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A Comparison of Ag and Ag-Alloy Sheathed Bi-2223 Tapes

Hua K. Liu, Zhong M. Zhang, Rong Zeng, Josip Horvat, and Miles Apperley

***Abstract*—Ag and Ag-alloy sheathed Bi-2223 tapes were fabricated by a powder-in-tube technique with different configurations of the precursor and restack sheath materials: Ag, AgAu7 wt%, AgSb0.6 wt%, AgMg0.2 wt%. Analysis of the I_c and volume fractions of the Bi-2223, Bi-2212, Bi-2201 and Bi-3221 phases indicated that volume fractions of Bi-2223 $> 90\%$, Bi-2212 $\sim 5\%$, Bi-2201 $\sim 0\%$ and Bi-3221 $< 2\%$, normally result in tapes with the highest I_c. The mechanical properties of the tapes revealed consistent results. Generally, the harder the sheath material, the higher tolerance to the bending strain and higher the tensile strength of the tape. The sequence of the alloys' hardness from highest to lowest was AgMg0.2 wt%, AgSb0.6 wt%, AgAu7 wt% or Ag.**

***Index Terms*—Ag and Ag-alloy sheath, Bi-2223 tapes, mechanical properties, phase volume fractions.**

I. Introduction

MANY groups [1]–[12] have investigated Ag and Ag alloys (including elements Au, Mg, Pd, Mn, Cu, Ni, and Ti) as the sheath materials for fabricating $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10-x}$ (Bi-2223) tapes suitable for applications such as power cables, current leads, and coils for transformers and motors. The Bi-2223 material is a brittle ceramic, so the sheath material must provide a strengthening mechanism for the filaments without diminishing the properties of the Bi-2223 during processing. In this paper we report the results for the tapes fabricated by a powder-in-tube technique with different configurations of Ag, AgAu7 wt% AgSb0.6 wt% and AgMg0.2 wt% as the precursor and restack sheath materials.

II. Experimental

Ag and Ag-alloy sheathed tapes with 37 filaments were fabricated using commercial Bi-2223 precursor material and powder-in-tube techniques. The sheath configurations of the tapes are listed in Table I.

Short length samples of tape were heat treated at a temperature in the range of 832 °C to 846 °C for the first stage (HT1), followed by a second stage (HT2: 825 °C for 40 h, slow cooled to 785 °C and then normal cooled to room temperature). An intermediate roll (IR) pass was performed between each heat treatment stage.

TABLE I
37 Filament Bi-2223 Tape Configurations

Tape number	Restack sheath	Precursor sheath
1	Ag	Ag
2	AgAu7wt%	AgAu7wt%
3	AgSb0.6wt%	Ag
4	AgAu7wt%	AgSb0.6wt%
5	AgSb0.6wt%	AgAu7wt%
6	AgMg0.2wt%	AgAu7wt%
7	Ag	AgSb0.6wt%

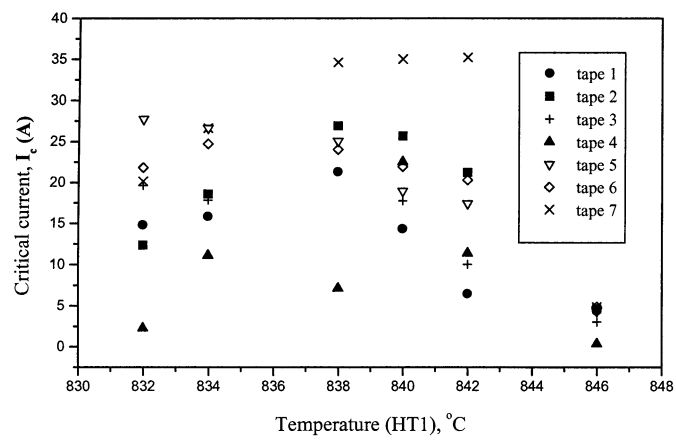

Fig. 1. Critical current (I_c) of short tapes measured at 77 K and self-field after HT2.

The phase compositions were determined from X-ray diffraction data. Assuming: a %Bi-2223 + b %Bi-2212 + c %Bi2201 + d %Bi3221 = 100%, the volume fractions of the phases were calculated by the peak intensity ($I_{2223}(0010)$, $I_{2212}(008)$, $I_{2201}(006)$, and $I_{3221}(300)$) of Bi-2223, Bi-2212, Bi-2201 and Bi-3221 phases, respectively, divided by the sum of their intensities.

The critical current (I_c) was measured in self-field at 77 K using a four-probe method and a 1 μV/cm criterion. The critical current density (J_c) vs. magnetic field (H) of the tapes was determined at 77 K in the directions of $H \perp c$ ($H//ab$) and $H//c$.

The bend strain tolerance was investigated by measuring the critical current at zero field (I_{co}) of a short sample and the I_c after one-way bending the sample around progressively smaller diameter formers in the range 110 to 20 mm. The sample was straightened after each bend cycle. The percentage of bend

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TABLE II
PHASES CONTENT (%) FROM X-RAY (HT 1: 834 °C).

	Tape 1		Tape 2		Tape 3		Tape 4		Tape 5		Tape 6		Tape 7	
	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2
Bi-2223	82.0	91.7	80.6	82.6	82.6	82.5	83.3	81.0	77.5	91.7	83.3	84.0	82.6	94.3
Bi-2212	12.3	5.5	12.1	11.6	13.2	11.7	13.3	14.0	18.6	4.6	14.2	10.1	9.9	4.7
Bi-2201	1.6	~0	1.6	~0	2.5	~0	2.5	0.8	~0	~0	0.8	~0	2.5	~0
Bi-3221	2.5	5.5	4.0	4.1	0.8	4.9	0.8	4.1	3.9	3.7	1.7	5.9	6.6	0.9

TABLE III
PHASES CONTENT (%) FROM X-RAY (HT 1: 838 °C).

	Tape 1		Tape 2		Tape 3		Tape 4		Tape 5		Tape 6		Tape 7	
	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2
Bi-2223	85.3	94.3	82	81.1	83.6	84.7	69.4	82.9	83.9	91.6	86.2	84.0	87.7	96.2
Bi-2212	10.1	3.8	9.8	17.8	7.8	12.7	16.0	12	10.7	5.6	6.9	10.9	5.3	2.9
Bi-2201	0.9	~0	1.6	~0	2.6	~0	9.7	0.9	1.8	~0	1.7	0.8	1.8	~0
Bi-3221	3.7	1.9	6.6	2.4	6.0	2.5	4.9	4.3	3.6	2.8	5.2	3.4	5.3	1

TABLE IV
PHASES CONTENT (%) FROM X-RAY (HT 1: 842 °C).

	Tape 1		Tape 2		Tape 3		Tape 4		Tape 5		Tape 6		Tape 7	
	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2	HT 1	HT 2
Bi-2223	86.4	95.7	83.3	84.3	88.5	95.2	20.9	86.4	82.0	93.5	89.3	88.5	87.0	94.8
Bi-2212	8.2	2.2	10.8	12.2	6.2	3.8	70.9	8.2	9.8	4.7	7.1	10.6	6.1	3.1
Bi-2201	0.9	~0	2.5	~0	1.8	~0	3.6	~0	2.5	~0	1.8	~0	1.7	~0
Bi-3221	4.5	2.2	3.3	3.5	3.5	1	4.5	5.5	5.7	1.9	1.8	0.9	5.2	2.1

strain was calculated by $\%\varepsilon = t/\Phi_f \times 100$, where t is the tape thickness and Φ_f is the former diameter.

Hardness measurements were performed at room temperature using a Leco Microhardness Testing Machine (M-400-Hl) and a 10 g load. Tapes (after heat treatment) were mounted in epoxy and polished to a 1 μm finish, across the transverse direction of the tape. The hardness of the sheath was measured across a line between the outermost 2223 filament and the tape edge. An error of 3% in hardness readings was estimated.

The tensile strength of the tapes was measured at room temperature using a Lloyd instruments, LRX Plus tensile testing machine.

III. RESULTS AND DISCUSSION

A. Optimum I_c Dependence on Alloy Sheath Configurations

Fig. 1 shows the I_c of the tapes measured at 77 K and self-field after HT2. It is clearly seen that the I_c of all tapes is very low when $HT1 = 846\,°\mathrm{C}$ compared with HT1 at other temperatures, and therefore 846 °C is well outside the optimum HT1 range. The highest I_c were achieved when $HT1 = 838\,°\mathrm{C}$ for tapes 1 and 5, 840 °C for tapes 2, 3 and 4, 834 °C for tape 6 and 842 °C for tape 7. These results indicate that the tapes with different configurations of precursor and restack sheath materials need optimized HT1 conditions when all other processing conditions are the same.

B. Optimum I_c Corresponds to Volume Fraction of Phases

Tables II–IV show the volume fractions of the Bi-2223, Bi-2212, Bi-2201 and Bi-3221 phases for the tapes after $HT1 = 834\,°\mathrm{C}$, 838 °C and 842 °C, and after HT2. Comparing the I_c in Fig. 1 and the phase analyzes in Tables II–IV, it can be seen that the highest I_c is achieved when the volume fractions are $2223 > 90\%$, $2212 \sim 5\%$, $2201 \sim 0\%$ and $3221 < 2\%$.

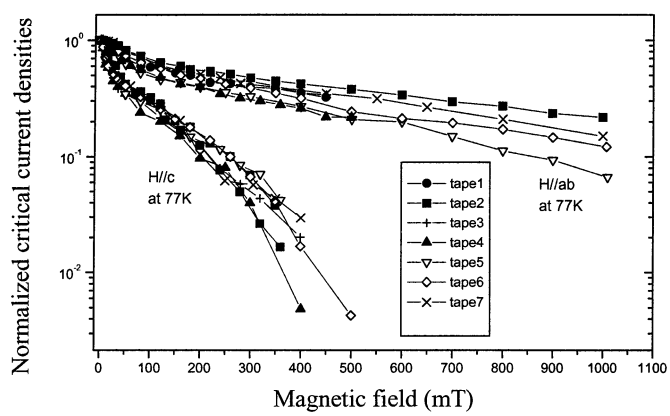

Fig. 2. Normalized J_c dependence on the magnetic field of the tapes at 77 K.

C. Normalized J_c – Field Dependence and the Sheath Materials

Fig. 2 shows the relationship between the normalized J_c and the applied magnetic field, with the field perpendicular ($H//c$) and parallel to the tape surface ($H//ab$) at 77 K for the different tapes 1, 3, 5, 6 & 7 with $HT1 = 838\,°\mathrm{C}$, and tapes 2 & 4 with $HT1 = 842\,°\mathrm{C}$. The relationship between J_c and magnetic field is characteristic of multifilamentary 2223 tapes fabricated using a PIT technique. No conclusive correlation between alloy type or configuration and I_c performance in field was highlighted.

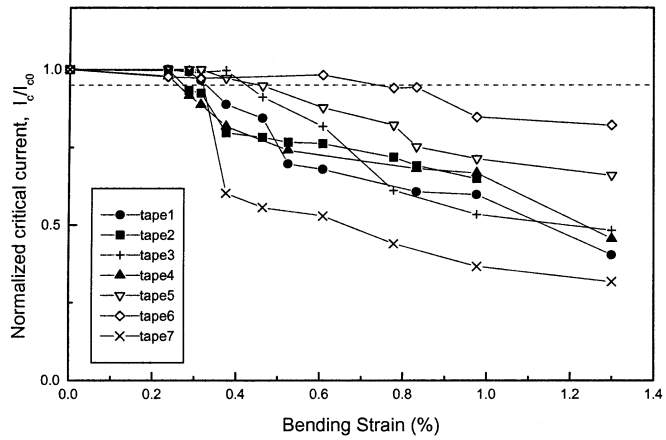

Fig. 3. Relative $I_c/I_{\rm co}$ as a function of bend strain.

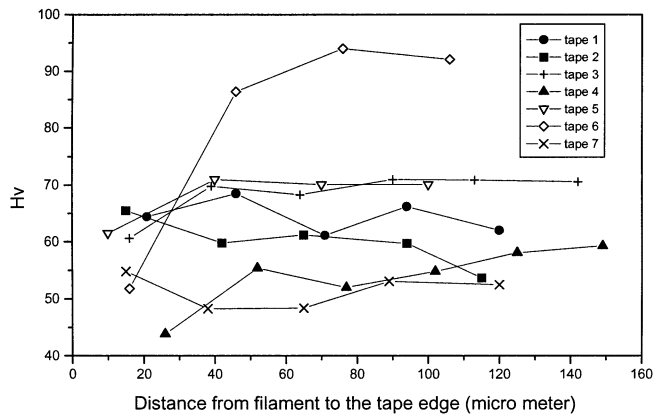

Fig. 4. The hardness profiles in the sheath materials of the tapes.

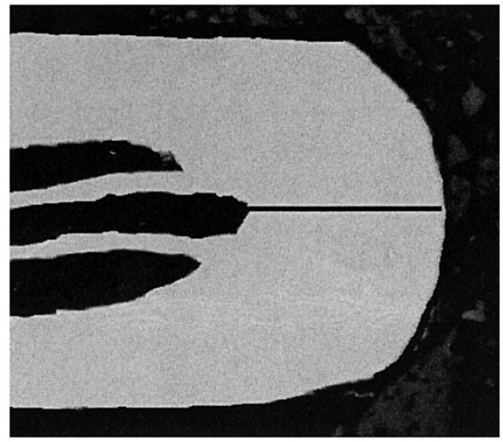

Fig. 5. A line shows the region in the tape cross-section on which the microhardness distribution was examined.

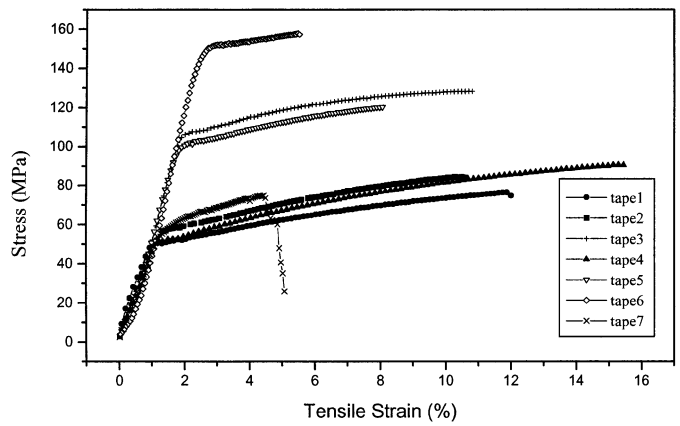

Fig. 6. The stress-strain relationship of the tapes measured at room temperature.

D. Bend Strain and the Sheath Materials

The results of the one-way bend test for the tapes 1 – 7 with $HT1 = 840\,^{\circ}$C are shown in Fig. 3. It was clearly observed that the tolerance of I_c to bending was quite different for the various tapes. The critical bend strain, $\varepsilon_{\rm crit}$ (bend strain when $I_c/I_{\rm co} = 0.95$) of tapes 1 and 7 was approximately 0.3%; while the $\varepsilon_{\rm crit}$ of tapes 3 and 5 was 0.42% and 0.47%. Tapes 2 and 4 had $\varepsilon_{\rm crit}$ of 0.28% and 0.25%. Tape 6 possessed the highest $\varepsilon_{\rm crit}$ of 0.73%, displaying best performance of I_c tolerance to bend strain. From these results it was concluded that tapes with like restack sheath materials had similar bend strain properties and that the improved tolerance to bend strain could be realted to the mechanical properties of the sheath materials.

E. Hardness Profiles and the Sheath Materials

The hardness of the sheath materials (tapes with $HT1 = 840\,^{\circ}$C) are shown in Fig. 4. A line in Fig. 5 shows the region in the tape cross-section on which the microhardness distribution was examined. From Fig. 4, tape 6 with Mg in the restack sheath shows the highest hardness of $\sim$ 90 Hv. The sheaths of tapes 3 and 5 containing Sb, show the next level of hardness at approximately 70 Hv. The lowest level of hardness ($50 \sim 60$ Hv) was measured in those tapes with Au or pure Ag in the restack sheath. The sequence of the sheath hardness from highest to lowest was therefore AgMg0.2 wt%, AgSb0.6 wt%, AgAu7 wt% or Ag. These results are consistent with the bend strain performance revealed in the previous section. Harder restack sheaths, such as those with Mg or Sb, must provide a mechanism by which the tolerance of the Bi-2223 to bend strain can be improved.

F. Tensile Strength and the Sheath Materials

The tensile strength of the tapes (with $HT1 = 840\,^{\circ}$C) are shown in Fig. 6. The best strengthening effect was showed by tape 6 in which the restack sheath contained Mg. Tape 3 and tape 5 in which the restack sheath contained Sb, had the next best strengthening effect. Tapes 2, 4 and 7 were similar to tape 1 (pure Ag sheath) indicating that the use of Au has negligible effect on tensile strength. This trend was also consistent with the assessment of the bend strain tolerance.

IV. Conclusions

Ag, AgAu7 wt%, AgSb0.6 wt% and AgMg0.2 wt% alloys were used as precursor and restack sheath materials for fabricating 37 filament Bi-2223 tapes using a PIT technique with a two-stage heat treatment process.

Analysis of the I_c and volume fractions of the Bi-2223, Bi-2212, Bi-2201 and Bi-3221 phases indicated that volume fractions of Bi-2223 $> 90\%$, Bi-2212 $\sim 5\%$, Bi-2201 $\sim 0\%$ and Bi-3221 $< 2\%$ normally result in tapes with the highest I_c

The normalized J_c dependence on magnetic field of the tapes at 77 K and $H//ab$ were compared. The relationship between J_c and magnetic field was characteristic of multifilamentary 2223 tapes fabricated using a PIT technique. No conclusive correlation between alloy type or configuration and I_c performance in field was highlighted.

The sequence of the critical bend strains, $\varepsilon_{\rm crit}$ of the tapes is 0.73% for tape 6, 0.42% & 0.47% for tapes 3 and 5, $\sim$ 0.3% for tapes 1 and 7, and 0.28% & 0.25% for tapes 2 and 4. Tapes with like restack sheath materials had similar bend strain properties. The variation in the bend strain tolerance of the tapes was consistent with the results of the hardness and tensile strength measurements. It was observed that the sequence of the sheath hardness and tensile strength from highest to lowest was AgMg0.2 wt%, AgSb0.6 wt%, AgAu7 wt% or Ag corresponding to the ranking of bend strain tolerance.

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