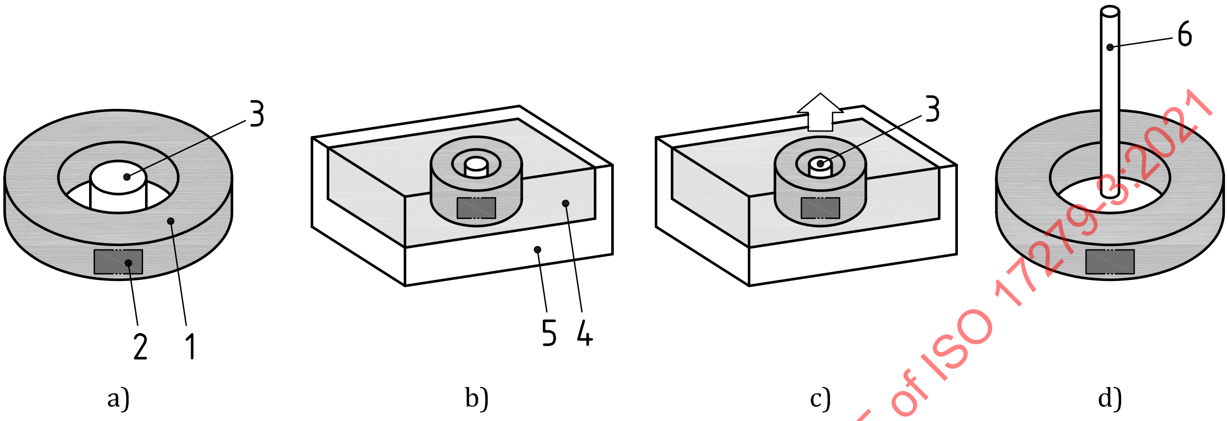
4.4.5 Testing

Testing shall be performed in accordance with a written procedure or method applicable to the 2G HTS. The written test procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number, date, revision number, identification of joints, complete testing requirements including method of testing, evaluation and reporting after evaluations.

The testing area shall include the joint and the accessible adjacent HAZ of base material. The test shall be done after joining and final heat-treated condition (oxygenation annealing), or otherwise required, and is carried out at the LN_2 cryogenic environment or other temperature determined by the manufacturer.

The joined specimen that I_c was tested and accepted shall be used for this test. The test shall be done at weld reinforced condition with commercially available materials considering thermal shrinkage coefficient so as not for joints to be damaged during the test.

In this technique, the time-dependent changes in a magnetic field generated by a current flowing in a circular loop containing an HTS joint are measured over a period of time lasting for hours or days. Figure 8 shows a schematic drawing of the principle of the method and measurement setup used to measure the joint resistance of a superconductor joint in a bath of liquid nitrogen (LN_2, 77 K or -196 °C).



Key

1 superconductor coil

2 joint

3 permanent magnet or electromagnet

4 styrofoam bath

5 liquid nitrogen or other cryogen

6 hall sensor

Figure 8 — Field-decay testing

The procedure is as follows.

1) Wind the superconductor coil with joints.

2) Insert the permanent magnet or electromagnet into the bore of superconductor coil with joints.

3) Fill the styrofoam container with liquid nitrogen or other cryogen. Then, the superconductor coil becomes superconducting in the presence of a magnetic field induced by the permanent magnet or the electromagnet.

4) Hold the permanent magnet or electromagnet in the liquid nitrogen or other cryogen for 10 min.

5) Lift the permanent magnet or the electromagnet out of the coil bore.

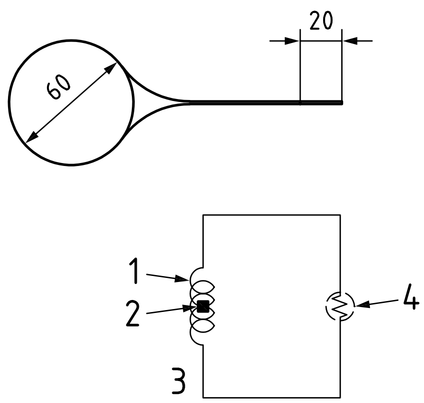
6) Place the hall sensor at the bore of the closed loop.

7) Measure the induced time-dependent magnetic field change by the Hall sensor and record it in the data acquisition system (DAS).

Figure 9 a) shows schematic sketch of 5 turns of 2G HTS coil wound coil with 60 mm inner diameter and 20 mm joint located outside of coil and circuit diagram which hall probe is inserted into the 2G HTS coil. Figure 9 a) also shows table of experimental data for recording.

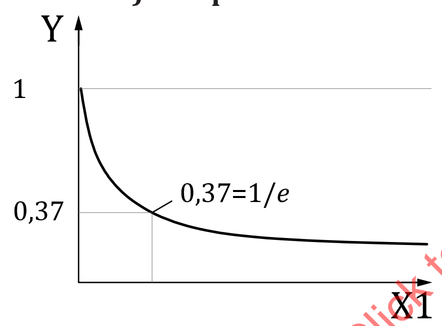
For an example of procedure, a Nd-Fe-B permanent magnet disk (0,35 tesla) is inserted into the 2G HTS loop bore. When liquid nitrogen (LN_2) is poured into the styrofoam container, the 2G HTS achieves superconductivity in the presence of the magnetic field induced by the Nd-Fe-B magnet (that is, fieldcooling occurred). After the permanent magnet is lifted out of the loop bore, a Hall sensor is placed at the centre of the closed loop. The induced magnetic field on the 2G HTS is measured by the Hall probe with an accuracy of 10^{-2} Gauss and recorded with a DAS. Figures 9 b) and c) shows the decay behaviour of the induced field in the closed-loop 2G HTS model coil with joint. The vertical axis is normalized to the initial magnetic field.

Dimensions in millimetres

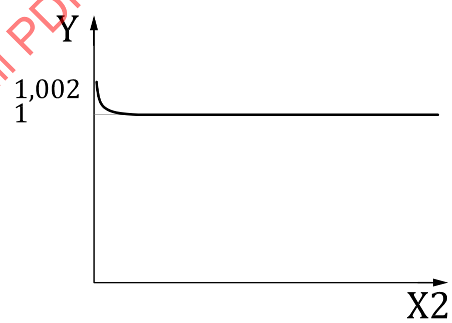


Parameters	Values
Inner diameter [mm]	60
Number of turns	5
Coil inductance [μH]	
Coil constant [mT/A]	

a) **Preparation**



b) **Test result**



c) **Test result**

Key

X1 time in s
X2 time in d
Y $B(t)/B(t_0)$ in tesla
1 2G HTS coil
2 Hall probe
3 LN_2 or other cryogenic environment
4 superconducting joint

Figure 9 — Test sample experiment preparation and test results

The field-decay rate and joint resistance of the 2G HTS model coil are given by Formulae (7) and (8), respectively:

$$B(t) = B(t_0)\, e^{-(Rj/L)t} \quad (7)$$

$$R = -L \times \ln[B(t)/B(t_0)] / t \quad (8)$$

where

$B(t)$ is the induced magnetic field at t in tesla;

$B(t_0)$ is the initial magnetic field in tesla;

R_j is the joint resistance in Ω;

L is the self-inductance of a closed loop in henry;

t is the time in s.

Figure 9 b) is an example of field-decay time as a function of $B(t)/B(t_0)$ at coil with resistive joint. The joint resistance (R_j) is calculated by applying t when $B(t)/B(t_0)$ is at 1/e which is 0,37. Figure 9 c) is an example of field-decay time as a function of $B(t)/B(t_0)$ at coil with resistance-free superconducting joint.

4.4.6 Acceptance criteria

The requirements of ISO 17279-1:2018, Table 6, shall be met.

4.4.7 Test teport

After the completion of the testing, the results shall be entered in the report. A form of the report is shown in Annex C.

4.5 In-field testing

4.5.1 General

This subclause defines the method of in-field testing of joints used in 2G HTS. An in-field technique is used to verify the joint I_c or J_c variations at different cryogenic conditions (20 K, 30 K, 50 K and 77 K) under different externally applied magnetic field (0 T; 0,35 T; 0,7 T; 1,0 T; 2,0 T and 3,0 T; where T is the magnetic strength unit in terms of tesla).

4.5.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program.

4.5.3 Test equipment

Calibrated instruments shall be used for testing.

4.5.4 Surface condition and preparation

Subclause 4.2.4 shall apply.

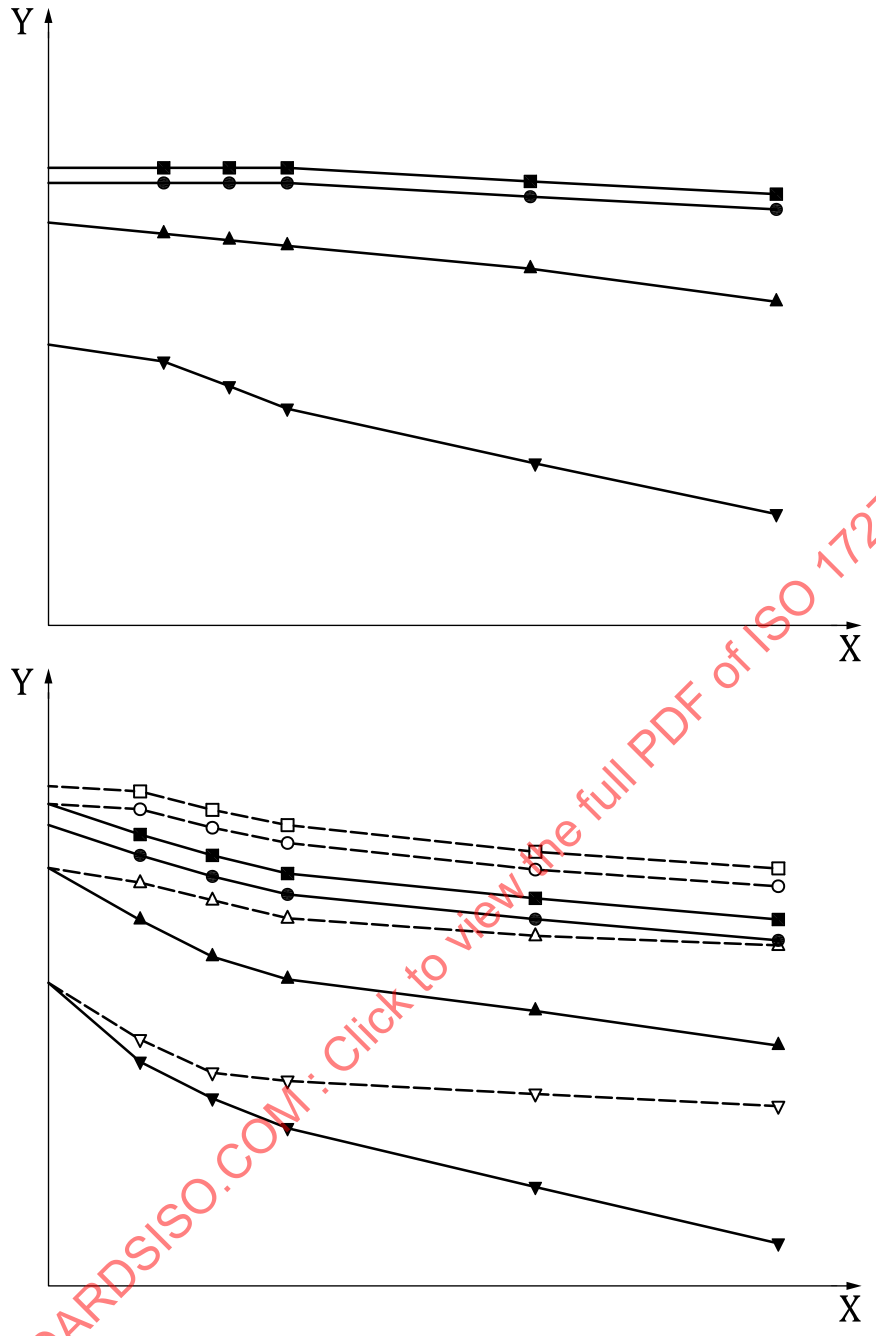
4.5.5 Testing

Testing shall be performed in accordance with a written procedure or method applicable to the 2G HTS. The written test procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number, date, revision number, identification of joints, complete testing requirements including method of testing, evaluation and reporting after evaluations.

The testing area shall include the joint and the accessible adjacent HAZ of base material. The test shall be done after joining and final heat-treated condition (oxygenation annealing), or otherwise required and is carried out at the LN_2 cryogenic environment or other temperature determined by the manufacturer. The specimen used for I_c test or a new specimen may be used for this test. The test shall be done at weld reinforced condition with commercially available materials considering thermal shrinkage coefficient so as not for joints to be damaged during the test.

In this technique, the magnetic field-dependent changes in a self-field critical current (I_c) values of the joined superconductor generated by a standard four-point-probe testing in 4.3.5.1 shall be measured in a bath of liquid nitrogen (LN_2) or other pre-determined cryogenic environment.

Figure 10 shows examples of normalized I_c variations, of which magnetic direction is parallel or perpendicular to the superconducting tape respectively, as a function of magnetic field and cryogenic temperatures. The magnetic fields applied can be determined according to manufacturer's requirement.



Key

X magnetic field in T

Y $I_c(B)/I_c$ (77 K, 0 T)

- ■ 20 K
- ● 30 K
- ▲ 50 K
- ▼ 77 K
- □ SF_20 K
- ○ SF_30 K
- △ SF_50 K
- ▽ SF_77 K

Figure 10 — Example of in-field test results

4.5.6 Acceptance criteria

The requirements of ISO 17279-1:2018, Table 7, shall be met.

4.5.7 Test report

After the completion of the testing, the results shall be entered in the test report. A form of a test report is shown in Annex D.

4.6 Tensile testing

4.6.1 General

This subclause defines the method of tensile testing of joints used in 2G HTS. A tensile testing is used to determine the strength of joint. The strength of 2G HTS is determined by joint strength.

4.6.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program.

4.6.3 Test equipment

Calibrated instruments shall be used for testing.

4.6.4 Surface condition and preparation

Subclause 4.2.4 shall apply.

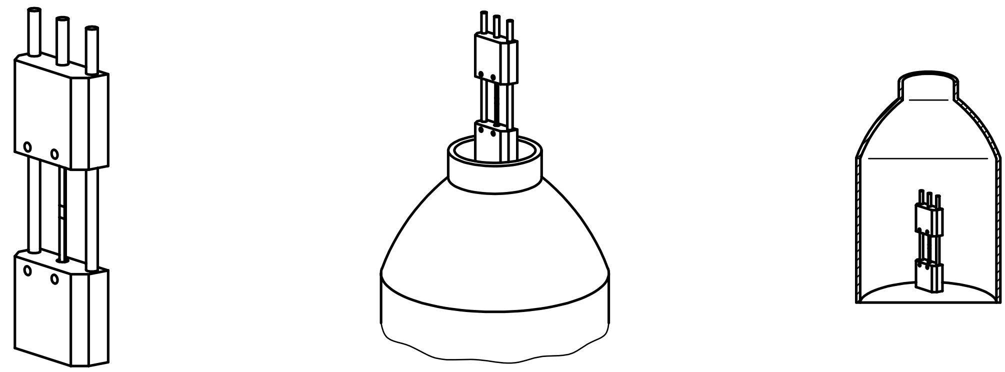
4.6.5 Testing

The test is similar to ordinary metal tensile test except that it carries out at the LN_2 cryogenic environment or other temperature determined by the manufacturer and the specimen is either as welded condition (lap, bridge or other joint types) or weld reinforced condition with commercially available materials considering thermal shrinkage coefficient.

Testing shall be performed in accordance with a written procedure or method applicable to the 2G HTS. The written test procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number, date, revision number, identification of joints, complete testing requirements including method of testing, evaluation and reporting after evaluations.

The testing area shall include the joint and the accessible adjacent HAZ of base material. The test shall be done after joining and final heat-treated condition (oxygenation annealing), or otherwise required and is carried out at the LN_2 cryogenic environment or other temperature determined by the manufacturer. The specimen used for I_c test or a new specimen may be used for this test. The tests in cryogenic conditions which show I_c can determine the critical tensile values.

The test may be done either at weld reinforced condition with commercially available materials considering thermal shrinkage coefficient or as-welded condition. Figure 11 shows the example of tensile tests in cryogenic condition.



a) Hold the specimen to the tensile tester   b) Insert the specimen into the cryogenic container   c) Under tensile testing

Figure 11 — Example of tensile test of 2G HTS in cryogenic condition

4.6.6 Acceptance criteria

The requirement of ISO 17279-1:2018, Table 8, shall be met.

4.6.7 Test report

After the completion of the testing, the results shall be entered in the test report. A form of a test report is shown in Annex E.

4.7 Bend testing

4.7.1 General

This subclause defines the method of bend testing of joints used in 2G HTS. A bend testing is used to determine the minimum bending diameter.

4.7.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program.

4.7.3 Test equipment

Calibrated instruments shall be used for testing.

4.7.4 Surface condition and preparation

Subclause 4.2.4 shall apply.

4.7.5 Testing

Testing shall be performed in accordance with a written procedure or method applicable to the 2G HTS. The written test procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number, date, revision number, identification of joints, complete testing requirements including method of testing, evaluation and reporting after evaluations.

The testing area shall include the joint and the accessible adjacent HAZ of base material. The test shall be done after joining and final heat-treated condition (oxygenation annealing), or otherwise required and is carried out at the LN_2 cryogenic environment or other temperature determined by the manufacturer. The specimen used for I_c test or a new specimen may be used for this test. The tests in cryogenic conditions which show I_c can determine the critical bending diameter value.

Dimensions in millimetres

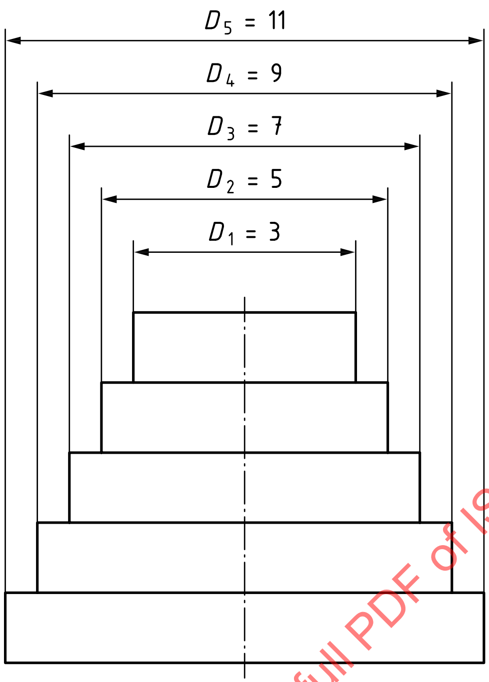


Figure 12 — Bend measurement tools

4.7.6 Acceptance criteria

The requirement of ISO 17279-1:2018, Table 9, shall be met.

4.7.7 Test report

After the completion of the testing, the results shall be entered in the test report. A form of a test report is shown in Annex F.

4.8 Critical magnetic field testing

4.8.1 General

This subclause defines the method of critical magnetic field testing of joints used in 2G HTS. A critical magnetic field testing is to verify the joint critical magnetic field (B_c) characteristic.

4.8.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program.

4.8.3 Test equipment

Calibrated instruments shall be used for testing.

4.8.4 Surface condition and preparation

Subclause 4.2.4 shall apply.

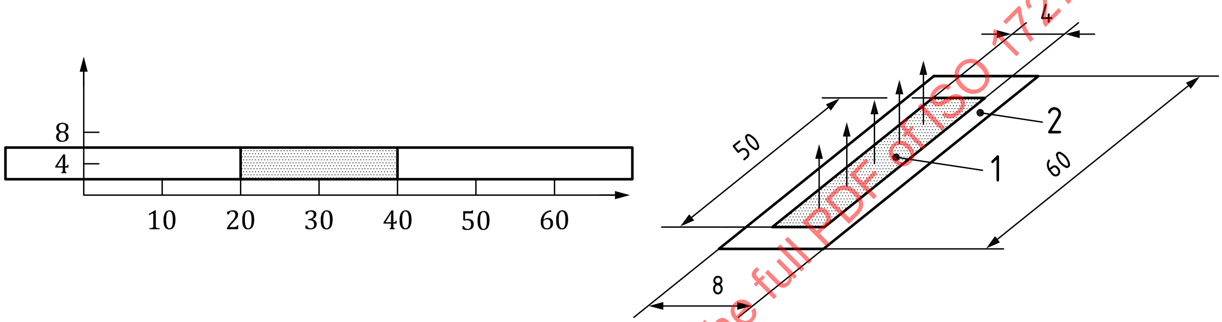
4.8.5 Testing

Testing shall be performed in accordance with a written procedure or method applicable to the 2G HTS. The written test procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number, date, revision number, identification of joints, complete testing requirements including method of testing, evaluation and reporting after evaluations.

The testing area shall include the joint and the accessible adjacent HAZ of base material. The test shall be done after joining and final heat-treated condition (oxygenation annealing), or otherwise required and is carried out at the LN_2 cryogenic environment or other temperature determined by the manufacturer. The specimen used for I_c test or a new specimen may be used for this test. The tests in cryogenic conditions which show I_c can determine the critical bending diameter value.

Critical magnetic field (B_c) may be tested, of which magnetic fields are perpendicular to the 2G HTS tape. Figure 13 illustrates the test for magnetic field distribution profile.

Dimensions in millimetres



Key

1 trap field

2 scanning area

Figure 13 — Magnetic field testing

4.8.6 Acceptance criteria

The requirements of ISO 17279-1:2018, Table 10, shall be met.

4.8.7 Test report

After the completion of the testing, the results shall be entered in the test report. A form of a test report is shown in Annex G.

4.9 Critical current density distribution testing

4.9.1 General

This subclause defines the method of critical current density distribution testing of joints used in 2G HTS. A critical current density distribution testing is to verify the joint critical current density distribution profiles and characteristics.

4.9.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program.

4.9.3 Test equipment

Calibrated instruments shall be used for testing.

4.9.4 Surface condition and preparation

Subclause 4.2.4 shall apply.

4.9.5 Testing

Testing shall be performed in accordance with a written procedure or method applicable to the 2G HTS. The written test procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number, date, revision number, identification of joints, complete testing requirements including method of testing, evaluation and reporting after evaluations.

The testing area shall include the joint and the accessible adjacent HAZ of base material. The test shall be done after joining and final heat-treated condition (oxygenation annealing), or otherwise required, and is carried out at the LN_2 cryogenic environment or other temperature determined by the manufacturer. The specimen used for I_c test or a new specimen may be used for this test. The tests in cryogenic conditions which show I_c can determine the critical current density distribution.

The technique for the non-destructive evaluation of the critical current density (J_c) distribution is to measure magnetic field distribution generated by the J_c distribution at the joint. The magnetic field due to J_c distribution can be measured by a magneto-optical technique or by a Hall sensor scanning technique.

4.9.6 Acceptance criteria

The requirements of ISO 17279-1:2018, Table 11, shall be met.

4.9.7 Test report

After the completion of the testing, the results shall be entered in the test report. A form of a test report is shown in Annex H.

4.10 Microscopic and X-ray diffraction testing

4.10.1 General

This clause defines the method of microscopic and X-ray diffraction testing of joints used in 2G HTS. Microscopic and X-ray diffraction testing are used to analyse the morphology and structure of the joined samples.

4.10.2 Qualification of test personnel

Testing shall be conducted by qualified personnel. Personnel qualification shall be done according to an appropriate quality management program.

4.10.3 Test equipment

Calibrated instruments shall be used for testing.

4.10.4 Surface condition and preparation

Subclause 4.2.4 shall apply.

4.10.5 Testing

Testing shall be performed in accordance with a written procedure or method applicable to the 2G HTS. The written test procedure or method shall include, at a minimum and either directly or by reference to applicable document(s), procedure identification number, date, revision number, identification of joints, complete testing requirements including method of testing, evaluation and reporting after evaluations.

The testing area shall include the joint and the accessible adjacent HAZ of base material for some distance from the joint edge. The testing shall be in the after joining and final heat-treated condition (oxygenation annealing), or otherwise required, and be free of all coatings and other surface conditions such as paint, plating, etc.

The testing area shall include the joint and the accessible adjacent HAZ of base material. The test shall be done after joining and final heat-treated condition (oxygenation annealing), or otherwise required and is carried out at room temperature. The specimen used for I_c test or a new specimen may be used for this test.

The joint may be examined by optical microscope (OM), scanning electron microscope (SEM), transmission electron microscope (TEM) or X-ray diffraction (XRD) to characterize the joint materials.

OM examines surface features and characteristics of microstructures, grains and grain boundaries of the joint. SEM detects the composition of the unknown materials of the joint and the joint surface topography and TEM can image and analyse the structure of materials using a high-energy electron beam transmitted through a very thin sample (<50 nm).

XRD measures the average spacing between layers or rows of atoms, determines the orientation of a single crystal or grain, finds the crystal structure of an unknown material and measures the size, shape and internal stress of small crystalline regions in the joint.

4.10.6 Acceptance criteria

The requirements of ISO 17279-1:2018, Table 12, shall be met.

4.10.7 Reporting

After the completion of the testing, the results shall be entered in the test report. A form of a test report is shown in Annex I.

Annex A
(informative)

Report of visual testing results

Manufacturer's WPS No.: ______________________

Test operator's name and qualification: ______________________

Test procedure No.: ______________________

Specimen No. and/or Part No.: ______________________

Joint information

2G HTS superconducting material type (YBCO, GdBCO, SmBCO, etc.): ______________________

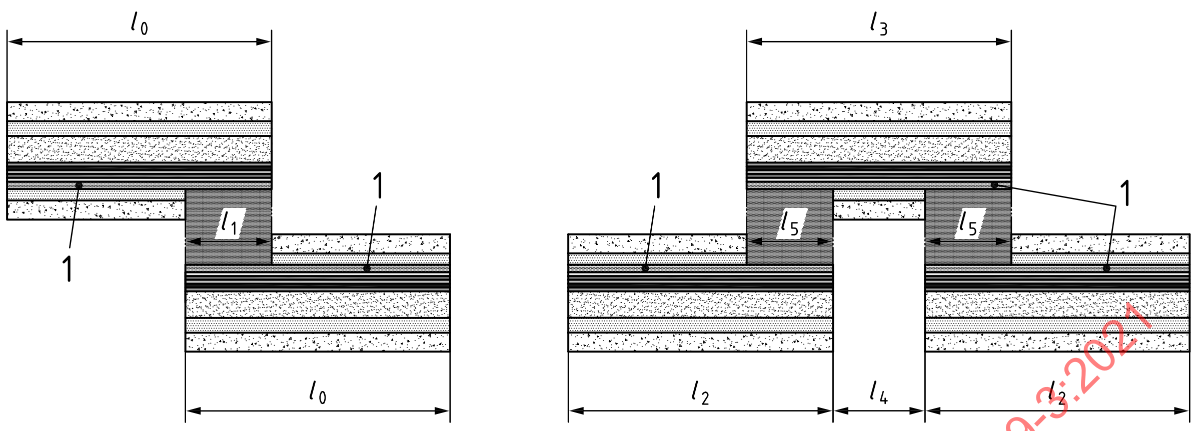
Joint width and length (mm): ______________________

Superconducting layer thickness (μm): ______________________

Equipment identification (model, serial number, and manufacturer): ______________________

Joint preparation (Cu and/or Ag layer removal): ______________________

Test specimen arrangement for joint, lap, bridge, or other and dimensions (sketch): ______________________



a) **Lap joint** b) **Bridge joint**

Key

1 REBCO-superconducting layer

l_0 length of two parts

l_2 length of two parts at bottom

l_4 distance between parts to join

l_1 overlap (joint length)

l_3 length of bridge part

l_5 overlap (joint length)

Figure A.1 — Lap joint and bridge joint

Testing sketch and/or photo		
Test method:	Direct	Indirect (Remote)
Visual aid, if any:		
Testing remarks		
Results 1) 2) 3) 4) 5)		

Conclusion	Accept	Reject

Test operator's name and signature:	
Organization:	Date:

Reviewed by name and signature:	
Organization:	Date:

Annex B
(informative)

Report of four-point-probe testing results

Manufacturer's WPS No.: ____________________

Test operator's name and qualification: ____________________

Test procedure No.: ____________________

Specimen No. and/or Part No.: ____________________

Joint information

2G HTS superconducting material type (YBCO, GdBCO, SmBCO, etc.): ____________________

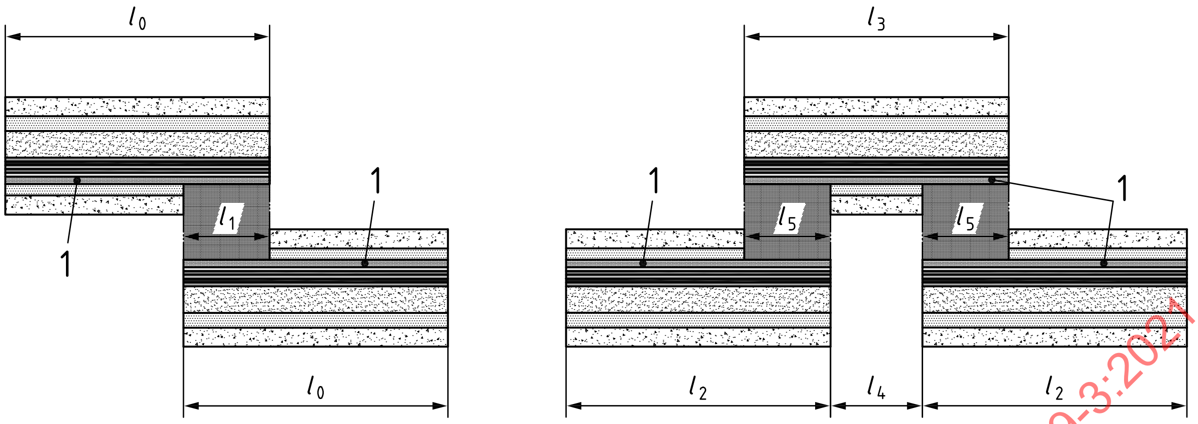
Joint width and length (mm): ____________________

Superconducting layer thickness (µm): ____________________

Equipment identification (model, serial number, and manufacturer): ____________________

Joint preparation (Cu and/or Ag layer removal): ____________________

Test specimen arrangement for joint, lap, bridge, or other and dimensions (sketch): ____________________



a) **Lap joint**

b) **Bridge joint**

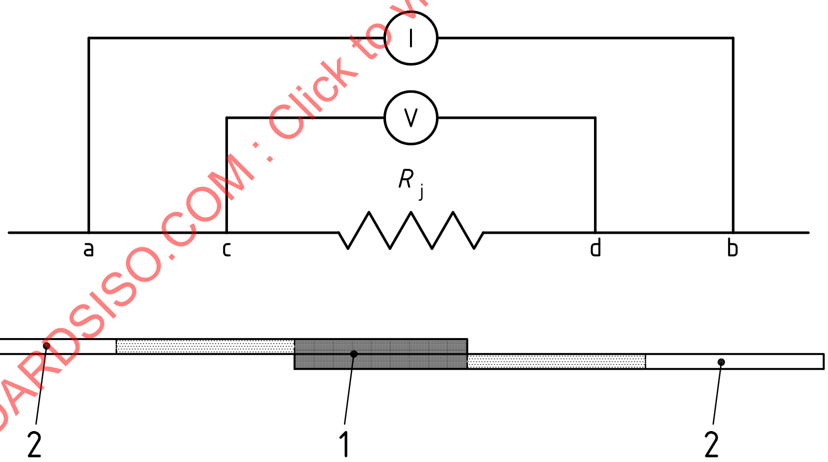
Key

REBCO-superconducting layer

l_0	length of two parts	l_1	overlap (joint length)
l_2	length of two parts at bottom	l_3	length of bridge part
l_4	distance between parts to join	l_5	overlap (joint length)

Figure B.1 — Lap joint and bridge joint

Testing sketch and/or photo (Example)



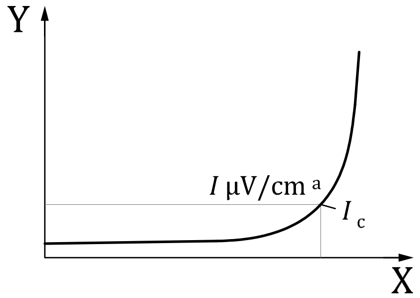
Key

1	joining area	2	heat-affected zone (HAZ)
a	Current lead 1.	b	Current lead 2.
c	Voltage tap 1.	d	Voltage tap 2.

Figure B.2 — Schematic of four-point-probe testing in lap-joined 2G HTS CC

Testing remarks

V–*I* curve (Example)



Key

X current in A

Y voltage µV

a Criterion.

Figure B.3 — *V-I* curve (example)

Results

1) Self-field critical current (I_c): ____________________

2) Critical current density (J_c): ____________________

3) *n*-value: ____________________

4) Cyclic thermal shock characteristic: ____________________

Test operator's name and signature: ____________________

Organization: ____________________ Date: __________

Reviewed by name and signature: ____________________

Organization: ____________________ Date: __________

Annex C
(informative)

Report of field-decay testing results

Manufacturer's WPS No.: ____________________

Test operator's name and qualification: ____________________

Test procedure No.: ____________________

Specimen No. and/or Part No.: ____________________

Joint information

2G HTS superconducting material type (YBCO, GdBCO, SmBCO, etc.): ____________________

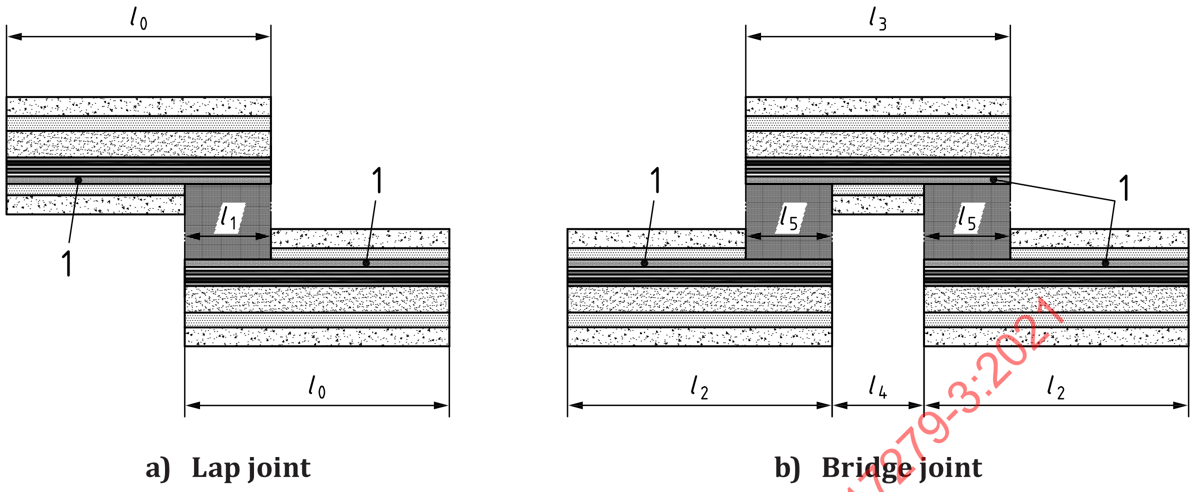
Joint width and length (mm): ____________________

Superconducting layer thickness (μm): ____________________

Equipment identification (model, serial number, and manufacturer): ____________________

Joint preparation (Cu and/or Ag layer removal): ____________________

Test specimen arrangement for joint, lap, bridge, or other and dimensions (sketch): ____________________



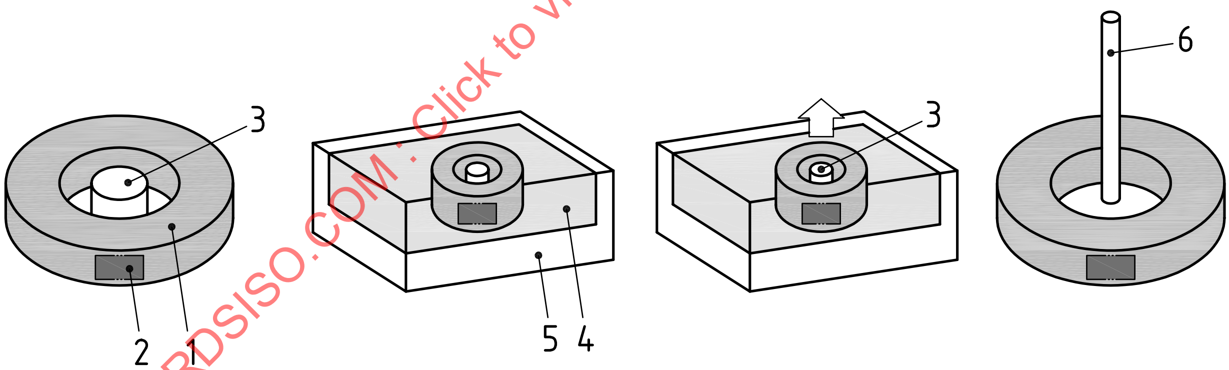
Key

REBCO-superconducting layer

l_0	length of two parts	l_1	overlap (joint length)
l_2	length of two parts at bottom	l_3	length of bridge part
l_4	distance between parts to join	l_5	overlap (joint length)

Figure C.1 — Lap joint and bridge joint

Testing sketch and/or photo (Example)



Key

1	superconductor coil	4	styrofoam bath
2	joint	5	liquide nitrogen or other cryogen
3	permanent magnet or electromagnet	6	hall sensor

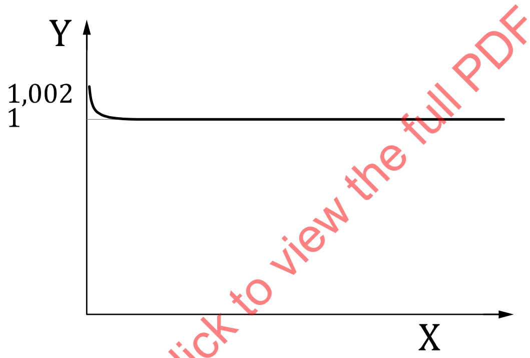
Figure C.2 — Field-decay testing

Table C.1 — Parameters and values

Parameters	Values	Parameters	Values
Conductor length [m]		Number of turns	5
Inner diameter [mm]	60	Outer diameter [mm]	
Coil inductance [μH]		Coil constant [mT/A]	
Permanent magnet applied		Electromagnet applied	
Data applied and produced $R = -L \times \ln[B(t)/B(t_0)] / t$			
$B(t_0)$, Initial magnetic field (tesla)		$B(t)$, Induced magnetic field at t (tesla)	
L, Self-inductance of a closed loop (henry)		T, time (s)	
R_j, Joint resistance (Ω)			

Testing remarks

Field-decay curve produced (Example)



Key

X time in d

Y $B(t)/B(t_0)$

Figure C.3 — Field-decay curve (example)

Results

1) Self-field critical current (I_c): ______

2) Critical current density (J_c): ______

3) n-value: ______

4) Cyclic thermal shock characteristic: ______

Test operator's name and signature: ______

Organization: ______ Date: ______

Reviewed by name and signature: ______

Organization: ______ Date: ______

Annex D
(informative)

Report of in-field testing results

Manufacturer's WPS No.: ____________________

Test operator's name and qualification: ____________________

Test procedure No.: ____________________

Specimen No. and/or Part No.: ____________________

Joint information

2G HTS superconducting material type (YBCO, GdBCO, SmBCO, etc.): ____________________

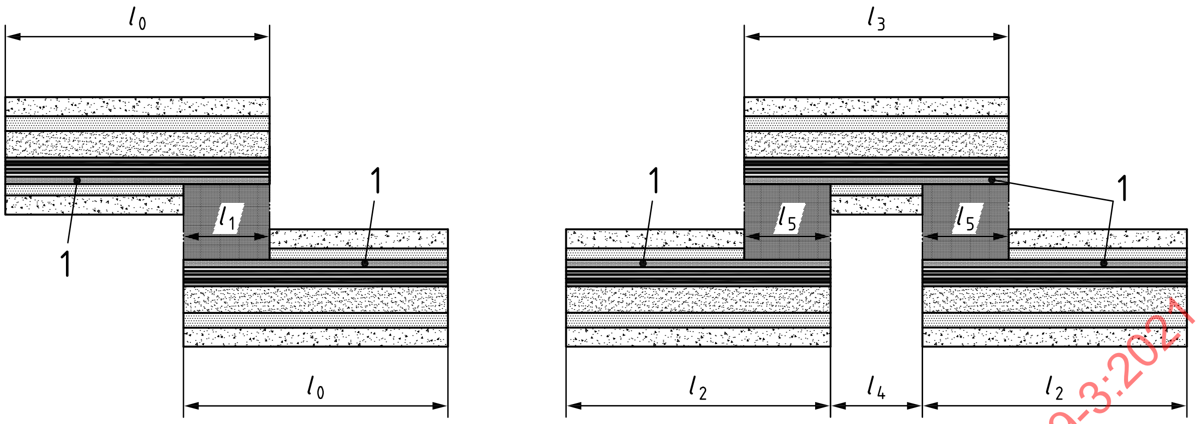
Joint width and length (mm): ____________________

Superconducting layer thickness (μm): ____________________

Equipment identification (model, serial number, and manufacturer): ____________________

Joint preparation (Cu and/or Ag layer removal): ____________________

Test specimen arrangement for joint, lap, bridge, or other and dimensions (sketch): ____________________



a) **Lap joint**

b) **Bridge joint**

Key

REBCO-superconducting layer

l_0 length of two parts

l_1 overlap (joint length)

l_2 length of two parts at bottom

l_3 length of bridge part

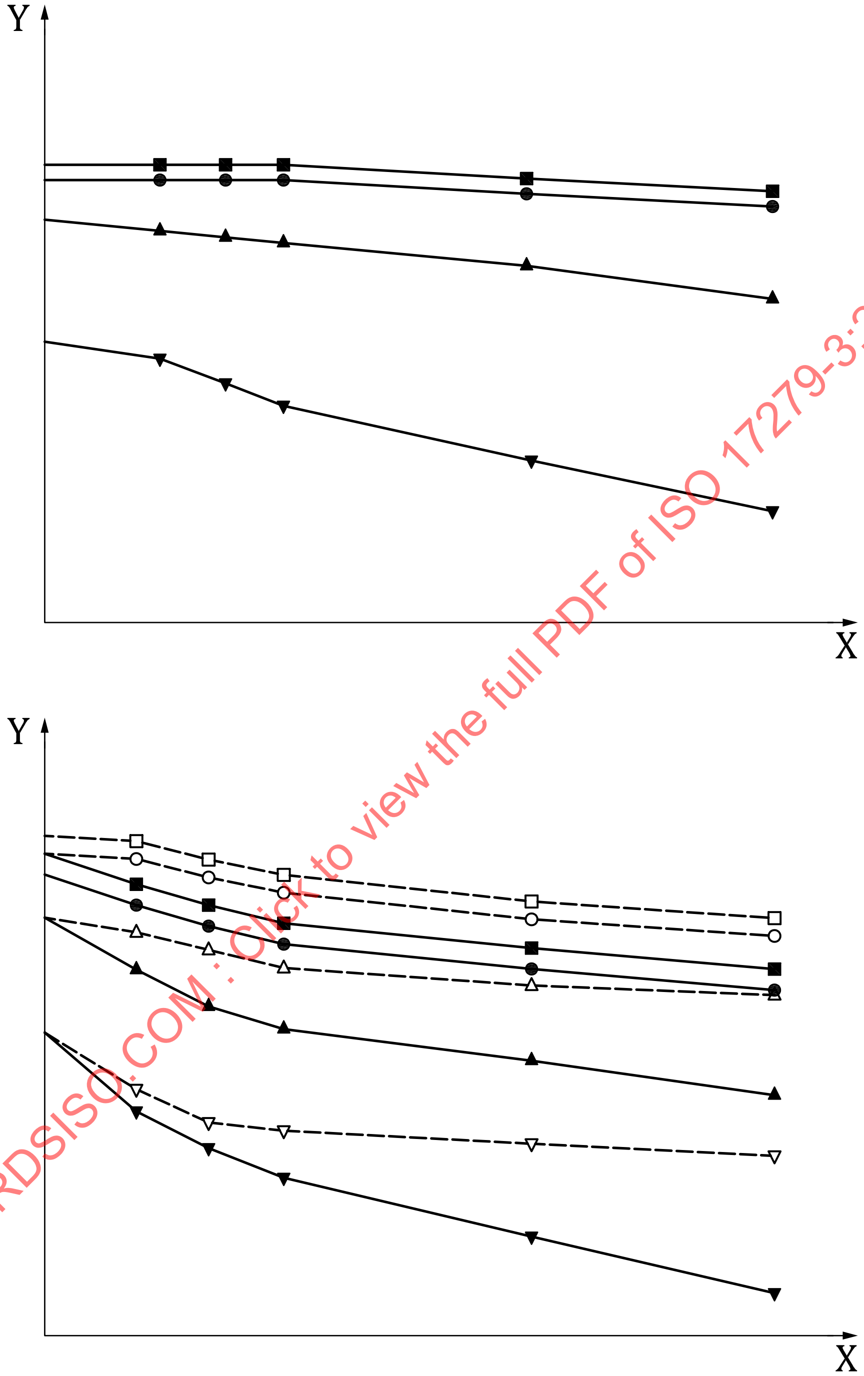
l_4 distance between parts to join

l_5 overlap (joint length)

Figure D.1 — Lap joint and bridge joint

Testing sketch and/or photo

In-field curve produced (Example)



Key

20 K	SF_20 K
30 K	SF_30 K
50 K	SF_50 K
77 K	SF_77 K

Figure D.2 — In-field curve (example)

Testing remarks

Results

Test operator's name and signature:			
Organization:		Date:	
Reviewed by name and signature:			
Organization:		Date:	

Annex E
(informative)

Report of tensile testing results

Manufacturer's WPS No.: ______________________

Test operator's name and qualification: ______________________

Test procedure No.: ______________________

Specimen No. and/or Part No.: ______________________

Joint information

2G HTS superconducting material type (YBCO, GdBCO, SmBCO, etc.): ______________________

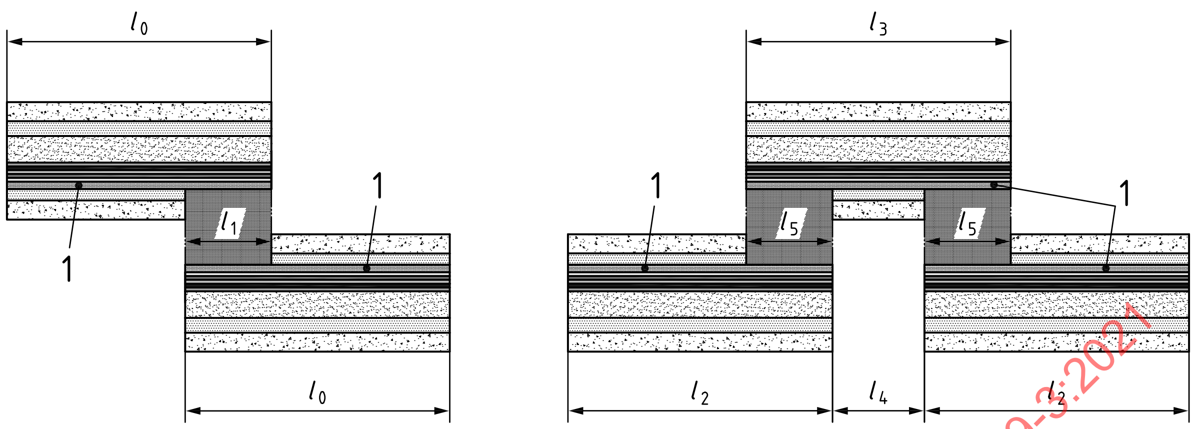
Joint width and length (mm): ______________________

Superconducting layer thickness (µm): ______________________

Equipment identification (model, serial number, and manufacturer): ______________________

Joint preparation (Cu and/or Ag layer removal): ______________________

Test specimen arrangement for joint, lap, bridge, or other and dimensions (sketch): ______________________



a) **Lap joint** b) **Bridge joint**

Key

REBCO-superconducting layer

l_0 length of two parts

l_1 overlap (joint length)

l_2 length of two parts at bottom

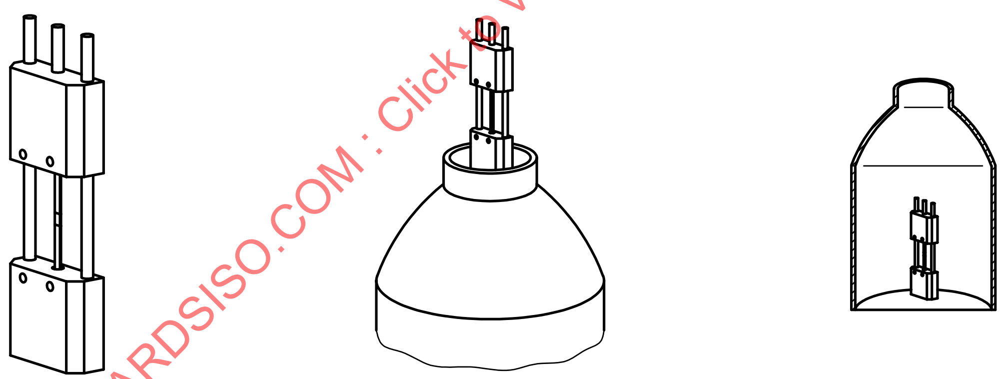
l_3 length of bridge part

l_4 distance between parts to join

l_5 overlap (joint length)

Figure E.1 — Lap joint and bridge joint

Testing sketch and/or photo (Example)



a) **Hold the specimen to the tensile tester** b) **Insert the specimen into the cryogenic container** c) **Under tensile testing**

Figure E.2 — Example of tensile test of 2G HTS in cryogenic condition

Testing remarks

Tensile testing curve produced

Results

1) Yield strength with reinforcement:	
2) Yield strength without reinforcement:	
3) Tensile strength with reinforcement:	
4) Tensile strength without reinforcement:	
Test operator's name and signature:	
Organization:	Date:
Reviewed by name and signature:	
Organization:	Date: