Progress in the development of high performance pnictide wires

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Outline

- Good superconducting property of pnictide
- Two main problems existing in the PIT wires
- Hot pressing effects on Sr$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ tapes
- Progress in the multifilament wire /Cu sheathed tapes
Iron superconductor

Iron-Based Layered Superconductor La[O_{1-x}F_x]FeAs (x = 0.05-0.12) with T_c = 26 K

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Abstract:
We report that a layered iron-based compound LaOFeAs undergoes superconducting transition under doping with F^- ions at the O^{2-} site. The transition temperature (T_c) exhibits a trapezoid shape dependence on the F^- content, with the highest T_c of ~26 K at ~11 atom %.
Main known Fe-based superconductors

Among them, the three phases most relevant for wire applications are 1111, 122, and 11 types with a $T_c$ of 55, 38 and 8 K, respectively.

1111 Phase LnOFeAs

122 phase $A\text{Fe}_2\text{As}_2$

(A=Ba, Sr, Ca)

111 phase LiFeAs

11 phase FeSe

$T_c \sim 55$ K

$T_c \sim 38$ K

$T_c \sim 18$ K

$T_c \sim 8$ K


Very high upper critical fields in iron pnictides

- Pnictides, e.g. 122 and 1111, could in principle provide fields up to 40-50 T at 20K.

An extrapolated $B_{c2}(0 \text{ K})$ can exceed 200 T, especially at 20 K, the $B_{c2}$ can be 40-50 T, suggesting a very encouraging application in high field magnets.


Putti et al., *SUST* 23, 034003 (2010)

High critical current densities in iron pnictides

The single crystal of both the 1111 and 122 type pnictides show high $J_c$ values.

The anisotropy of the pnictides is relatively small.

$J_c$ //a/ $J_c$ //c

<table>
<thead>
<tr>
<th>Type</th>
<th>$J_c$ @ 5K @ 0 T</th>
<th>$J_c$ //a/ $J_c$ //c</th>
</tr>
</thead>
<tbody>
<tr>
<td>1111</td>
<td>$\sim 3 \times 10^6$ A/cm²</td>
<td>2.5</td>
</tr>
<tr>
<td>122</td>
<td>$\sim 3 \times 10^6$ A/cm²</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>$\sim 10^6$ A/cm²</td>
<td></td>
</tr>
</tbody>
</table>


IBS: high-field applications

Possible application area

Shimoyama, *SuST* 27 (2014) 044002
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- Progress in the Cu sheath and multifilament wire
Fabrication technique for pnictide wires

Powder-in-tube method:
Simple, easy for fabrication
Has been used for Bi2223 superconductor

1. Powdering
   - Precursors
   - Metal tube

2. Deformation
   - Swaging and drawing
   - Rolling
   - In-situ pnictide raw powders
   - Ex-situ reacted pnictide powders

3. Sealing
   - Wire or tape
   - Arc Welding

4. Sintering
   - 800-1200°C
   - Under Ar atmosphere

Invited presentation M4OrB-02 given at CEC-ICMC 2017, July 09-13, 2017, Madison, WI (USA).
Challenges for high-$J_c$ pnictide wire

1) How to solve weak-linked problem

Critical misorientation angle

YBCO : 3-5°

Pnictide 122: 9°


2) How to achieve high density core
Hysteresis in transport $J_c$: signature of weak links

A hysteretic phenomenon observed for $J_c$ in an increasing and a decreasing field indicated a weak-link behavior, similar to that of the cuprates.

To overcome the weak-link problem, one effective method is to engineer textured grains to minimize deterioration of $J_c$ across high-angle grain boundaries, like the Bi2223.
Texturing process of PIT Sr122 tapes

Fe or Ag tube used sheath material

Large deformation ratio

Photograph of the final 122 tapes

Transport $J_c$ of flat-rolled 122 tapes

**Fe-sheathed Sr-122 tape**

At 4.2 K/10 T, $J_c = 1.7 \times 10^4$ A/cm²

The degree of texturing F: ~0.4

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**Ag-sheathed Ba-122 tape**

At 4.2 K and 10 T: $J_c = 5.4 \times 10^4$ A/cm²

The degree of texturing F: ~0.69

Average Hv: ~135

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Scripta Mater. 99 (2015) 33
The textured PIT seems an effective method to overcome the weak-link problem in pnictide wires, but...

- There are still existed some impurity phases and pores, and the degree of texture is still low, e.g. only about 0.4.

- Suggesting that there is more room for improvement.

\[ F = \frac{(\rho - \rho_0)}{(1 - \rho_0)} \]

Where \( \rho = \frac{\sum I(00l)}{\sum I(hkl)} \) and \( \rho_0 = \frac{\sum I_0(00l)}{\sum I_0(hkl)} \) are the intensities of each reflection peak \((hkl)\) for the oriented and random samples, respectively. The value of \( F \) for the as-rolled tape, \( F \approx -0.4 \), for the Fe sheath.
Challenges for high-$J_c$ pnictide wire

1) How to solve the weak-link problem

2) How to achieve high density core

Cracks and voids are important reasons for low critical current density values
Hot pressing of Ag-sheathed Sr122 tapes

Mixed powders (10% excess K) / (900°C, 35 h)

Ag tube used sheath material

Wire of 1.9 mm in diameter

Rolled into tapes (0.44 mm)

Sintering (850°C, 10-60 min)

"Sintered"

Hot pressing 850°C, 10-60 min

"HP"

Suppress the voids and cracks

XRD, SEM, R(H), PPMS, V-I
Cross section of 122/Ag tapes by Hot Pressing

Hot pressing significantly decreased the tape thickness, *ie.* from 0.44 mm to 0.3 mm.
Evolution of microstructure

- **Sintering**
- **Hot pressing**

**Planar view**

- No microcracks

**Longitudinal Cross-section**

- **Sintered tapes**: loose microstructure from more voids, and/or cracks
- **HP tapes**: higher density with fewer voids
High transport $J_c$ in HP 122/Ag tapes

$$J_c = 5.1 \times 10^4 \text{ A/cm}^2 \ (4.2 \text{ K, 10 T})$$

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Hot pressing is very effective to achieve high density core, thus significant increase in $J_c$-$B$.

Outline

- Progress in the multifilament wire / Cu sheathed tapes
- Hot pressing effects on Sr$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ tapes
- Two main problems existing in the PIT wires
- Good superconducting property of pnictide
By pressure optimization

Record transport $J_c$ values were achieved in 122/Ag tapes: $J_c > 10^5$ A/cm$^2$ (4.2 K, 10 T)

The superior $J_c$ can be attributed to higher grain texture and improved densification.

Zhang et al., *APL* 104 (2014) 202601
By temperature optimization

The new record transport $J_c$ values were achieved in 122/Ag tapes: $J_c \sim 1.2 \times 10^5 \text{ A/cm}^2$ (4.2 K, 10 T)

1. The $J_c$ was over $10^5 \text{ A/cm}^2$ at 13 T;
2. The $J_e$ was about $2.6 \times 10^4 \text{ A/cm}^2$ at 10T.

Texture and hardness: which is dominant?

Similar tendency appeared in the $J_c$ and texture parameter.

The hardness was almost saturated as soon as the hot press was applied.
At 4.2K, 10 T, $I_c=437$ A, $J_c \sim 150,000$ A/cm$^2$

At 4.2K, 14 T, $J_c \sim 140,000$ A/cm$^2$

At 4.2K, 27 T, $J_c \sim 55,000$ A/cm$^2$

The anisotropy of $J_c$ at 10T is 1.37

He Huang, et al., arXiv:1705.09788
Analysis on the superconducting core

**Good crystallinity**

**Clean grain boundary**

Vickers hardness \( \sim 132 \)

**RT:** Homogeneous

**MT:** high quality superconducting phase

**XRD:** Good crystallinity, texture

**Good connectivity!**
Microstructure analysis: EBSD

High texture degree!

- F value ≈ 0.87

Small misorientation angle

- 42.8% number fraction of misorientation angle < 9°

Neighboring grains marked with different color

Most grains smaller than 2 μm
Pinning property

The dominant pinning is Grain boundary pinning

The Small grain size is beneficial to the improvement of vortex pinning property.

Similar with the HP Sr-122, Nb$_3$Sn and MgB$_2$ superconducting wires

function $f = Ah^p(1-h)^q$

The $h_{\text{max}}$ value is close to 0.2
Optimization of hot pressing parameter

Different papers related to HP process

- **Sr122**
  - 10 Mpa, 850°C, 30 min
  - $F \sim 0.87$
  - $H_v = 97.3$

- **Sr122**
  - 30 Mpa, 850°C, 30 min
  - $F \sim 0.58$
  - $H_v = 154$

- **Sr122**
  - 30 Mpa, 900°C, 30 min
  - $F \sim 0.52$
  - $H_v = 132$

- **Ba122**
  - 15 Mpa, 880°C, 60 min
  - $F \sim 0.87$

Different papers related to HP process:

- APL 104(2014)202601
- arXiv:1705.09788
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Sr-122/Ag-Fe multifilamentary wires

7/114 filamentary Sr122 tapes

Weak field dependence of Jc

Yao et al., JAP 1118, 203909 (2015)
Fabrication and transport properties of Sr-122/Ag-Monel multifilamentary wires by rolling process

The transport $J_c$ achieved 36 kA/cm$^2$ at 4.2 K/10T

Very weak magnetic field dependence at high fields.

Yao et al., *SuST*, 30, 075010 (2017)
Density is an important factor in the Jc improvement

Hardness of the Sr-122 phase decreases with the decrease of annealing temperature
Axial compressive strain increases from 0.06% to 0.6%, $J_c$ exhibits almost no degradation.

$n$-values are in the range of $26.5 \sim 31.1$, indicating:

- Good homogeneity of the Sr-122 filaments;
- Weak dependence on compressive strain.
Copper as the sheath material

Good property of copper: Low cost, high thermal stability

Reaction layer is the main problem

Low sintering temperature is one way
Copper as the sheath material

The thickness of the reaction layer increased with heat temperature increasing.

From several micron to 25 micron
Even at 740°C, an impurity phase is produced when the sintering time is longer than 30 min.
$J_c$ property

4.2K, 10T, $J_c \approx 3.5 \times 10^4$ A/cm²  
$J_e \approx 10^4$ A/cm²  

At 4.2K, 26T, $J_c \approx 1.6 \times 10^4$ A/cm²  

Copper is a promising sheath material for Pnictide superconductor
100m long Sr-122 tapes by rolling process

Minimum $J_c > 12000 \text{A/cm}^2$

Transport $J_c$ distribution along the length of the first 100 m long 7-filament Sr122 tape
Prospects

**Iron Based Superconductor**

Much lower cost and better mechanical properties expected
Thank you for your attention!