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4MO-2-02

# Copper stabilized dense $MgB_2$ wires fabricated by two types of methods: mechanical milling and internal Mg diffusion

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# 1−1 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

## Progress of $MgB_2$ 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

## Progress of $MgB_2$ wires

- *In situ* and *ex situ*-processed wires are commercially available from Hyper Tech and Columbus, respectively
- R & D phase: internal Mg diffusion (IMD), high pressure treatment (CHPD, HIP), mechanical alloying/milling (MA/MM), vapor deposition, and so on

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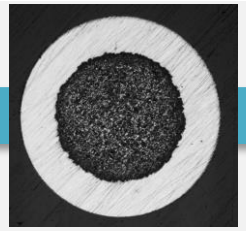
## Hitachi's R&D activity on $MgB_2$ wire

| | Step 1<br>Enhance $J_c$ | Step 2<br>Copper-stabilization | Step 3<br>Multicore | Step 4<br>Elongate (~km)<br>Tune up |
|---|---|---|---|---|
| Typical<br>*In situ* |  |  |  | |
| MM | This study | | | |
| IMD | Collaborating with Kumakura group | This study | | |
| Thin film | | | | |

1MP1-13: Mechanical property
4MP2-09: Persistent joint

The superior $J_c$ was confirmed.
Kodama M *et al* 2017 *Supercond. Sci. Technol.* **30** 044006

4MP2-02: $MgB_2$ film on Cu tape

# 1−3 Introduction

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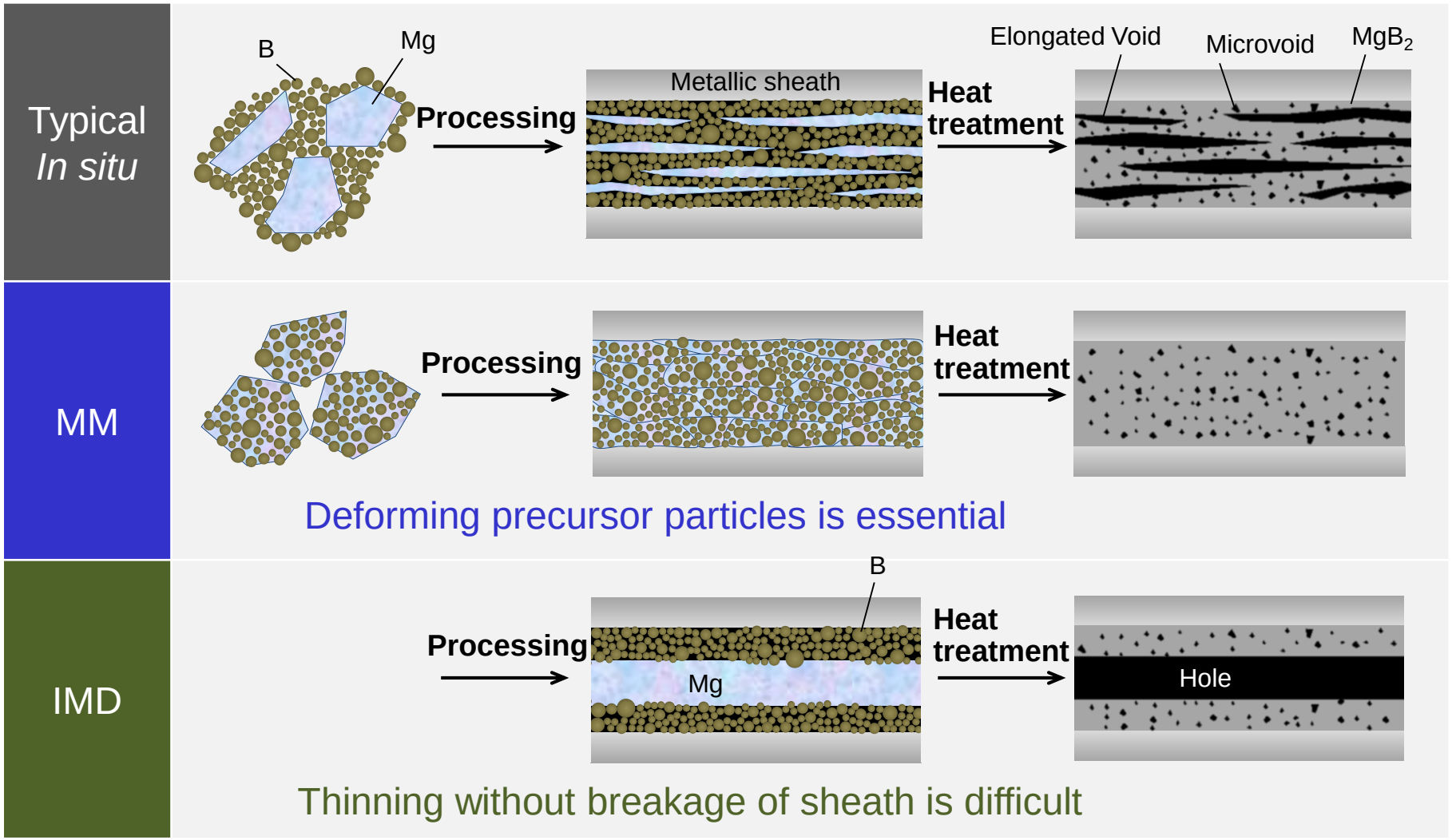


Because Cu is a soft material, Cu-stabilization of MM and IMD is more difficult.

# 1−4 Aims

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## Mechanical milling (MM)

- To clarify the way to deform the precursor particles and improve $J_c$.
- To realize high $J_c$ in Cu-stabilized monocore wires.

## Internal Mg diffusion (IMD)

- To clarify the fabrication way without the breakage of sheath and confirm high $J_c$ in Cu-stabilized monocore wires.

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# 2−1 Method of MM

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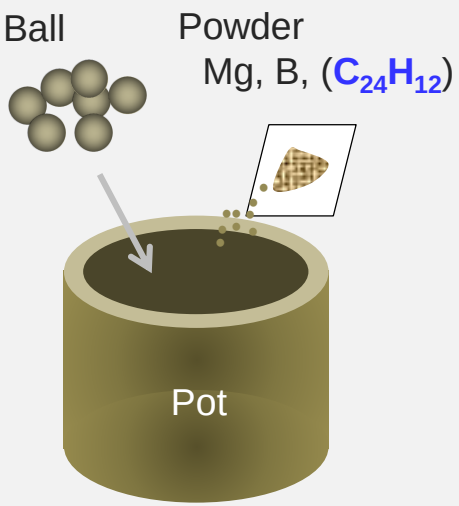
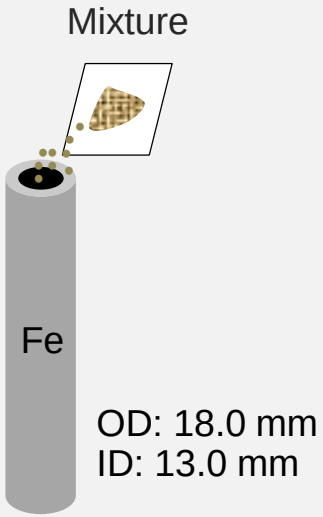
We investigated the influence of powder composition and wire processing method.

**Planetary milling**

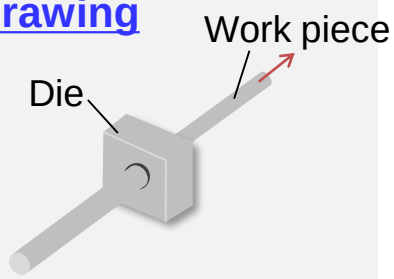



**Powder packing**

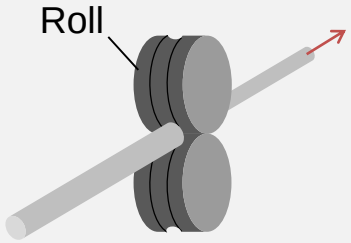



**Wire processing**

Drawing




Cassette rolling




**Heat treatment**


| Specimen | Composition | Wire processing method | Diameter |
|---|---|---|---|
| Wire-1 | Pure: Mg + 2B | Drawing | 0.5 mm |
| Wire-2 | Pure: Mg + 2B | Drawing + Cassette rolling | 0.5 mm |
| Wire-3 | $C_{24}H_{12}$-added: Mg + 2(0.98B + 0.02C) | Drawing + Cassette rolling | 0.5 mm |

# 2−2 Results of MM

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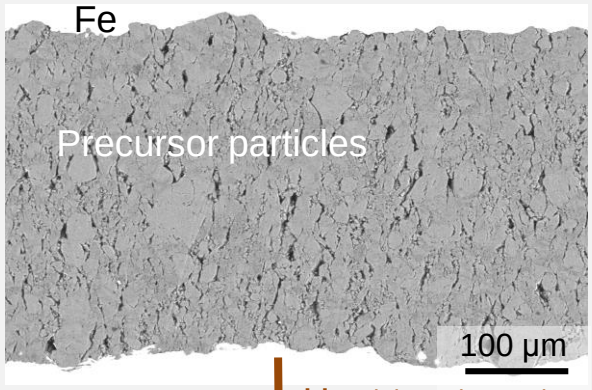
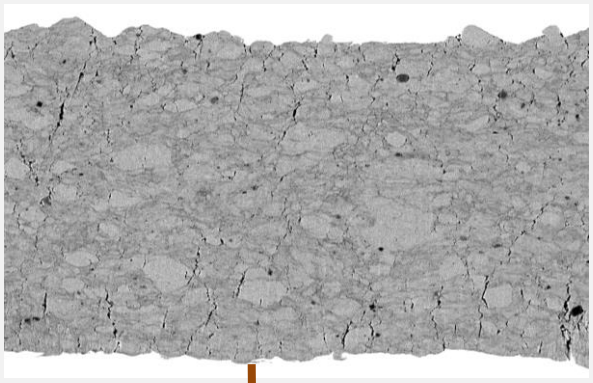
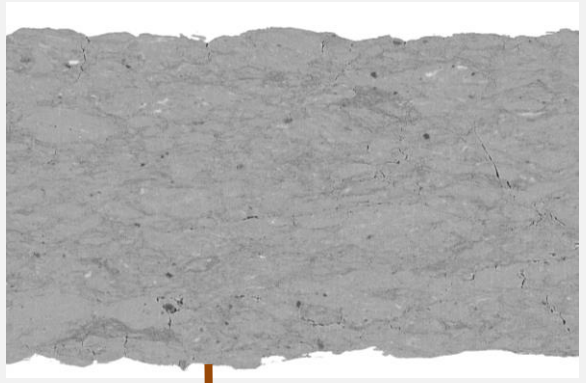
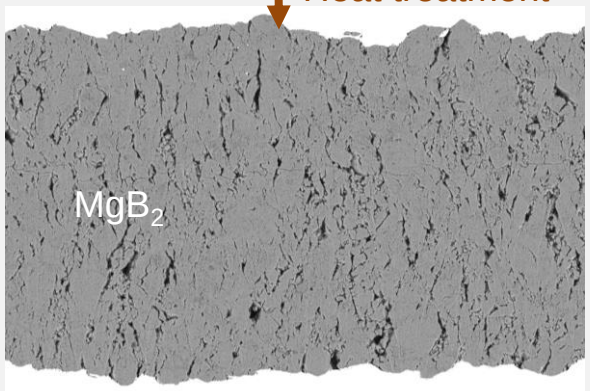
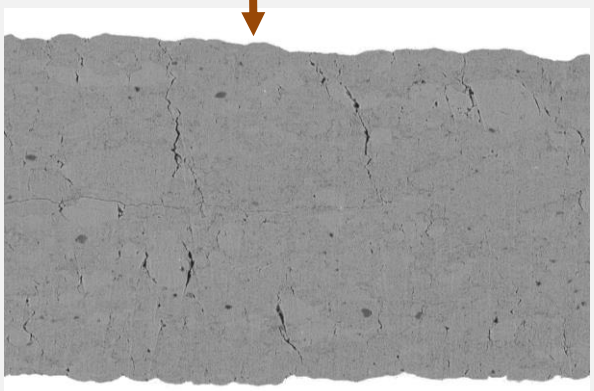
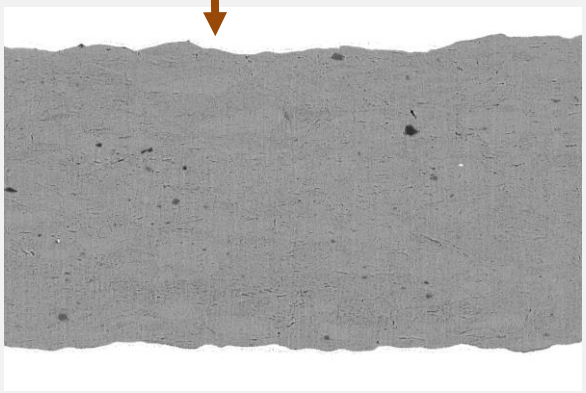
## BSE images of longitudinal sections

| Wire-1<br>Pure, Only drawing | Wire-2<br>Pure, + Cassette rolling | Wire-3<br>$C_{24}H_{12}$, + Cassette rolling |
|---|---|---|
|  |  |  |
| Heat treatment | Heat treatment | Heat treatment |
|  |  |  |

Cassette rolling and $C_{24}H_{12}$ addition are effective to obtain excellent microstructure.

PCT International Publication No. WO 2017/130672

# 2−3 Results of MM

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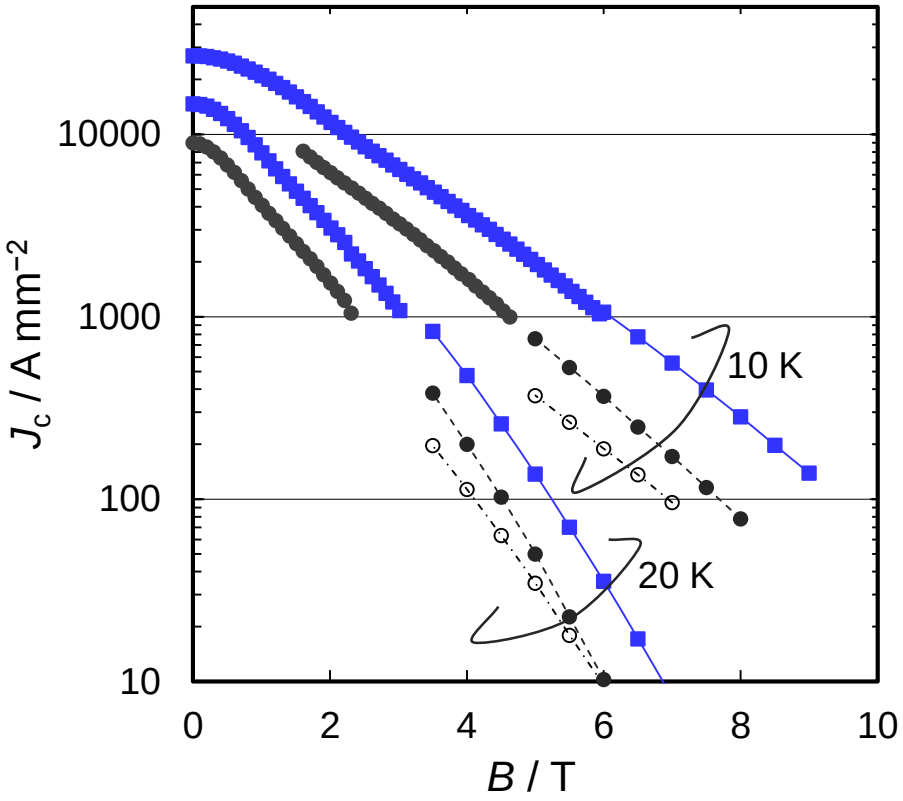
## $J_c$−$B$ properties




Higher $J_c$: magnetization method
Lower $J_c$: transport method

**Wire-1**
Pure, Only drawing

**Wire-2**
Pure, + Cassette Rolling

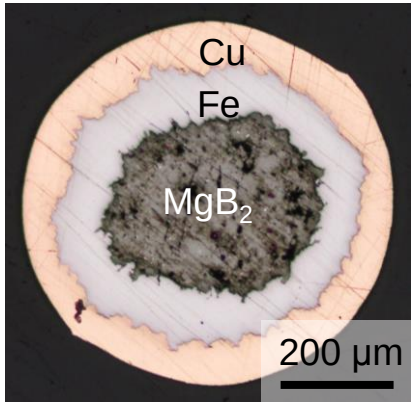
**Wire-3**
$C_{24}H_{12}$, + Cassette Rolling

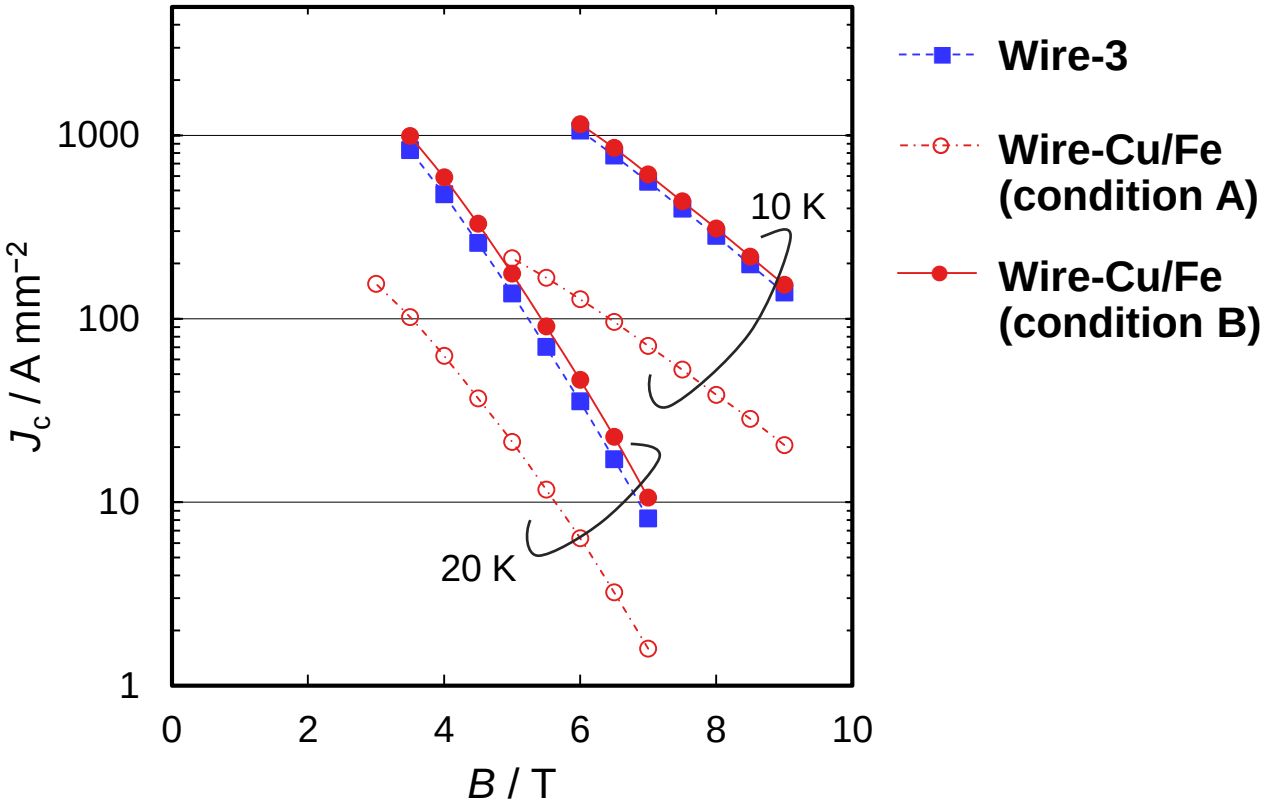
Cassette rolling and $C_{24}H_{12}$ addition improve $J_c$.

The high $J_c$ of Wire-3 is caused by not only carbon substitution but also high electrical connectivity (0.23 for Wire-2 and 0.35 for Wire-3).

# 2−4 Results of MM

We also fabricated the **Cu-stabilized** MM wire, **Wire-Cu/Fe**.




In the case of Cu-stabilized wire, it was more difficult to find a suitable condition because Cu is soft. Now, we found the condition where high $J_c$ is obtained.

# 2−5 Comparison with *in situ* and MA

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## Milling energy

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

$$\frac{E}{m} = c\beta \frac{(\omega_p r_p)^3}{r_v} t$$

$m$: powder mass, $c$~0.1
$\beta$: ball to powder mass ratio,
$\omega_p$: revolution angular velocity
$r_p$: revolution radius, $r_v$: pot radius
$t$: milling duration

**- Mechanical milling (MM)**

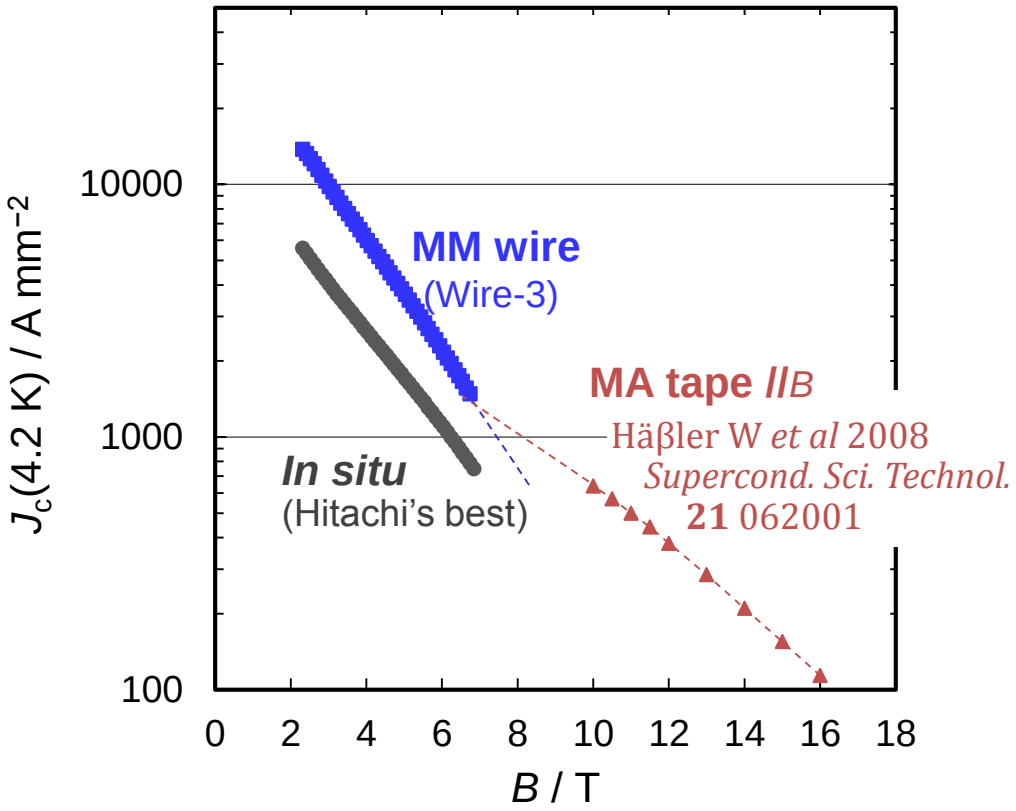
$10^6$–$10^7$ J kg$^{-1}$

**- Mechanical alloying (MA)**

~$10^9$ J kg$^{-1}$

## $J_c$–$B$ properties

Our results:
magnetization method




The MM wire has higher $J_c$ than Hitachi's best *in situ* wire.

While MA tape has higher $J_c$ at high magnetic fields,
our MM wire has higher $J_c$ at middle and low magnetic fields.

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# 3−1 Method of IMD

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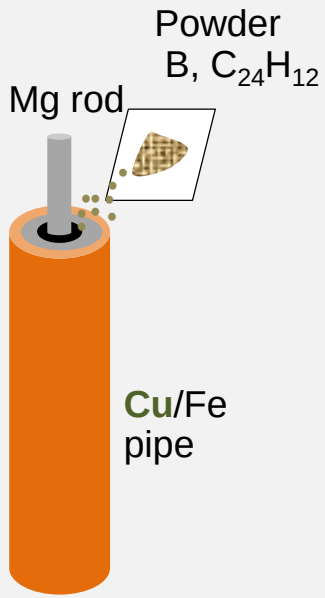
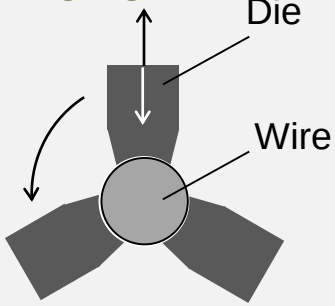
We investigated the influence of Cu thickness and wire processing method.

**Powder packing**

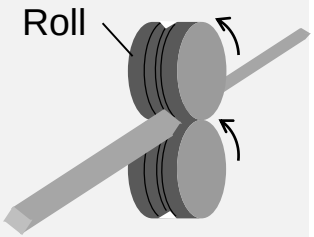



**Wire processing**

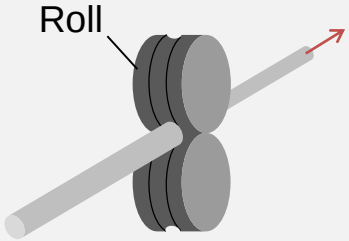
**Swaging**



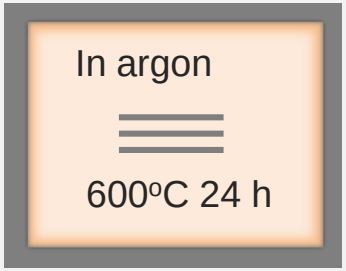

**Groove rolling**




**Cassette rolling**




**Heat treatment**



# 3−2 Results of IMD

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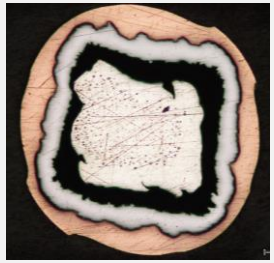
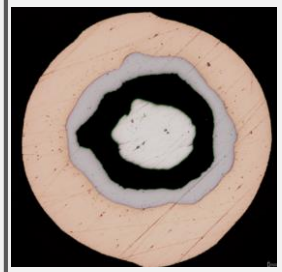
| Specimen (Cu ratio) | Total area reduction ratio (%) 44 | 90 | 96 | 99.8 |
|---|---|---|---|---|
| Wire-1 (28 %) | Swaging | 6.5 mm  | | |
| Wire-2 (28 %) | Swaging | Groove rolling | Cassette rolling | 1.0 mm  |
| Wire-3 (57 %) | Swaging | Groove rolling | Cassette rolling | 1.0 mm  |

In wire-3, we thinned 1.0 mm in diameter and the length reached 100 m.
Thicker Cu is effective to make the thickness of sheath homogeneous.

# 3−3 Results of IMD

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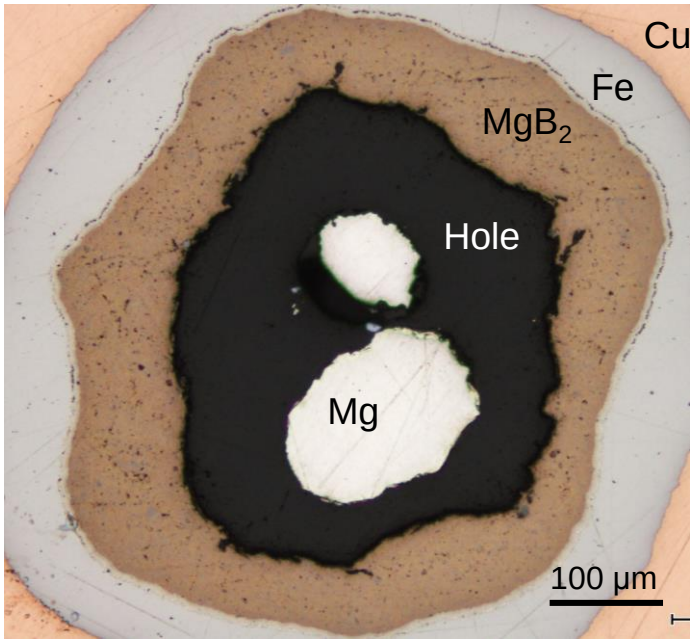
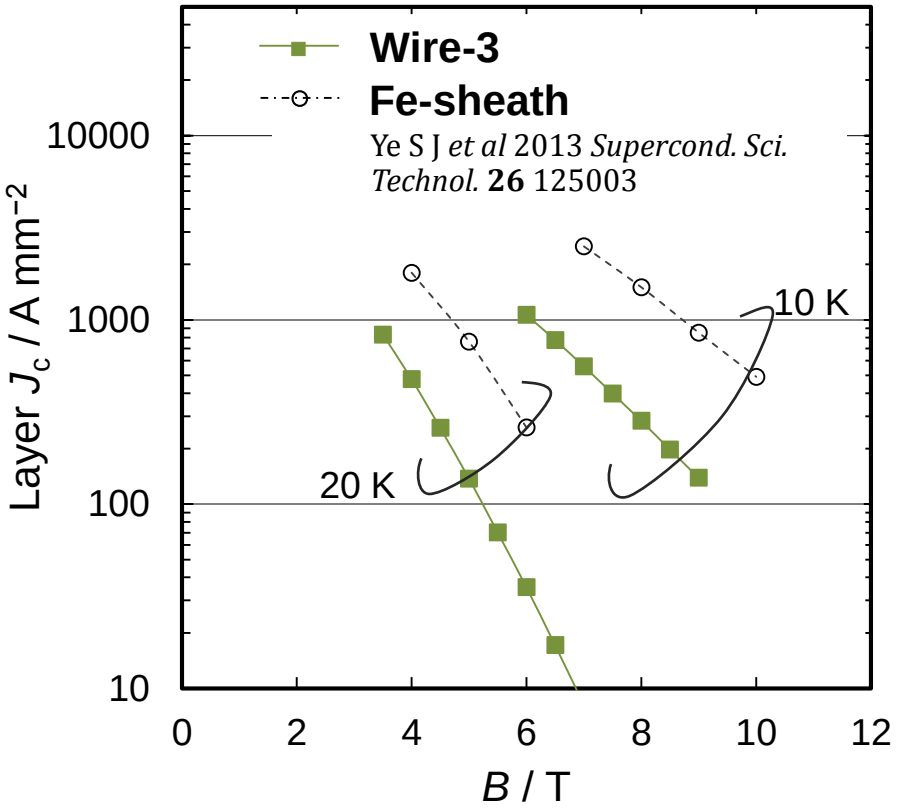
## Optical micrograph of Wire-3




## Layer $J_c$−$B$ properties




The microstructure of the $MgB_2$ layer in Wire-3 seems to be good, but the layer $J_c$ is not so high.

# 3−4 Results of IMD

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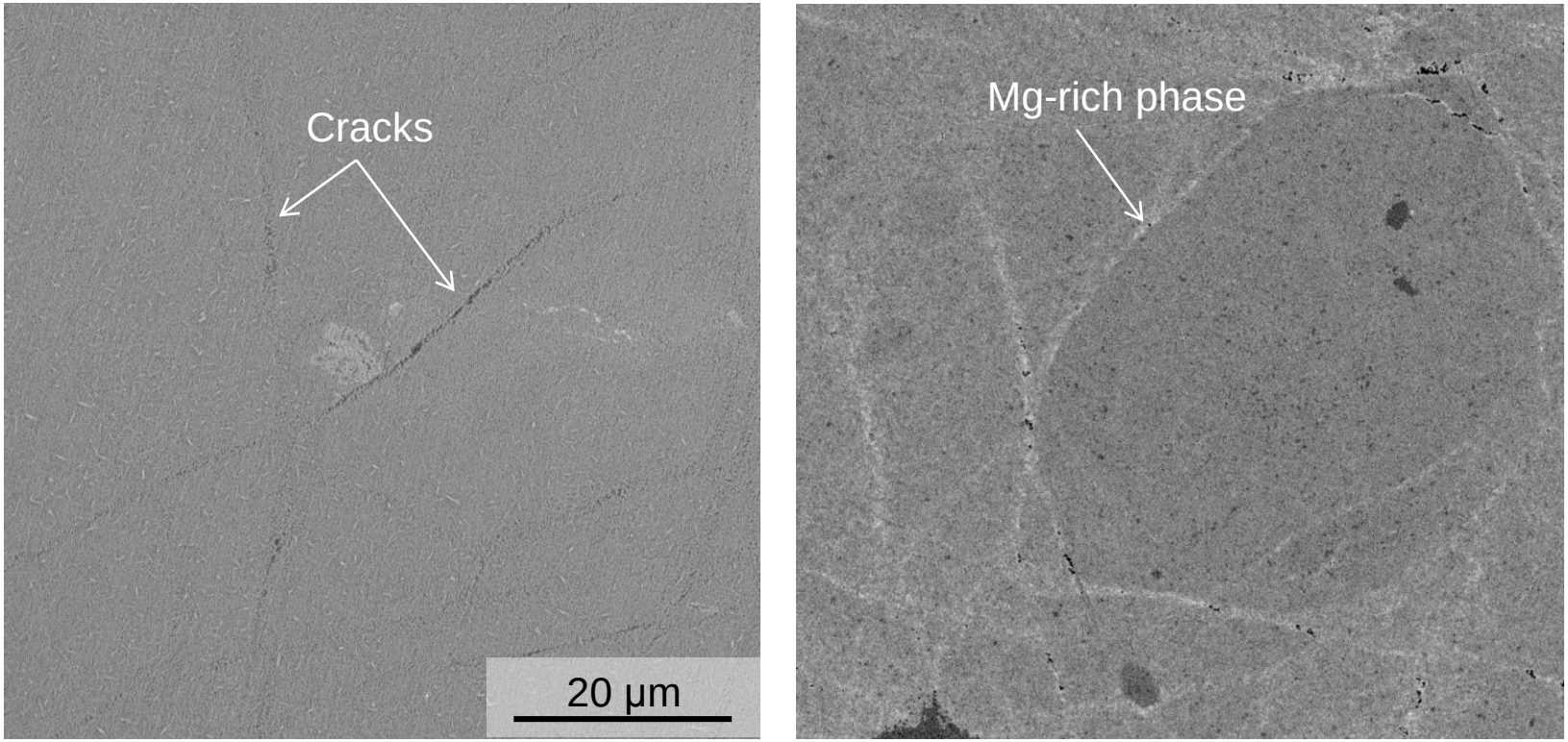
## BSE images of traverse sections of Wire-3

Boron layer → Heat treatment → $MgB_2$ layer




The low $J_c$ of wire 3 is because supercurrent is blocked by Mg-rich phase, which is formed by the condensation of Mg to the cracks of the boron layer.

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# 4. Conclusion

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## Mechanical milling (MM)

- We found that cassette rolling and $C_{24}H_{12}$ addition are effective to deform mechanically milled precursor particles and improve $J_c$.
- We also confirmed a sufficiently high $J_c$ for a Cu-stabilized monocore wire.

## Internal Mg diffusion (IMD)

- We successfully manufactured a 100-meter-long Cu-stabilized monocore wire, but the $J_c$ has room for improvement.
- To improve the $J_c$, cracks in boron layer need to be inhibited.

# Acknowledgements

We thank to

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# Appendix 1

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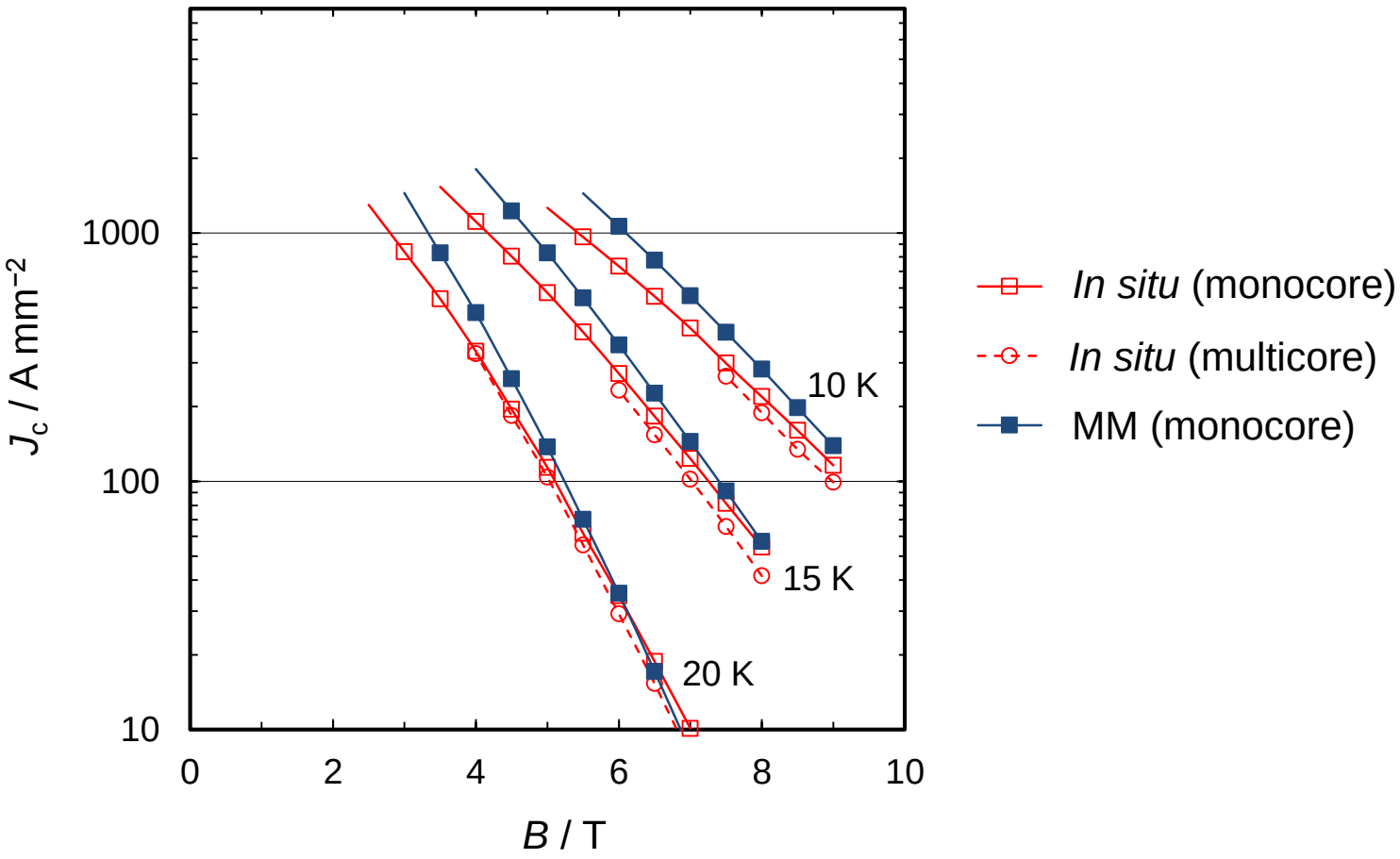
## $J_c$–$B$ properties of *in situ* and MM wires



# Appendix 2

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## BSE images of longitudinal sections of *in situ* and MM wires