Continuous Processing of AgMg-Sheathed Bi$_2$Sr$_2$CaCu$_2$O$_8$ Tapes

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Abstract—The critical current of the tapes prepared using continuous processing is significantly enhanced and processing time reduced, compared with that of traditional processing. The effect of conductor pulling speed on the microstructure, phase purity and therefore critical current of the tape is investigated using ESEM, XRD and DC transport measurements.

I. INTRODUCTION

The Ag-sheathed Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi2212) tape has its advantage over (Bi,Pb)$_2$Sr$_2$CaCu$_2$O$_8$ (Bi2223) tape in processing, i.e. a partial melting process can be applied. Also, the critical current density of both conductors is very similar at 4.2 K. Those facts make us to choose Bi2212 as conductor to fabricate HTC insert coils for high field application at low temperature, such as a HTSC insert coil for a 25 T NMR. The partial melting process increases the mass density of the core, improve the connectivity and the alignment of the Bi2212 grains. However, for large size coils, the melting processing is very difficult to apply, because their thermal mass makes controlling the melting time difficult. The fabrication of Ag-sheathed Bi2212 coil using a react-wind-sinter technique (R-W-S) is advantageous over the wind-and-react or react-and-wind techniques in terms of reducing handling damages and achieving high critical current density over a long length. In this technique, long lengths of the Ag-sheathed Bi2212 tape are reacted uniformly by pulling the tape continuously through a precisely defined temperature profile. Our previous work [1] has investigated the feasibility of the R-W-S process to the Ag-sheathed Bi2212 tapes, mainly on monofilamentary tapes. In this paper, we present our new results of the application of R-W-S process to the high alloy AgMg-sheathed Bi2212 multifilamentary tape. Since we do not consider the winding process in the paper, the process is also called continuous processing (CP).

II. EXPERIMENTAL

The multifilamentary Bi2212 tape was fabricated by the well-established powder in tube technique (PIT). The commercial powder of nominal stoichiometric composition of Bi$_2$Sr$_1.5$Ca$_2$Cu$_3$O$_y$ was used as the precursor. The sheathed material is pure Ag for the inner tube and Ag alloy for the outer tube containing 1.2 at% Mg. After drawing and rolling process, the final tape dimensions are 3 mm in width and 0.22 mm in thickness.

The continuous processing was carried out in a quartz furnace whose three hot zones could be controlled separately, which is the same furnace as used in [1], but the temperature profile was changed (Fig. 1). The figure shows that the furnace consists of three hot zones: (1) a homogeneous zone as long as 585 mm located roughly in the middle of the furnace with a temperature variation of $\pm 1^\circ$C, (2) a homogeneous zone as long as 585 mm located in the middle of the furnace with a temperature variation of $\pm 3^\circ$C and (3) two zones with a gradient of about 3 $^\circ$C/cm. From those configurations, the peak temperature is 866$\pm 3$ $^\circ$C. The tapes were pulled through the furnace by using a 20 V DC motor, which provided with very precise linear speed.

The melting temperature used for the CP was optimized in a small furnace with a uniform hot zone of longer than 10 cm using traditional processing (TP, Fig. 2).

The $I_c$ of the samples was determined using the four-probe DC technique at 4.2 K using a 1 $\mu$V/cm criterion. The distance between the two voltage taps is about 2.5 cm. The phase composition of the samples was determined by X-ray diffraction (XRD). The microstructure characterization was carried out.

Fig. 1. Temperature profile of the furnace used for the continuous processing

Fig. 2. Critical current vs. melting temperature by traditional processing

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III. RESULTS

When a sample was pulled through the furnace with a constant speed, its temperature was a function of position, like the profile in Fig. 1. At the same time, since the position of a moving sample is a function of time, the temperature of the sample is also a function of time. Therefore, the temperature of the sample during CP could be drawn against time, such as profile "a" in Fig. 3.

Fig. 4 demonstrates the results of \( I_c \) of the samples with different pulling speeds. The figure shows that the \( I_c \) increases with increasing pulling speed, but after reaching 16.6 mm/min, it drops.

Fig. 5 shows XRD patterns of the as-continuously-processed (as-CPed) samples with different pulling speeds and the same

\[ I_c \text{max of TP} \]
\[ I_c [A] \]
\[ \text{Melting temperature can be obtained from Fig. 1} \]
\[ \text{Pulling Speed [mm/min]} \]
\[ 0 \, 5 \, 10 \, 15 \, 20 \, 25 \]
\[ 0 \, 20 \, 40 \, 60 \, 80 \, 100 \, 120 \, 140 \, 160 \]

\[ I_c [A] \]
\[ \text{Pulling Speed [mm/min]} \]
\[ 0 \, 5 \, 10 \, 15 \, 20 \, 25 \]
\[ 0 \, 20 \, 40 \, 60 \, 80 \, 100 \, 120 \, 140 \, 160 \]

IV. DISCUSSION

From Fig. 4, it is seen that, with increasing the pulling speed, the \( I_c \) of the CPed samples increases and drops only after reaching 16.6 mm/min, or 1 m/h. This result is encouraging from the point of view of reducing processing time. Also, as will be discussed later, the production could be increased without limitation by forcing conductor moving in a zigzag route in the furnace. Furthermore, with the same melting temperature, the \( I_c \) of the CPed sample is almost two times of that of the TPed sample (Fig. 3, curve "c"). This is different from our previous results of the monofilamentary tape [1], where the \( I_c \) of CP tape is lower than that of TPed one.

The fact that the CPed sample is about two times of that of the TPed sample does not imply that the processing parameters for CP were not properly selected. This is because of the following reasons. First, TP consists of a much longer pre-annealing process, which suppressed bubbling effectively. Whereas for CP, the pre-annealing time was not long enough therefore bubbles always appeared. Secondly, the highest \( I_c \) is only 94 A obtained in a short furnace, whose temperature and atmosphere could be controlled more precisely than the one used for CP. Thirdly, a sample was TPed using exactly the same temperature-time profile as CP did (curve "b" in Fig. 3). The results showed that such a sample had even lower \( I_c \) value. This led us to find the real reason of the \( I_c \) enhancement.
For TP, the temperature along the tape length is identical at all time. However, for CP, the temperature of a tape is different from point to point when it is in the gradient zones. It is well known that the solidification under a uniform gradient temperature condition is the feature of directional solidification. Directional solidification is a method to prepare materials of a preferred grain orientation parallel to the sample axis, along which the temperature gradient applies.

The mechanism of grain alignment in Bi2212 tape by TP is still not fully understood. Hellstrom [2] proposed a constrained-volume model, which gives a reasonable phenomenological explanation of the texture formation. In this model, the Bi2212 grains that initially nucleate and grow with their basal planes nearly parallel to the tape plane can grow to large size, whereas grains aligned at other orientations cannot grow large but be expend for growing other grains. His model is based on the fact that the growing speed of Bi2212 phase along ab-plane is much faster than that of c-direction. According to this model, in CP, for those Bi2212 grains whose basal planes are parallel to the temperature gradient direction, their ab-planes would grow even faster than in TP, therefore the misalignment grains can be further eliminated or the grain alignment can be enhanced.

Bi2212 phase forms in peritectic reaction [3], [4].

Bi2201 + (Sr,Ca)CuO₂ + L → Bi2212.

According to our DTA data, the recrystallization temperature of Bi2212 phase is around 860 °C. From the melting temperature down to 860 °C, as the temperature decreases, the content of the Bi2201 phase in the liquid increases. We propose that in the cooling zone, a small number of Bi2201 can grow to large size by directional solidification, instead of forming more grains. In the subsequent cooling process around 860 °C, the large Bi2201 grains are beneficial to the formation of aligned Bi2212 grains since they can serve as matrices for Bi2212 grains to grow on epitaxially. Also, around 860 °C, the Bi2212 can directly nucleate from the liquid [2] and, with the help of the directional solidification, grow to large aligned grains.

So far, it has been discussed that with CP the Lₖ level of the tape is higher and the processing time is shorter than those of TP. However, we did not mention the bubbling problem. Our results showed that there was Lₖ fluctuation along the length in CPed tape (14% on an average) which was caused by bubbling. The problem existed because our pre-annealing time was not long enough. It has been confirmed that with a long time pre-annealing, the bubbling in CP disappears.

If the designed pre-annealing time and melting time are tₐ and tₘ, respectively, with the tape going through the furnace in a constant speed vₙ, we have:

\[
\frac{L_v}{L_m} = \frac{t_v}{t_m} = \frac{v_v}{v_m}.
\]
$L_n$ and $L_m$ are the length of annealing zone and melting zone, respectively. Typically, the melting time is around 0.6 h, and pre-annealing time 10 h, then

$$\frac{L_n}{L_m} = 10/0.6 \approx 16.$$  

Supposing we reduce the length of our melting zone to 0.2 m, we still need a furnace at least 3.2 m long. This is not economical from the point view of engineering. The alternative is to let the tape zigzag in the pre-annealing zone to increase the effective furnace length. This work is undergoing in our laboratory.

V. CONCLUSION

The continuous processing is an alternative technique of traditional processing to solve the problem of uniform partial melting for long AgMg-sheathed Bi2212 multifilamentary tape. It is also found that the process has advantage in improving the texture and therefore enhancing $I_c$. This is due to a directional solidification involved in it.

REFERENCES