High critical current density in textured $Sr_{1-x}K_xFe_2As_2$ tapes for high field applications

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1. Introduction

The discovery of superconductivity in the iron pnictides has generated a great deal of research interest, not only in basic physics, but also in the field of applied superconductivity. In addition to their high transition temperature, T_c, the Fe based superconductors were reported to have a rather high upper critical field, H_{c2}, and low H_{c2} anisotropy. Data reported so far has revealed many similarities between iron pnictide and cuprate superconductors, such as a layered crystalline structure and superconductivity induced by carrier doping. However, there are some distinct differences, such as a highly symmetric order parameter based on *s*+- wave in the iron pnictides compared to a *d*-wave pairing. Therefore, different characteristics of high-angle GBs can be expected. Indeed, Katase et al. [1] performed a systematic study on the misorientation dependence of inter-grain J_c using an epitaxially grown Ba122 bi-crystal. The critical angle (θ_c) of the transition from a strong link to a weak link for Ba122 was found to be 9 ^{o}, which is substantially larger than the value of 3~5 ^{o} reported for YBCO. A remarkable transport inter-grain J_c of ~10^5 A/cm^2 at 4 K and self field has been observed in samples of high misorientation angle of 45^o. Such excellent properties suggest that the Fe based superconductors are promising for use in high magnetic field generation at liquid helium.

Earlier results indicate that the global critical current is limited by intergrain currents across grain boundaries in iron based superconductors. Some of which can be ascribed to extrinsic factors such as porosity, the amorphous phase at grain boundaries, and micro-cracks. Concerning the main intrinsic factor, J_c across the grain boundary decreases with grain boundary misorientation angle similar to that observed in the cuprates YBCO. In order to improve the grain connectivity of the iron based superconductors, a number of experimental techniques, including metal additions [2-4], rolling induced texture process [5], and hot isostatic press method [6], have been attempted. In this work, we report the further improvement of the transport critical current properties in textured $Sr_{0.6}K_{0.4}Fe_2As_2$ tapes with Sn additions. We observed a high transport critical current density of >10 kA/cm^2 at 4.2 K in 14 T field. Such a value is by far the highest ever reported for Fe based wires [7]. The influences of Sn addition, microstructure, and the annealing process on achieving superior J_c properties will be discussed.

2. Experimental

The $Sr_{1-x}K_xFe_2As_2$ polycrystalline precursors were prepared by a one-step PIT method developed by our group. In order to compensate for loss of elements during the milling and sintering procedures, the starting mixture contains 10-20% excess K. The precursors were ground to a powder in an agate mortar and pestle. For Sn doped samples, 5-10 wt% Sn was added to the precursor powder and then the mixture was ground in a mortar for half an hour. The final powders were filled and sealed into an iron tube, which was subsequently swaged and drawn down to a wire of 1.9 mm in diameter. The as-drawn wires were then cold rolled into tapes (0.6 mm in thickness) with a reduction rate of 10~20%. The tapes were finally sintered following two different processes:

sample was directly inserted into a furnace that was preheated to 1100^{o}C, and removed from the furnace after 1~30 minutes (high temperature annealing process: Batch I), sample was sintered at 800-950^{o}C for 1~30 minutes and then decreased to 600^{o}C for 5 h (low temperature annealing process: Batch II).

Phase integrity and texture of $Sr_{0.6}K_{0.4}Fe_2As_2$ grains were investigated using x-ray diffraction (XRD), for which iron sheath was mechanically removed after cutting the edges of the tape. Microstructure was studied using a scanning electron microscopy (SEM). DC magnetization measurements were carried out using a physical property measurement system (PPMS). The transport current I_c at 4.2 K and its magnetic field dependence were evaluated at the High Field Laboratory for Superconducting Materials (HFLSM) at Sendai, by standard four-probe method, with a criterion of 1 μV/cm, then the critical current was divided by the cross section area of the superconducting core to get the critical current density J_c. For each set of tapes, I_c measurement was performed on several samples to ensure the reproducibility.

3. Results and discussions

The degree of grain texture was determined by XRD analysis. X-ray diffraction patterns of $Sr_{1-x}K_xFe_2As_2$ bulk precursor, as-rolled tape, low temperature annealed tape, and high temperature annealed tape are shown collectively in Figure 1. The relative intensity of (103) peak with respect to that of (002) peak in all tape samples, when compared to the bulk precursor, is strongly reduced, indicating enhanced *c*-axis orientation. In order to have quantitative information about the texture of the $Sr_{1-x}K_xFe_2As_2$ phase, we have evaluated the *c* axis orientation factor F by the Lotgering method as follows.

$$F=(\rho-\rho_0)/(1-\rho_0),$$

Where $\rho=\sum I(00l)/\sum I(hkl)$, $\rho_0=\sum I_0(00l)/\sum I_0(hkl)$, I and I_0 are the intensities of each reflection peak (hkl) for the oriented and random samples, respectively. The value of F for the as-rolled tape, was 0.316, the value of F for low temperature annealed tape was 0.348, and the value of F for high temperature annealed tape was 0.565, respectively. The cold deformation of the $Sr_{1-x}K_xFe_2As_2$ tapes during the tape fabrication processes induces a relevant texture. In particular, the texture greatly improved after high temperature heat treatments.

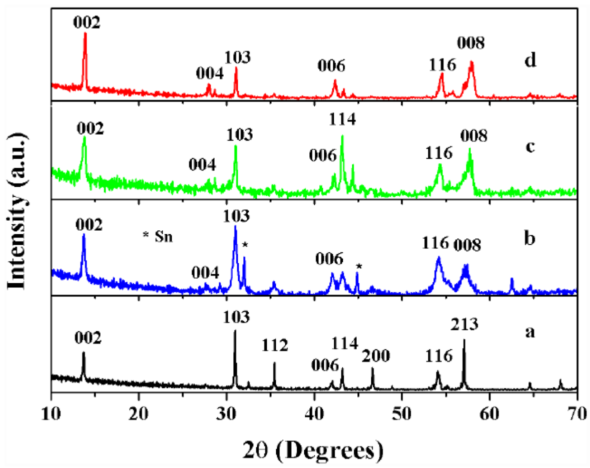

Figure 1 X-ray diffraction patterns for $Sr_{1-x}K_xFe_2As_2$ precursor bulk (a), as-rolled tape (b), tape annealed at low temperature (c) and tape annealed at high temperature (d).

Figure 2 presents the temperature dependent magnetic moment of samples measured in the magnetic field parallel to the *c*-axis. It is evident from the zero-field cooled (ZFC) signal that the diamagnetic signal does not saturate but continuous to decrease to lower temperature indicating some degrees of inhomogeneity in the sample annealed at high temperature. Note that low temperature annealing with longer time sharpens the T_c transition and reduces the inhomogeneities. Additionally, as shown more clearly in figure 2, low temperature annealing increased the onset T_c from 27.3 K to 32.5 K.

High critical current density in applied magnetic fields is essential for wire applications. Figure 3 shows the transport J_c measured as a function of applied magnetic fields along with reported values of other Fe-based superconducting wires and conventional Nb based superconducting wires. For the Batch II samples heated at low temperature, only data above 2 T are shown, because at lower field region, I_c is too high to be measured with our current apparatus. It can be seen that both samples demonstrate excellent J_c performance. Remarkably, the J_c of the tapes sintered at low temperature exhibits very weak field dependence and maintains a reasonably high value of 1.4×10^4 A/cm^2 at 14 T, this J_c value is the highest ever reported for the iron based superconducting wires or tapes so far. It is about a factor of two higher than the best Ba-122 wire recently reported in ref. [6]. Another interesting feature is the comparison of the superconducting properties of the present tapes with those of classical superconductors. The J_c value of 1.7×10^4 A/cm^2 was achieved at 10 T for the tapes sintered at low temperature, which exceeded the value of NbTi conductors. To compare with the J_c of Nb_3Sn, the data above 14T for Batch II in Fig.3 is extrapolated from low fields. As can be seen, a crossover with the J_c of Nb_3Sn would take place at around 19.5 T, as shown in figure 3. This indicates that the 122 superconducting wires may be competitive with well established Nb based conductors used in MRI and NMR for high field generation.

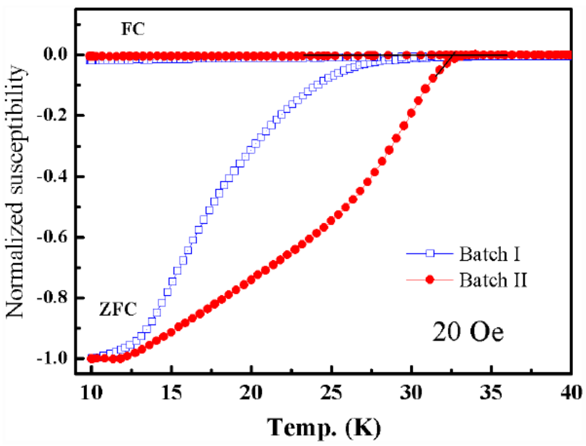

Figure 2 Temperature dependence of magnetic susceptibility measured with field of 20 Oe for Batch I and Batch II samples.

It shows a grain boundary network in the textured $Sr_{0.6}K_{0.4}Fe_2As_2$ tape at low magnification TEM images, which are not shown here. The tape sample exhibits a layered structure with good alignment. Figure 4 (a) shows EDX line scan across one of grain boundary. Previous studies reported that the grain boundaries are usually coated by amorphous oxide layers. In contrast, we observed that the grain boundaries in Sn doped tapes are often filled with Sn rich materials (see fig.4 (b)), note that the thickness of these interfaces are around 2-3 nm. Clearly, Sn and its alloy as flux can improve the crystallization of grain boundaries, diminish the formation of amorphous layer, and hence improve intergranular connectivity. In order to investigate the effect of annealing process on the tapes, we studied the difference in microstructures of the tapes heated at different temperatures. Figure 4 (c) and (d) present scanning microscopy photomicrographs of Batch I and II tapes. Well-developed texture structures can be seen in both samples.

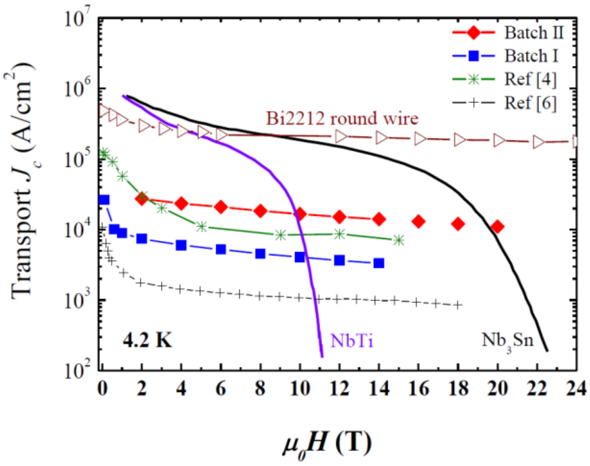

Figure 3 The transport J_c values at 4.2 K obtained in this experiment plotted as a function of applied magnetic fields along with other Fe-based superconducting wires. The conventional Nb based and Bi2212 superconducting wires are also included for reference.

As mentioned above, the J_c values of textured 122 pnictide tapes have reached over 10^4 A/cm^2 in a field of 14 T at 4.2 K. The well developed grain texture in our samples is a main reason for the superior J_c performance, since the misalignment in crystalline orientation at grain boundaries is a crucial weak-link in connectivity. Secondly, as shown by TEM study, Sn can promote the crystallization at grain boundaries, diminish the formation of amorphous layer, and hence much improved intergranular connectivity. Thirdly, low temperature synthesis results in highly dense material, which further contributes to good connectivity.

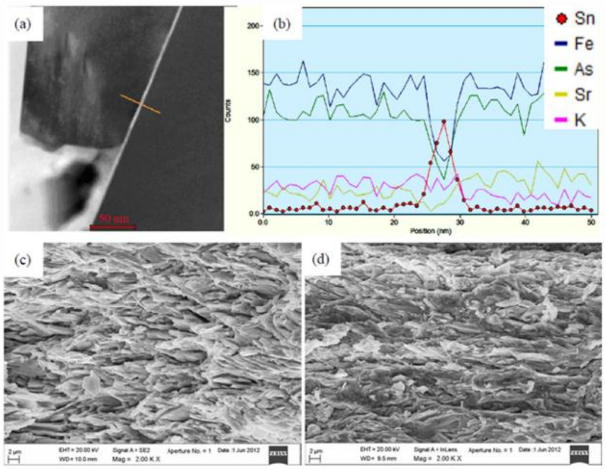

Figure 4 (a) A STEM image of the Sr122 grain boundary. (b) The EDS line scan (as denoted in (a)) indicates that the grain boundary is filled with Sn rich material. Typical SEM images for $Sr_{0.6}K_{0.4}Fe_2As_2$ tapes annealed at high temperature (c) and low temperature (d).

Our present results clearly show that textured Sr122 superconducting tapes, fabricated by the low-cost powder-in-tube process, exhibited extremely high and nearly isotropic transport J_c, as well as independent of the field behavior, demonstrating the potential for high field magnet applications. As the cumulative knowledge of pnictide PIT process grows, it is expected that the critical currents will continue to increase. We believe that the current PIT process can be applied industrially to fabricate high performance pnictide wires and tapes, as already demonstrated by the production of Bi-2223 and MgB_2 wires and tapes.

4. Conclusion

In summary, excellent transport J_c values under high magnetic field were observed in the textured $Sr_{1-x}K_xFe_2As_2$ superconducting tapes that exhibit very small anisotropy. The well aligned superconducting grains and strengthened intergrain coupling achieved by Sn addition are responsible for this high J_c performance. With further improvement of critical current density and wire fabrication technology, use of $Sr_{1-x}K_xFe_2As_2$ for very high field application is feasible.

References

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