High-performance Ba$_{1-x}$K$_x$Fe$_2$As$_2$ superconducting tapes with grain texture engineered via a scalable fabrication

Shifa Liu$^{1,2}$, Chao Yao$^{1,2,*}$, He Huang$^{1}$, Chiheng Dong$^{1,2}$, Wenwen Guo$^{1,2}$, Zhe Cheng$^{1,2}$, Yanchang Zhu$^{1}$, Satoshi Awaji$^{3}$ and Yanwei Ma$^{1,2,*}$

ABSTRACT Nowadays the development of high-field magnets strongly relies on the performance of superconducting materials. Iron-based superconductors (IBSs) exhibit high upper critical fields and low electromagnetic anisotropy, making them particularly attractive for high-field applications, especially in particle accelerator magnets, nuclear magnetic resonance spectrometers, medical magnetic resonance imaging systems and nuclear fusion reactors. Herein, through an industrially scalable manufacturing strategy, a practical-level critical current density up to $1.1 \times 10^5$ A cm$^{-2}$ at 4.2 K in an external magnetic field of 10 T was achieved in Cu/Ag composite-sheathed Ba$_{1-x}$K$_x$Fe$_2$As$_2$ (Ba122) superconducting tapes. The preparation strategy combines flat rolling to induce grain texture and subsequent hot-isostatic-pressing densification. By varying the parameters of rolling, the degree of grain texture was engineered. It is found that the transport properties of the Ba122 tapes can be enhanced by applying a large amount of deformation during rolling, which can be attributed to the improved degree of $c$-axis texture. Microstructure characterizations on the highest-performance tape demonstrate that the Ba122 phase has a uniform element distribution and small grains with good connectivity. Grain boundary pinning is consequently enhanced as proved by large currents circulating through the sample even at 25 K. Our work proves that Cu/Ag composite-sheathed Ba122 superconducting tapes can be a promising competitor for practical high-field applications in terms of the viable, scalable and cost-effective fabrication strategy applied and the high transport properties achieved in this work.

Keywords: iron-based superconductors, critical current density, scalable, grain texture, hot isostatic pressing

INTRODUCTION

Iron-based superconductors (IBSs) discovered in 2008 have attracted much attention due to their unique superconducting mechanism and potential value in practical applications [1–3]. To date, among several tens of reported IBSs [4–6], "122" iron-pnictide compounds such as Sr$_{1-x}$K$_x$Fe$_2$As$_2$ (Sr122) and Ba$_{1-x}$K$_x$Fe$_2$As$_2$ (Ba122) hold great promise for high-field magnet applications [7,8], because they have moderately high critical transition temperatures $T_c$ (up to 38 K), high upper critical fields $H_{c2}$ (above 75 T) and low anisotropy $\gamma$ (<2) [8–11]. For such applications, superconducting wires and tapes with high in-field transport critical current densities ($J_c$) are crucial. Tremendous advances have been made in $J_c$ enhancement of iron-pnictide wires and tapes prepared by a powder-in-tube (PIT) method over the past decade [4,12,13]. In order to obtain high $J_c$, besides high-quality precursor powder, there are two major issues that need to be resolved, namely the poor connectivity of Ba122 grains due to the microstructural defects such as pores and cracks which are extrinsically induced during the PIT process and intrinsic weak links at the high-angle grain boundaries between mismatched grains [14,15]. Pores and cracks hinder the supercurrent flow inside superconducting polycrystals, while weak-link behavior results in an exponential decay of inter-grain $J_c$ as a function of grain boundary angle when it is larger than a so-called critical angle ($\theta_c$) [16]. Actually, Ba122 exhibits a much higher tolerance for mismatched grains than REBa$_2$Cu$_3$O$_7$ ($RE$ = rare earth elements) cuprate superconductors [17–19]. The $\theta_c$ for cobalt-doped BaFe$_2$As$_2$ epitaxial films is about 9°, larger than the $\theta_c$ of 5° for YBa$_2$Cu$_3$O$_7$-$\delta$. Even
for misorientation angles larger than $\theta_c$, cobalt-doped Ba122 films show a much slower decay of $J_c$ than YBa$_2$-Cu$_3$O$_7$-δ. On the other hand, measurements on Ba122 bulks reveal that a large $J_c$ results from small grains [20]. This attribute even has called into question whether grain texture is still crucial or not for high $J_c$-performance in iron-pnictide wires and tapes.

In “122” iron-pnictide tapes, the $c$-axis texture can be mechanically introduced by deforming round wires into thin tapes through flat rolling [21,22]. In order to explicitly clarify the role of grain texture in $J_c$ improvement for Ba122 tapes, some extrinsic ingredients such as impurity phases, composition inhomogeneity, pores and cracks should be eliminated as much as possible. With the uniaxial pressing densification process, a high transport $J_c$ above $10^4$ A cm$^{-2}$, which is a widely accepted threshold for practical applications, has been reported in $c$-axis-textured Sr122 and Ba122 iron-pnictide tape samples [23–25]. However, strictly limited by the size of pressing heads, this manufacturing route is problematic to be scaled up for processing long wires and tapes. Moreover, the widely used uniaxial pressing, either cold pressing or hot pressing, not only enhances the mass density, but also further improves the grain texture simultaneously, making it complicated to investigate the contribution of mass densification and grain alignment to the $J_c$-performance separately.

As an alternative to uniaxial pressing for densification, the hot isostatic pressing (HIP) process utilizing high-pressure argon gas as media can effectively reduce the pores and cracks in superconducting cores. The $J_c$ values of $\sim 10^4$ A cm$^{-2}$ at 4.2 K and 10 T were measured in HIP round wires with randomly oriented grains [26,27]. The mass density of iron-pnictide cores of wires and tapes can be indicated with Vickers hardness. It is reported that the mass density of Ba122 cores in HIP processed wires can be significantly enhanced to nearly 100%, showing Vickers hardness even higher than that in uniaxially pressed tapes [24,26–29]. Compared with uniaxial pressing, HIP technique is much more flexible and economic for large-scale producing, since long wires and tapes can be processed in winding state in space-limited furnaces. However, it can hardly induce any grain alignment as done by rolling and uniaxial pressing, and further efforts over the past several years have failed to improve $J_c$ values of HIP-treated round wires to a practical level at a field of 10 T.

For Ba122 superconducting tapes, grain alignment introduced by the rolling process can be well preserved after heat treatment by the HIP densification process [30]. Herein, the flat rolling and a subsequent HIP process were combined to obtain $c$-axis texture and well-connected superconducting grains. Since mass densification and $c$-axis texture were achieved through two separate processes, the effect of grain alignment on transport $J_c$ can be studied based on highly dense Ba122 phase. The starting wire diameters for rolling were varied to induce different degrees of texture for the purpose of revealing the correlation between grain textures and transport $J_c$ in Ba122 tapes. Besides, copper was used as the sheath material to partially replace silver in purpose of reducing the fabrication cost and enhancing the mechanical strength of the tapes. Finally, as a result, $J_c$ was enhanced to $1.1 \times 10^5$ A cm$^{-2}$ at 4.2 K and 10 T, which confirms the indispensability of texture for high performance in Ba122 tapes.

**EXPERIMENTAL SECTION**

Ba122 tapes were prepared by the ex situ PIT method.

The preparation of Ba$_{1-x}$K$_x$Fe$_2$As$_2$ ($x = 0.4$) precursor was detailed in the Ref. [30]. Fig. 1a–c illustrate the PIT and cold working deformation process. The precursor was ground into powder using an agate mortar, and sealed into a silver tube with an outer diameter of 8.0 mm and an inner diameter of 5.0 mm. These steps were done in an argon-filled glovebox to avoid contact with oxygen and moisture. The silver tube was first swaged into an outer diameter of 3.4 mm and then drawn into a wire with an outer diameter of 1.93 mm. The wire was cut into several pieces and each piece was sealed into a copper tube with an outer diameter of 4.0 mm and an inner diameter of 2.0 mm. The Cu/Ag composite-sheathed wires were again deformed by swaging and drawing. The final diameters of these wires were 1.3, 1.5, 1.7 and 1.9 mm respectively. After that, these wires were rolled into tapes with thickness of 0.3 mm after 4 or 5 passes. Finally, these tapes were sintered for 1 h at 740°C by HIP at 150 MPa in argon atmosphere.

The field-dependent critical current measurements were performed at the High Field Laboratory for Superconducting Materials at Sendai by a standard four-probe method, with a criterion of 1 µV cm$^{-1}$. It needs to be pointed out that the test was carried out under decreasing fields. For further analysis, several short pieces of these Ba122 tapes were chemically treated to remove the metal sheath to obtain the bare Ba122 cores or were embedded in conductive resin and mechanically ground and polished. The Vickers hardness testing was performed on the polished cross sections by using the Wilson 402MVD tester. The magnetic-field- and temperature-dependent...
The magnetic property of the tape was characterized by SQUID-VSM on the magnetic property measurement system (MPMS). X-ray diffraction (XRD, Bruker D8 Advance) measurements were conducted on the surfaces of the Ba122 cores with Cu Kα1 radiation. The scanning electron microscopy (SEM, Zeiss SIGMA) observation was performed on the cross sections of the Ba122 cores after they were mechanically broken. By using an EDAX Hikari camera equipped on the SEM, the grain texture was quantitatively represented by the electron backscatter diffraction (EBSD) technique. Vibratory polishing was applied on the sample for EBSD analysis to eliminate the stress of the polished surface. The element distribution on the polished cross section was analyzed by an electron probe micro-analyzer (EPMA, JXA-iSP100). The magneto-optical (MO) imaging was performed on a cryostat (Montana Instruments) by placing a Bi-substituted iron-garnet film on the top of the polished superconducting core. Magnetic fields perpendicular to the sample surface were provided by a homemade magnet.

RESULTS

Fig. 1d shows the optical images of the four Ba122 superconducting tapes rolled from round wires with different diameters of 1.3, 1.5, 1.7 and 1.9 mm. The as-obtained tapes are labeled as tape-1.3-mm, tape-1.5-mm, tape-1.7-mm and tape-1.9-mm, respectively. The typical cross-sectional images present a Ba122 superconducting core surrounded by an inner silver barrier and an outer copper sheath. In order to quantify the amount of deformation during rolling, a reduction ratio \( r \) can be defined as \( r = (D_0 - d) / D_0 \), where \( D_0 \) is the initial diameter and \( d \) is the final tape thickness (in this work \( d = 0.3 \) mm). The calculated \( r \) values for tape-1.3-mm, tape-1.5-mm, tape-1.7-mm and tape-1.9-mm are 0.77, 0.80, 0.82 and 0.84, respectively. Vickers hardness of the Ba122 cores was measured on the cross sections of the tapes. The average values for these tapes are 202, 197, 203 and 212, respectively, which are comparable to that of the previously reported HIP samples [27,30]. The high Vickers hardness usually indicates a high mass density of the superconducting cores.

In Fig. 2a, \( J_c \) values of the four Ba122 tapes were plotted as a function of the applied magnetic field. Among the four tapes, transport \( J_c \) of tape-1.9-mm is the highest, reaching \( 1.1 \times 10^5 \) A cm\(^{-2} \) at 4.2 K and 10 T, which is a record value for Cu/Ag composite-sheathed IBS tapes and surpasses the threshold for practical applications. It is still above \( 10^5 \) A cm\(^{-2} \) even at 12 T, and slightly decreases to \( 9.4 \times 10^4 \) A cm\(^{-2} \) at 14 T, showing very weak field dependence. For tape-1.7-mm, tape-1.5-mm and tape-1.3-mm, the \( J_c \) values are \( 9.5 \times 10^4 \), \( 9.2 \times 10^4 \) and \( 5.8 \times 10^4 \) A cm\(^{-2} \) at 4.2 K and 10 T, respectively. It is obvious that when the initial diameter of the as-drawn wires becomes smaller,
i.e., the reduction ratio is lowered, the $I_c$ values of the tapes decrease. Fig. 2b shows the resistance transition curves of the four tapes in the self-field. The inset in Fig. 2b shows the resistivity of the four tapes as a function of temperature in a range from 25 to 250 K. It is worth noting that the resistance measurements were performed on the bare Ba122 cores, and thus the result reflects the intrinsic property of the Ba122 phase in the tapes. For comparison, the resistivity of each tape is normalized by dividing by its resistivity value at 40 K. A distinctive feature of the resistance transition curves is that the four curves almost overlap with a $T_c$ difference within 0.1 K. Therefore, it can be inferred that the Ba122 polycrystals in these tapes have little difference in the element content and phase purity. The onset $T_c$ values of the four tapes are all around 38.2 K, indicating that high-quality Ba122 phase was obtained in these tapes.

The grain orientation and phase composition for the Ba122 tapes were investigated by XRD, as shown in Fig. 2c. The pattern of the randomly oriented Ba122 precursor powder is also presented for comparison. Generally, for all the samples, Ba122 phase is the main phase, while in the tape samples, diffraction peaks of iron were also detected, which is ascribed to unreacted iron formed in HIP sintering. The intensity of all the XRD patterns was normalized by the intensity of the (103) peak of Ba122 phase. Compared with the precursor powder, the intensity of (00l) peaks in these tapes is strongly increased, which is significant evidence of the presence of c-axis texture in these tapes. According to the Lotgering method [31], the degree of texture can be evaluated by an orientation factor $F = (\rho - \rho_0)/(1 - \rho_0)$, 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) in the range of 2θ from 10° to 60° for the tape samples and the randomly oriented precursor powder, respectively. For tape-1.3-mm, tape-1.5-mm, tape-1.7-mm and tape-1.9-mm, the calculated $F$ values are 0.38, 0.42, 0.42 and 0.46, respectively. In Fig. 2d, the transport $J_c$ (4.2 K, 10 T) and Lotgering orientation factor $F$ are plotted as a function of the reduction ratio $r$. 

![Figure 2](image-url) (a) Critical current density as a function of the applied magnetic field for tape-1.9-mm, tape-1.7-mm, tape-1.5-mm, tape-1.3-mm. (b) The temperature-dependent resistivity of the tapes in the self-field. (c) XRD patterns of precursor powder and the cores of the tapes. The Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ diffraction peaks have been indexed. Solid rhombus indicates the diffraction peaks related to iron. (d) Transport $J_c$ (4.2 K, 10 T) and Lotgering orientation factor $F$ as a function of the reduction ratio $r$. 

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reduction ratio \( r \). It clearly shows that the Ba122 tapes with a larger reduction ratio have a higher degree of texture and a higher transport \( J_c \), and there is a positive and very strong correlation between grain texture and transport \( J_c \). Considering the high Vickers hardness of around 200 for the superconducting cores in all the tapes, it can be inferred that high texture plays an important role in the realization of high \( J_c \)-performance.

In order to link the high transport properties in these tapes to their microstructures, detailed characterizations were carried out on the sample tape-1.9-mm, which possesses the highest \( J_c \) value. First of all, the grain morphology of the tape was viewed on the cross section by SEM, as shown in Fig. 3a–c. Fig. 3b is a partially enlarged view of the area in the white dash-line frame. To describe the spatial relationship between the viewing angle and the tape, three principal axes are defined, the normal direction (ND), the rolling direction (RD) and the transverse direction (TD), as shown in the inset of Fig. 3b. The images clearly show the influence of rolling process on the grain alignment in the tapes. The maximum thickness of the core is about 60 µm with plate-like grains of about 5 µm in size. These plate-like grains are aligned along a direction approximately parallel to the tape surface due to the pressure component in the ND applied during the rolling process. Fig. 3c shows that the growth of Ba122 grains is suppressed near the interface between the silver barrier and the Ba122 core as indicated by the white arrow. Further element distribution mapping was performed on the polished cross section of tape-1.9-mm through the EPMA technique, as shown in Fig. 3d–i. The Ag mapping shows that near the Ag-Ba122 interface, there is a 1–3 µm wide area where Ba122 and Ag coexist, as can be seen in Fig. 3i. The secondary electron image (SEI) in Fig. 3d shows a dense Ba122 phase embedded in the silver layer. A few defects were also observed. The white arrows indicate several small holes and the red oval indicates a barium-riched particle as verified by the distribution map of barium. The particle in the green oval with a diameter of around 3 µm comes probably from the polishing suspension. As shown in Fig. 3e–h, except for the barium-riched area, all the four elements (Ba, K, Fe and As) are uniformly distributed, which is crucial for the realization of high transport \( J_c \).

Despite the XRD and SEM results presenting strong evidence for the \( c \)-axis texture of the Ba122 grains in these tapes, quantitative and visualized characterizations through EBSD technique performed on the well-polished cross section of tape-1.9-mm can further provide valuable information. Fig. 4a shows the inverse pole figure (IPF)
The IPF maps in [001] direction for tape-1.9-mm. (b) The grain size map in gray scales ranging from black to white on increasing grain size. The grain boundaries are colored based on the grain misorientation angles. (c) The distribution of out-of-plane misorientations in the selected area. The inset shows the ND-IPF derived from IPF map in (a). (d) The distribution of the grain size of tape-1.9-mm is presented in two ways: the number fraction and the area fraction.

In this sample, the majority of the out-of-plane misorientation angles are distributed from 5° to 40°, showing a relatively low degree of texture than in hot-pressed tapes [25]. The inset in Fig. 4c is the IPF of grain orientations. Fig. 4b presents Ba122 grains in the same location as Fig. 4a with gray scales ranging from black to white indicating the grain size. Grain boundaries in Fig. 4b are colored based on the grain misorientation angles, as shown in the legend below. The distribution of grain size is given in Fig. 4d in two ways: number fraction and area fraction. The grain size ranges from 0.1 to 2.0 µm, which is smaller than that in hot-pressed tapes [25]. Grains around 0.5 µm in size account for the largest proportion of the total area, and most of them are roughly c-axis textured. Besides, there are also a few relatively larger grains, about 1-2 µm in size. However, as Fig. 4a and b show, lots of tiny grains (smaller than 0.2 µm in size) are randomly oriented with high-angle grain boundaries, which is definitely an impediment of the transport currents. This can be attributed to the relatively low sintering temperature and short holding time of the HIP process that may not be beneficial to the growth of grains.

MO imaging is a powerful tool that can visualize the distribution of magnetic flux. Through this method, one can directly observe the real-time magnetic field profile produced by the magnetization currents flowing in a superconductor and gain a wealth of information on homogeneity, grain connectivity and the intra- and intergranular \( J_c \). Fig. 5a shows the optical image of the sample for MO imaging, and its dimension is 1.75 mm×1.30 mm×0.025 mm. Fig. 5b–f show the MO images of the sample at Meissner state acquired by applying an external field on the zero-field cooled sample. At fields less than 125 Oe (1 Oe = 79.577 A m\(^{-1}\)), the magnetic flux was excluded from the bulk due to the large shielding currents, except for a breakthrough at a crack.
produced by polishing. The flux begins to penetrate gradually into the whole sample at 314 Oe. Fig. 5c–f clearly show the flux entering from the edges into the center in a dendritic path. However, flux is still precluded from the center region even at the maximum attainable field, indicating a large circulating current inside the Ba122 bulk. The MO images of the sample in the remanent state obtained by decreasing the field from 1568 Oe to zero between 5 and 30 K are shown in Fig. 5g–l. A rooftop pattern of the magnetic flux was observed up to 30 K, indicating a uniform global current flow throughout the whole sample. It is noteworthy that the pattern of the trapped flux changes little below 20 K. Even at 25 K, the magnetic flux still cannot penetrate the entire sample, indicating that tape-1.9-mm has pretty good performance at high temperatures.

The resistance transition curves of the sample tape-1.9-mm in different magnetic fields were measured to evaluate the upper critical field $H_{c2}$, anisotropy $\gamma$ and the pinning potential $U_0$. Fig. 6a shows the $R$-$T$ curves of different magnetic fields in directions of B//tape and B⊥tape, showing a transition broadening with increasing magnetic fields. The upper critical field $H_{c2}$ and the irreversibility field $H_{irr}$ are defined by 90% and 10% of the normal state resistivity, as shown in Fig. 6b. By using the Werthamer-Helfand-Hohenberg formula $H_{c2}(0) = -0.693T_c(dH_{c2}/dT)$ [32], with $dH_{c2}/dT$ at $T = T_c$, the $H_{c2}^{||}(0)$ and $H_{c2}^{\perp}(0)$ are estimated to be 240 and 110 T, which are very high values even compared with (Ba, K) Fe$_2$As$_2$ single crystals [33]. The anisotropy is defined as $\gamma = H_{c2}^{||}/H_{c2}^{\perp}$ and varies from 2.0 to 3.6 at temperatures from 37.7 to 38.4 K, as plotted in the inset. Actually, $\gamma$ of Ba122 decreases with decreasing temperature [11], which means that the anisotropy of the sample tape-1.9-mm will be less than 2 at temperatures below 37.7 K. The results are quite similar to those in (Ba, K)Fe$_2$As$_2$ single crystals, suggesting that Ba122 has small anisotropy as its intrinsic property. Furthermore, since the resistance in the low-resistance region is induced by the creep of vortices [34], the temperature dependences of the resistivity can be described as the equation $\rho(T, B) = \rho_0 \exp[-U_0/k_BT]$, where $\rho_0$ is a parameter, $k_B$ is the Boltzmann constant and $U_0$ is the flux-flow activation energy. By plotting $\ln \rho(T, B)$ as a function of $1/T$, one can obtain $U_0/k_B$ from the slope of the linear part, as shown in Fig. 6c. The values of the activation energy $U_0/k_B$ range from 8500 K at 0.1 T to 3100 K at 9 T for the parallel fields and from 7500 K at 0.1 T to 2500 K at 9 T for the vertical fields, showing relatively weak field dependence compared with MgB$_2$ [35]. For comparison, $U_0$ values for Sr122 [36], YBCO [37], Bi2212 [38] and MgB$_2$ [35] are included in Fig. 6d.

To summarize, these results indicate that our Ba122 tapes have very high intrinsic flux-pinning strength, high upper critical field $H_{c2}$, low anisotropy $\gamma$ and large activation energy $U_0/k_B$, which are the fundamental reasons for the high performance in high magnetic fields.

The flux pinning mechanism in tape-1.9-mm was analyzed based on the Dew-Hughes model [39]. First of all, the isothermal hysteresis loops of the tape were measured and the magnetic critical current density $J_c^{mag}$ was calculated based on the Bean model with the equation $J_c^{mag} = 20\Delta M/w(1-w/3l)$ [40], where $\Delta M$ is the dif-
ference between the upper and lower branches of the hysteresis loops, \( w \) and \( l \) are the width and length of the sample \((l > w)\), respectively. The irreversibility field \( H_{irr} \) is determined by the linear part of the Kramer plot: 

\[
K_r(B) = J_{c}^{1/2}B^{1/4}
\]
to \( K_r = 0 \), as shown in the inset of Fig. 7. Fig. 7 presents the normalized pinning force density \( f = F_p/F_{p,\text{max}} \) as a function of \( \delta = H/H_{irr} \). The data points can be fitted by the equation 

\[
f = Ah^p(1-\delta)^q\]

with \( p = 0.47 \), \( q = 1.87 \). The fitting curve peaks at \( h_0 = 0.20 \), indicating that the pinning mechanism is more close to the grain boundary pinning when compared with the hot pressed tape whose \( h_0 \) locates at 0.22 [25,27,41]. This is in accordance with the fact that the sample tape-1.9-mm has relatively small grains. Smaller grains correspond to increased grain boundary density and thus are favorable for enhancing the pinning force. As we put forward above, texture is critical to the transport performance of the Ba122 tapes. Therefore, one can conclude that these \( c \)-axis-textured small grains of \(~0.5 \mu m\) in size in Fig. 4a are the desired ones and account for the high transport performance. On the other hand, for those tiny grains (smaller than 0.2 \( \mu m \) in size) which have high-angle grain boundaries with adjacent grains, if they can be transformed to be \( c \)-axis textured to reduce the weak-linked grain boundaries, the transport performance of the Ba122 tape will definitely be further improved because these tiny grains can provide more grain boundaries as the flux pinning centers.

**DISCUSSION**

One of the major achievements of this work is that the transport \( J_c \) exceeding \( 10^5 A/cm^2 \) (4.2 K, 10 T) was achieved in Cu/Ag composite-sheathed Ba122 tapes, which is currently a record value for low-cost Cu/Ag composite IBS tapes and wires. This value also exceeds a widely accepted threshold for practical applications, and more importantly was achieved through a scalable fabrication route. Besides, relevant characterizations have shown that these tapes have pure Ba122 phase with high density and good uniformity. In this case, because the extrinsic factors were eliminated as much as possible, we emphasized the significant role of grain texture in

**Figure 6** (a) The temperature-dependent resistivity of tape-1.9-mm in various magnetic fields for \( B/\text{tape and } B/\perp \text{tape.} \) (b) \( H_{c2} \) and \( H_{irr} \) for both field directions. The inset presents the anisotropy \( \gamma = H_{c2}/H_{irr} \) at different magnetic fields. (c) The Arrhenius plot to define the values of \( U_0/k_B \). (d) The pinning potential \( U_0/k_B \) as a function of magnetic field.
achieving high transport $J_c$. Another distinct feature of our tapes is the small grain size (mostly ~0.5 µm). Based on the pinning mechanism analysis showing the grain boundaries as the main pinning centers, we put forward that small grains are beneficial to the transport performance of Ba122 tapes, provided that they are textured. Despite the many favorable properties in the highest-$J_c$ tape-1.9-mm, several performance-hindering features were also found, suggesting that the $J_c$ value of HIP-sintered Ba122 tapes is still far from reaching its maximum. As revealed in both XRD and EBSD analyses, HIP-sintered Ba122 tapes have a relatively low degree of texture than the hot-pressed tapes with a record $J_c$ value as high as $1.5 \times 10^5$ A cm$^{-2}$ (4.2 K, 10 T) [24]. This can be ascribed to the different ways in which high pressure was applied. For HIP-sintered Ba122 tapes, the high isostatic pressure provided by argon may not contribute much to further improve the grain texture. In order to enhance the texture, more attention should be paid to the optimization of rolling process since it is the main means of introducing pre-texture. Increasing the wire diameter before rolling in this work is a proven way to obtain higher pre-texture in Ba122 tapes. Reducing the final tape thickness may also produce similar benefits, but will face some difficulties in deformation uniformity.

**CONCLUSION**

In summary, Cu/Ag composite-sheathed Ba122 iron-pnicted tapes with practical-level transport $J_c$ were prepared through a scalable and cost-effective fabrication route that includes ex situ PIT method, cold rolling process and HIP technique. By tuning the rolling-induced grain alignment, it is found that the transport $J_c$ of the tapes is closely and positively correlated to the degree of grain texture, proving that grain texture plays a critical role in improving $J_c$ for iron-based superconducting wires and tapes. Detailed characterizations show that the highest-$J_c$ sample tape-1.9-mm has pure Ba122 phase with high density and good uniformity, excellent grain connectivity, favorable performance at temperatures up to 25 K, ultrahigh $H_{c2}$ up to 240 T, low anisotropy and high pinning potential. Quantitative analysis by means of EBSD reveals that c-axis-textured small grains (~0.5 µm) account for the high transport $J_c$. On the other hand, several performance-hindering features were also found, such as relatively low degree of texture compared with hot-pressed tapes and randomly oriented tiny grains (less than 0.2 µm). Therefore, there is still room for the enhancement of the transport properties of Cu/Ag composite-sheathed Ba122 tapes. This work proves the feasibility of large-scale low-cost preparation of high-performance IBS superconductors and will certainly promote the practical research of IBSs.

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Author contributions Liu S designed the experimental plan, and performed sample preparation and most of the characterizations. Yao C and Dong C provided significant guidance on data analysis and co-authored this article. Huang H and Guo W measured the critical currents of the Ba122 tapes at 4.2 K under external magnetic fields. Cheng Z and Zhu Y contributed to the preparation of Ba122 precursor. Awaji S performed the high-field critical current test system and gave useful advice and Zhu Y directed the project and also provided significant guidance on data analysis and writing.

Conflict of interest The authors declare that they have no conflict of interest.
Shifa Liu received his BSc degree from the School of Materials Science and Engineering of Tsinghua University and is currently a PhD candidate at the Institute of Electrical Engineering, Chinese Academy of Sciences and University of Chinese Academy of Sciences under the supervision of Prof. Yanwei Ma. Liu’s research work focuses on the practical research of iron-based superconductors, particularly through the hot isostatic pressing technique.

Chao Yao is an associate professor at the Institute of Electrical Engineering, Chinese Academy of Sciences. He received his PhD from the University of Chinese Academy of Sciences in 2014 and B.Eng. from Beijing University of Posts and Telecommunications in 2008. He is a member of Youth Innovation Promotion Association, Chinese Academy of Sciences. His research focuses on the fabrication of high-performance iron-based superconducting wires based on powder-in-tube method.

Yanwei Ma is a professor at the Institute of Electrical Engineering, Chinese Academy of Sciences. He received his PhD degree from Tsinghua University in 1996. In 1998–2004, he worked at the Institute for Materials Research, Tohoku University (Sendai, Japan), National Institute for Materials Science (Tsukuba, Japan) and Universite de Rennes 1 (France), respectively. His group is specialized in the development of superconducting wires and nanomaterials for energy storage, and fabrication of graphene-based supercapacitors. He currently serves as international board member for many prestigious journals, such as Superconductor Science and Technology, Physica C: Superconductivity and its Applications, etc.