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Research status of the manufacturing technology and application properties of Bi-2223/Ag tapes at Innost

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Abstract

The first production line of Bi-2223/Ag tapes in China has been installed in the end of 2001 with an annual production capacity of 200 km at Innova Superconductor Technology Co., Ltd. (Innost). Bi-2223/Ag tapes can be manufactured reproducibly with length up to 1 km, critical current I_c over 90 A (77 K, 0 T) and engineering critical current density J_e over 9 kA/cm^2. Innost's Bi-2223/Ag tapes are being used for producing China's first HTS power cable system (30 m, 3 phase, 35 kV/25 kA), which will be put into trial operation next year. Also, Innost's products will be used for other research projects of HTS applications such as HTS motor, HTS magnet and HTS transformer in China. In order to meet the requirements of HTS applications, tremendous research efforts have been made not only in enhancing the performance and uniformity of the Bi-2223/Ag tapes, but also in improving their application properties, which include reducing AC losses and thermal conductivity, increasing insulating properties and so on. Methods for improving productivity and yield will be also introduced.

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Keywords: Manufacturing technology; Application properties; Bi-2223/Ag tape

1. Introduction

As the most promising material at the moment for superconducting electrical engineering applications, Ag-sheathed Bi-2223 tapes have to surpass threshold technical requirements, improve the performance uniformity of long length tapes and carry out diversified designs to meet the requirements of special application [1–4].

The best critical current density (J_c) achieved in commercially available tapes is ~50 kA/cm^2 (77 K, 0 T) [5], still much lower than the potential value of ~200 kA/cm^2 [6]. To shorten the difference between the actual J_c and the potential value, much effort has been made especially in eliminating voids and secondary phases, improving the grain alignment and grain connectivity [7].

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Some applications require unit length of 300–500 m or even 1 km. Not only the engineering current density (J_e), but also the performance uniformity along the whole length, determines the suitability of the Bi-2223 tapes for the applications. Furthermore the availability of diversified tape-design for insulating, lower AC losses and thermal conductivity, has to be considered for special application such as HTS transmission cable, magnet and current leads, etc.

In this paper, the research status of the manufacturing technology and application properties of Bi-2223/Ag tapes at Innost are reported.

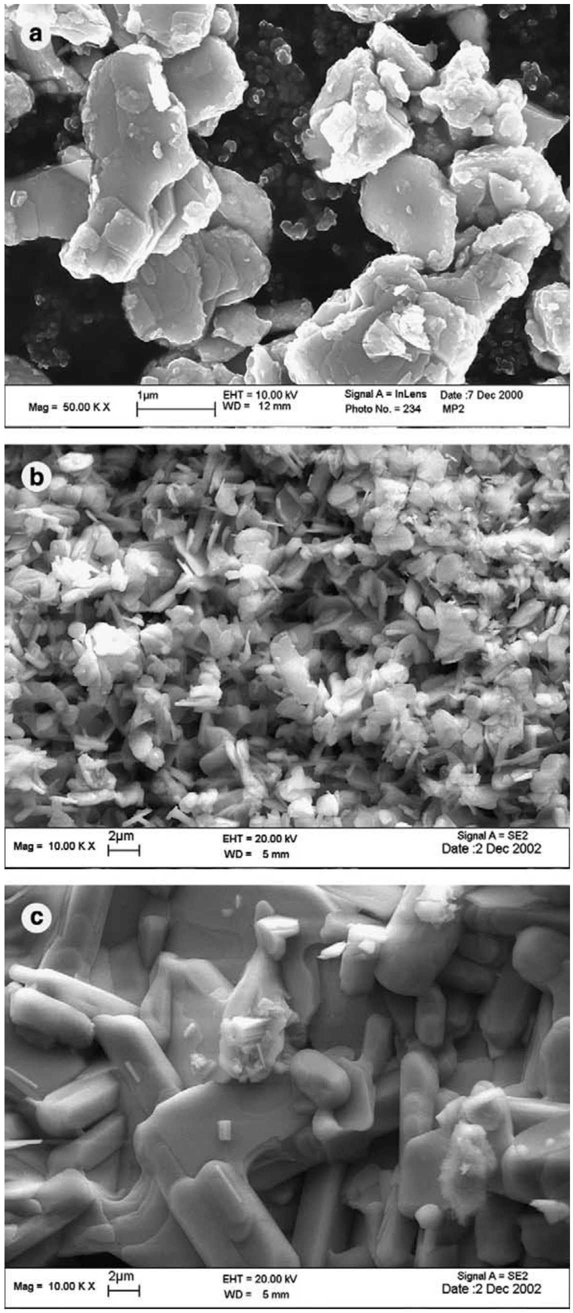

Fig. 1. Powder B and Powder C were obtained with varied pretreatment of precursor A. Powder B had small particle size and better phase assemblage than powder C.

2. Progress in manufacturing technology

Bi-2223/Ag tape was made using standard powder-in-tube (PIT) processes. A pure Ag tube was filled with precursor with a powder packing density of ~40%. After being drawn into round wires of 2 mm in diameter and cut into 37 monofilaments, which were then re-packed into a Ag alloy tube, the composite was subjected to the same drawing process to a final diameter of ∅ = 1.5 mm. The wire was then rolled to a flat tape 0.25 mm in thickness and 4 mm in width. A first heat treatment was performed at 820 °C, using a flowing 8.5% O_2-balance N_2 atmosphere. Subsequently further heat treatments were given, after an intermediate rolling step.

2.1. Precursor powder processing

Commercially available powders from Merck KGaA or self-made powders are used as precursors with an optimum composition of $Bi_{1.8}Pb_{0.33}$-$Sr_{1.87}Ca_2Cu_3O_x$. The synthesis technique and the reaction parameters applied during thermal treatment specify the properties and reactivity of precursors. A spray-dried method [8] was used to produce the powder (powder A, see Fig. 1) at Innost. The reactivity of the precursors was evaluated by the oxygen release amount [9].

The precursor was then applied pre-treatment process before being filled into the Ag tube. Fig. 1 shows the SEM photographs of powder B and powder C obtained after sintering precursor A at 810 °C for 15 h and 820 °C for 30 h, respectively. All the sintering was performed in air. Compared to powder C, powder B had smaller particle size and better phase assemblage, and consequently higher transport performance after being fabricated into Bi-2223/Ag tapes.

2.2. Drawing and rolling

Homogeneity is the key point for wire drawing. Introduction of a new on-line measurement of the instantaneous drawing stress revealed a significant variation along the wire length during each drawing pass of the BSCCO wires. We studied the main factors contributing to the drawing stress and its variation, which include the mechanical hardening of the silver and silver alloy during working, compaction of the BSCCO powder, and the high sensitivity of the intermediate annealing conditions [10]. The drawing speed, reduction rate, die configuration were also optimized. Based on the research results a significant improvement in homogeneity along the wire length has been achieved (Fig. 2).

The uniformity of the following flat rolling process was available, due to the achieved homogeneity of the wire drawing. The number of steps, the reduction per step, the roll diameter, the aspect ratio of width to thickness of the final tape, and the lubrication condition has to be controlled to avoid shearband formation and sausaging which reduces the effective cross-sectional area of the current path and disturbs the texture of the Bi-2223 grains [1]. A continuous on-line measurement device of tape width and tape thickness has been built up to guarantee uniformity on dimension and finally on J_e. Fig. 3(a) and (b) show the variations of tape width and tape thickness along the tape length, which is within ±0.1 and ±0.01 mm, respectively.

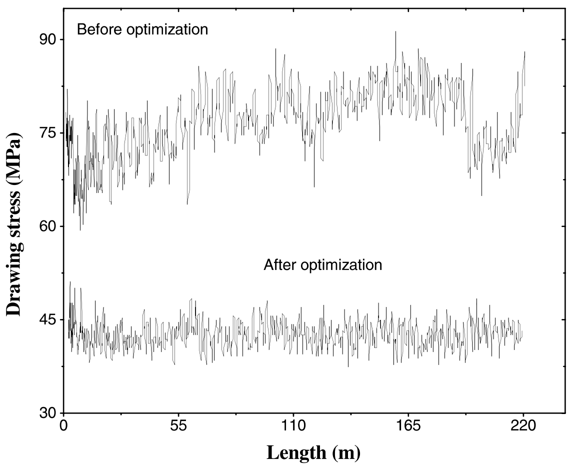

Fig. 2. Significant improvement in homogeneity along the wire length has been achieved after introduction of an on-line measurement of the instantaneous drawing stress.

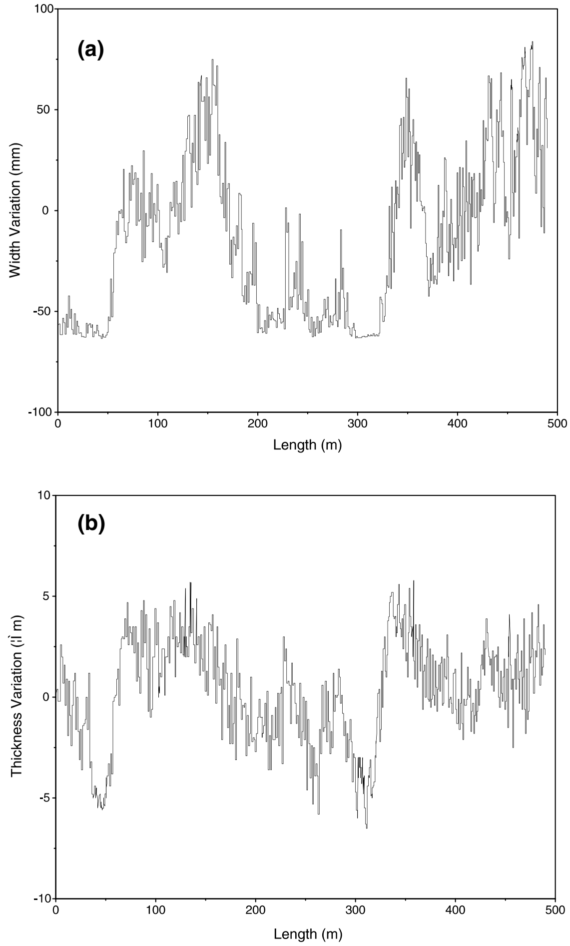

Fig. 3. Variation of tape width and tape thickness along the tape length is within ±0.1 and ±0.01 mm, respectively.

2.3. Thermo-mechanical treatment

Detailed investigations of the thermodynamics and the phase formation mechanism during the heat treatment have led to the understanding of the limits of the commonly used processing route.

Several important parameters including sintering temperature, soaking time, oxygen pressure, ramp and cooling rate have been optimized to realize the complete transformation of Bi-2212 to Bi-2223 phase. We also pay much attention to the intermediate deformation (ID) step between two heat treatments, which is widely regarded to be necessary for densifying the core, enhancing the preferred orientation of Bi-2223 and thus improving the transport property [5]. The results showed that J_e reaches a maximum value with an optimum ID reduction, which has a competition fashion between improvement of the grain connectivity and introduction of cracking. XRD analyses indicate that the optimum ID reduction increases as increasing the volume fraction of residual Bi-2212 after initial heat treatment [11]. Furthermore, a significant enhancement of J_e has been achieved by post-annealing the fully reacted Bi-2223/Ag tapes at lower temperature under reduced oxygen partial pressure. The enhancement of J_e is due to raising the critical temperature T_C, minimizing residual Bi-2212, and improving grain connectivity and flux pinning [12,13].

2.4. Process control and quality management

Lowest cost, highest performance is the simple key to commercialization of HTS wires. Boosting productivity and yield is the hot topic for many manufacturers, including Innost. The actions being taken are: (a) carry through a firm testing procedure for raw materials including precursor powder and silver tubes, (b) introduce on-line measurement of important processing parameters to ensure process consistency, and (c) increase manufacturing capacity to meet the increasing application requirements. Fig. 4 demonstrates the histogram of production yield in last years.

2.5. Typical properties of Bi-2223/Ag tape

Fig. 5 shows the I_c distribution of the Bi-2223 tape of this year with 400 m in length. Defined as 1 μV/cm criterion for every 10-m interval, I_c was over 90 A (77 K, 0 T) and J_e was over 9 kA/cm^2. The I_c variance along the whole tape length is within 5 A. Fig. 5 also reveals the significant advances in J_e since the installation of the production line of HTS wires in 2001. A recent result indicates short length performance of up to 117 A, corresponding to the J_e of near 12 kA/cm^2. A critical tensile stress (5% I_c degradation, 77 K, 0 T) $\sigma_c \geqslant 100$ MPa and critical bending radius $R_c \leqslant 25$ mm was achieved with the standard sheath combination of Ag–AgMgNi.

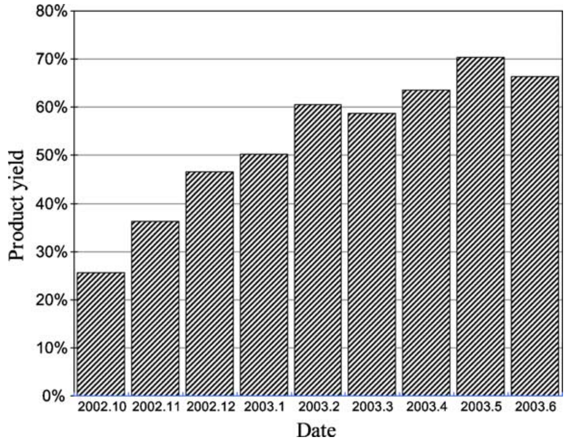

Fig. 4. Histogram of production yield.

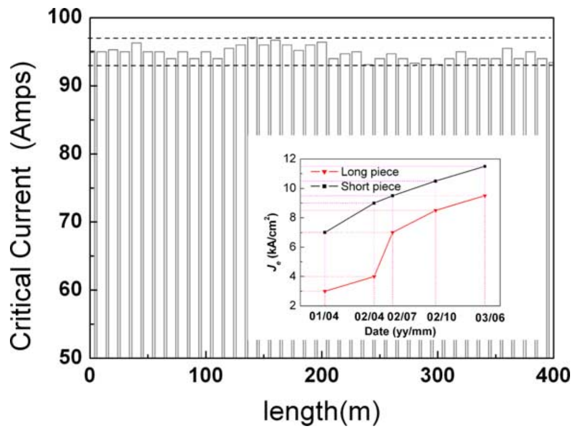

Fig. 5. I_c distribution of the Bi-2223 tape with 400 m in length. I_c was measured by 1 V/cm criterion for every 10-m interval.

3. Application properties

Influence of tape aspect ratio and sheath material on measured coupling loss and hence the effective matrix resistivity has been investigated for AC application in cables, transformer, etc. The AC losses (at 45 Hz and in parallel field direction) decrease with increasing the aspect ratio. The order of AC losses of tape with different sheath materials is: Ag>AgAu>AgSb>AgMgNi [14]. Another important method to reduce AC losses, introducing of a resistive barrier between filaments combined with filament twisting, is just underway.

Recently, sheathed HTS current leads made by stacking Bi-2223/Ag tape have received considerable attention. To develop sheath materials with lower thermal conductivity, we fabricated BSCCO tapes with varied sheath combination of AgAu, AgSb and AgMgNi and characterized the thermal conductivity at 4.2–100 K. From Fig. 6 we can see that the addition of Au decreases the thermal conductivity remarkably. The first batch of Bi-2223 tapes providing to our customer were made by sheath combination of AgAu–AgAu with $I_c = 75$–85 A (77 K, 0 T) and $J_e = 8$–9 kA/cm^2.

To commercialize broader markets, HTS wire is seeking for a position in electronic application such as probing coil and small size of magnet. Bi-2223/Ag fine wire or thin tape is a suitable candidate. The typical dimensions of Innost's thin tape are 1.4 mm in width and 0.1 mm in thickness, J_e is as high as 10 kA/cm^2, and the critical bending diameter is lower than 25 mm (5% I_c degradation, 77 K, 0 T). However, attention should be paid to the brittleness of fine wires when used for prototype applications.

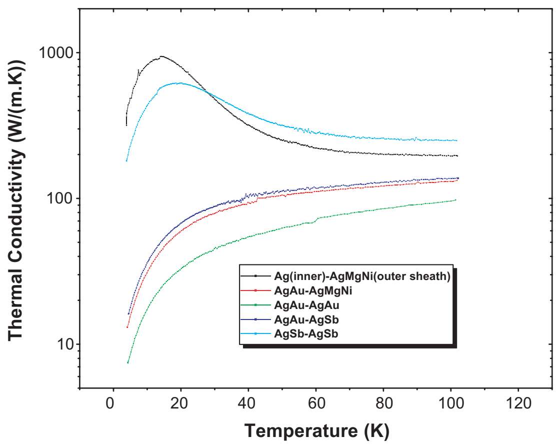

Fig. 6. Thermal conductivity of variably sheathed BSCCO tapes from 4.2 to 100 K.

Since the first half of last year we have developed insulated wires and tinned wires to satisfy the requirement of insulating, soldering and protecting the wires from penetration of liquid nitrogen. A breakdown voltage of 300–1000 V was achieved with an insulating coating of 10–20 μm.

Innost's Bi-2223/Ag tapes are being used for producing China's first HTS power cable system (30 m, 3 phase, 35 kV/25 kA), which will be put into trial operation next year. Also, Innost's varying-designed-products will be used for other research projects of HTS applications in China such as HTS motor, HTS magnet, HTS transformer, HTS fault current limiter, HTS MRI and HTS magnetic levitation.

4. Summary

Commercial manufacturing technology of Bi-2223/Ag tapes has been developed and a significant enhancement of the electrical performance has been achieved at Innost. Bi-2223/Ag tapes with length up to 1 km, I_c over 90 A (77 K, 0 T) and J_e over 9 kA/cm^2 are being provided for major electric power application such as China's first HTS power cable system (30 m, 3 phase, 35 kV/25 kA). Introduction of continuous on-line measurement of important processing parameters helps to guarantee high quality, reproducibility and homogeneity of the production line. To meet the requirements of the special HTS prototypes for other research projects, diversified tape-designs have been carried out to improve their application properties, which include reducing AC losses and thermal conductivity, increasing insulation properties and so on.

Acknowledgements

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