Enhancement of critical current density in AgSn-sheathed (Sr,Na)Fe$_2$As$_2$ superconducting tapes

T Suwa$^1$, S Pyon$^1$, T Tamegai$^1$ and S Awaji$^2$

$^1$ Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
$^2$ High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

Email: tamegai@ap.t.u-tokyo.ac.jp

Abstract. We have fabricated (Sr,Na)Fe$_2$As$_2$ tapes by using AgSn alloy as a sheath material. In the tape sintered at 750°C, transport $J_c$ reached 47 kA/cm$^2$ at 4.2 K and 50 kOe, which is larger than that of the Ag-sheathed (Sr,Na)Fe$_2$As$_2$ tape. This result indicates that we have succeeded in reducing the sintering temperature by more than 100°C keeping the high $J_c$ value, which is very promising for practical applications. In the SEM images of polished longitudinal cross section of the tapes, the improvement of interface flatness by using AgSn alloy as a sheath material is confirmed.

1. Introduction
Superconductivity in layered iron-based superconductors was first discovered by Kamihara et al. in LaFeAs(O,F) in 2008 [1]. Soon after the discovery, several types of high temperature superconductors in iron pnictides were discovered. Among them, superconducting wires and tapes have been fabricated mainly by using (AE,K)Fe$_2$As$_2$ materials (AE = Ba or Sr), so called ‘122-type’ [2-8], because of their high upper critical field $H_{c2}(0)$ [9, 10] and low anisotropy $\gamma(\sim 2)$ [10, 11], as well as their high transition temperature $T_c$ (36-38 K) [12, 13]. At present, the transport $J_c$ for (AE,K)Fe$_2$As$_2$ tapes has reached 10$^3$ A/cm$^2$ [14, 15], which is the level for practical applications, at 4.2 K and 100 kOe.

Recently, a new material joined this kind of research, namely (Sr,Na)Fe$_2$As$_2$ [16, 17]. The reported transport $J_c$ at 20 K up to 25 kOe is comparable to that in (AE,K)Fe$_2$As$_2$ tapes in the same condition. Following this study, we have fabricated (Sr,Na)Fe$_2$As$_2$ tapes by using Ag sheath and achieved transport $J_c$ as high as 19 kA/cm$^2$ at 4.2 K and 140 kOe [18].

This year, excellent $J_c$ characteristics in AgSn-sheathed (Ba,K)Fe$_2$As$_2$ tapes was reported [19]. In this report, $J_c$ in AgSn-sheathed tapes sintered at 750°C was as high as that in Ag-sheath tapes sintered at 850°C. Following this report, in the present work, we report the fabrication of (Sr,Na)Fe$_2$As$_2$/AgSn tapes and their $J_c$ characteristics. In the tape sintered at 750°C, transport $J_c$ reached 47 kA/cm$^2$ at 4.2 K and 50 kOe, which is larger than that of the Ag-sheathed (Sr,Na)Fe$_2$As$_2$ tape sintered at higher temperature of 875°C. We performed a scanning electron microscope observations and compositional analyses with an energy dispersive x-ray spectroscopy (SEM-EDX).
2. Experiments
First, we fabricated Ag-Sn alloy tube in the same way as reported in Ref. [19]. Sn concentration of the tube was 5%. In fabricating superconducting tapes of (Sr,Na)Fe$_2$As$_2$, we basically followed the method reported in Ref. [17]. Since it is reported that a sample with Na concentration $x = 0.55$ exhibited the highest $T_c$ (36.5 K), we selected $x$ as 0.55 [16]. Polycrystalline samples were synthesized at 720°C for 18 h in a stainless steel pipe, where pellets of starting materials (SrAs, NaAs, Fe$_2$As) were placed. Then, the reacted materials were ground into powder, pelletized, and reacted at 720°C for 18 h again. The prepared polycrystalline materials were ground into powder with an agate mortar and pestle in a nitrogen filled glove box. The ground powder was tightly packed into a Ag-Sn alloy tube with outer and inner diameters of 4.0 and 2.6 mm, respectively. The tube was groove-rolled into a wire with 1.3 x 1.3 mm$^2$ cross section. Then, the wire was flat-rolled into a tape form with a thickness and width of 0.25 and 2.2 mm, respectively. The tape was cold-pressed under a pressure of 0.54 GPa. Finally, the tape was heated for sintering. Sintering temperature was 700°C, 750°C, 775°C, 800°C, 825°C, and 850°C, and the sintering temperature dependence of $J_c$ was studied.

Magnetic measurements were conducted using a commercial SQUID magnetometer (MPMS-XL5, Quantum Design), and magnetic $J_c$ was estimated. Transport $J_c$ was measured at 4.2 K by the standard four-probe method in magnetic fields up to 140 kOe. SEM images of the core were taken using SEM-EDX (S-4300, Hitachi High-Technologies equipped with EMAX x-act, HORIBA).

3. Results and discussion
3.1. Magnetic $J_c$ estimated from magnetic hysteresis curves
We fabricated (Sr,Na)Fe$_2$As$_2$/AgSn tapes by sintering them at various temperatures, and estimated magnetic $J_c$ through magnetic measurements with the field perpendicular to the flat surface of the tape. Figure 1(a) shows the magnetic field dependence of magnetic $J_c$ in the tape sintered at 750°C, which recorded the highest $J_c$ among tapes sintered at various temperatures. The obtained $J_c$ at 4.2 K was as high as 110 kA/cm$^2$ and 65 kA/cm$^2$ at 50 kOe when the magnetic field was applied parallel and perpendicular to the tape surface, respectively. These values are higher than the record value for Ag-sheathed tapes sintered at 875°C. When we sintered a Ag-sheathed tape at 875°C, strong reaction between the core and Ag sheath was observed. However, when we fabricated a AgSn-sheathed tape by sintering at 750°C, no clear reaction was observed between the AgSn sheath and the core.

Figure 1(b) shows sintering temperature dependence of magnetic $J_c$ at 4.2 K and 50 kOe for AgSn-sheathed and AgSn tapes. It is obvious that the best sintering temperature was lowered by more than 100°C in AgSn-sheathed tape. Similar behavior has been reported for (Ba,K)Fe$_2$As$_2$ tape in Ref. [19]. It was conjectured that using AgSn as a sheath material lead to the hardening of the core and enhancement of $J_c$. However, when the (Sr,Na)Fe$_2$As$_2$ tape was sintered at 850°C, the core reacted with the AgSn sheath severely. This was probably caused by the fact that the melting point of AgSn is about 900°C when Sn concentration is 5%, which is about 60°C lower than that of pure Ag.

3.2. Transport $J_c$ measurements at 4.2 K in magnetic fields up to 140 kOe
Figure 2(a) shows $I$-$V$ characteristics of (Sr,Na)Fe$_2$As$_2$ tape at 4.2 K up to 140 kOe, from which we evaluated transport $J_c$ with the criterion of 1 μV/cm. Figure 2(b) shows magnetic field dependence of $J_c$ in the tapes sintered at various temperatures. In the tape sintered at 750°C, transport $J_c$ reached 47 kA/cm$^2$ at 50 kOe, which is larger than the largest $J_c$ of the Ag-sheathed (Sr,Na)Fe$_2$As$_2$ tape. All AgSn tapes exhibited high and field-insensitive $J_c$. However, the transport $J_c$ was lower than the magnetic $J_c$, and we can further improve $J_c$ by clarifying the origin of this discrepancy.

First, these $I$-$V$ measurements were conducted three months after fabricating these tapes. Then, deterioration of the (Sr,Na)Fe$_2$As$_2$ tapes possibly has something to do with residual Na in the core. When
this (Sr,Na)Fe$_2$As$_2$ tape is processed at high sintering temperatures, a part of Na segregates from the core. In fact, when we polish the surface of the tape in the air, we can observe bubbles are coming out of the core as shown in figure 3(b). These bubbles are most probably NaOH, which is caused by the reaction between the segregated Na in the core and H$_2$O in the air. This reaction can lead to deterioration of the core. The segregation of Na is possibly caused by the fact that the optimal doping level of Na in (Sr,Na)Fe$_2$As$_2$ is higher than that of K in (Ba,K)Fe$_2$As$_2$. So, there is a possibility that controlling the Na doping level leads to higher quality superconducting tapes which are more stable in the air.

3.3. SEM images of the core

Figures 4(a)–(d) are SEM photographs of the interface between the core and the sheath on the polished longitudinal cross section of (Sr,Na)Fe$_2$As$_2$ tapes. Figures 4(a) and 4(c) are the Ag-sheathed tape, and figures 4(b) and 4(d) are the AgSn-sheathed tape. One observes that the shape of the core in the Ag-sheathed tape is distorted as shown in figure 4(a). Such distortion could be caused by the softness of the Ag. It is clearly observed in figure 4(c) that the interface between the core and the sheath is much less
Figure 3. Optical images of the (Sr,Na)Fe$_2$As$_2$/Ag tape sintered at 875°C on the polished longitudinal cross section of the tapes (a) before and (b) after NaOH bubbles coming out.

straight. On the other hand, one observes that the shape of the core in the AgSn-sheathed tape is more regular as shown in figure 4(b), and the interface between the core and the sheath is more straight as shown in figure 4(d). This is due to the hardness of the AgSn. These differences can lead to the enhancement and homogeneity of $J_c$. Such improvements of the interface morphology were also reported in the AgSn-sheathed (Ba,K)Fe$_2$As$_2$ tapes in Ref. [19].

Figure 4. SEM images of the interface between the sheath and the (Sr,Na)Fe$_2$As$_2$ core of the Ag-sheathed tape ((a) and (c)) sintered at 875°C, and the AgSn-sheathed tape ((b) and (d)) sintered at 750°C. The observation was conducted on the polished longitudinal cross section of the tapes.
4. Summary
We have fabricated and characterized AgSn-sheathed (Sr,Na)Fe$_2$As$_2$ superconducting tapes prepared under different sintering temperatures including magnetic $J_c$, estimated from magnetic hysteresis curves, transport $J_c$ up to 140 kOe, and SEM images. In the tape sintered at 750°C, the value of magnetic $J_c$ at 4.2 K was as high as 110 kA/cm$^2$ and 65 kA/cm$^2$ at 4.2 K and 50 kOe when the magnetic field was applied parallel and perpendicular to the tape surface, respectively. In the same tape, transport $J_c$ reached 47 kA/cm$^2$ at 4.2 K and 50 kOe, which is larger than that of the Ag-sheathed (Sr,Na)Fe$_2$As$_2$ tape. These results indicate that we have succeeded in reducing the sintering temperature by more than 100 °C, keeping the high $J_c$ value. SEM images of the core of the tapes clarified the improvement of smoothness of the interface between the core and the sheath by using AgSn alloy as a sheath material, which probably helped to improve the homogeneity of $J_c$ in the core.

Acknowledgements
This work was supported by a Grant-in-Aid for Scientific Research (A) (17H01141), a Grant-in-Aid for Young Scientists (B) (16K17745), and the Japan-China Bilateral Joint Research Project by the Japan Society for the Promotion of Science (JSPS).

References
[1] Kamihara Y, Watanabe T, Hirano M and Hosono H 2008 J. Am. Chem. Soc. 130 3296
[2] Ma Y W, Gao Z S, Qi Y P, Zhang X P, Wang L, Zhang Z Y and Wang D L 2009 Physica C 469 651
[3] Togano K, Matsumoto A and Kumakura H 2011 Appl. Phys. Express 4 043101
[4] Pyon S, Tsuchiya Y, Inoue H, Kajitani H, Koizumi N, Awaji S, Watanabe K and Tamegai T 2014 Supercond. Sci. Technol. 27 095002
[5] Pyon S, Yamasaki Y, Kajitani H, Koizumi N, Tsuchiya Y, Awaji S, Watanabe K and Tamegai T 2015 Supercond. Sci. Technol. 28 125014
[6] Weiss J D, Tarantini C, Jiang J, Kametani F, Polyanaskii A A, Larbalestier D C and Hellstrom E 2012 Nat. Mater. 11 682
[7] Pyon S, Suwa T, Park A, Kajitani H, Koizumi N, Tsuchiya Y, Awaji S, Watanabe K and Tamegai T 2016 Supercond. Sci. Technol. 29 115002
[8] Tamegai T, Suwa T, Pyon S, Kajitani H, Takano K, Koizumi N, Awaji S and Watanabe K 2017 IOP Conf. Ser. Mater. Sci. Eng. 279, 012028
[9] Putti M et al. 2010 Supercond. Sci. Technol. 23 034003
[10] Wang Z S, Luo H Q, Ren C and Wen H H 2008 Phys. Rev. B 78 140501R
[11] Yuan H Q, Singleton J, Balakirev F F, Baily S A, Chen G F, Luo J L and Wang N L 2009 Nature 457 565
[12] Rotter M M, Tegel M, Johrendt D, Schellenberg I, Hermes W and Pöttgen R 2008 Phys. Rev. B 78 020503
[13] Sasmal K, Lv B, Lorenz B, Guloy A M, Chen F, Xue Y Y and Chu C W 2008 Phys. Rev. Lett. 101 107007
[14] Zhang X, Yao C, Lin H, Cai Y, Chen Z, Li J, Dong C, Zhang Q, Wang D, Ma Y, Oguro H, Awaji S and Watanabe K 2014 Appl. Phys. Lett. 104 202601
[15] Gao Z, Togano K, Matsumoto A and Kumakura H 2014 Sci. Rep. 4 4065
[16] Shinozohara N, Tokiwa K, Fujihisa H, Gotoh Y, Ishida S, Kihou K, Lee C H, Eisaki H, Yoshida Y and Iyo A 2015 Supercond. Sci. Technol. 29 115002
[17] Iyo A, Shinozohara N, Tokiwa K, Ishida S, Tsuchiya Y, Ishii A, Asou T, Nishio T, Matsuzaki K, Takeshita N, Eisaki H and Yoshida Y 2015 Supercond. Sci. Technol. 28 105007
[18] Suwa T, Pyon S, Park A, Tamegai T, Tsuchiya Y, Awaji S and Watanabe K 2017 J. Phys.: Conf. Ser. 871 012062
[19] Togano K, Gao Z, Matsumoto A, Kikuchi A and Kumakura H 2017 Supercond. Sci. Technol. 30 015012