First performance test of a 30mm iron-based superconductor single pancake coil under a 24T background field

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Abstract
A 30 mm inner diameter iron-based superconductor (IBS) single pancake coil (SPC) was firstly fabricated and tested under a 24 T background field. This SPC was successfully made using the seven-filamentary Ba1−xKxFe2As2 (Ba122) tape by the wind-and-react method. This IBS coil shows the highest $I_c$ value at a magnetic field reported so far. For example, the transport critical current of this Ba122 SPC achieved 35 A at 4.2 K and 10 T, which is about half of that of a short sample. This indicates that the non-insulation winding process together with the stainless steel tape is suitable for an IBS. Even more encouraging is the fact that the $I_c$ of this SPC is still as high as 26 A under a 24 T background field, which is still about 40% of that at zero external magnetic field. These results clearly demonstrate that IBSs are very promising for high-field magnet applications.

Keywords: iron-based superconductor, single pancake coil, high background field, transport performance, wind-and-react method

(Some figures may appear in colour only in the online journal)

1. Introduction
Since 2008, iron-based superconductors (IBSs) [1] have attracted wide interest for both basic research and practical applications, because they have a high superconducting transition temperature ($T_c$), large critical current density ($J_c$) over 1 MA cm$^{-2}$ in thin films, very high upper critical field above 100 T and low anisotropy [2, 3]. After ten years of development, remarkable progress of high-performance Sr/BaKFeAs (Sr/Ba122) iron-based superconducting tape has been made [4–7]. Currently, the record high transport $J_c$ value of Ba1−xKxFe2As2 (Ba122) tapes is as high as 0.15 MA cm$^{-2}$ at 4.2 K and 10 T by the hot-pressing process [8]. It is noteworthy that this hot-pressed sample also retained a high value of $5.4 \times 10^4$ A cm$^{-2}$ at 4.2 K and 27 T. This suggests that IBSs are quite attractive for the construction of high-field magnets needed for nuclear magnetic resonance
spectrometers, particle accelerators, fusion reactors and also magnetic resonance imaging systems.

For practical applications, the 100 m class Sr$_1-x$K$_x$Fe$_2$As$_2$ (Sr122) tapes were fabricated in 2017 [9]. An average $I_c$ of $1.3 \times 10^4$ A cm$^{-2}$ at 4.2 K and 10 T was reached over the 115 m length, showing good longitudinal uniformity. Besides high current carrying capacity [10, 11], the Sr/Ba122 IBS tapes also showed good mechanical strength [11, 12], excellent reversible compressive strain (>0.6%) [13, 14], and small anisotropy [8, 15]. However, good results for IBS coils were not yet achieved at both high and low magnetic fields, even when the inner diameter of the double pancake coil was as large as 71.5 mm [9].

In this paper, we successfully fabricated high transport $I_c$ seven-filamentary Ba122/Ag/AgMn tape and a single pancake coil (SPC). Though the inner diameter of the Ba122 SPC is as small as 30 mm, its transport $I_c$ value still maintained about half that of the short sample at 4.2 K and 10 T. Meanwhile, the $I_c$ value was still as high as 26 A under a 24 T background field, which is about 40% of that at zero external magnetic field. Our results clearly indicate that the IBSs are very promising for high-field magnet applications.

2. Seven-filamentary Ba122/Ag/AgMn tapes

2.1. Experimental details

The starting materials for preparing a Ba122 precursor are small Ba fillings (99%), K pieces (99.95%), As (99.95%) and Fe (99.99%) powders [8]. To compensate for the loss of elemental K during the sintering process, additional K around 20 at% was added. The prepared powders were put into the milling jar and mixed by the ball milling process. All procedures were handled in an Ar atmosphere. After the ball milling, the powders were loaded into a Nb tube, and then heat-treated at 900 °C for 35 h. The sintered precursor was ground into fine powder. To improve grain connectivity of the Ba122, 5 wt% Sn powder was added and mixed with precursor powders in an agate mortar. The final powder was packed into a silver tube, which was drawn into mono-filamentary wire. The mono-filamentary wire was then cut and bundled into a AgMn0.4 tube and finally deformed into seven-filamentary Ba122/Ag/AgMn wire with diameter of 1.65 mm. This wire was then rolled into tape with thickness of 0.33 mm. Short seven-filamentary Ba122/Ag/AgMn samples were cut from the long tape, and then sintered at 880 °C for 0.5 h. The cross section of the wire was observed using an optical microscope. The temperature dependence of the resistivity was carried out using a four-probe method by a physical property measurement system (Model: PPMS-9). Transport critical current $I_c$ at 4.2 K and its magnetic field dependence were measured by the standard four-probe method with a criterion of 1 $\mu$V cm$^{-1}$. The magnetic field dependence of transport $I_c$ values for all samples were evaluated at the High Field Laboratory for Superconducting Materials in Sendai.

2.2. Results and discussions

The specification of Ba$_{0.8}$K$_{0.4}$Fe$_2$As$_2$/Ag/AgMn tape is shown in table 1. As shown from table 1, the ratio of non-superconductor to Ba122 superconductor is around 5. The transport $I_c$ value of seven-filamentary Ba122/Ag/AgMn tape is 72 A at 4.2 K and 10 T. The magnetic field dependence of transport $I_c$ data at 4.2 K for seven-filamentary Ba122/Ag/AgMn tape is shown in figure 1. The transport $I_c$ is about $3 \times 10^3$ A cm$^{-2}$ at 4.2 K and 10 T. This value is almost three times that of our previous seven-filamentary Sr$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ tape [9]. The inset of figure 1 shows the optical micrograph of a transverse cross section of sintered seven-filamentary Ba122/Ag/AgMn tape. It can be seen that the central Ba122 filament is thinner and broken, compared with the other six surrounded filaments. Obviously, this broken central Ba122 filament is harmful to the transport $I_c$ values and their uniformity. These problems should be further solved by optimizing the deforming process.
3. Ba122 single pancake coils

3.1. Experimental details

Ba122 SPCs were designed by the Institute of High Energy Physics (IHEP), Chinese Academy of Sciences. The SPCs were wound using non-insulation Ba122/Ag/AgMn tapes together with 0.1 mm stainless steel tapes by the wind-and-react method. The specifications of an SPC are listed in Table 2. The dimensions of the SPC were a 30 mm inner diameter and a 34.8 mm outer diameter. Figure 2(a) shows the outer view of the Ba122 SPC. The silver voltage taps were placed at the 2nd turn and the 3.5th turn. The distance between the two taps is about 150 mm. The heat treatment was performed at 850 °C for 0.5 h in an Ar atmosphere. After the heat treatment, the SPCs were impregnated with epoxy resin. The transport properties of all SPCs were firstly tested at liquid helium and zero external magnetic field by the Institute of Plasma Physics, Chinese Academy of Sciences. Two weeks later, some of SPCs were inserted coaxially in the 38 mm bore of a 25 T resistive magnet at the High Magnetic Field Laboratory, Chinese Academy of Sciences. Figures 2(b) and (c) show the Ba122 SPC before the testing and the 25 T resistive magnet.

| Parameter             | Unit | Value |
|-----------------------|------|-------|
| Inner diameter        | mm   | 30    |
| Outer diameter        | mm   | 34.8  |
| Height                | mm   | 4.62  |
| Thickness of stainless steel tape | mm | 0.1 |
| Turns                 |      | 4.5   |
| Total length of IBS wire | mm | 450 |

Table 2. Specification of the Ba122 SPC.

3.2. Results and discussions

A transport critical current $I_c$ of the SPC at 4.2 K was measured by the standard four-probe method with a criterion of 1 $\mu$V cm$^{-1}$. Therefore, the critical criterion is $1 \mu$V cm$^{-1} \times 15$ cm = 15 $\mu$V. At zero external magnetic field, the $I_c$ values are 76 and 77 A, when the excitation rates are 50 and 70 A min$^{-1}$, respectively. These $I_c$ values are twice as large as those of our previous double pancake coil (DPC) [9]. In order to evaluate the transport properties of the Ba122 SPC at high field, the same coil was tested again at liquid helium temperature and with a 25 T high-field resistive magnet. The $I_c$ value is about 66 A at zero external magnetic field, which is slightly decreased. One main reason may be that the SPC was exposed to air for two weeks. Figure 3 shows the $I_c$ data of the SPC with the magnetic field, including the self-field and the external magnetic field. In case the self-field generated by the straight tape was small, the transport current of the short...
Ba122 tape with the external magnetic field was also added in figure 3. When the inner diameter of this SPC is as small as 30 mm, its $I_c$ value is still as high as 35 A at 10 T, which is about half of that of the straight short sample. For our previous DPC [9], the $I_c$ value was reduced from 23 A (0 T) to 5 A (5 T) at 6 K, when the inner diameter of the DPC was as large as 71.5 mm. One possible reason is that a violent vibration happened to the tape during the insulator wrapping process, which is very harmful to the brittle superconducting core. These results indicate that the 0.33 mm thick seven-filamentary Ba122/Ag/AgMn tape was not seriously damaged during coil construction, and that the non-insulation winding together with the stainless steel tape is suitable for the iron-based superconductor.

From figure 3, we can also see that the $I_c$ of the Ba122 SPC is weakly dependent on the magnetic field, like the short tape. However, though it is a promising improvement on our previous work [9], the discrepancy between the short sample data and the coil data is still considerable. There are some possible reasons for the transport current degradation of the SPC. (1) The strength of this Ba122/Ag/AgMn tape is still not strong enough for the coil winding process. The brittle superconducting core is helpless once a violent force happens to the tape. Fortunately, IBS wires or tapes can be fabricated using stronger metals, such as Cu, Monel, stainless steel, etc. (2) There may be some low $I_c$ points in the long wire. It is necessary to further test $I_c$ uniformity of the long wire before it can be used for coil winding. (3) The heat treatment of the short tape and the SPC was different. According to our experience, the better temperature is 880°C rather than 850°C, but the former is closer to the melting point of AgMn.

4. Conclusion

In conclusion, we successfully made a seven-filamentary Ba122/Ag/AgMn SPC with an inner diameter of 30 mm. This SPC was made using non-insulation Ba122/Ag/AgMn tape together with stainless steel tape by the wind-and-react process. The transport properties of the Ba122 SPC were firstly tested at liquid helium temperature and with a 24 T external magnetic field. Like the straight Ba122 short tape, the transport current of the SPC was also independent of the background field and still large under a high magnetic field.

For example, the transport $I_c$ value of the SPC was still 26 A at a 24 T background field, which is about 40% of that at zero external magnetic field. These results suggest that IBSs are very promising for high-field magnet applications.

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