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Invited presentation WB3-2-INV was given at ISS 2017, December 13-15, 2017, Tokyo, Japan.

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30th International Symposium on Superconductivity
(Tokyo, 14th December 2017)

WB3-2-INV

Recent progress on the development of MgB_2 wires in Hitachi

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Introduction

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Potentials of MgB_2 wires

Promising for helium-free superconducting applications

- T_c is relatively high (~40 K)
- Manufacturing cost is low
- Round shape is producible

MgB_2 applications

- 0.5 T OpenSky MRI was launched by Paramed
- R & D phase: 1.5−3.0 T MRI, SMES, motor, generator, cable, and so on

MgB_2 wires

- *In situ* and *ex situ* wires are commercially available from Hyper Tech and Columbus, respectively
- R & D phase: internal Mg diffusion (IMD), high pressure treatment (CHPD, HIP), and so on

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Introduction

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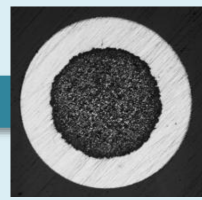
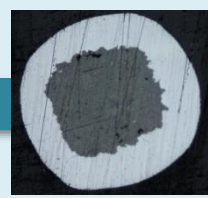
Hitachi's R&D activity on MgB_2 wire

	Step 1 **Enhance J_c**	Step 2 **Multicore**	Step 3 **Elongate (~km) Tune up**
PIT Typical *In situ*			
Dense PIT Mechanical milling			
Thin film EB deposition			

Kusunoki T *et al*
IEEE Trans. Appl. Supercond. **27** (2017) 6200204

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1. **Tuning of *in situ* PIT process**
2. **Multicore *in situ* PIT wire**
3. **Next generation dense PIT wire**

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2. Multi-core *in situ* PIT wire

3. Next generation dense PIT wire

1−1 Background Tuning of *in situ* PIT process

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As factors to determine J_c of MgB_2, the following is especially important.

Electrical connectivity

Rowell J M *Supercond. Sci. Technol.* **16** (2003) R17
Yamamoto A *et al Supercond. Sci. Technol.* **20** (2007) 658

$K = \Delta\rho_G / \Delta\rho$ $\Delta\rho = \rho(300\text{ K}) - \rho(40\text{ K})$
$\Delta\rho_G = 6.32\ \Omega\text{ cm}$

Effective cross-sectional area ratio for current

J_c should be proportional to K

Intrinsic residual resistivity

Matsushita T *et al Supercond. Sci. Technol.* **21** (2008) 015008

$\rho_0 = K \times \rho(40\text{ K})$

Degree of dirtiness as a superconductor

The Increase in ρ_0 leads to the enhancement of the flux pinning strength by grain boundaries and B_{c2}

1−2 Background Tuning of *in situ* PIT process

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In *in situ* PIT wires, it is well known that these manufacturing conditions crucially affect J_c.

(a) The area reduction ratio of cold work

Tanaka K *et al IEEE Trans. Appl. Supercond.* **15** (2005) 3180

(b) The choice of starting boron powder

Chen S K *et al Supercond. Sci. Technol.* **18** (2008) 1473
Mahmud M A A *et al IEEE Trans. Appl. Supercond.* **19** (2009) 2756

(c) Heat treatment condition

Yamamoto A *et al Appl. Phys. Lett.* **86** (2005) 212502
Matsumoto A *et al Appl. Phys. Lett.* **89** (2006) 132508

(d) Carbon addition

Dou S X *et al Appl. Phys. Lett.* **81** (2002) 3419
Kumakura H *et al Appl. Phys. Lett.* **84** (2004) 3669

1−3 Purpose & Method

Tuning of *in situ* PIT process

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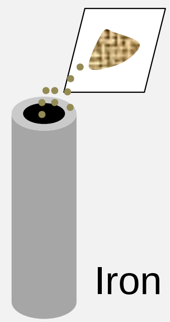
Purpose To improve J_c in *in situ* process

Method We prepared monocore wires and investigated the relation between manufacturing conditions and J_c determination factors (K & ρ_0).

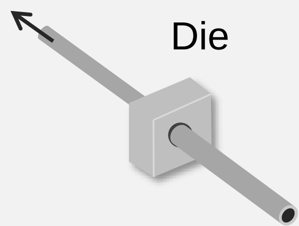
Powder packing



Magnesium
Boron
Carbon additive

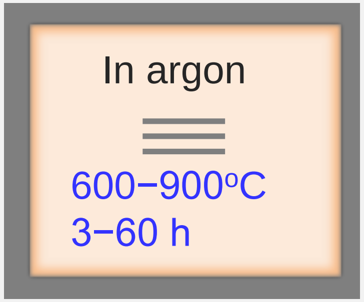
Iron pile

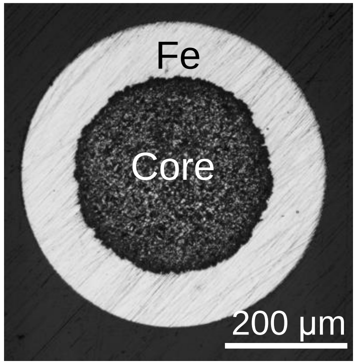
Cold work



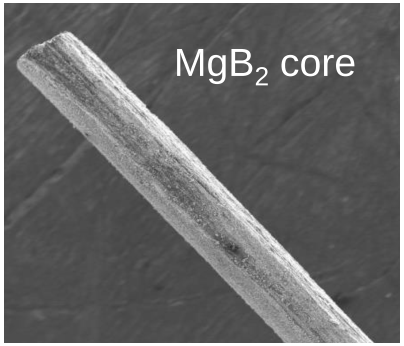
99.98% area reduction
(0.5 mm in diameter)

Heat treatment





Remove iron sheath →



→ Measure the resistivity of only MgB_2 core (estimate K & ρ_0)

1−4 Result (1) Tuning of *in situ* PIT process

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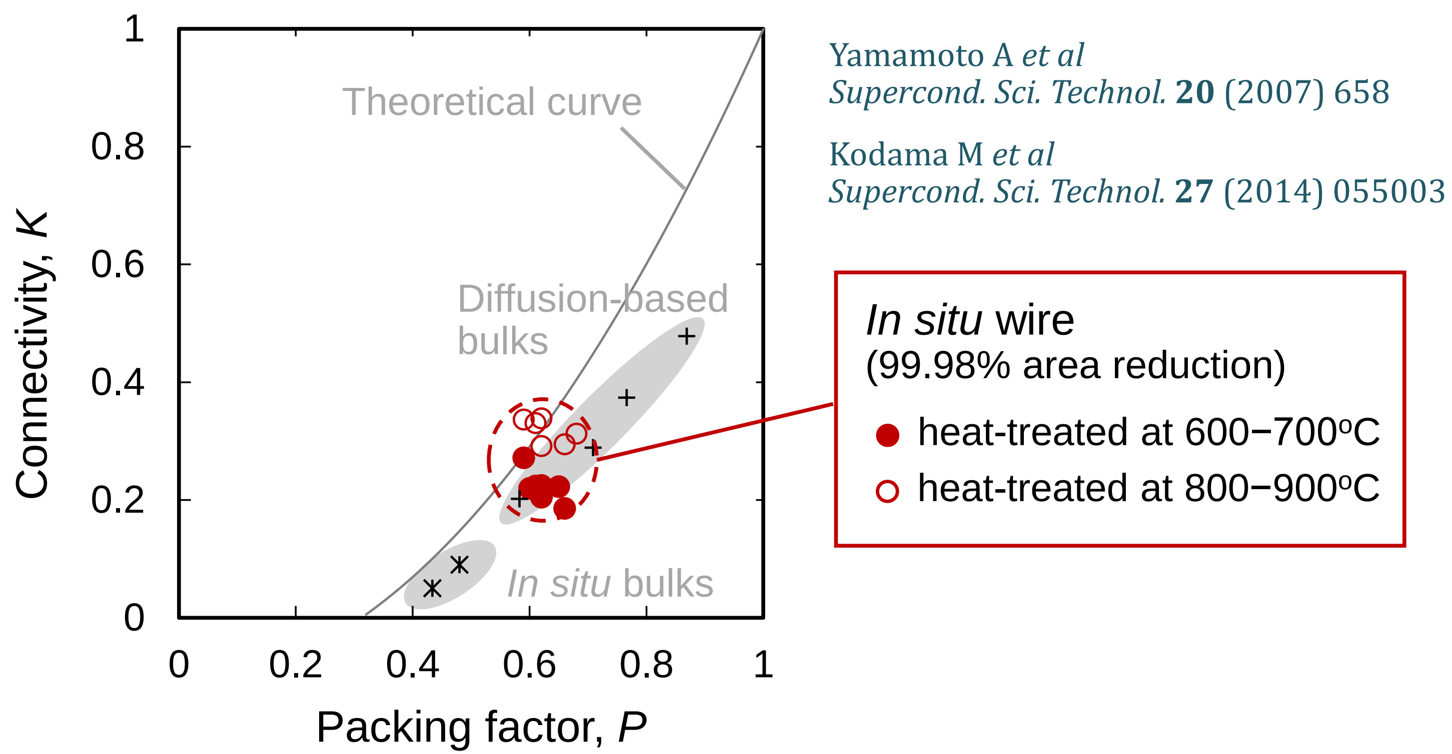
(a) Cold work



Yamamoto A *et al*
Supercond. Sci. Technol. **20** (2007) 658

Kodama M *et al*
Supercond. Sci. Technol. **27** (2014) 055003

The cold work with the large area reduction is essential to enhance the packing factor and connectivity.

1−5 Result (2) Tuning of *in situ* PIT process

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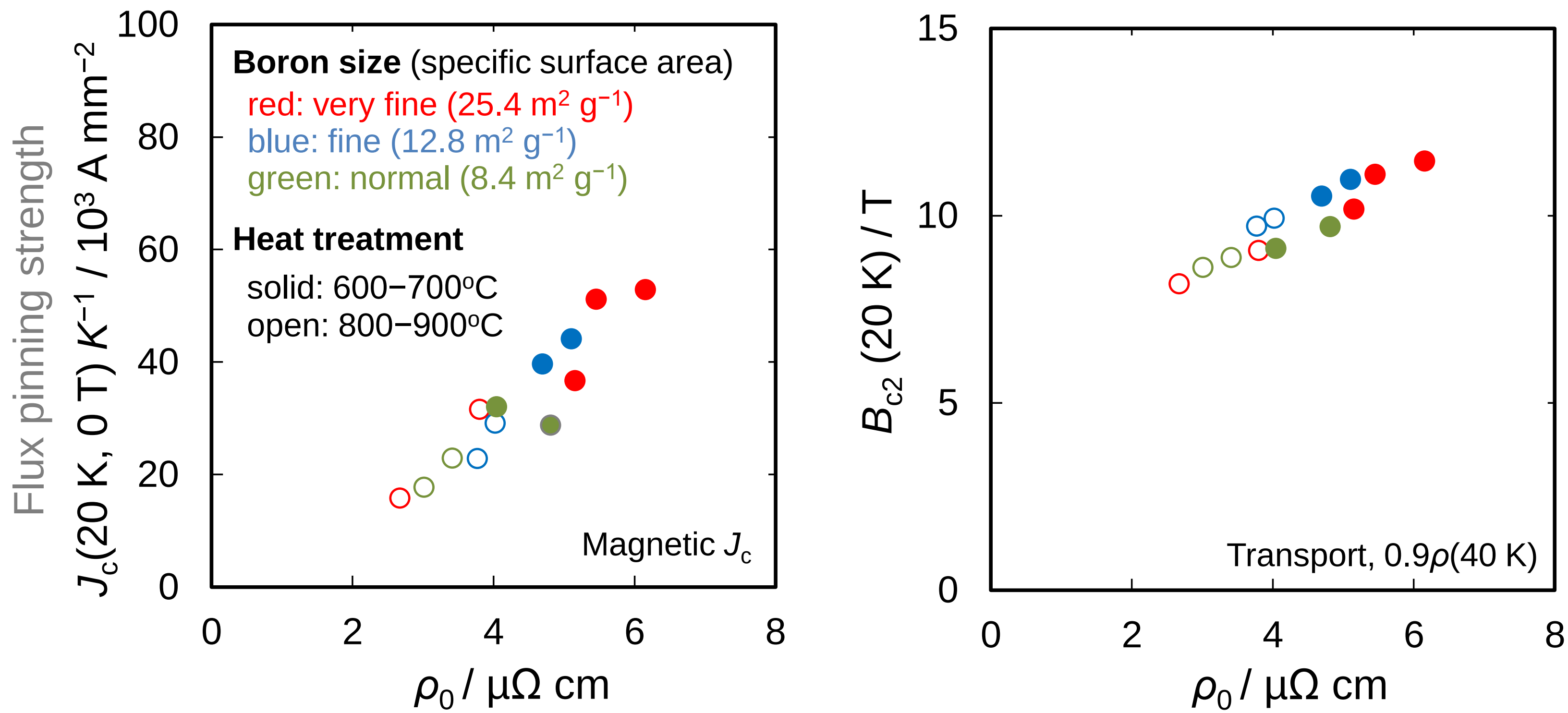
(b) Boron size, (c) Heat treatment condition

Kodama M *et al*
Supercond. Sci. Technol. **29** (2016) 105016



The use of finer boron powder and lower-temperature heat-treatment make MgB_2 dirtier, resulting in the improvement of flux pinning strength and B_{c2}.

1–6 Result (3) Tuning of *in situ* PIT process

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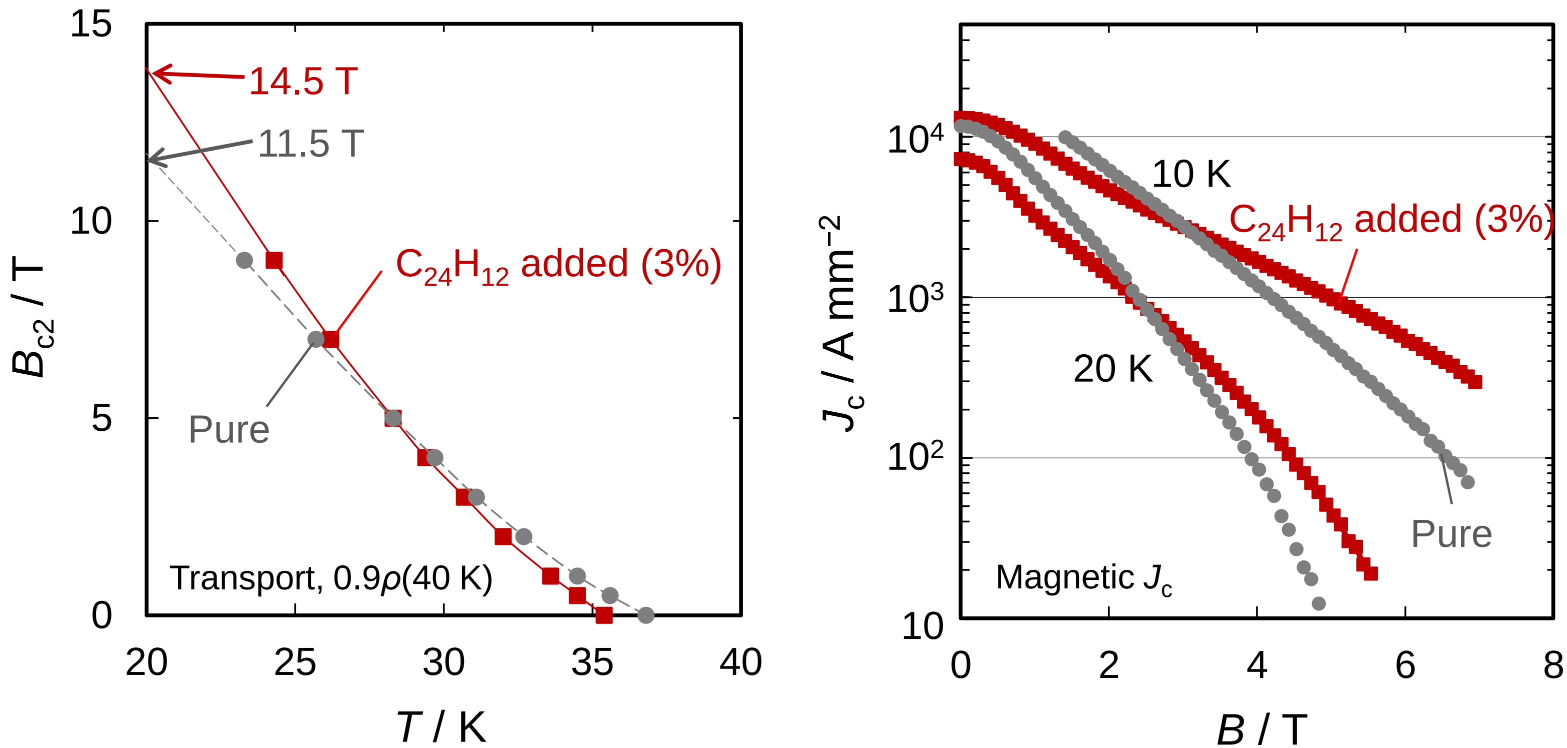
(d) Carbon addition

Ye S J *et al Supercond. Sci. Technol.* **27** (2014) 085012
Kodama M *et al Supercond. Sci. Technol.* **30** (2017) 044006



As proposed by Ye *et al* (Kumakura group), we confirmed that coronene ($C_{24}H_{12}$) is a good carbon additive.

1−7 Result (4) Tuning of *in situ* PIT process

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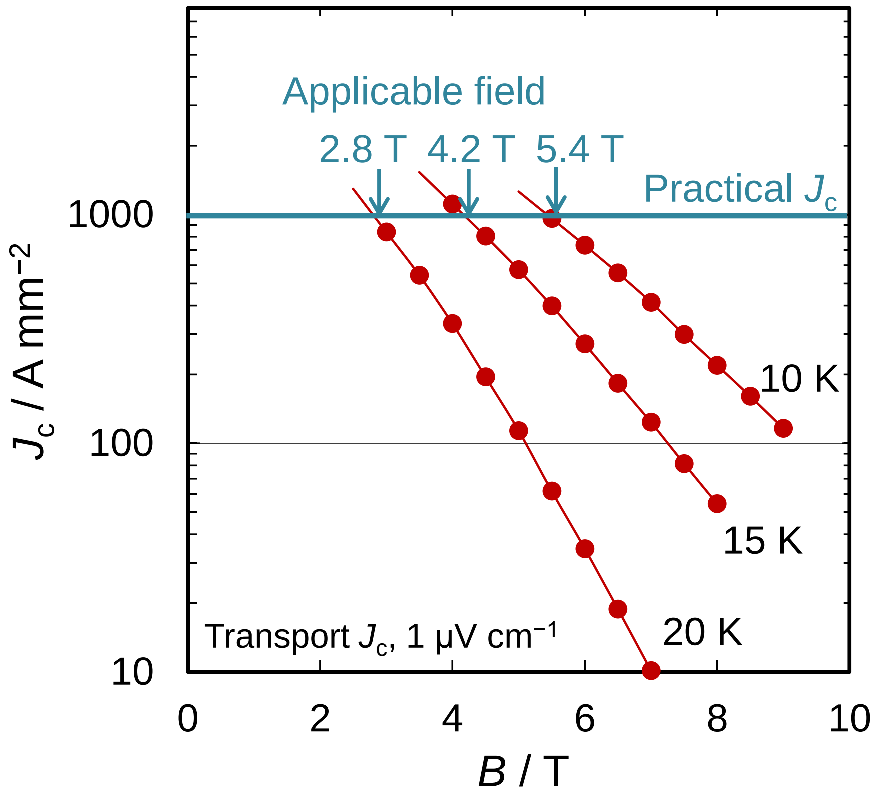
J_c property (optimum conditions)

Kodama M *et al*
Supercond. Sci. Technol. **30** (2017) 044006



The very fine boron (PVZ NanoBoron, specific surface area: 25.4 m^2 g^{-1}) was used.

Coronene (3%) was added.

Cold work with large area reduction (99.8%) was conducted.

The wire was heat-treated at low temperature (600ºC) for long duration (24 h).

Based on the clarified relation between manufacturing conditions and J_c determination factors, we obtained sufficiently high J_c for typical *in situ* process.

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2−1 Purpose & Method Multicore *in situ* PIT wire

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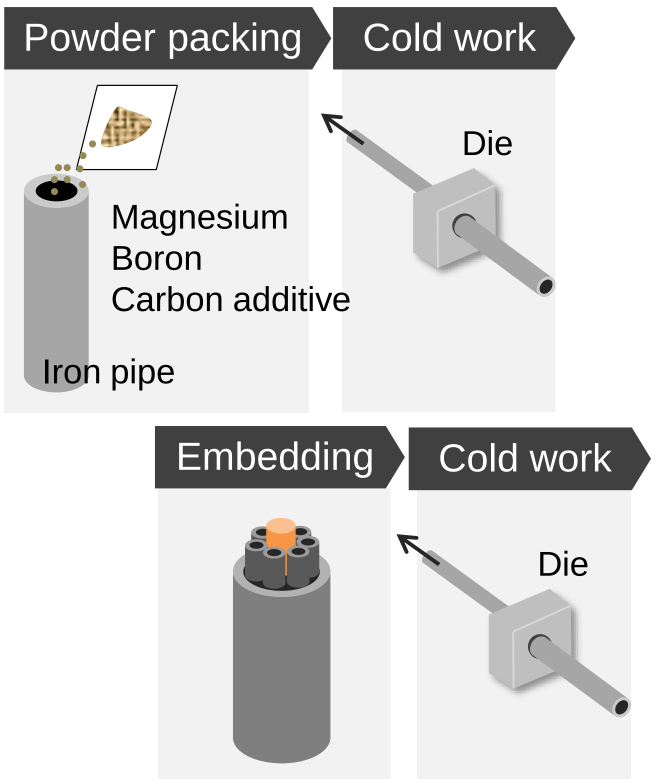
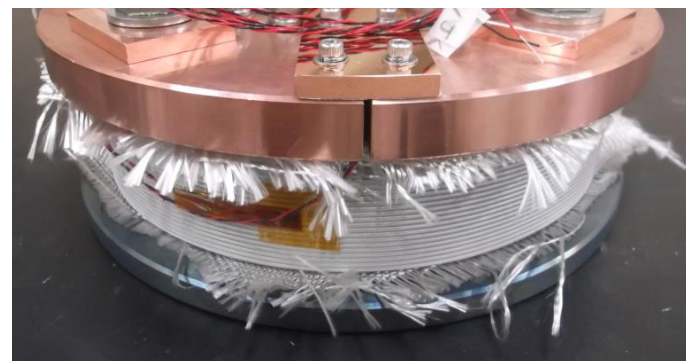
Purpose To prove the homogeneity of *in situ* multicore wire

Method We fabricated a coil from 300-meter-long wire and compared its performance with that of the short sample.

Wire preparation



Coil fabrication and evaluation



Braid insulation
Wind & React process
Resin impregnation
Conduction cooling

2−2 Result (1) Multicore *in situ* PIT wire

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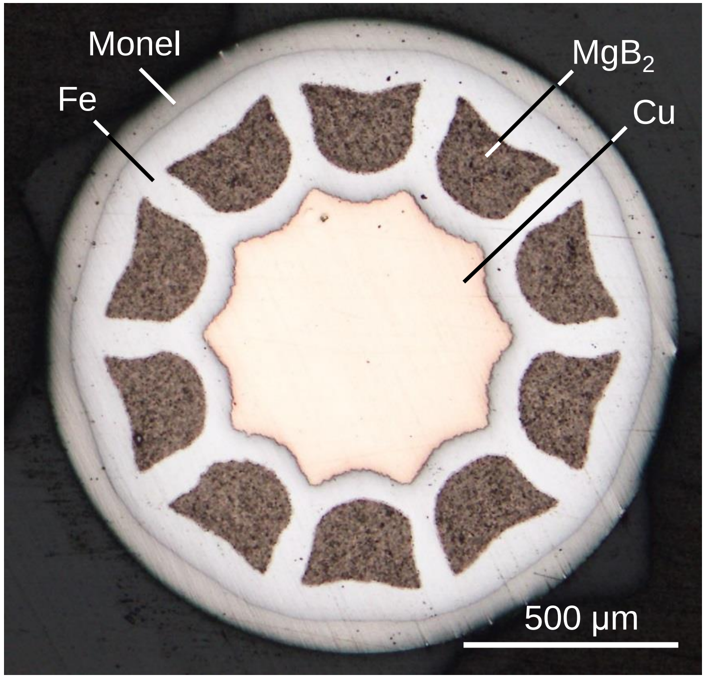
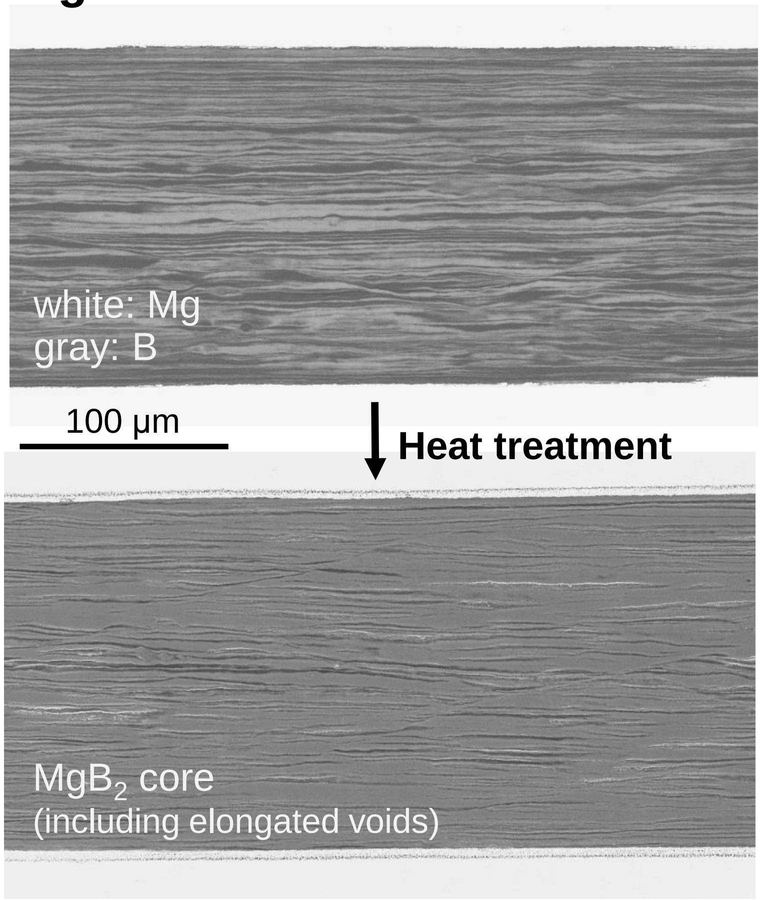
Traverse section



Tanaka H *et al*
IEEE Trans. Appl. Supercond. **27** (2017) 4600904

Kodama M *et al*
Supercond. Sci. Technol. **30** (2017) 044006

Longitudinal sections



The size of MgB_2 cores is homogeneous and MgB_2 is well connected.

2−3 Result (2) Multicore *in situ* PIT wire

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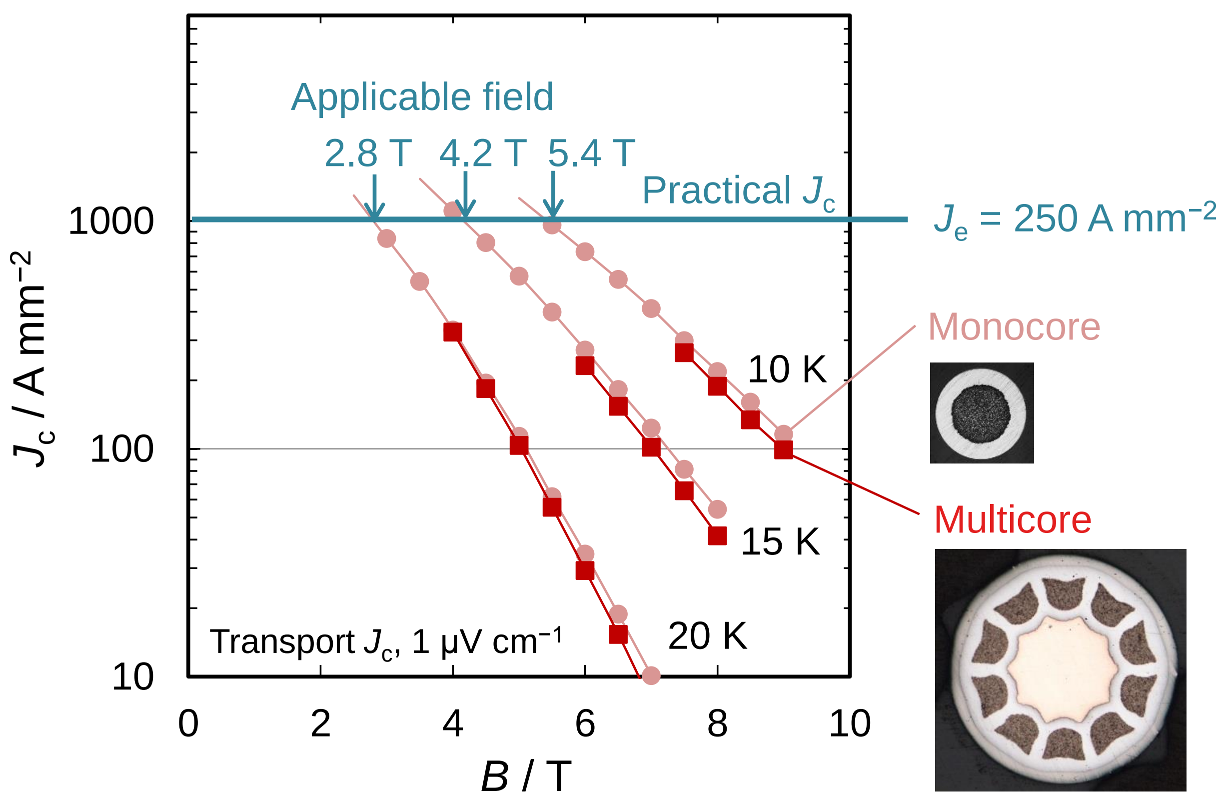
J_c property of short sample

Tanaka H *et al*
IEEE Trans. Appl. Supercond. **27** (2017) 4600904



The J_c of multicore wire is almost the same as that of monocore wire.

2−4 Result (3) Multicore *in situ* PIT wire

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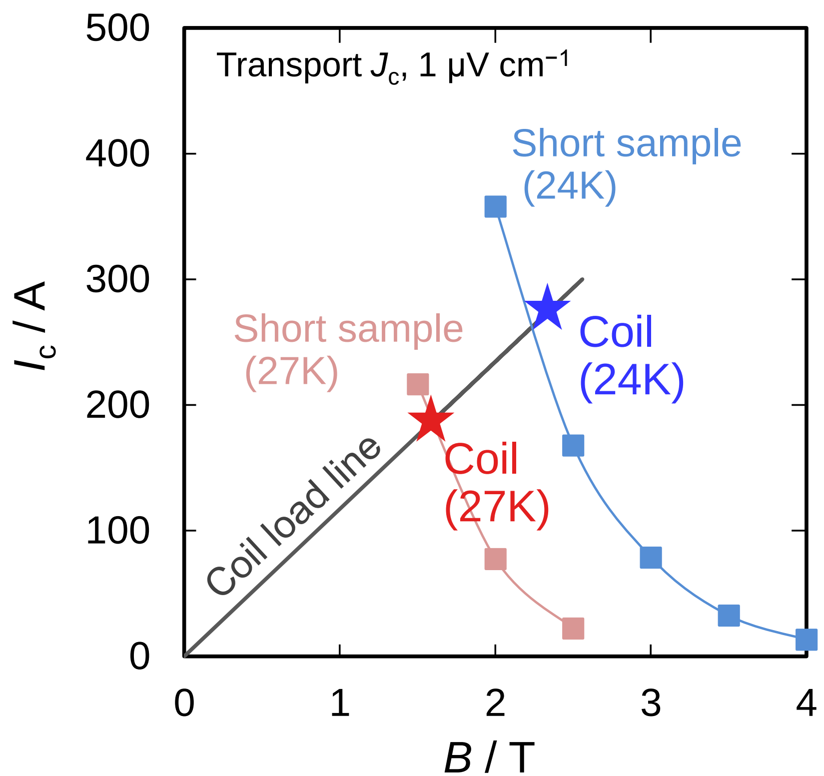
The result of coil evaluation

The specification of wire	
Diameter	1.5 mm
Length	300 m

The specification of coil	
Inner diameter	120 mm
Outer diameter	190 mm
Height	41 mm
Inductance	55 mH

Tanaka H *et al*
IEEE Trans. Appl. Supercond. **27** (2017) 4600904



The coil was successfully driven in I = 286 A and B_{max} = 2.3 T at 24 K.
The coil I_c is nearly equal to the value expected from the short sample.

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3−1 Concept Next generation dense PIT wire

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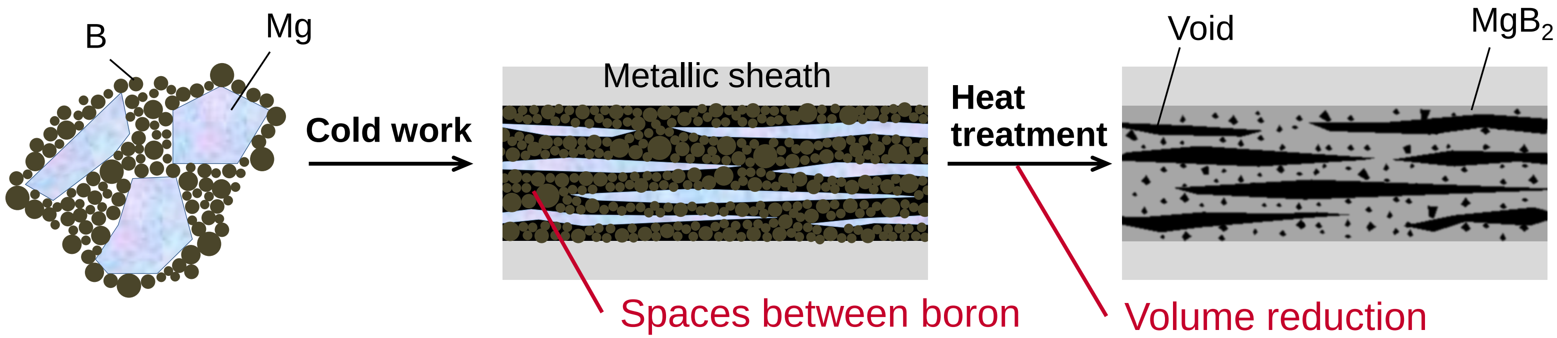
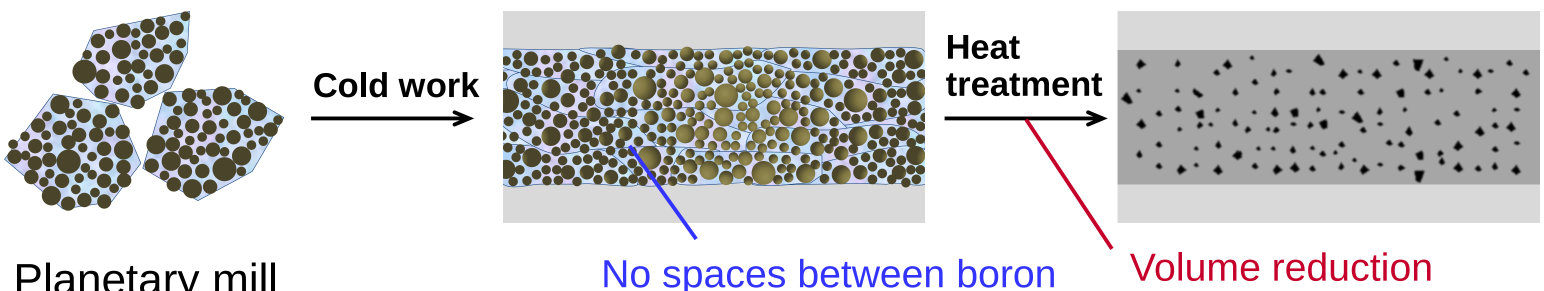
PIT (typical *in situ*)



Dense PIT

Kodama M *et al Supercond. Sci. Technol.* **30** (2017) 044006



Planetary mill

Partial generation of MgB_2 (Mechanical alloying)

Häßler W *et al Supercond. Sci. Technol.* **26** (2013) 025005

Metal-matrix-composite structure (Mechanical milling)

Takahashi M *et al Supercond. Sci. Technol.* **26** (2013) 075007

3−2 Issue Next generation dense PIT wire

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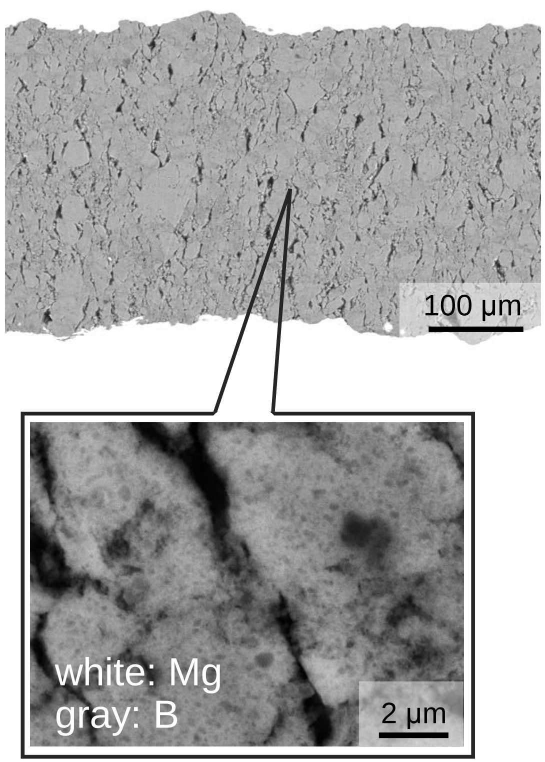
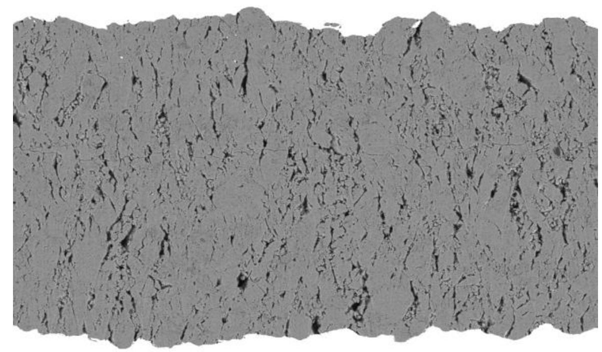
Longitudinal sections (fabricated from mechanically milled powder)



Heat treatment →



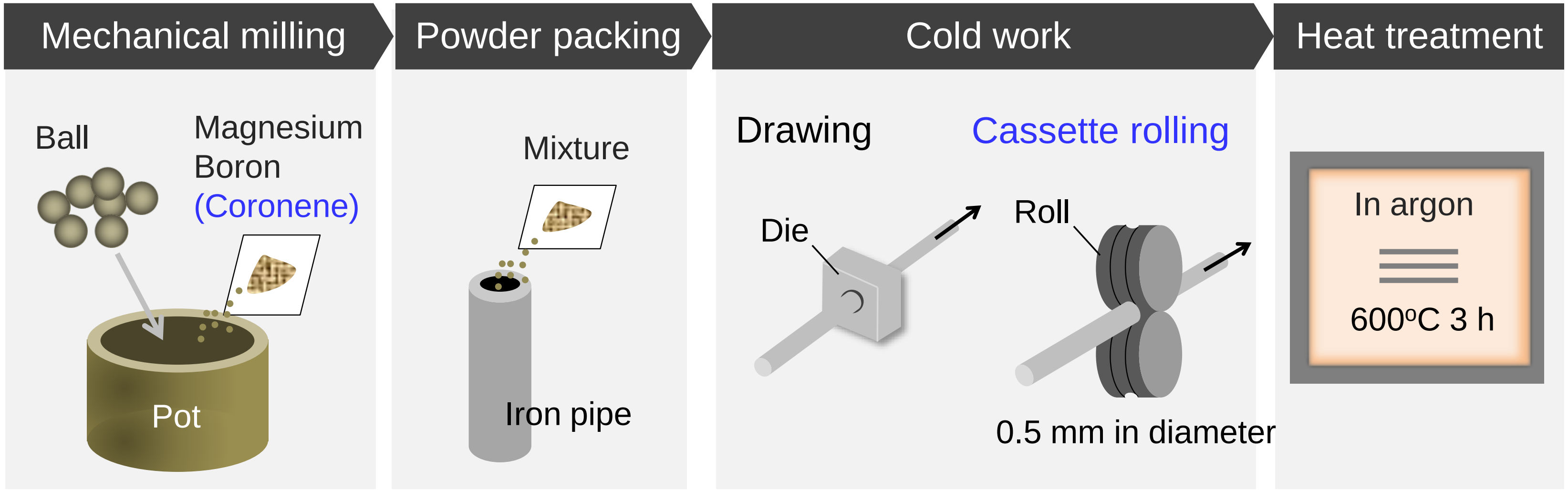
Metal-matrix-composite particles are difficult to be deformed.

MgB_2 core is not connected well.

3−3 Purpose & Method Next generation dense PIT wire

Purpose To find the way to deform the metal-matrix-composite particles
To prove the concept of dense PIT wire (high packing factor & J_c)

Method We investigated the influence of powder composition and cold work method.



Specimen	Powder composition	Cold work method
Wire-1 (normal)	Undoped	Drawing
Wire-2	Undoped	Drawing + Cassette rolling
Wire-3	Coronene doped (2%)	Drawing + Cassette rolling

3−4 Result (1) Next generation dense PIT wire

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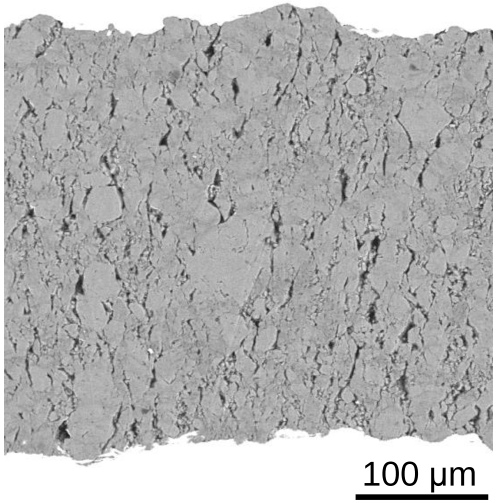
Longitudinal sections (after cold work)

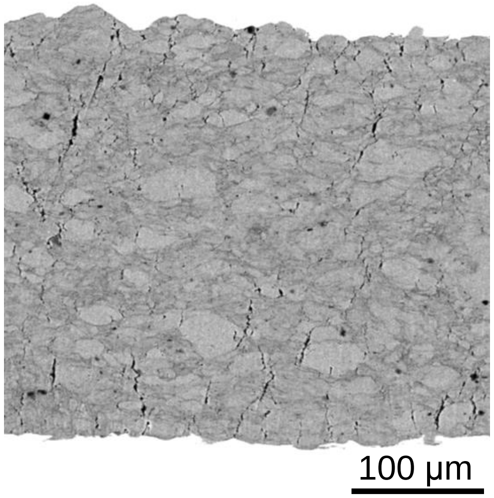
Wire-1 (normal)

Undoped
Only drawing



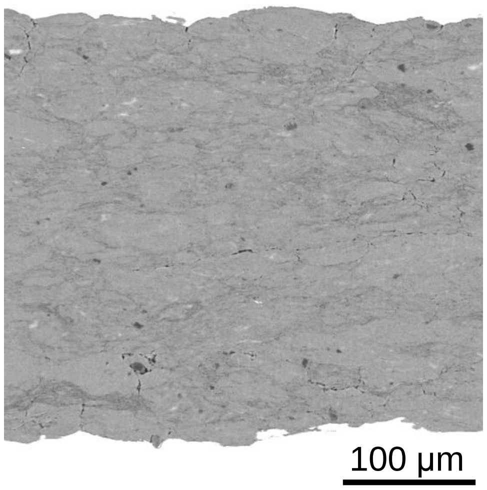
Wire-2

Undoped
+ Cassette rolling



Wire-3

Coronene-doped (2%)
+ Cassette rolling



Coronene addition and cassette rolling are effective to obtain a well-connected core.

PCT International Publication No. WO 2017/130672, WO 2017/179349

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3−5 Result (2) Next generation dense PIT wire

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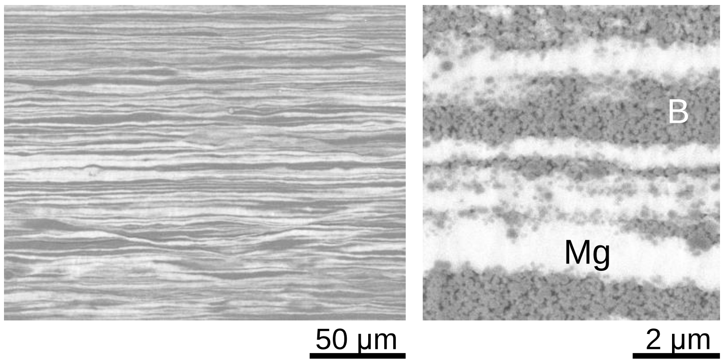
Longitudinal sections

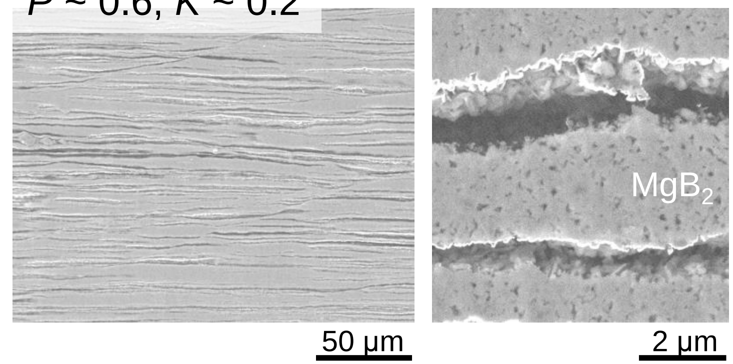
Kodama M *et al Supercond. Sci. Technol.* **30** (2017) 044006

PIT wire (Typical *in situ*)

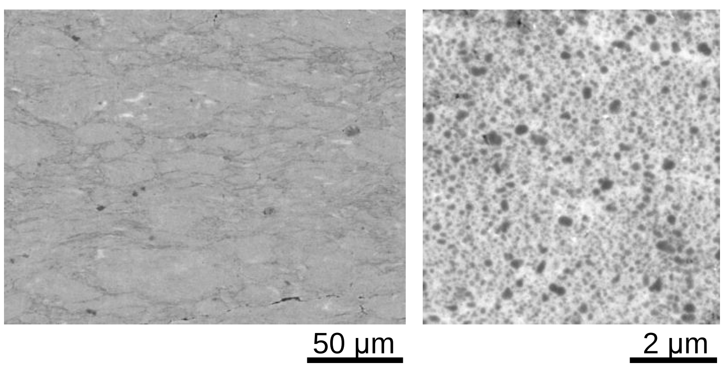


Heat treatment →

P ~ 0.6, *K* ~ 0.2

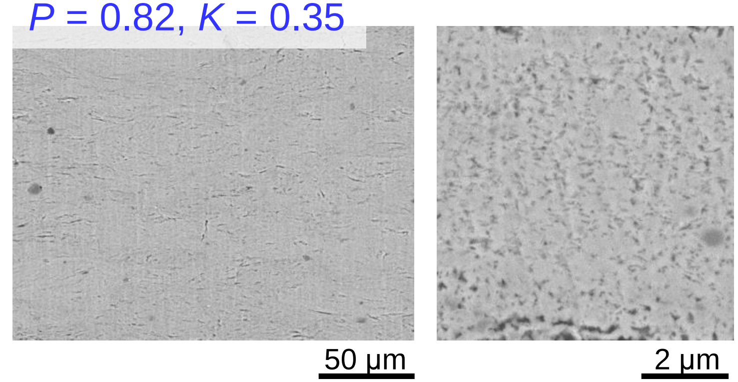


Dense PIT wire (Mechanical milling)



Heat treatment →

P = 0.82, *K* = 0.35



We confirmed higher packing factor and higher connectivity for the dense PIT wire.

3−6 Result (3) Next generation dense PIT wire

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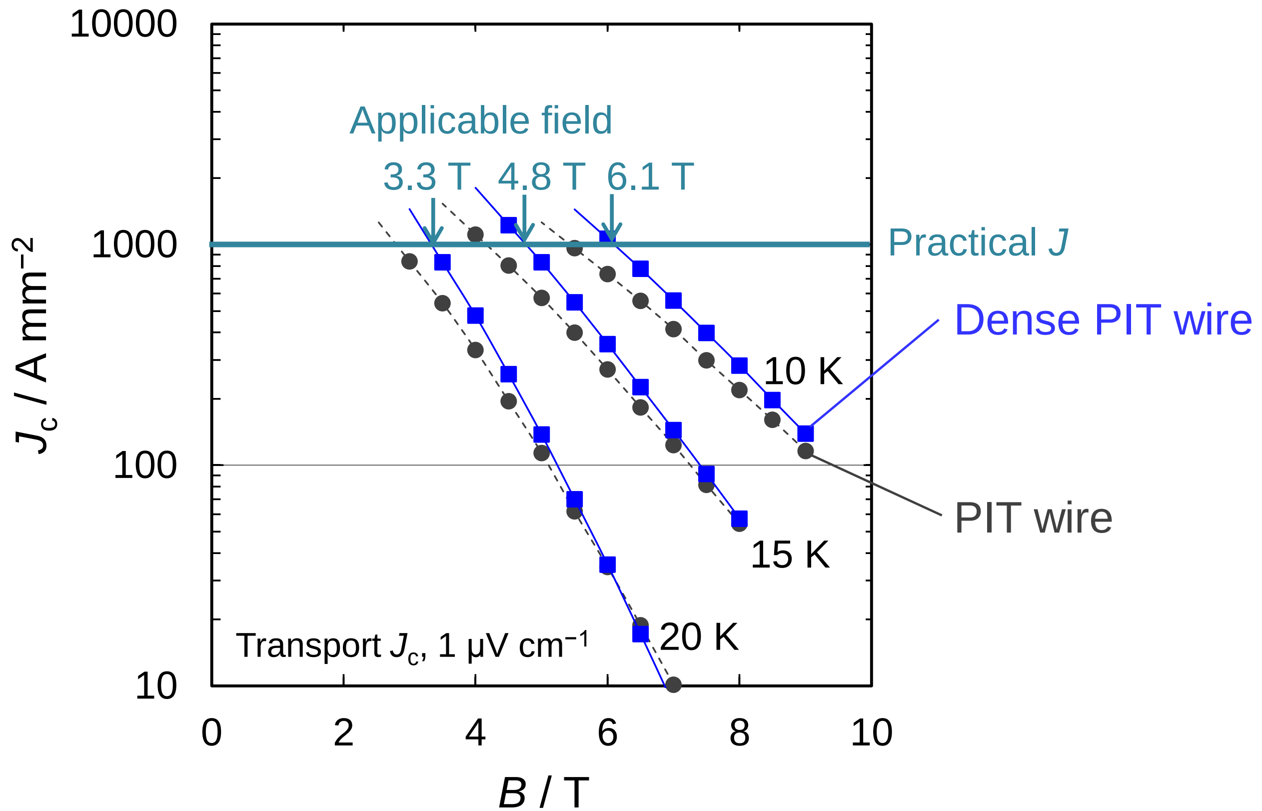
J_c property

Kodama M *et al Supercond. Sci. Technol.* **30** (2017) 044006



The dense PIT wire has higher applicable fields than the PIT wire.

Conclusions

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Using accumulated knowledge and accurate evaluation, we optimized the manufacturing conditions (cold work, boron choice, carbon addition, and heat treatment) and improved J_c of the *in situ* PIT wire.

We prove the homogeneity of a 300-meter-long multicore *in situ* PIT wire from the evaluation as a coil.

We demonstrated that the wire fabricated from mechanically milled powder had denser MgB_2 core and higher J_c than typical *in situ* PIT wires.

Acknowledgements

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