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The tensile property of commercial Bi2223 tapes: a report on the international round-robin test

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Abstract
In order to establish the test method of mechanical properties of oxide composite superconductors, an international round-robin test (RRT) has been carried out under the programme of VAMAS activity, for which eight research groups participated. The present RRT made the following guideline clear for assessing the mechanical property of Ag/Bi2223 multifilamentary tapes. Owing to the constitution of the brittle superconductive oxide layer embedded in the ductile metal matrix, the stress–percentage extension (R–A) curve shows a three-stage behaviour, that is, the true elastic region is very narrow and is followed by the quasi-elastic region before reaching the macroscopic plastic region. For assessing the elastic constant, it is recommended to look for the maximum slope carefully by enlarging the initial part of the R–A curve. The following three quantities, elastic constant, yield strength and tensile strength, can be reasonably determined with good accuracy by the procedure reported in this paper. The percentage extension after fracture is, however, excluded from the standard procedure, because it scatters to a great extent owing to the nature of the test sample as well as the experimental limitation.

1. Introduction

When Bi2223 tapes are used to fabricate superconducting magnets, complicated stresses are exerted in the winding stage of the manufacturing process and a large electromagnetic force is applied during operation. While the elastic modulus and thermal contraction coefficient are intrinsic properties, the tensile strength, elongation and ductility are very sensitive to the microstructure. So their microstructure dependence has been investigated by several research groups [1–3]. When testing the tensile property, it has been made clear that the stress–extension curve shows a three-stage behaviour [4] and sharp stress drops [5] due to the multiple fracture phenomenon. Consequently it is necessary to assess

Table 1. Specification of samples tested here.

Sample	Dimension Width × Thickness (mm^2)	Critical current at 77 K, SF (A)	Matrix	Filament no
VAM1	3.7 × 0.27	50	Ag/Ag alloy	57
VAM2	2.95 × 0.182	28	Ag alloy	19
VAM3	3.14 × 0.254	42	Ag alloy	37

Table 2. Test conditions employed by the eight research groups.

Group	Strain measurement	Sample length (mm)	Distance between chucks (mm)	Ram speed (10^{-3} mm s^{-1})
A	Compliance	70	40	10
B	Extensometer	70	45	11
C	Compliance	40	30	2.0–5.0
D	Extensometer (1)	100	ca 70	8.3
E	Extensometer (2)	60/120	–	2.5
F	Extensometer	115	77	50
G	Compliance	–	100	1.7–10
H	Extensometer	100	50	3.3–8.3

quantitatively the mechanical properties and their relation to the microstructure.

In order to establish the test method of the mechanical property of oxide composite superconductors, the committee of the VAMAS/TWA16-subgroup proposed an international round-robin test (RRT). Their first effort has been focused on the multifilamentary Bi2223 tapes. Eight research groups attended the present project. Firstly, an individual group carried out the tensile test using their own professional technique for three common Bi2223 tapes. The stress–extension curves and the experimental details were reported as the first RRT. In this paper, we report on their summary and point out some problems for providing a common test method in the next step.

2. Experimental procedure

The samples tested here are the commercially available Bi2223 multifilamentary tapes, the details of which are listed in table 1. These are supplied by Vacuumschmertz and NST, and are the same as the samples for the I_c measurement under VAMAS/TWA16 activities conducted by Wada *et al*, NRIM [6]. The samples were delivered to eight research groups, called A to H respectively, which do not correspond to the sequence of affiliations appearing in the author list of this paper.

The tensile test was carried out at room temperature. The machines used by the eight groups were different from each other, and the manufacturers of these were Instron, NMB, MTS, Shimadzu and Lloyd Instruments. The capacity of load cells ranged between 0.5–5 kN owing to the respective test machine.

The conditions of the tensile test employed by individual groups are summarized in table 2. Group A adopted a compliance method. The change of total elongation from sample, sample holder and tensile shaft was measured by using a linear voltage differential transformer (LVDT). Taking the rigidity into consideration, the exact elongation was estimated. Group B used a commercial extensometer with a gauge length of 5 mm. Group C measured the total elongation and then the contribution from the sample was assessed. Group D used double extensometers, which were installed symmetrically to the tape sample. The extension was essentially determined from the average of two signals. Group E used the non-contact type extensometer using double light beams. Group H used the same type of single extensometer as group D.

As listed in table 2, the total lengths of tape ranged between 40–120 mm. The distance between chucks ranged from 30–100 mm. The ram speed employed there ranged between 50 and 1.7 μm s^{-1}.

The method of gripping (chucking) the sample employed by individual groups differed as follows.

Group A: The sample was mounted on to the holder placed in horizontal position in order to avoid bending the sample and then the holder was vertically mounted on to the test machine.
Group B: The sand papers were pasted at the grip part of the sample, then the sample was fixed to the plate chuck with a knurl.
Group C: The specimen was clamped by Cu–Be pieces on the G10 frame.
Group D: Two parallel plane faced aluminium chucks were used, and their two plane sides were squeezed by a screw system.
Group E: The sample was soldered to the clamping blocks using Pb–Sn solder.
Group F: A sand paper of 800 was placed in both sides of the sample at two ends. Clamping blocks with a size of W20 × H12.7 mm^2 were used to fix the sample.
Group G: The self-tightening grips were used. The roller had a cross-hatched serrated finish and the back-plate had a horizontal grooved surface.
Group H: The wedge-shaped chuck was used.

According to the ISO standard 6892 [7], the technical terms used in the tensile test are defined strictly. Two lengths are present: the original gauge length (L_o) between the chuck ends and the extensometer gauge length (L_e). For each, the percentage elongation and percentage extension are defined as the increase in the respective length. As shown in table 2,

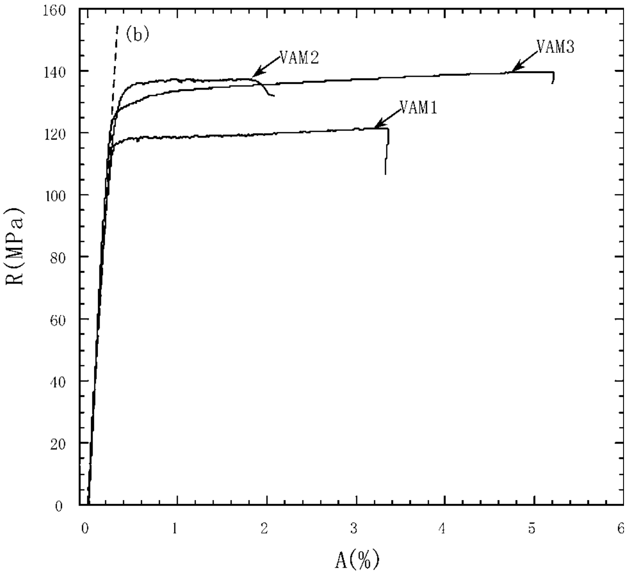

Figure 1. Typical R–A curve for three different tapes, VAM1, VAM2 and VAM3.

two quantities should be used separately depending on the technique for measuring length change. Assuming a uniform and homogeneous length change over the sample, however, two quantities are made the same as each other. Thus, the length change is represented as percentage extension in this paper. No symbol of percentage extension is, however, given in the ISO standard. Here the symbol used for the percentage extension is $A = 100 \times (L_e - L_{eo})/L_{eo}$, where L_e and L_{eo} are the gauge length at a given moment and at the beginning of the test, respectively. The symbol A_f is the percentage elongation (extension) after fracture. The symbol used here for the stress is R, which is the force at any moment during the test divided by the original cross-sectional area. The modulus of elasticity (elastic constant) E is determined from the initial linear portion of the stress–extension (R–A) curve. The 0.2% proof strength and the tensile strength are expressed by $R_{p0.2}$ and R_m, respectively.

3. Experimental results

A typical stress–extension curve is shown in figure 1. In order to accurately assess the mechanical properties from such a curve, various techniques are known to have been applied up to now. At the first step of the present RRT, however, we have fixed no common guideline among researchers. The majority used a conventional procedure as described in the following. The elastic constant (E) was assessed from the initial slope by drawing the straight line by eye. The 0.2% proof strength ($R_{p0.2}$) was determined by drawing the 0.2% off-set line by eye. A detailed description is mentioned later in section 4.3.2. The tensile strength (R_m) was assessed from the maximum load. The percentage extension after fracture (A_f) corresponded to the abrupt drop of load.

The reported values of four parameters are listed in tables 3–5. Compared with the data of the monofilamentary tape with pure silver sheath [4, 5], the elastic constant is almost the same, but the proof strength increased largely owing to the use of the alloy sheath. From these, the average value, the standard deviation and the COV (=standard deviation/average) were calculated for each parameter as listed in the table. Looking at the COV, its small value less than 5% is requisite for the standardization. The present results realized this standard level for $R_{p,0.2}$ and R_m, but did not satisfy it for E and A_f.

Table 3. Summary of the tensile tests reported by the eight groups for the samples VAM1.

Group	E (GPa)	$R_{p0.2}$ (MPa)	R_m (MPa)	A_f (%)
A-1	45.0	123.9	126.2	3.5
A-2	42.6	122.7	125.0	3.7
B	74.9	118.0	123.0	4.3
C	56.5	110.0	110.0	–
D	71.0	113.2	117.0	2.3
E	–	116.0	118.0	2.3
F	–	119.4	126.3	4.4
G	–	114.0	117.0	–
H	68.6	113.6	117.0	3.8
Average	59.8 ± 12.6	117.1 ± 4.5	120.3 ± 5.4	3.5 ± 0.8
COV (%)	21	3.8	4.4	23

Table 4. Summary of the tensile tests reported by the eight groups for the samples VAM2.

Group	E (GPa)	$R_{p0.2}$ (MPa)	R_m (MPa)	A_f (%)
A-1	46.8	129.3	131	1.6
A-2	45.6	130.3	131.5	1.9
B	65.4	136.0	137.0	1.4
C	62.8	126.0	126.0	–
D	76.3	128.3	129.3	0.8
E	–	120.4	121.0	1.1
F	–	125.7	127.5	0.8
G	–	130.0	132.0	–
H	75.6	118.6	120.0	1.5
Average	62.1 ± 12.2	126.8 ± 5.3	127.9 ± 5.3	1.3 ± 0.4
COV (%)	20	4.2	4.1	31

Table 5. Summary of the tensile tests reported by the eight groups for samples VAM3.

Group	E (GPa)	$R_{p0.2}$ (MPa)	R_m (MPa)	A_f (%)
A-1	49.6	122.7	134.0	4.5
A-2	48.8	125.9	137.3	5.6
B	64.6	128.0	137.0	4.2
C	66.0	121.0	123.0	–
D	78.3	124.3	135.7	3.8
E	–	123.0	–	–
F	–	120.4	131.1	4.5
G	–	122.0	137.0	–
H	71.9	117.0	128.3	2.8
Average	63.2 ± 10.8	122.8 ± 3.2	132.3 ± 4.9	4.2 ± 0.8
COV (%)	17	2.6	3.7	19

4. Discussion

4.1. Initial slope

The COV about the elastic constant has resulted in a large number as mentioned above. Here we discuss its reason and propose a more precise procedure. In general, there are alternative methods to determine the elastic constant

Table 6. Results of the tensile test reported by group D.

Sample	Cross section (mm^2)	E (GPa)	$R_{p0.2}$ (MPa)	R_m (MPa)	A_f (%)	Type of load cell
VAM1-D	0.999	–	114	115	1.4	FZK
VAM1-E	0.999	73	114	121	3.8	MTS
VAM1-F	0.999	69	113	118	3.7	MTS
VAM1-G	–	71	113	114	0.3	MTS
VAM2-F	0.5369	81	127	129	0.9	MTS
VAM2-G	0.5369	74	127	128	1.0	FZK
VAM2-H	0.5369	74	131	131	0.5	FZK
VAM3-D	0.7976	77	124	136	4.9	MTS
VAM3-E	0.7976	78	128	142	5.0	MTS
VAM3-G	0.7976	80	121	129	1.6	MTS

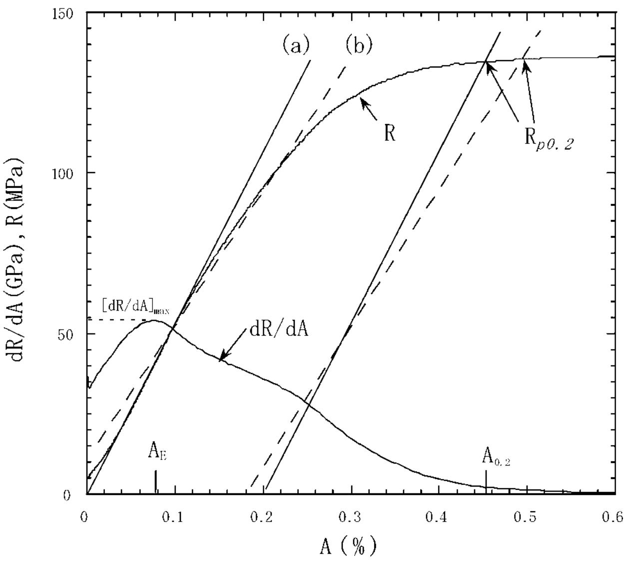

Figure 2. Extension dependence of R and dR/dA for tape VAM2. Here A_E and $A_{0.2}$ are the extensions corresponding to $[dR/dA]_{max}$ and $R_{p0.2}$, respectively.

from the initial slope of the R–A curve, or the slope in the unloading/reloading curve. Firstly the unusual behaviour in the initial part of the R–A curve is discussed.

In order to make the elastic region experimentally clear, the R–A curve was differentiated. Figure 2 shows the change of dR/dA as a function of elongation together with the change of stress for one of the VAM2 tapes. The slope increases and reaches a maximum ($[dR/dA]_{max}$). At the beginning of the R–A curve, such a concave curve is often observed due to the initial margin of the sample bend. Before the maximum, however, the slope should be constant consistent with $[dR/dA]_{max}$, when the initial margin is corrected. After $[dR/dA]_{max}$, it tended to decrease gradually with increasing extension. As discussed previously [4], the behaviour is divided into three stages. In figure 2, three stages I, II and III appear in the extension ranges $A < A_E$, $A_E < A < A_{0.2}$ and $A_{0.2} < A$, respectively. The first true elastic region is very narrow (stage I) and followed by a gradual decrease of the slope of the R–A curve (stage II). The start of stage II corresponds to the generation of microcracks. Then the macroscopic yielding takes place (stage III). It is emphasized that stage II appears characteristically in between the ordinary elastic stage I and the plastic stage III.

It is important to understand the relation of the mechanical properties to the microstructure [8]. Microcracks appearing in stage I are characterized as small cracks, which isolate in the SC matrix and do not generate voltage. There are many kinds of stress concentration site, for instance, voids, open grain boundary (GB), triple point of GB and so on. They already exist before the testing. Macroscopic cracks are large cracks appearing in stage III, which lie from end to end and disturb the current flow resulting in the voltage generation. At stage I, a fairly large amount of microcracks, including their nucleation sites, exist. At stage II, the existing microcracks grow, but do not progress to macroscopic cracks. The reason for this is that the work hardening of the Ag component reduces the stress bearing by the oxide component [8].

As stage II appears inevitably for Ag/Bi2223 tapes as discussed above, the true elastic region is very limited at the initial part. As shown in figure 2, it is necessary to draw correctly the slope as shown by line (a). When drawing line (b), the elastic constant results in the smaller value. The reason why the observed values of elastic constant, as listed in tables 3–5, scatter so largely is attributed to the slope change in stage II.

Besides the intrinsic behaviour just mentioned above, the initial part of the R–A curve is influenced by the experimental set-up: the bending of the sample, the deflection of load axis, the loose gripping of the sample, and so on. They always bring nonlinear influence to the R–A curve. The effects from the sample bending and the load axis deflection can be subtracted by using symmetric double extensometers. Group D has carried out the precise strain measurement by using double extensometers. As listed in table 6, the elastic constant was determined with COV of 2.8%, 5.2% and 1.9% for VAM1, VAM2, and VAM3, respectively. Their value is the highest among the reported data as listed in tables 3–5.

4.2. Unloading/reloading test

The elastic constant is usually assessed from the unloading/reloading test as proposed in IEC Standard 61788-6 [9] for the Cu/Nb–Ti composite superconductors. In the present study, the unloading/reloading test was carried out by three groups, B, E and F. A typical result obtained by group B is shown in figure 3. All the results give the same tendency. The result reported by group E is described as below.

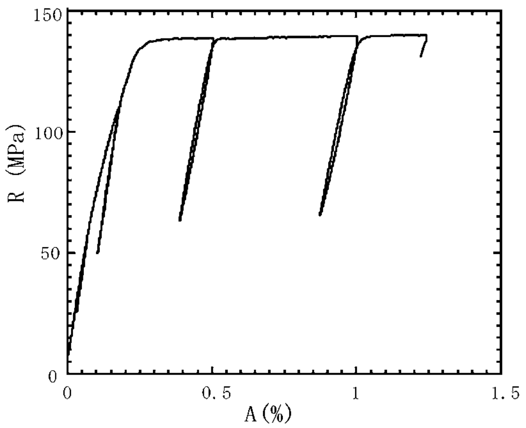

Figure 3. Unloading/reloading test, where the unloading took place at 0.05, 0.15, 0.5 and 1% of percentage extension for tape VAM2.

Table 7. Slope of the stress–elongation curve from the unloading/reloading test. The condition of reloading is described in section 4.2.

Sample	E_{1u} (GPa)	E_{1r} (GPa)	E_{2u} (GPa)	E_{2r} (GPa)
VAM1-1	63.9	59.5	–	–
VAM1-2	93.7	93.2	75.0	78.0
VAM1-3	50.8	45.2	42.4	43.7
VAM1-4	77.9	62.6	56.7	56.9
VAM2-3	56.1	50.5	48.2	45.3
VAM2-4	88.0	63.1	–	–
VAM2-5	62.5	65.9	63.0	65.9
VAM3-1	58.2	68.7	95.0	74.5
VAM3-2	72.2	77.4	67.4	67.3
VAM3-3	68.9	73.6	57.8	62.6

The condition to measure the elastic constant is selected as follows:

E_{1u} is the slope from the linear regression on unloading in the extension range about 0.5%;
E_{1r} is the slope from the linear regression on reloading in the extension range about 0.5%;
E_{2u} is the slope from the linear regression on unloading in the extension range about 1%;
E_{2r} is the slope from the linear regression on reloading in the extension range about 1%.

Table 7 shows the elastic constant thus determined. The elastic constant tends to decrease with an increase of the extension range. Therefore this unloading/reloading test is not appropriate to assess a correct elastic constant for the present tapes.

4.3. Guideline to determine the mechanical properties

Now a common guideline for determining the following mechanical properties is recommended.

4.3.1. Elastic constant. The elastic constant is assessed as the maximum slope of the R–A curve. In order to ensure a correct drawing, the R–A curve should be enlarged in the extension region by less than 0.6%, for instance as shown in figure 2. Plotting the $\mathrm{d}R/\mathrm{d}A$–A curve at the same time is helpful to find the maximum slope. While slope (a) in figure 2 is the maximum, another slope (b) results in a lower elastic constant by 11%. This slope (b) is re-plotted in figure 1.

4.3.2. Yield strength. The 0.2% proof strength ($R_{p0.2}$) is determined by drawing the 0.2% off-set line after the straight line with the maximum slope is drawn. As shown in figure 2, the 0.2% proof strength is given by $R_{p0.2}$ (a), while $R_{p0.2}$ (b) gives the value determined from slope (b). Both values of 0.2% proof strength are consistent each other within 1% accuracy, although the two slopes differ by 11%.

4.3.3. Tensile strength. The tensile strength (R_m) was assessed from the maximum load. As shown in tables 3–5, the consistency among the reported data is very high. It is possible to determine the tensile strength without any special care.

4.3.4. Percentage extension (elongation) after fracture. The percentage extension after fracture (A_f) corresponded at the abrupt drop of load. As shown in tables 3–5, its reported values are very scattered. The present sample consists of a brittle oxide layer and ductile metal matrix. During the tensile test, the multiple fracture of the oxide layer has been observed [5]. One of those weakest points might become the site of overall fracture. Such inhomogeneous behaviour causes a large variation of fracture elongation. Also, as the parallel tape is mounted in the present test, the fracture was very often observed near the gripping. Therefore, the large variation of fracture extension cannot be avoided due to any experimental procedure reported by the present eight research groups. So it is suggested that the fracture extension should be excluded from the guideline.

5. Conclusion

The present RRT made the following guideline clear for assessing the mechanical property of Ag/Bi2223 multi-filamentary tapes. Owing to the constitution of the brittle superconductive oxide layer embedded in the ductile metal matrix, the R–A curve gives a three-stage behaviour, that is, the true elastic region is very narrow and is followed by the quasi-elastic region before reaching the macroscopic plastic region. Consequently, special care should be paid when assessing the elastic constant. It is important to look for the maximum slope carefully by enlarging the initial part of the R–A curve.

It is concluded that the following three quantities can be reasonably determined with good accuracy by the procedure described in the text: elastic constant, yield strength and tensile strength. However, the percentage extension to fracture should be excluded from the standard procedure, because it scatters to a great extent owing to the nature of the test sample as well as the experimental limitation.

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