

Effect of wire fabrication by swaging on the microstructure and critical currents of *in situ* PIT MgB₂ wires

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Background

One problem of *in situ* PIT MgB₂ wires is the low mass density of superconducting core.
We studied the effect of mechanical working mode on the microstructure and J_c values.

1. Groove rolling + drawing
2. Groove rolling + roller drawing
3. Swaging

Outline

- 1. Introduction**
- 2. Mono filamentary short MgB₂ wires(~1m length)**
- 3. 7-filamentary MgB₂ short wires(~2m length).**
- 4. Mono-filamentary MgB₂ ~10m long wires.**

Why the J_c of *in situ* PIT processed MgB₂ wire is low?

The packing density of MgB₂ core is ~50%.

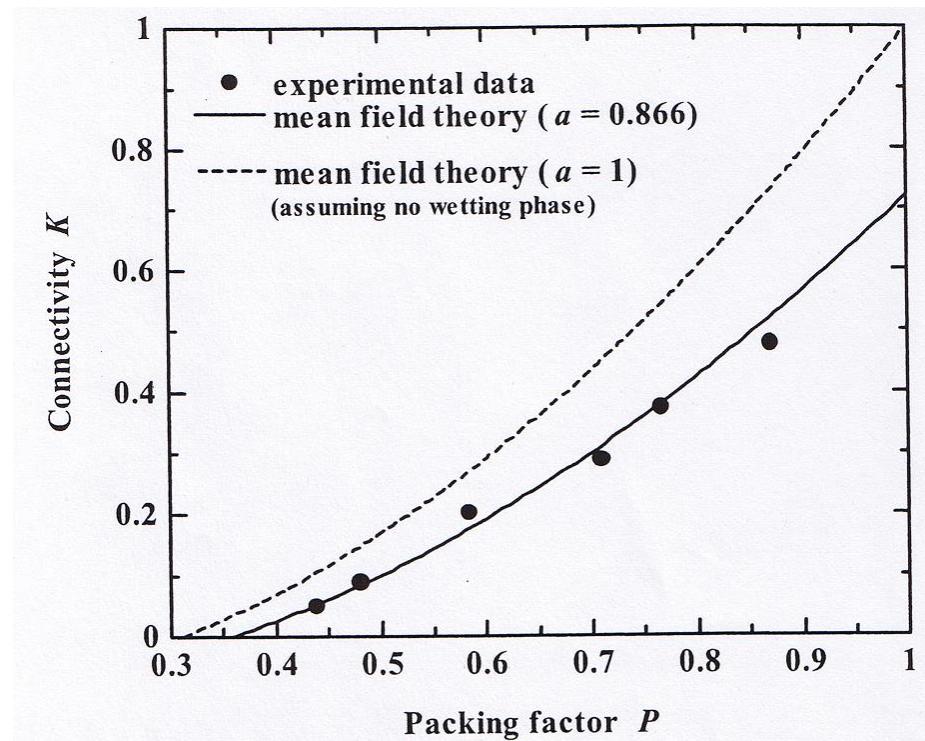


Very small connectivity

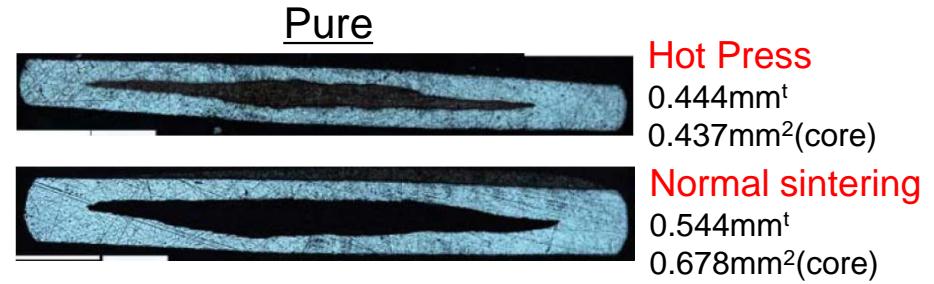
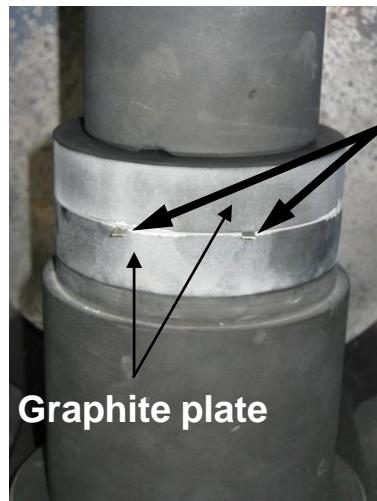
Connectivity:
Fractional area that carries electric current

Connectivity of our PIT MgB₂ wires (J. Rowell SUST16 (2003), R17)

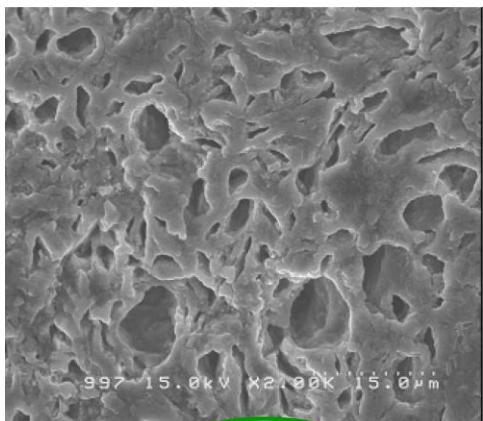
	$\rho(40K)$ $\mu\Omega \cdot cm$	Connectivity (%)	J_c (4.2K, 10T) $\times 10^4 (A/cm^2)$
Pure	116	9.0	0.25
10%SiC	324	8.2	1.20
30%SiC	407	6.0	1.55
10%C ₉ H ₁₂ 10%C ₉ H ₁₂ ⁺ 10%SiC	152 221	9.9 10.0	1.29 3.18
Nano Mg+ 10%SiC	114	14.7	2.7



Effect of Hot Pressing on microstructure and J_c values

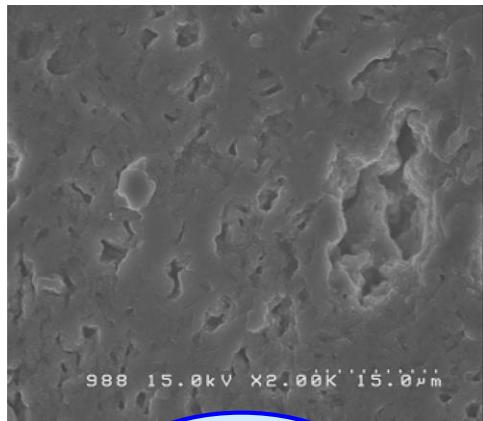


Normally sintered

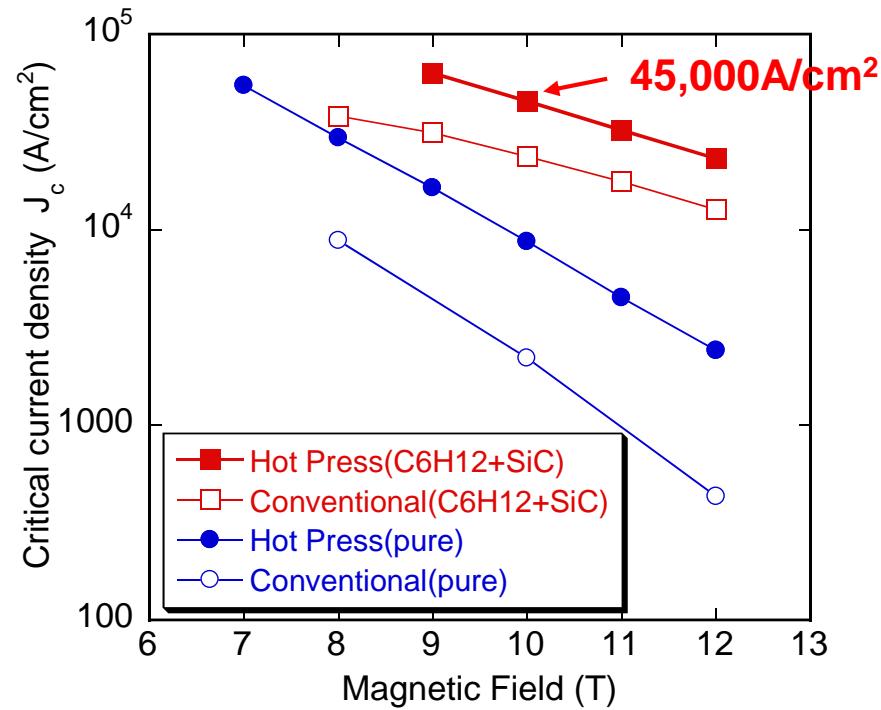


Density:
~50%

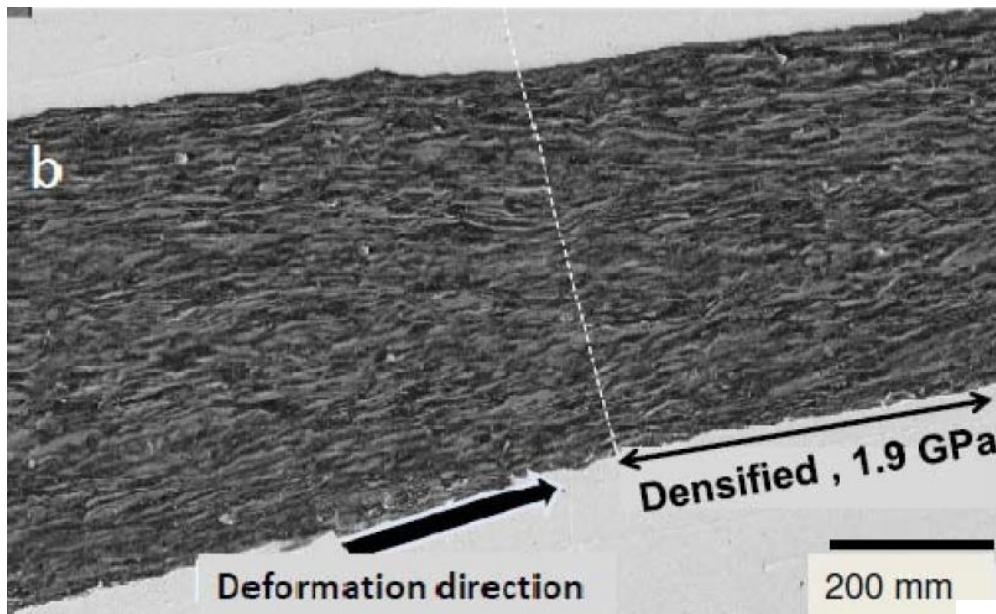
Hot Pressed(100MPa)



Density:
~70%



Improvement of MgB₂ core density by Cold High Pressure Densification(CHPD)

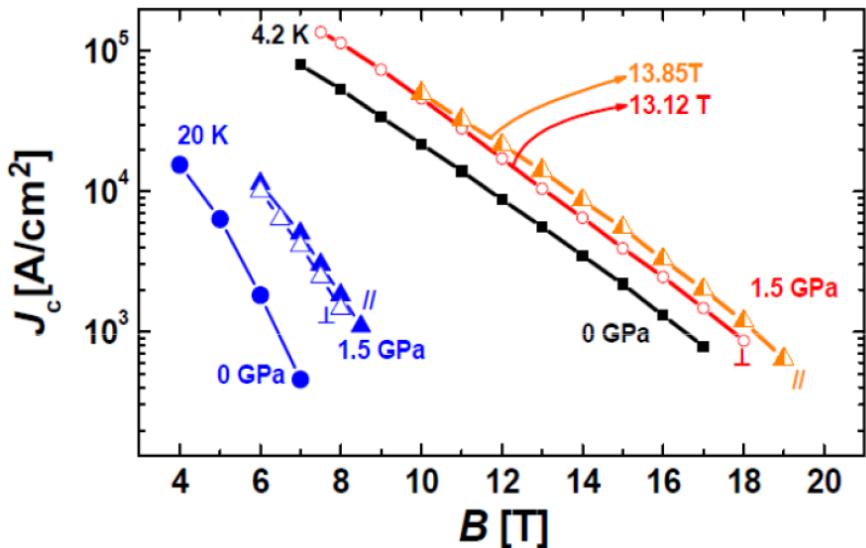


CHPD system



Cold Hydrostatic Pressure Densification (CHPD)

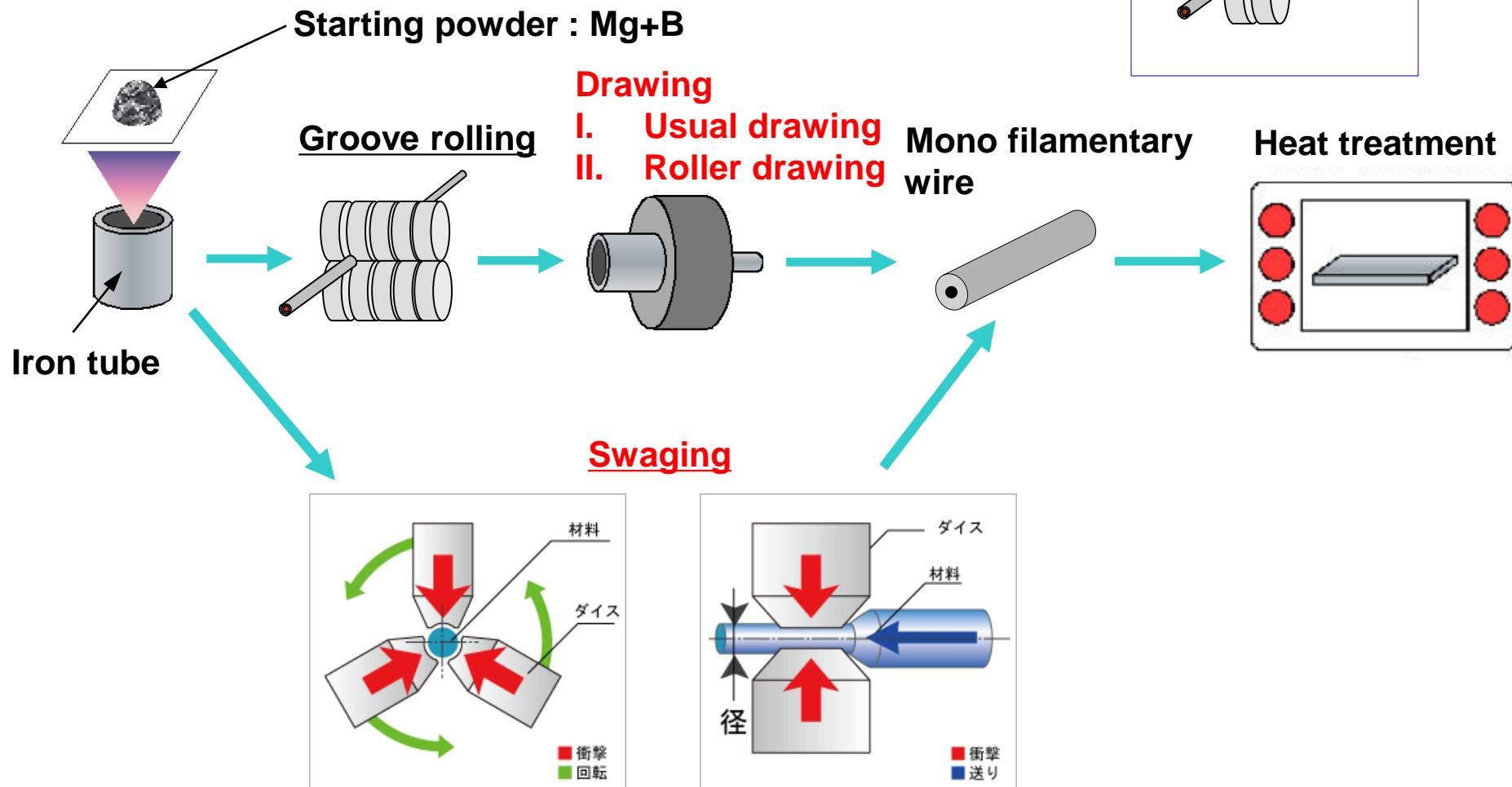
Increase of density from ~45% to ~58%



R. Flükiger, et al.(University of Geneva)
(100 years of Superconductivity, CRC Press)

Fabrication of MgB₂ mono-filamentary wire

In situ PIT method



Sample preparation

PIT mono and 7-filamentary MgB ₂ /Fe wire		
Raw powder	Mg(99.5%), <45μm	<ul style="list-style-type: none">pure B powder1.5, 4.5% C-coated B(CCB)5, 10mol% C₂₄H₁₂ added BAmorphus B (98%), <250nm (PAVEZYUM(Turkey))
Metal tube	Fe tube Outer dia.: 6mm, Inner dia.: 3.5mm	
Mechanical processing	<ul style="list-style-type: none">(a) Swaging(b) Groove rolling + CRD (roller drawing)(c) Groove rolling + Drawing	
Wire diameter	1.0 mm	
Heat treatment	600, 650 and 700°C/ 1 hour	

Comparison of microstructure among three PIT MgB₂ wires

100μm

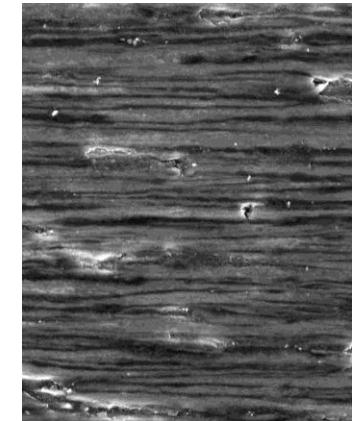
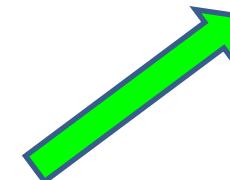
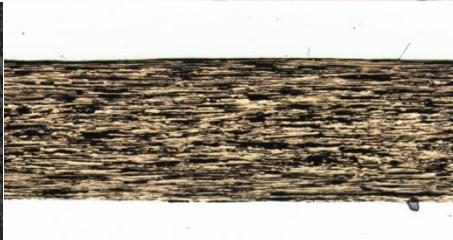
Before heat treatment

Swaging

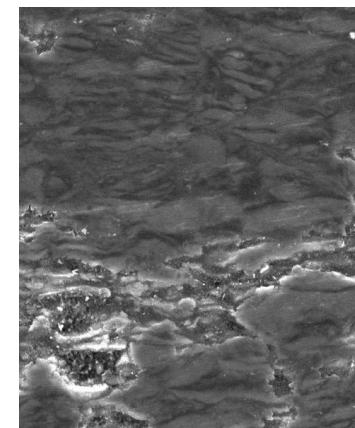
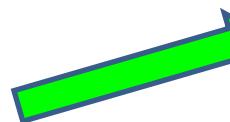
400μm



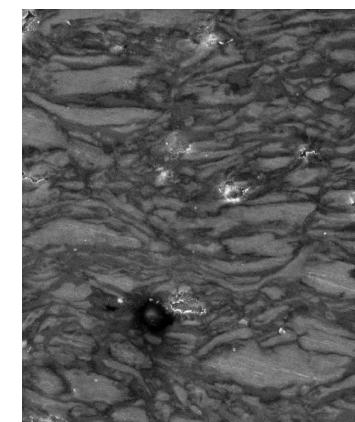
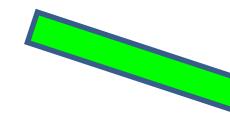
400μm



Groove rolling +
roller drawing



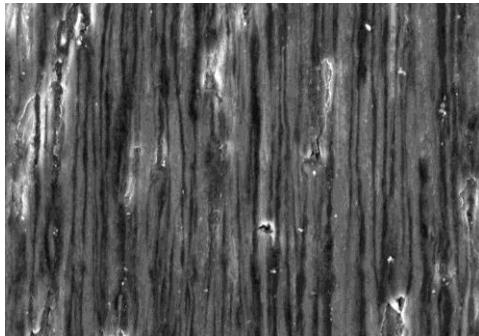
Groove rolling +
drawing



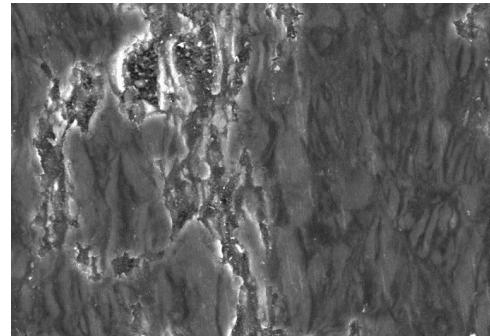
Microstructures of Mg/B and MgB₂ core before and after the heat treatment

Before H.T.

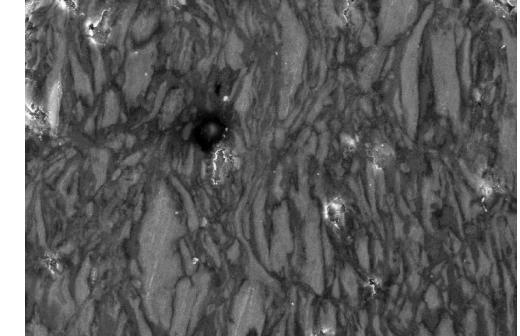
Swaging



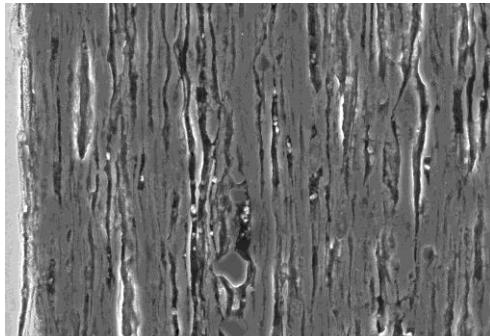
Groove rolling+
roller drawing



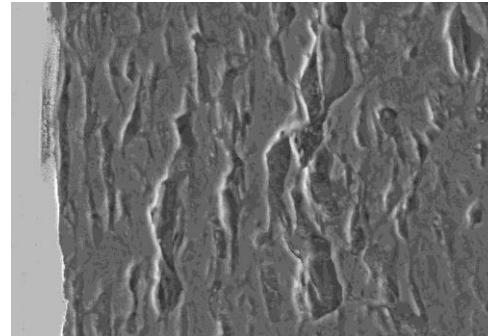
Groove rolling+
drawing



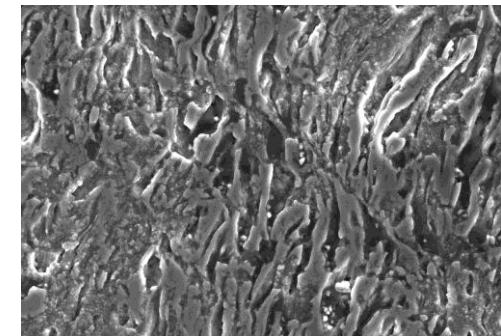
After H.T.



100μm



100μm



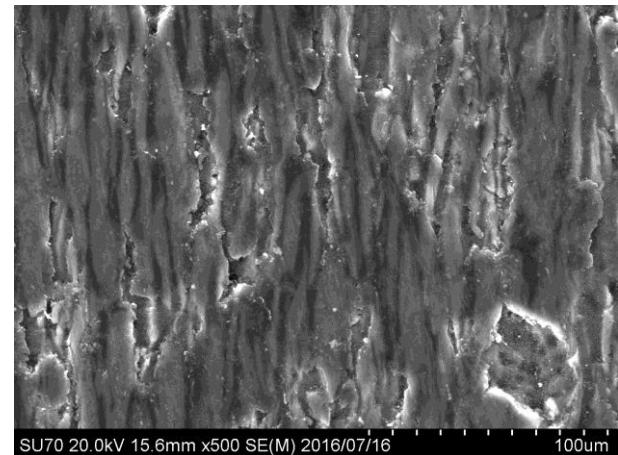
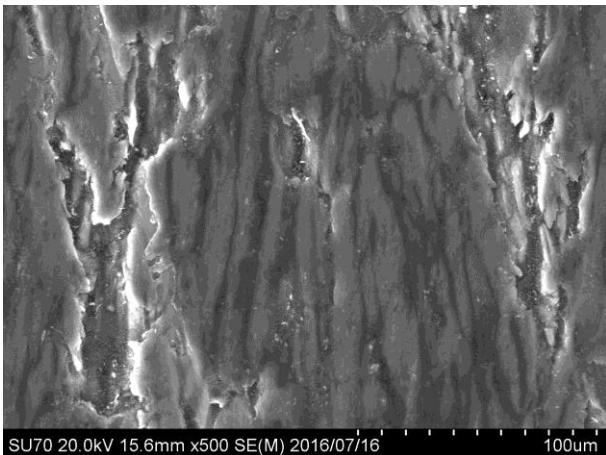
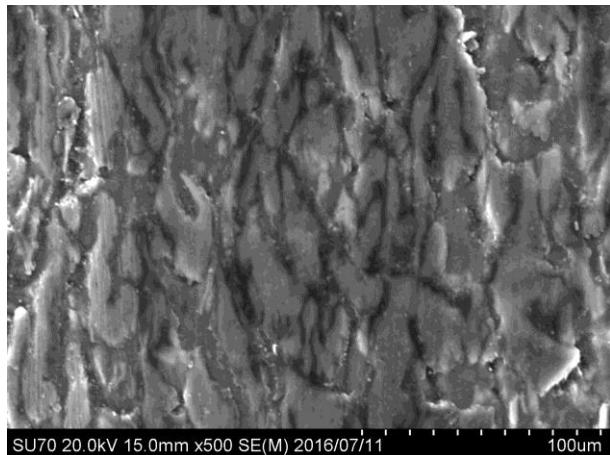
100μm

Deformation of Mg-B core by swaging (central area of Mg-B core)

Billet dia. 6.0mm → Φ 2.8mm

Φ 2.3mm

Φ 1.94mm



50μm

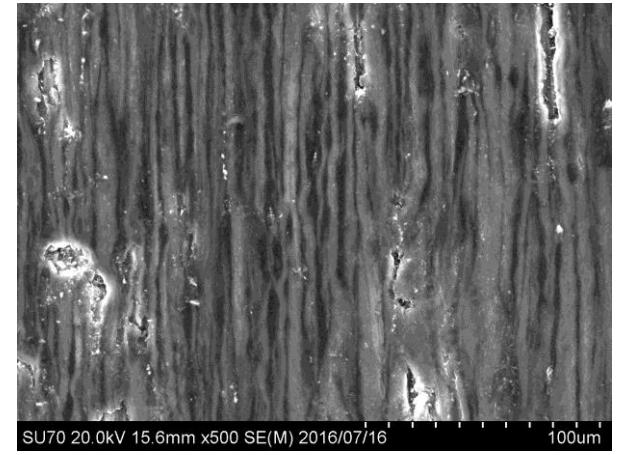
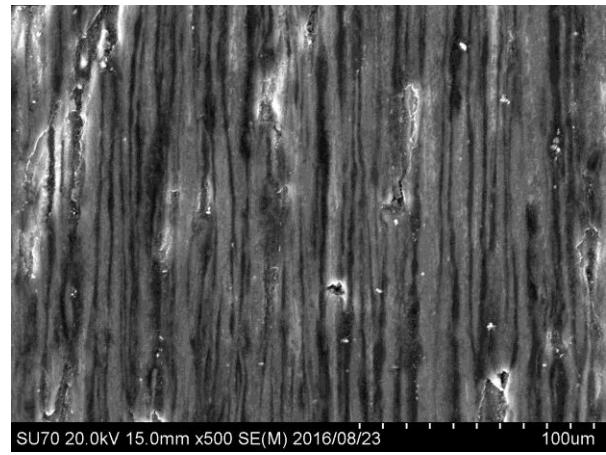
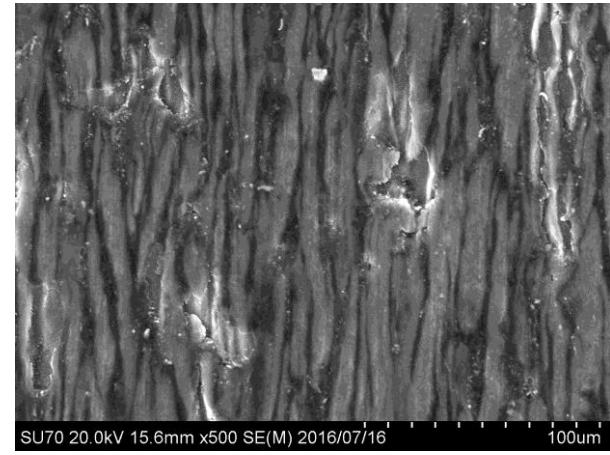
50μm

50μm

Φ 1.57mm

Φ 1.32mm

Φ 1.17mm



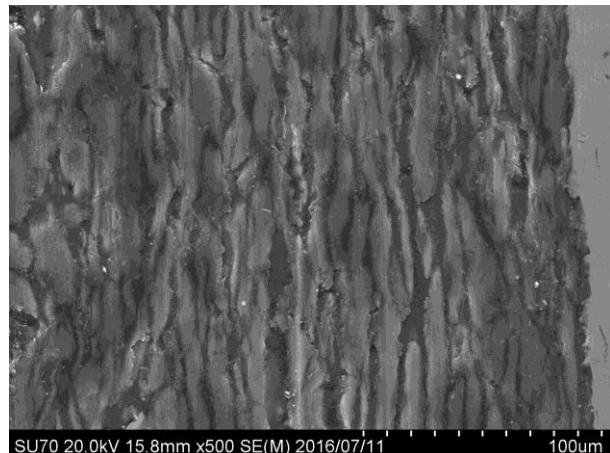
50μm

50μm

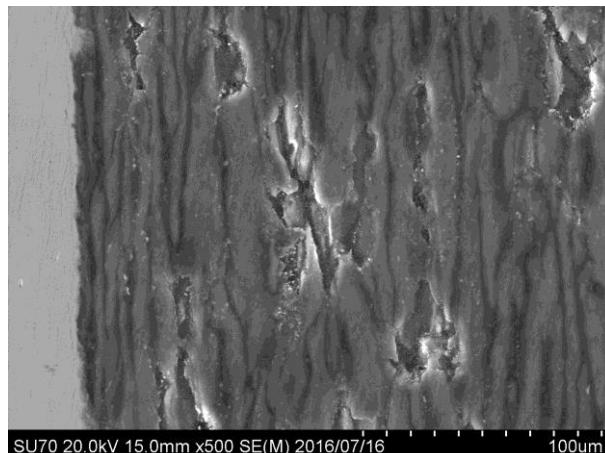
50μm

Deformation of Mg-B core by swaging(interface of Mg-B core and Fe sheath)

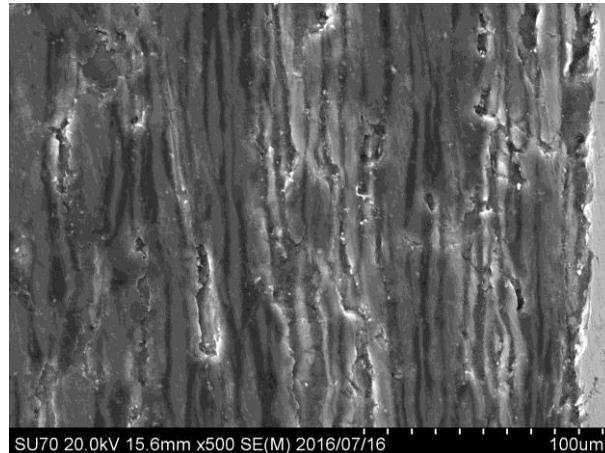
Billet dia. 6.0mm → Φ 2.8mm



SU70 20.0kV 15.8mm x500 SE(M) 2016/07/11

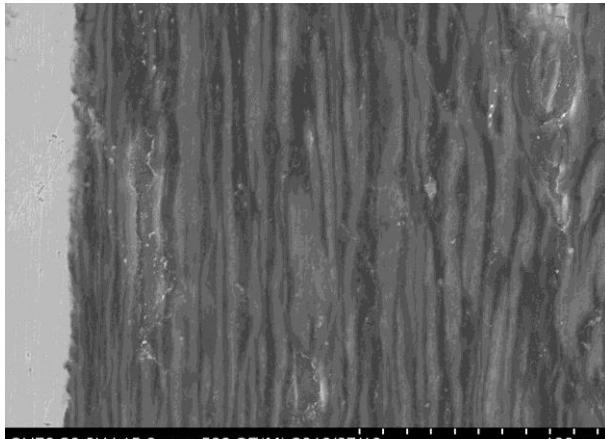


SU70 20.0kV 15.0mm x500 SE(M) 2016/07/16



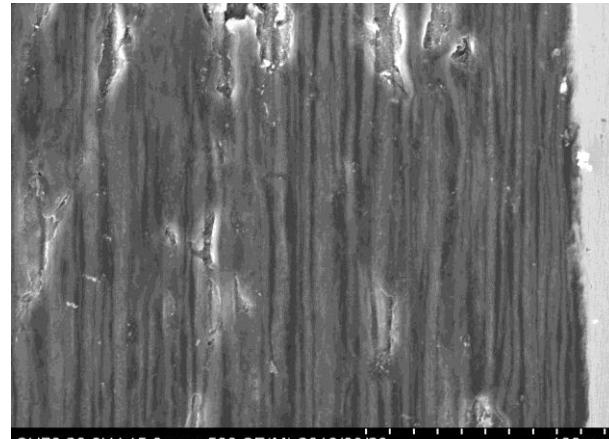
SU70 20.0kV 15.6mm x500 SE(M) 2016/07/16

Φ 1.57mm



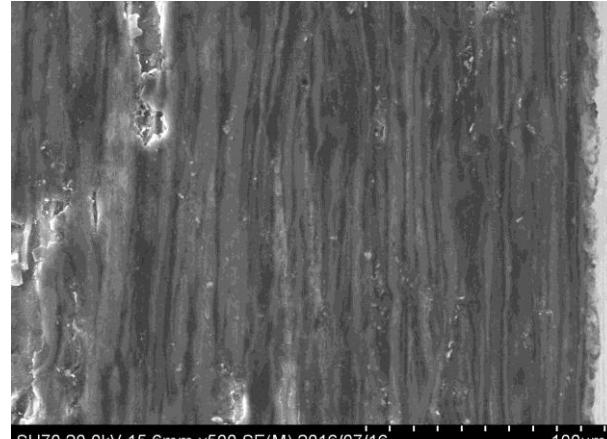
SU70 20.0kV 15.6mm x500 SE(M) 2016/07/16

Φ 1.32mm



SU70 20.0kV 15.0mm x500 SE(M) 2016/08/23

Φ 1.17mm



SU70 20.0kV 15.6mm x500 SE(M) 2016/07/16

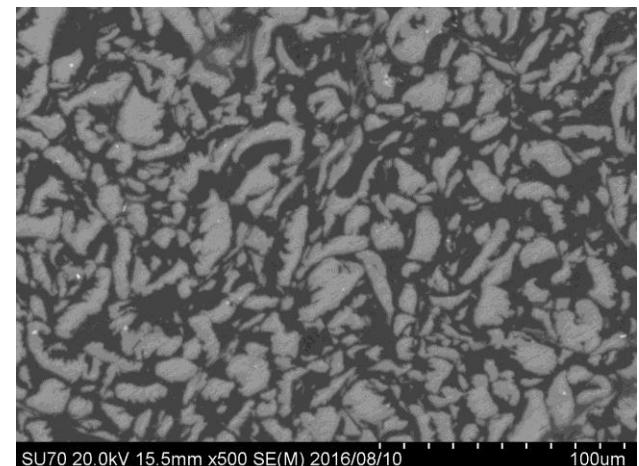
50 μ m

50 μ m

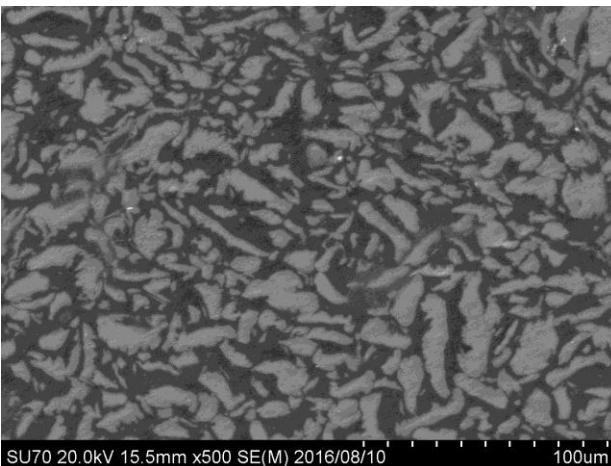
50 μ m

Deformation of Mg-B core by swaging (central area of Mg-B core) Transverse cross section

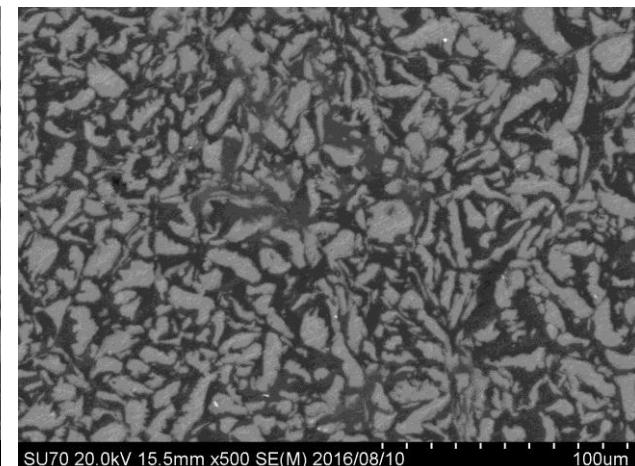
Billet dia. 6.0mm → Φ 2.8mm



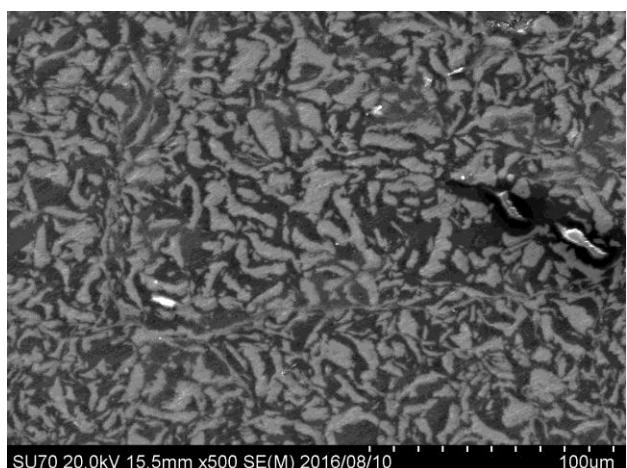
Φ 2.3mm



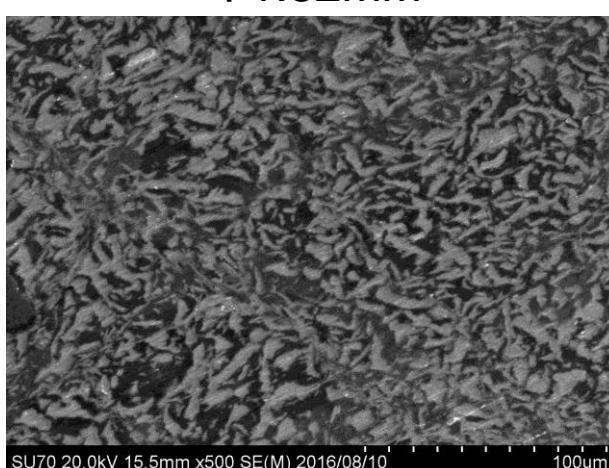
Φ 1.94mm



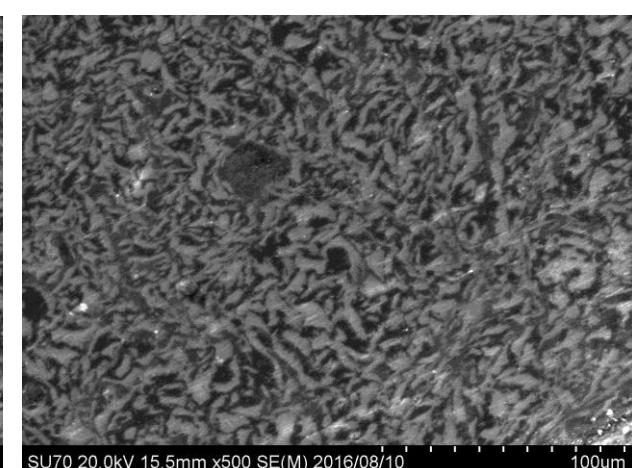
Φ 1.57mm



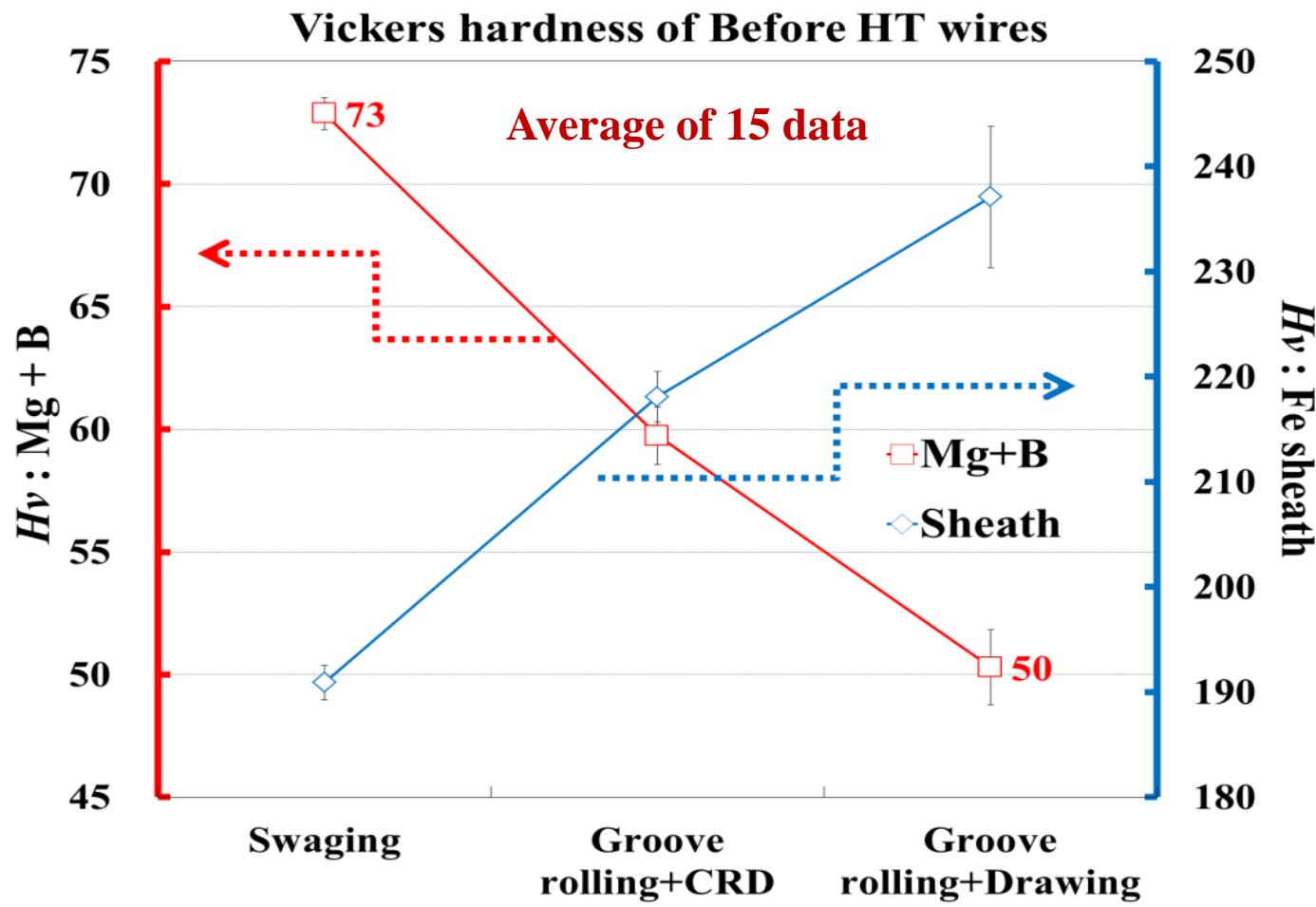
Φ 1.32mm



Φ 1.17mm

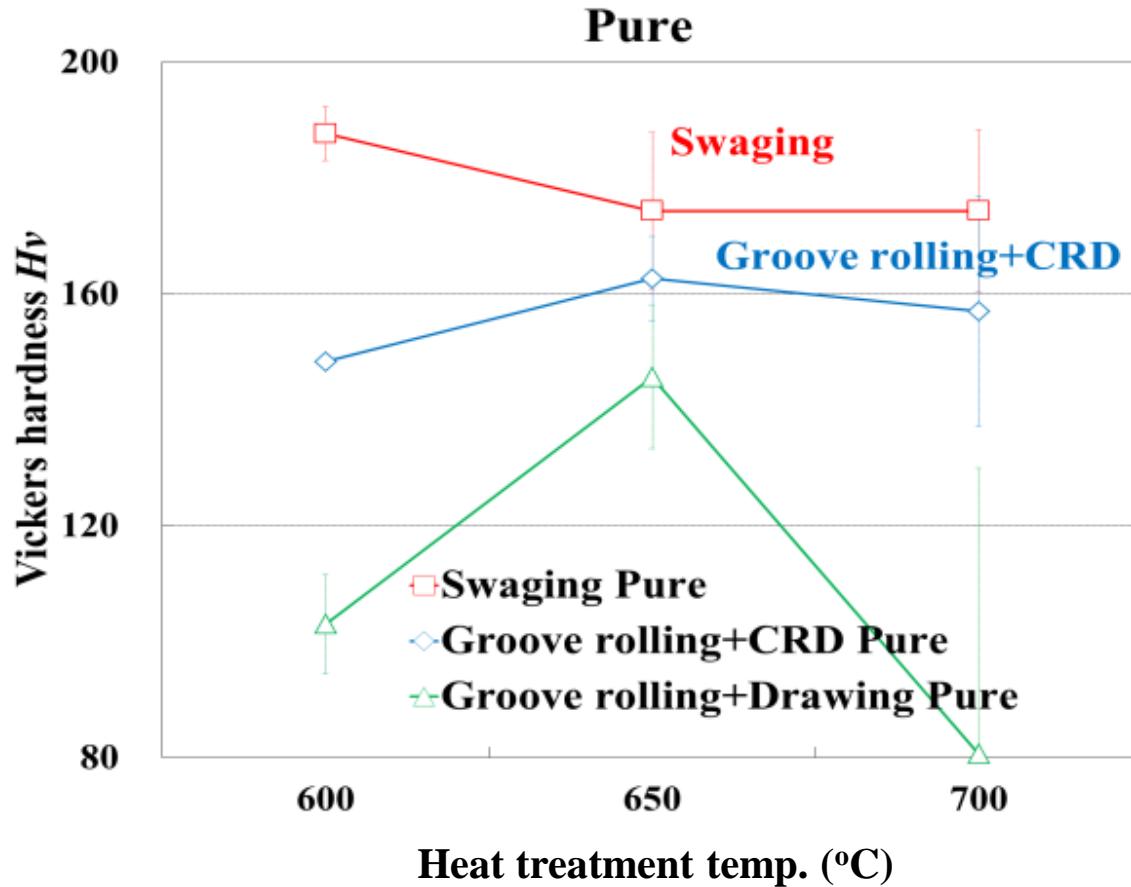


Vickers hardness, H_v , of core(Mg+B) and Fe sheath before heat treatment



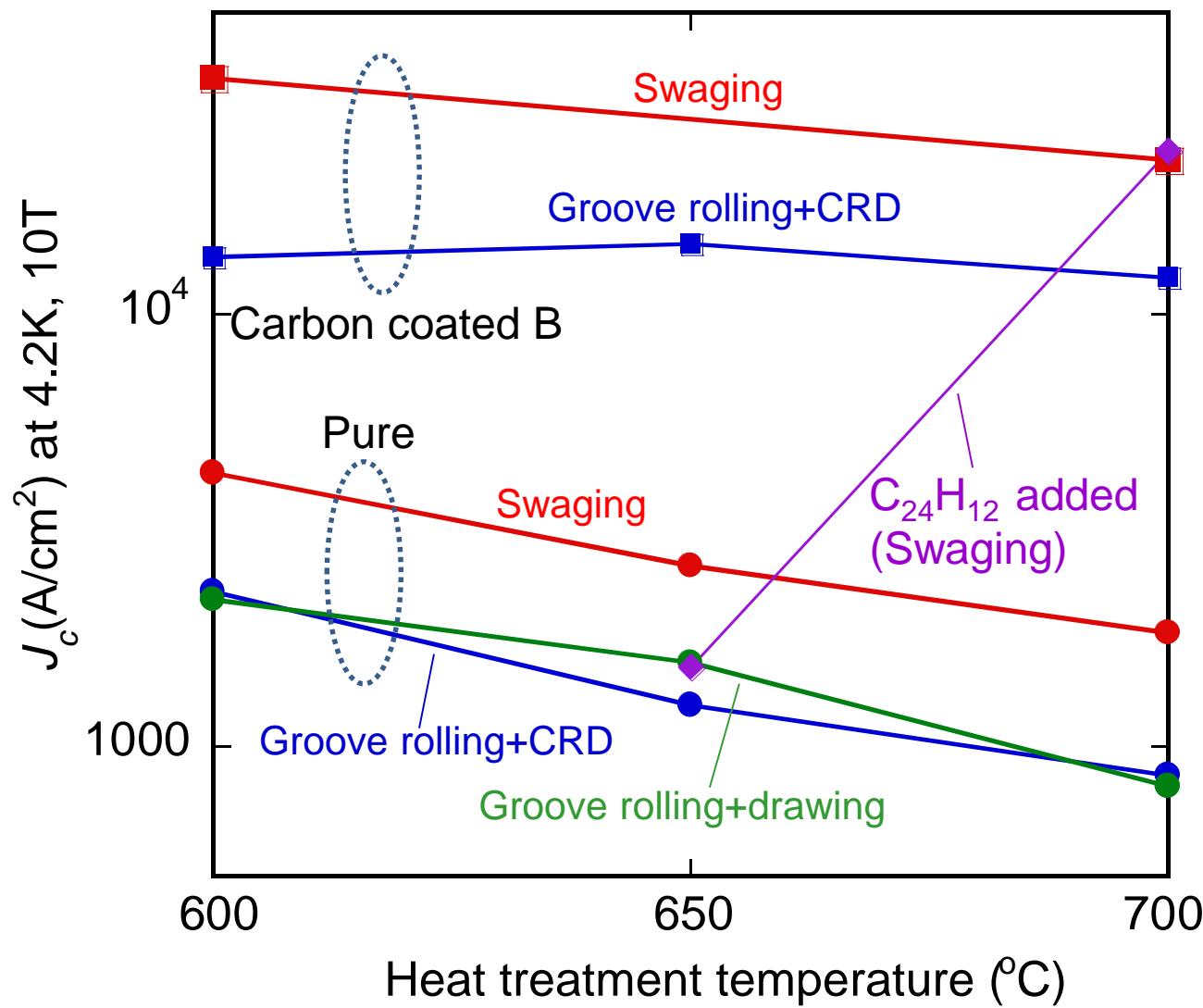
Density of Mg+B for swaging is higher than those for other mechanical drawings.

Vickers hardness (H_v) of MgB₂ core for three wires

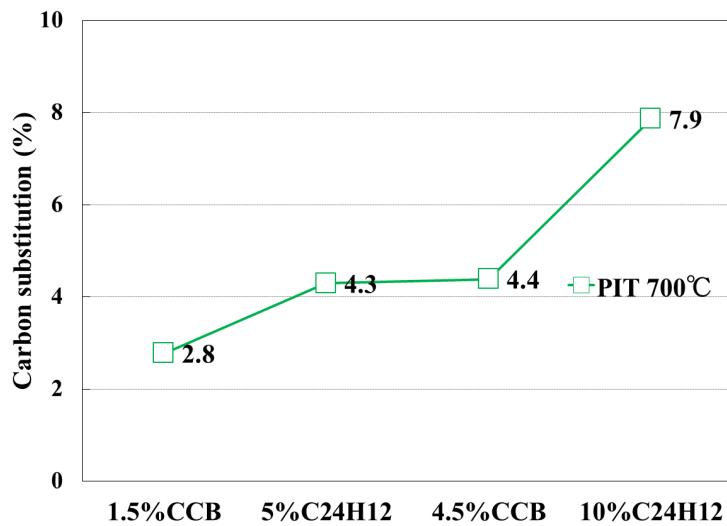
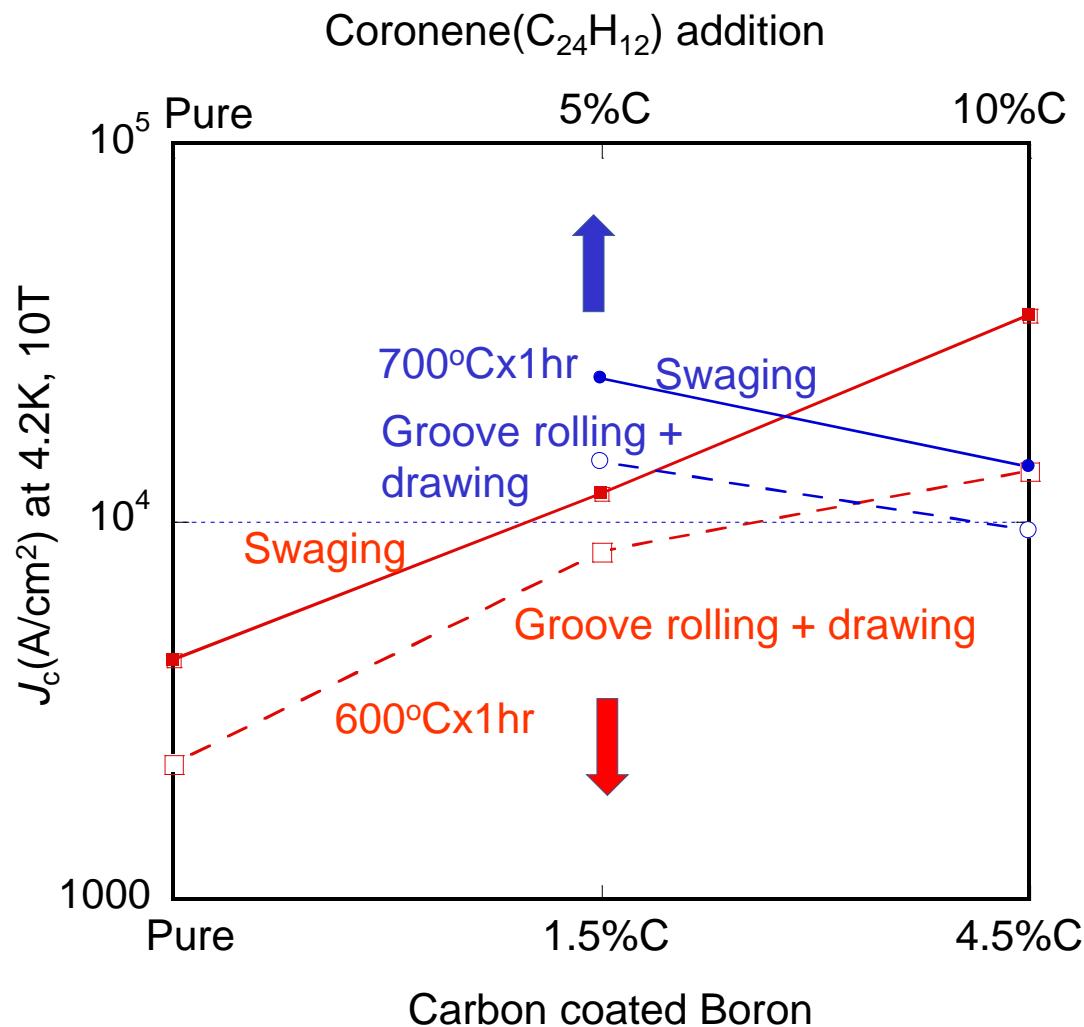


Density of MgB₂ for swaging is higher than those for other mechanical drawings.

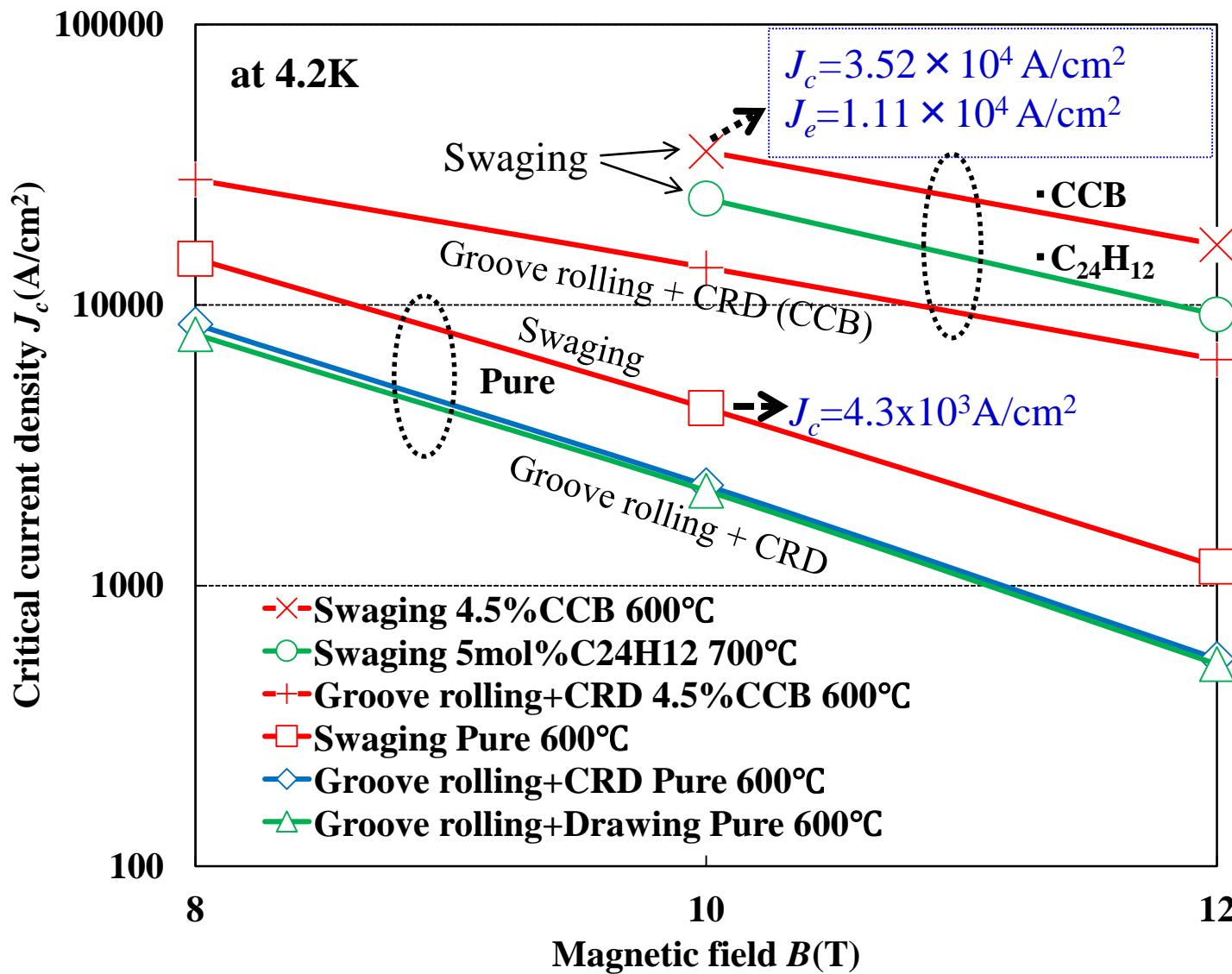
Heat treatment temperature dependence of J_c at 4.2K, 10T



Carbon doping level dependence of J_c at 4.2K, 10T



J_c - B curves of PIT MgB₂ mono-filamentary wires

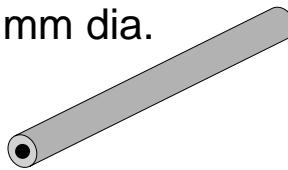


Fabrication of MgB₂ 7-filamentary wire

Swaging

Single core swaged wire

1mm dia.

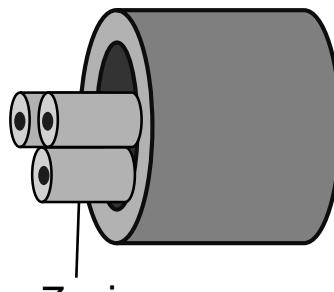


4.5%CCB



Iron tube

6mm outer dia.
3.5mm inner dia.



7-filamentary wire



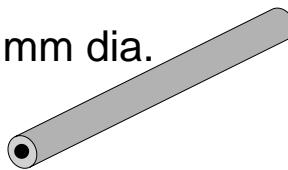
swaging

Φ1.0mm

Groove rolling+ roller drawing

Groove rolled and roller-drawn single core wire

1mm dia.

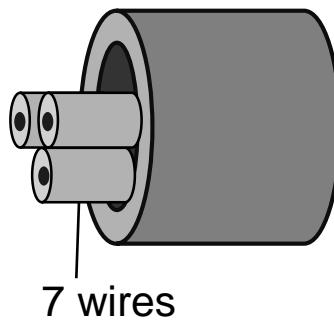


4.5%CCB



Iron tube

6mm outer dia.
3.5mm inner dia.



7-filamentary wire

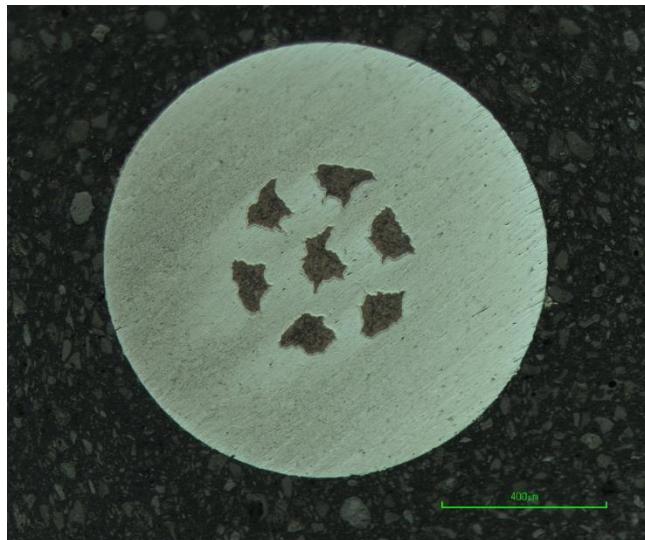


Groove rolling
+ roller-drawing

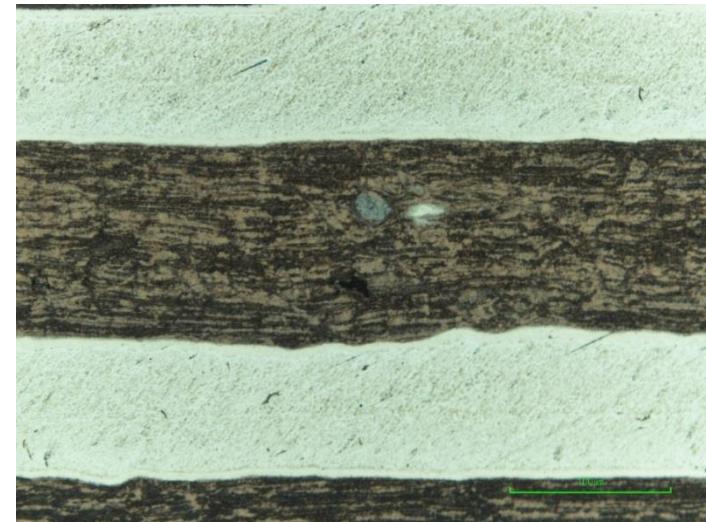
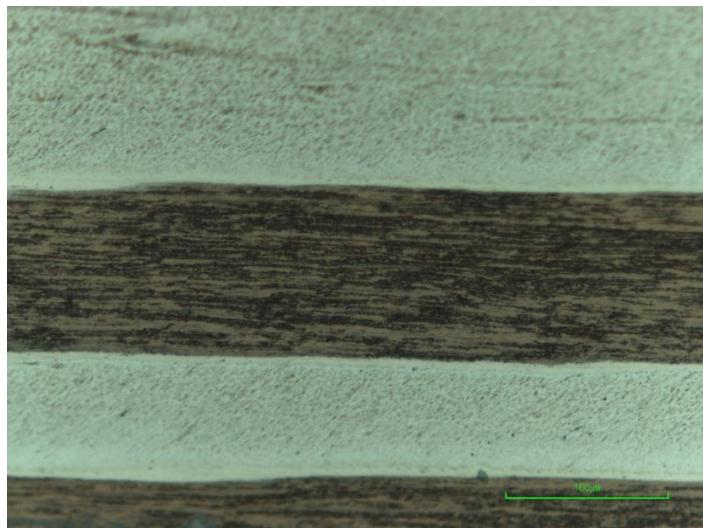
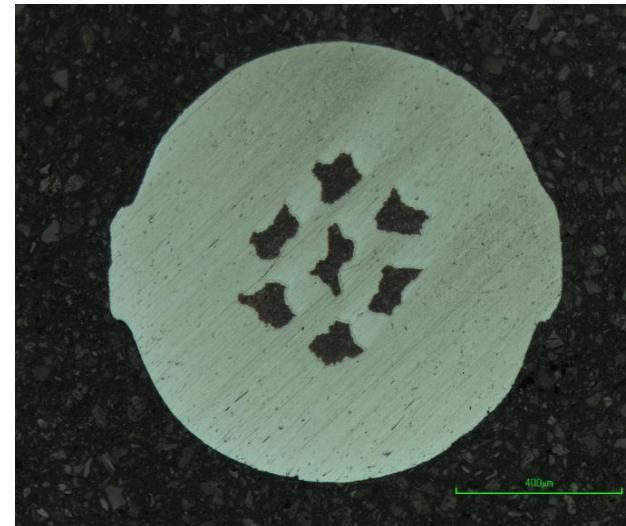
Φ1.0mm

Cross sections of 7-filamentary PIT MgB₂ wires cold worked with swaging and roller drawing(carbon coated B powder)

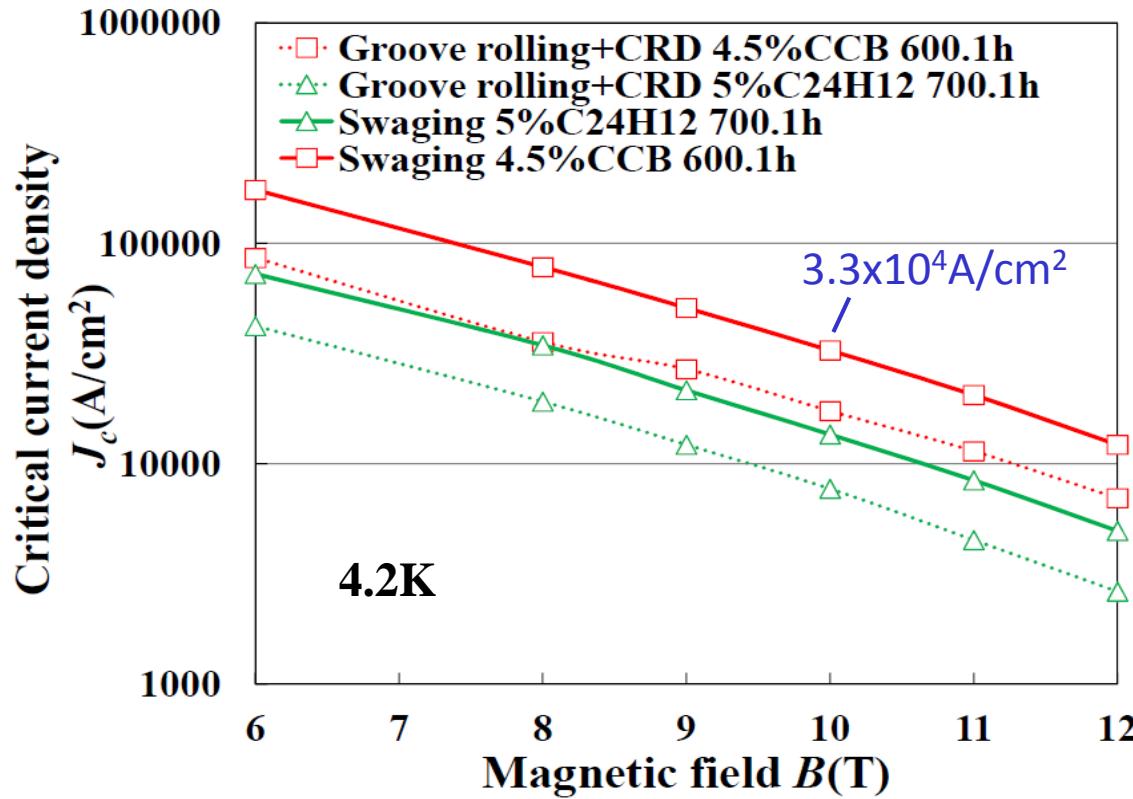
Swaging (600°Cx1hr)



Groove rolling + Roller drawing (600°Cx1hr)



J_c -B curves of PIT MgB₂ 7-filamentary wires



Vickers hardness of MgB₂ filaments

7 filamentary wire, 1.0mm dia.	Wire	HT condition	1	2	3	4	5	Average
	Swaging 4.5%CCB	600	297.0	303.0	308.0	225.0	323.0	302.7
	Swaging 5%C24H12	700	446	360	411	498	NV	405.7
Wire	HT condition	1	2	3	4	5	Average	
Roller Drawing 4.5%CCB	600	208.0	169.0	217.0	165.0	250.0	198.0	
Roller Drawing 5%C24H12	700	313	297	317	332	209	309.0	

Fabrication of 10m class wires by swaging

Fe tube :
Outer dia.: $\Phi 12$
Inner dia.: $\Phi 7$
Length : 100mm

+

4.5%C coated
B powder



Swaging



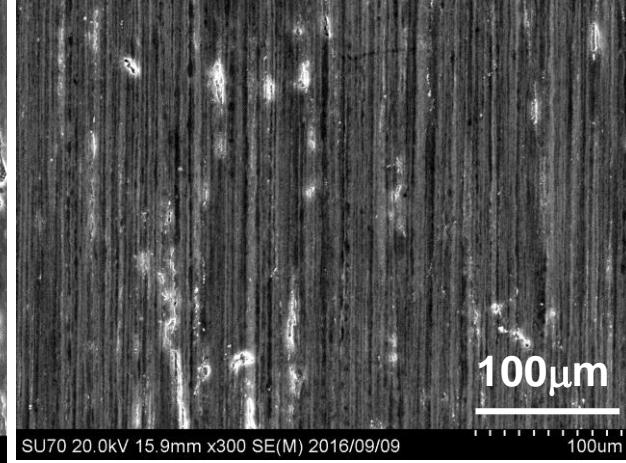
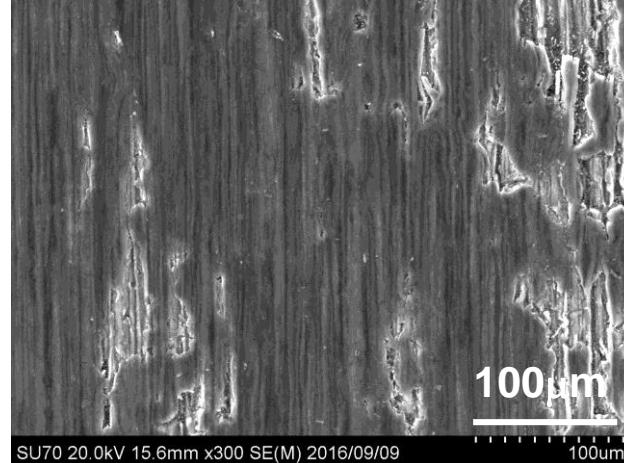
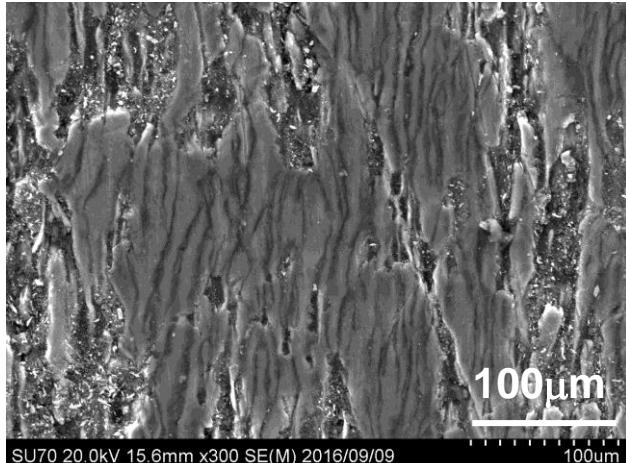
$\sim 2\text{m}$ long wire x 5

Microstructure of Mg-B core(central area)

$\Phi 3.54\text{mm}$

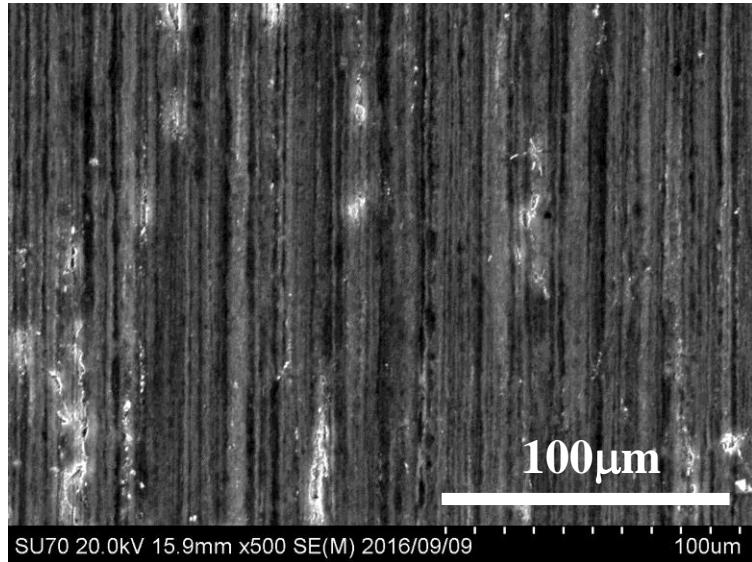
$\Phi 1.61\text{mm}$

$\Phi 1.10\text{mm}$

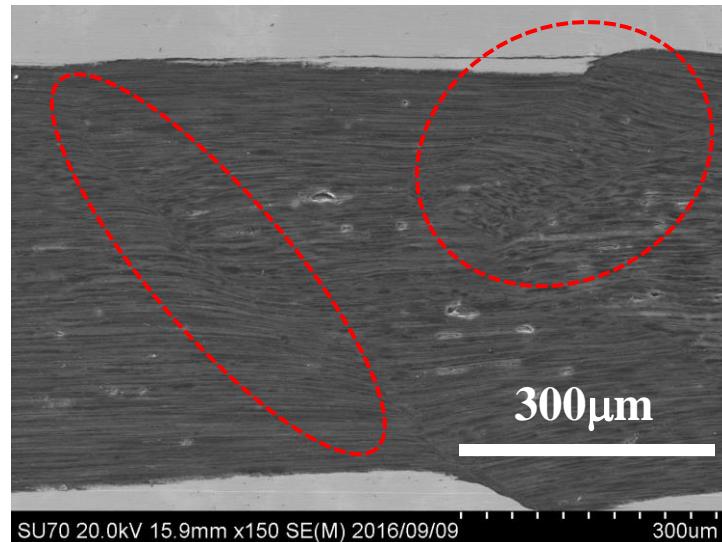


Microstructure of Mg-B(MgB₂) cores for 100% swaging

Before heat treatment(Φ1.1)

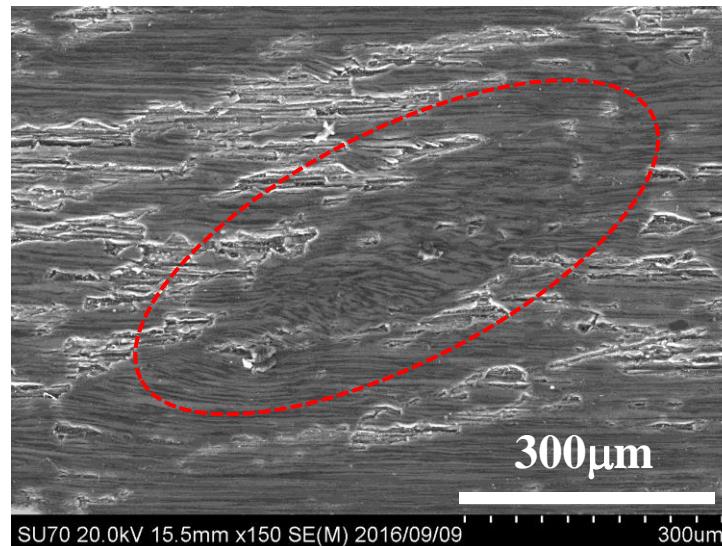


Before heat treatment(Φ1.1)



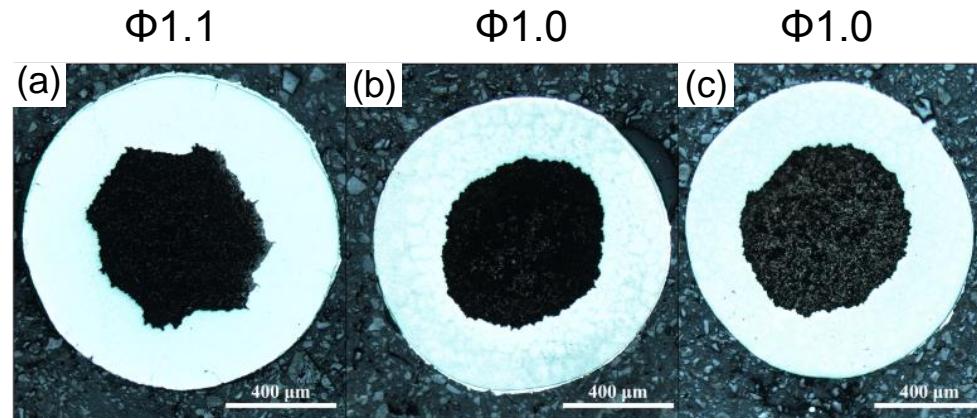
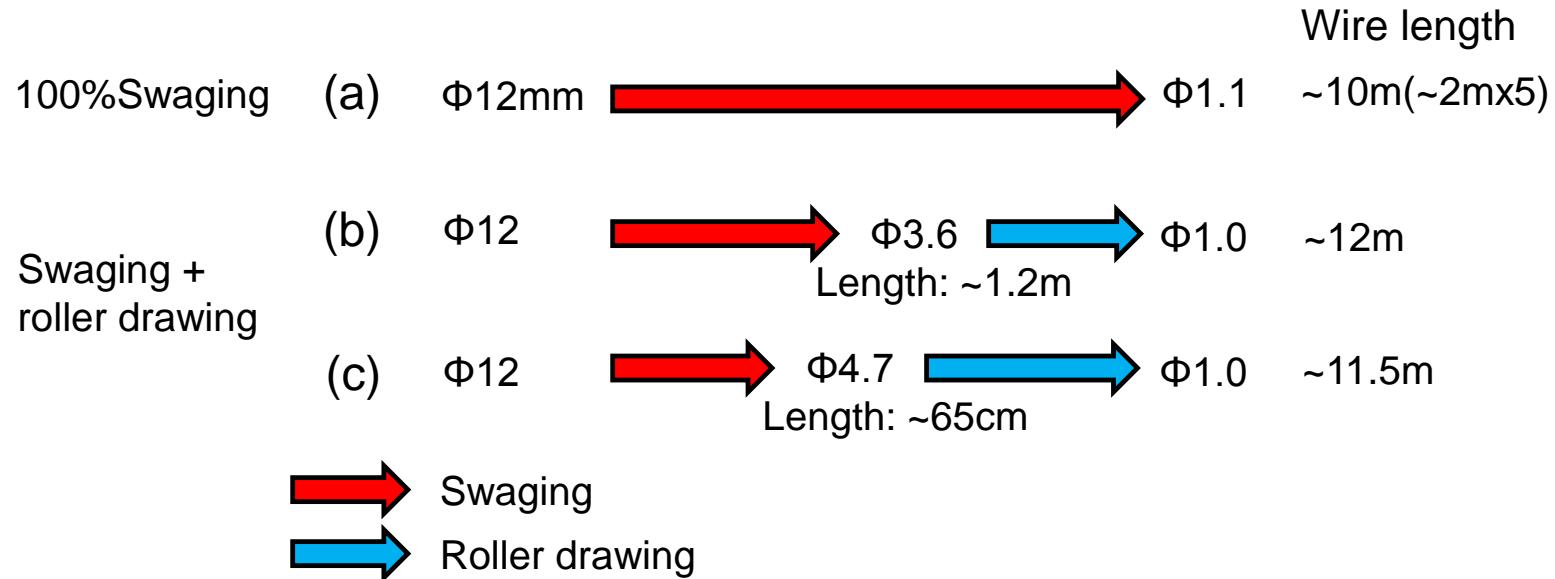
Vickers hardness

	Hv
100% swaging	202
Groove rolling + drawing	156-165



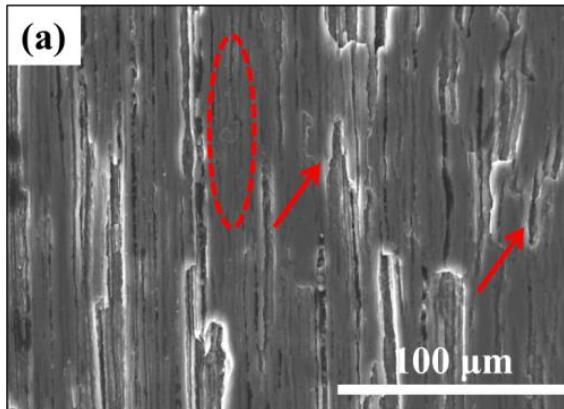
Fabrication of 10m class wires by swaging + roller drawing

Fe tube : Outer dia. $\Phi 12$, inner dia. $\Phi 7$ inner dia., length 100mm

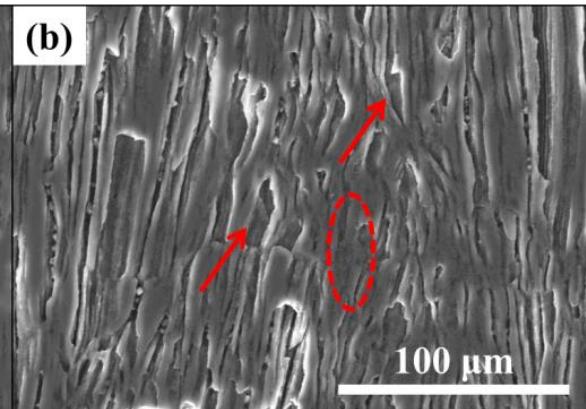


Microstructure of MgB₂ cores after the heat treatment

Swaging
(Φ12 → Φ1.1)

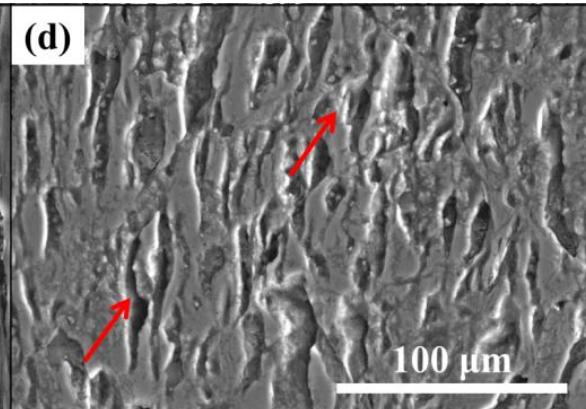
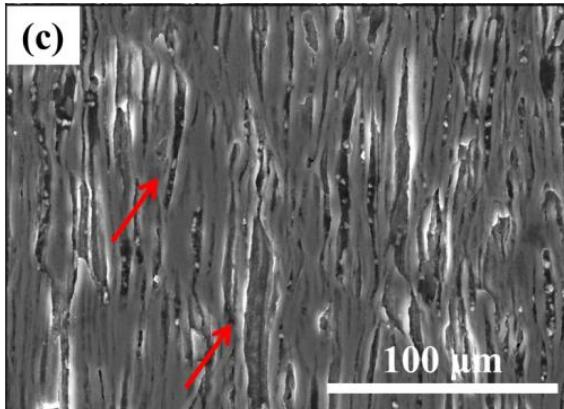


Swaging
(Φ12 → Φ3.6 → Φ1.0)
Drawing



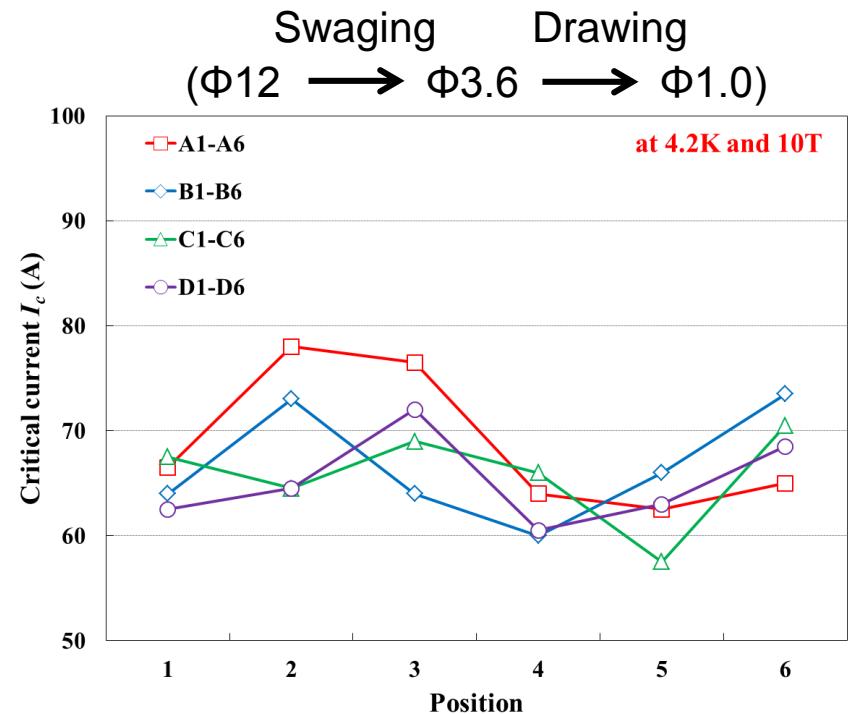
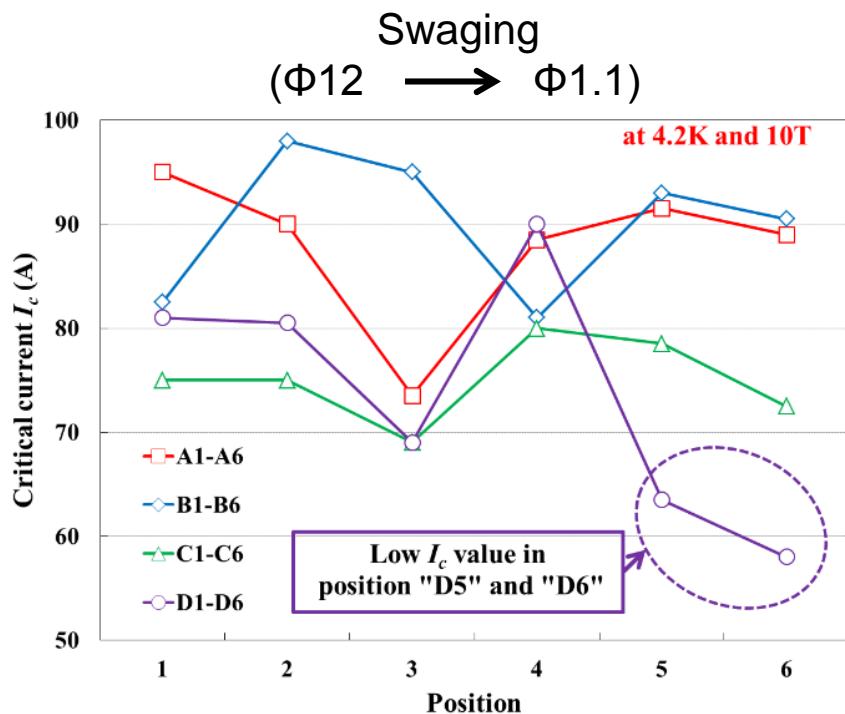
Swaging
(Φ12 → Φ4.7 → Φ1.0)
Drawing

Groove rolling+
roller drawing

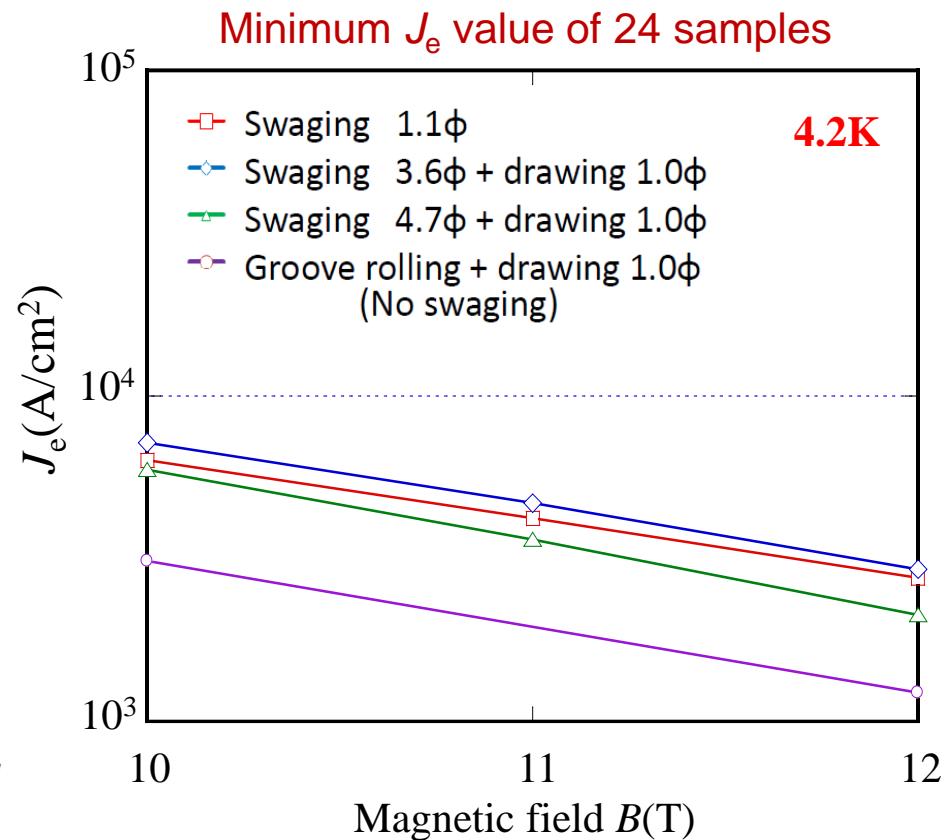
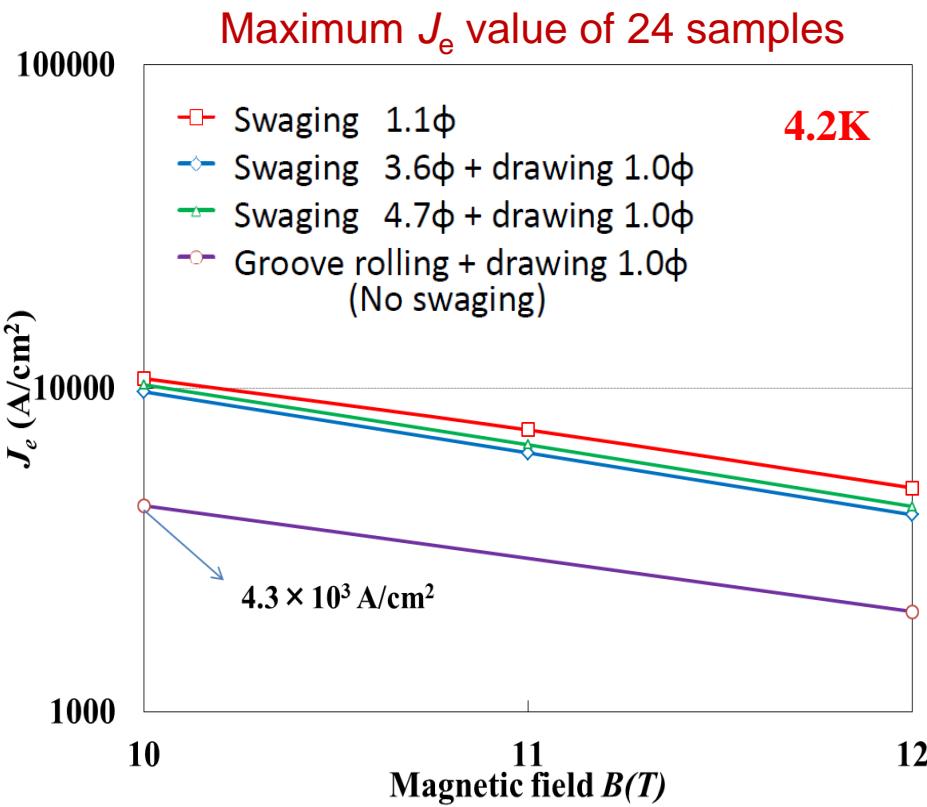


I_c scattering of ~10m long wires

I_c values of 24 short wires sampled from ~10m long wires



J_e -B curves at 4.2K of ~10m long PIT wires

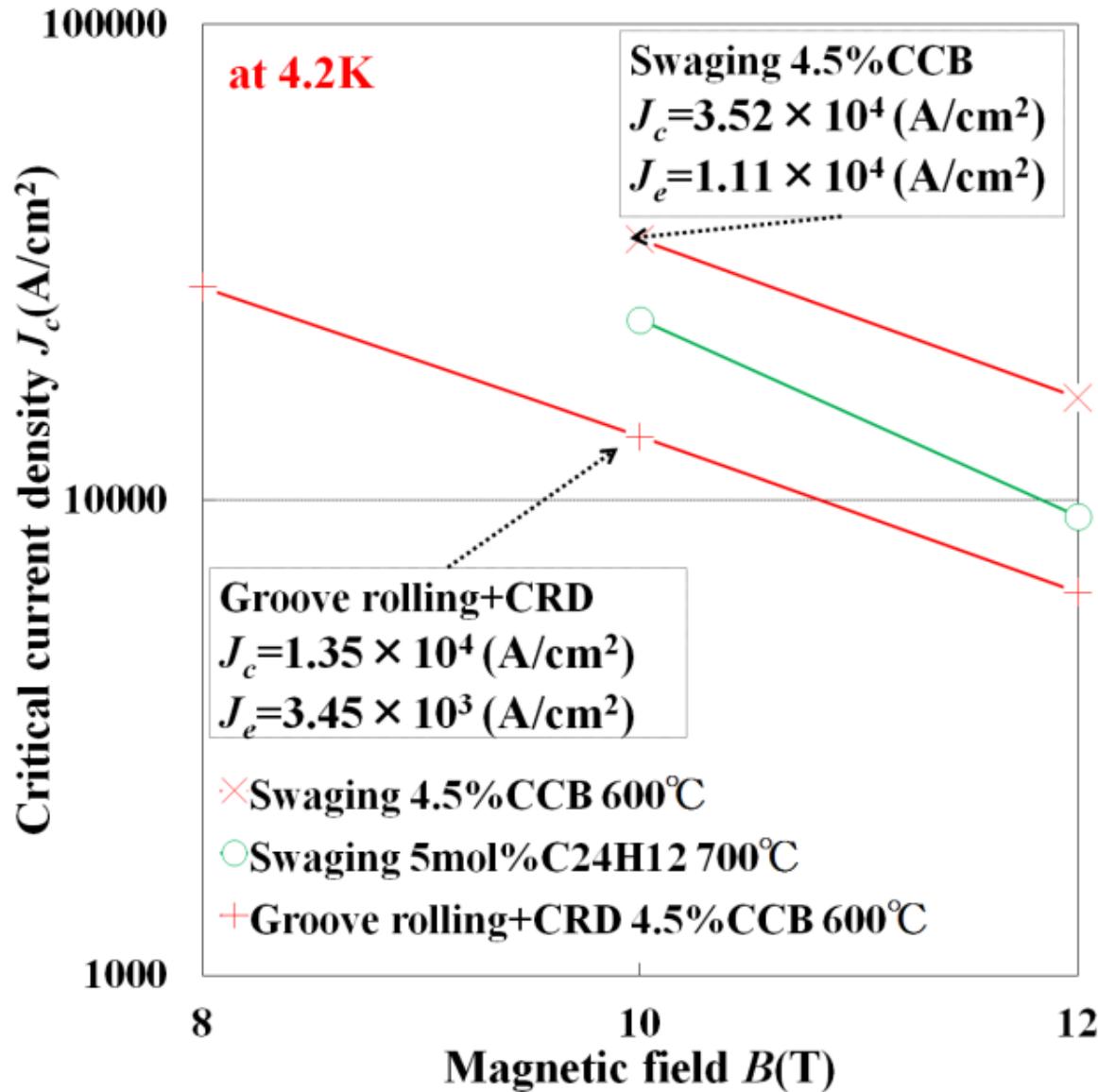


J_c (average) at 4.2K and 10T

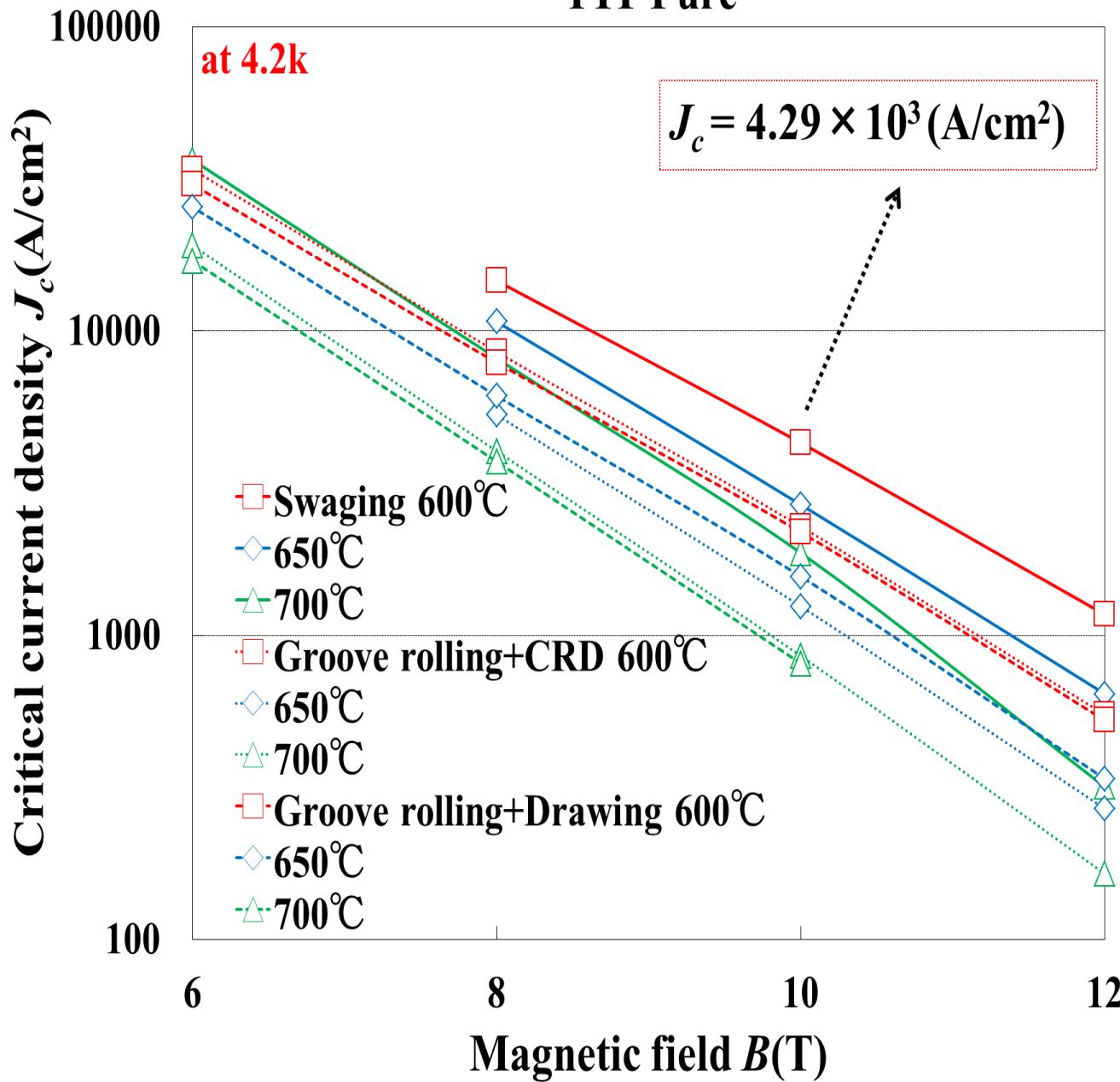
- | | |
|-------------------------------|--|
| $8,600 \text{ A}/\text{cm}^2$ | ◻ Swaging 1.1φ |
| $8,490 \text{ A}/\text{cm}^2$ | ◊ Swaging 3.6φ + drawing 1.0φ |
| $8,550 \text{ A}/\text{cm}^2$ | ▲ Swaging 4.7φ + drawing 1.0φ |
| $3,710 \text{ A}/\text{cm}^2$ | ○ Groove rolling + drawing 1.0φ (No swaging) |

Summary

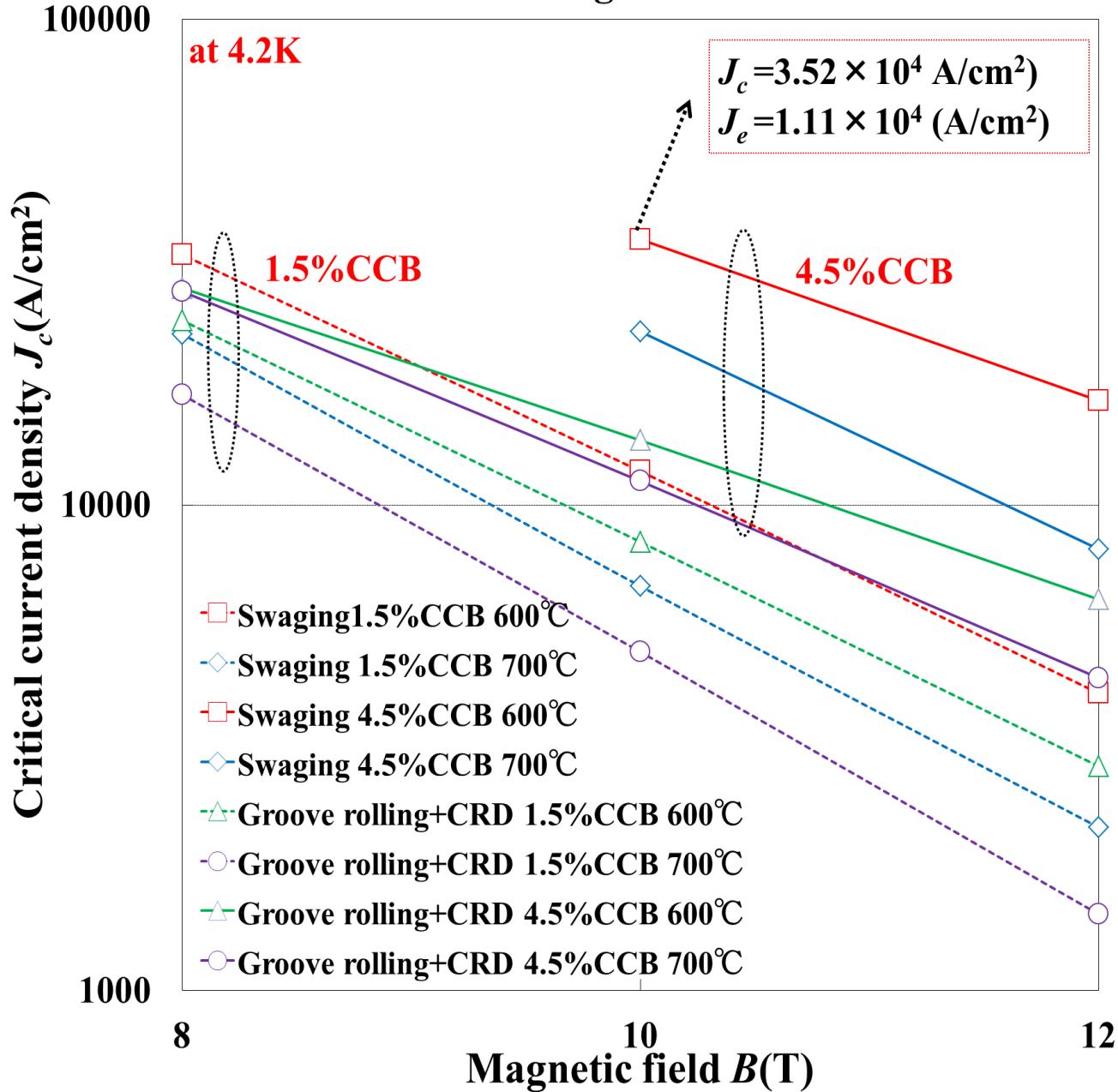
1. Fiber structure of Mg particles are obtained by the wire fabrication with swaging.
2. Vickers hardness of MgB_2 for swaged wire is higher than those of the rolled and drawn wires.
3. These two factors(1. and 2.) increases J_c of the wire.
4. Highest J_c and J_e are $3.5 \times 10^4 \text{ A/cm}^2$ and $1.1 \times 10^4 \text{ A/cm}^2$ at 4.2K and 10T for swaging and C-coated B powder.
5. Microstructure and J_c of 7-filamentary wire is similar to mono-filamentary wire.
6. High degree of cold working by swaging brings about distortion of Mg-B core and large I_c scattering.
7. Combination of swaging and drawing is effective for long wire fabrication.



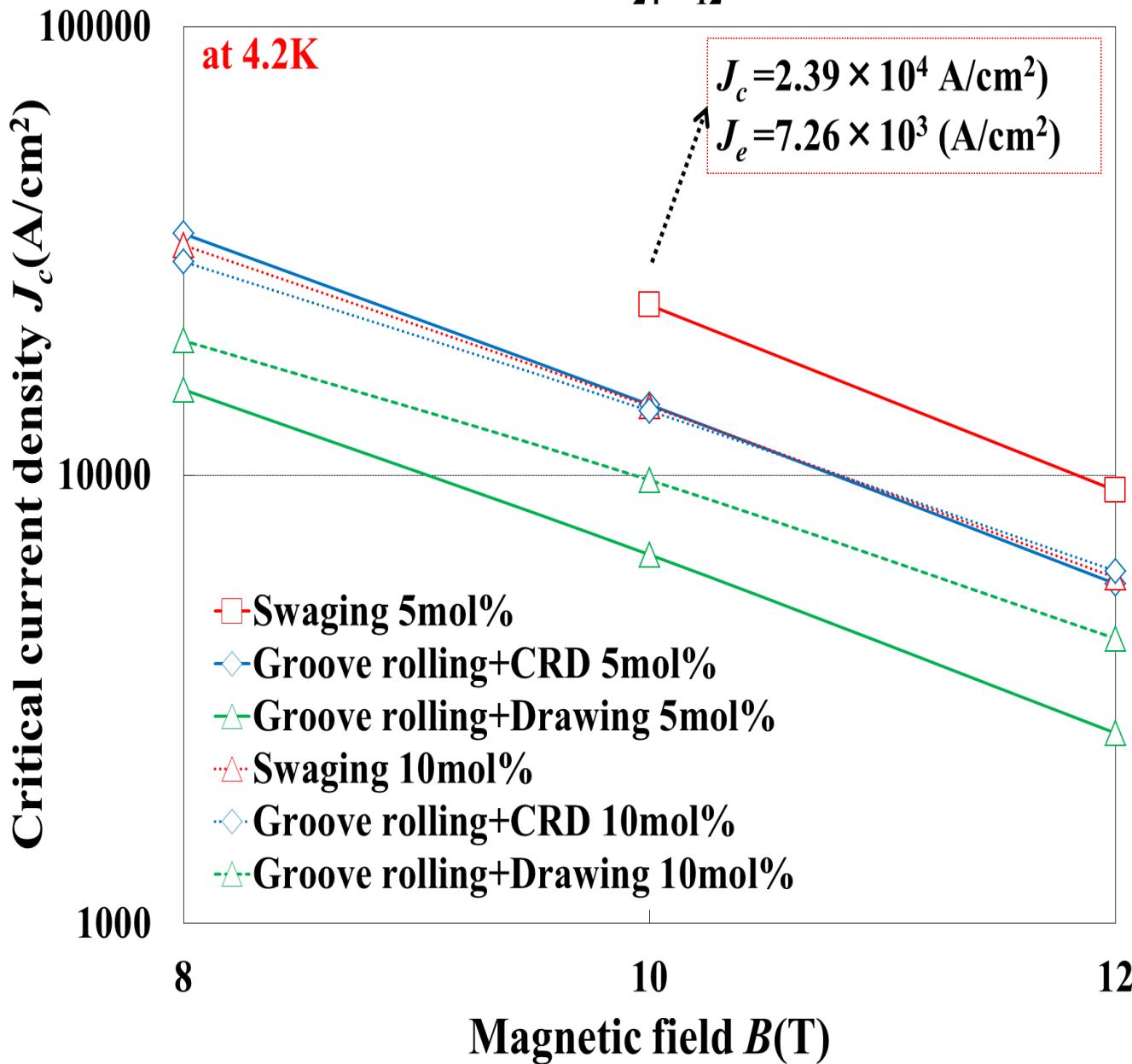
PIT Pure

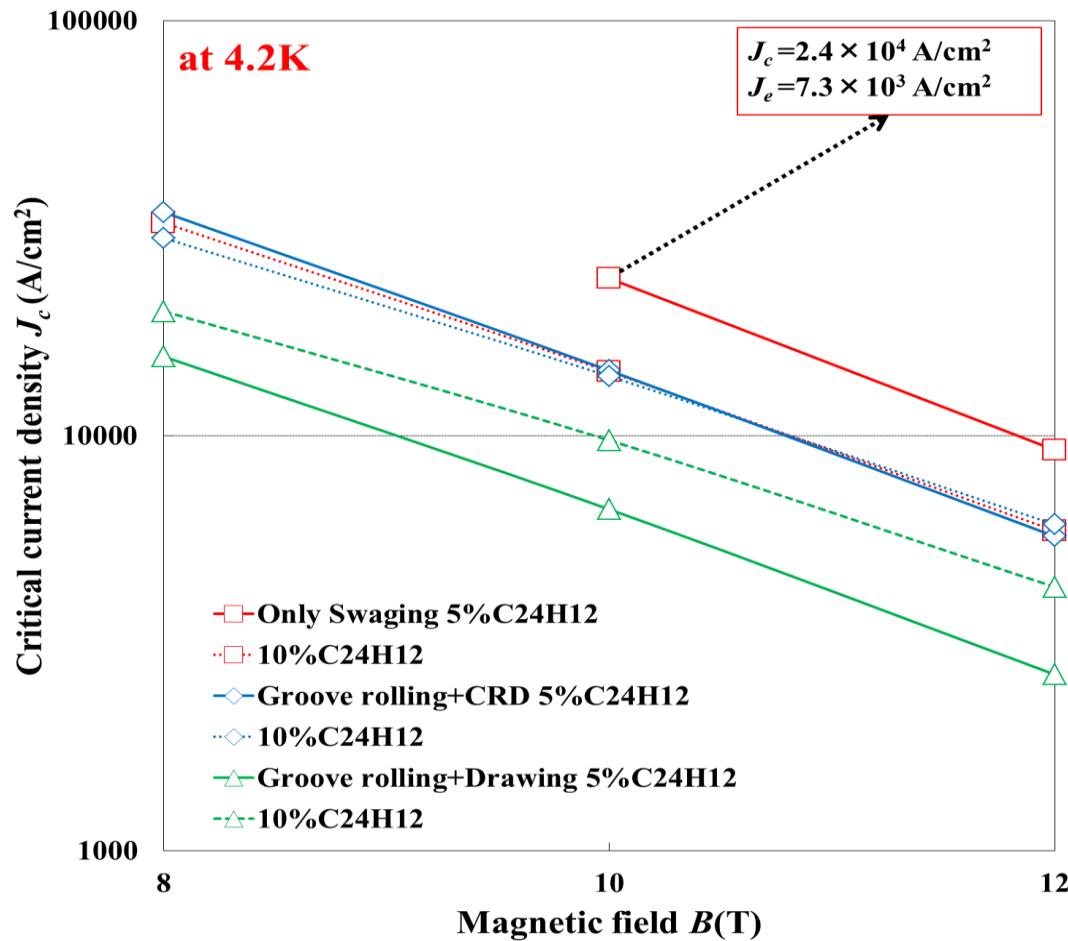


PIT Mg +CCB

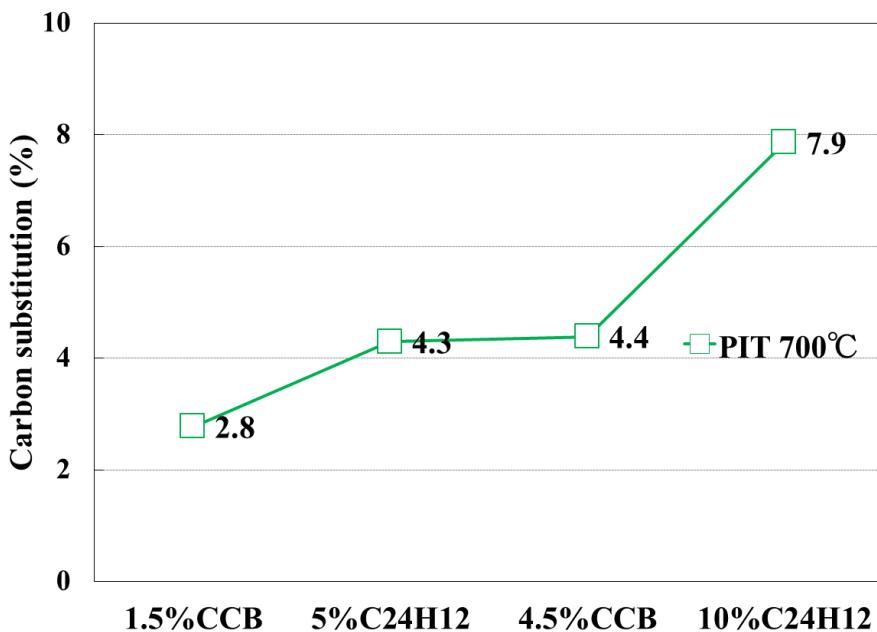


PIT 700°C C₂₄H₁₂ added

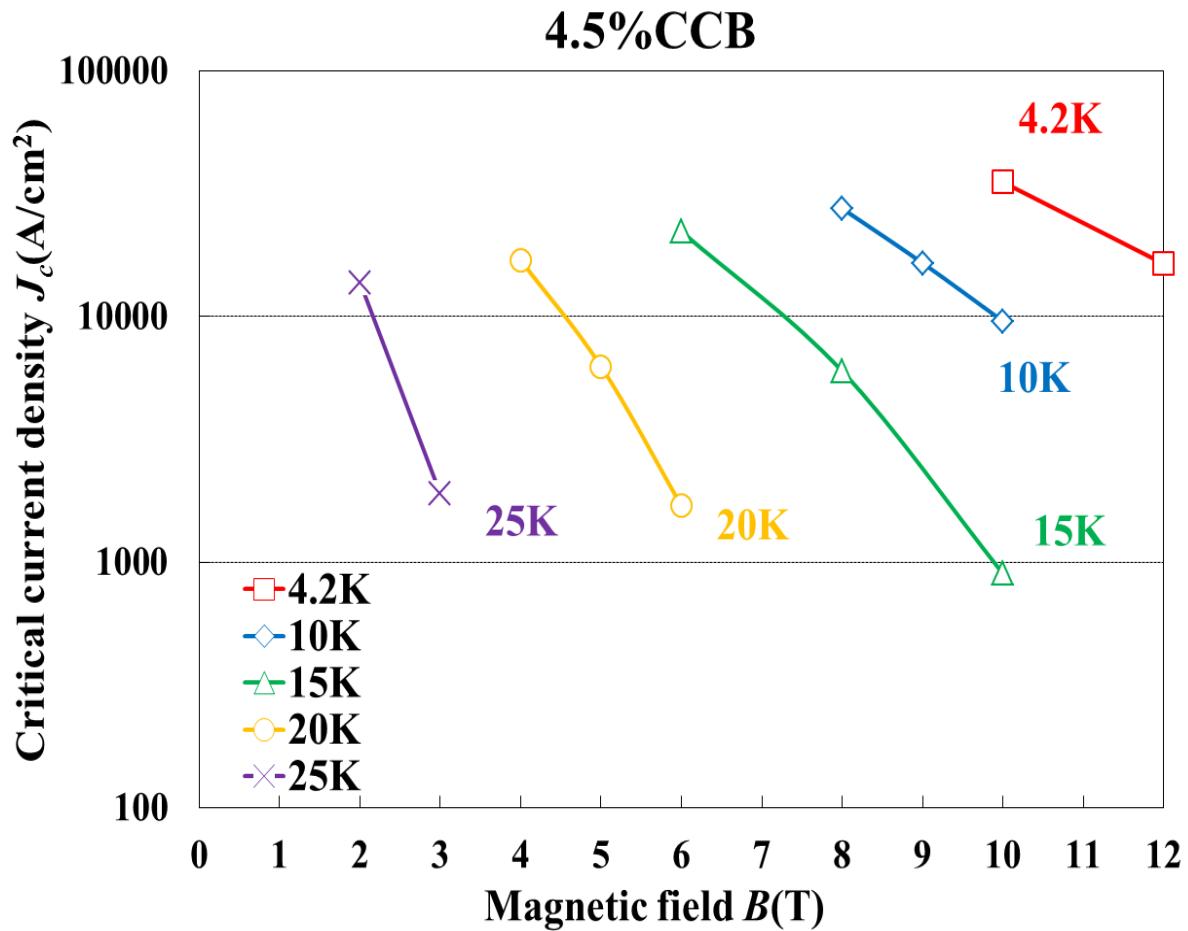




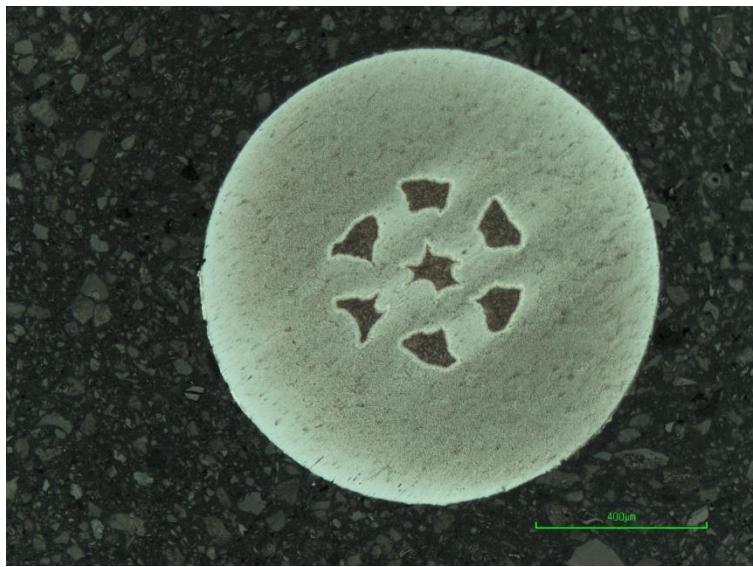
The amount of carbon substitution for B in MgB₂ core for the swaged wires

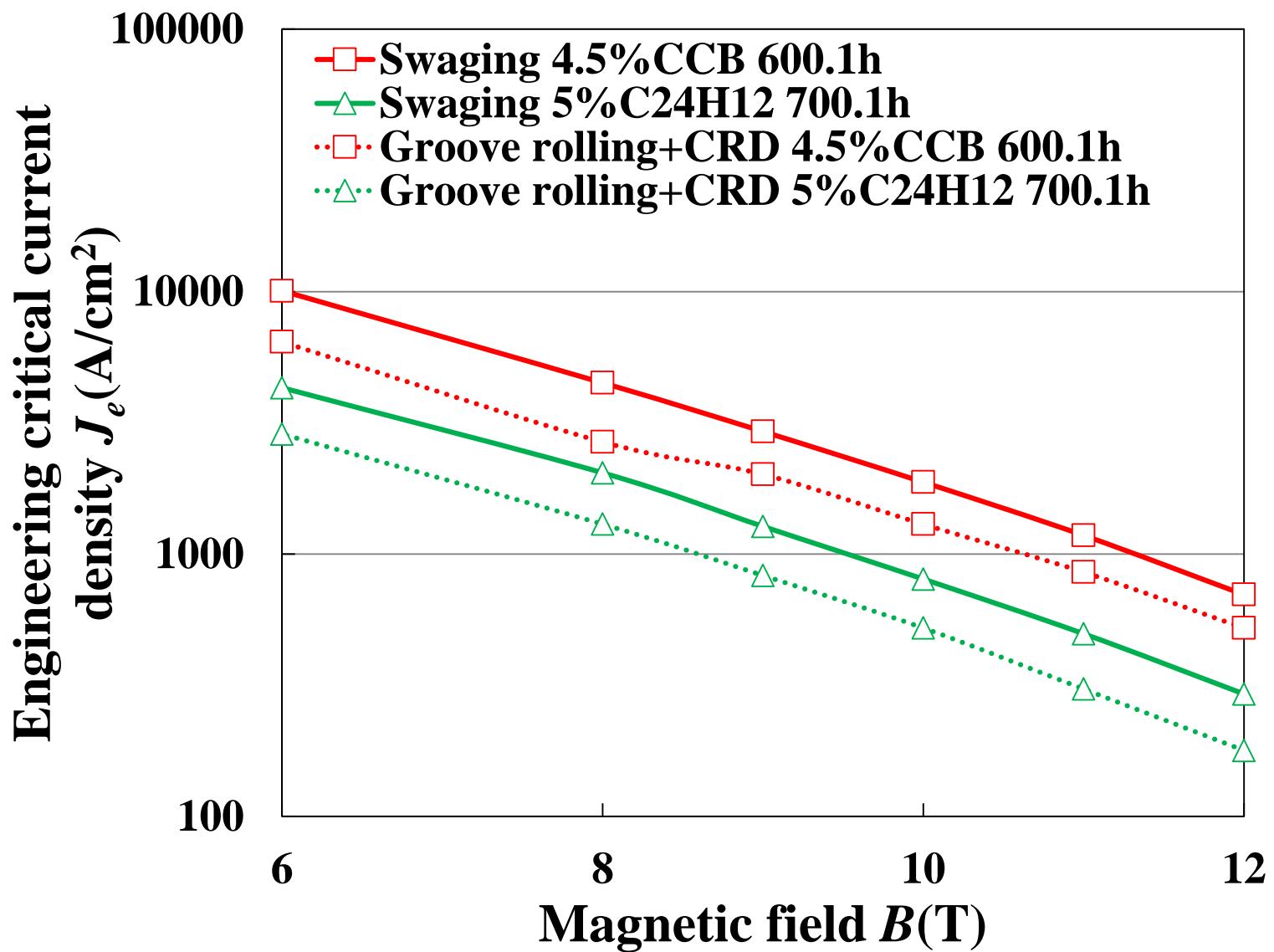


PIT wires 700°C, 1h			
Dopant	a-axis (nm)	c-axis (nm)	T _c ^{onset} (K)
Pure	0.3103	0.3553	37.1
1.5%CCB	0.3097	0.3544	35.6
4.5%CCB	0.3094	0.3545	32.8
5%C ₂₄ H ₁₂	0.3094	0.3556	32.3
10%C ₂₄ H ₁₂	0.3087	0.3551	31.6

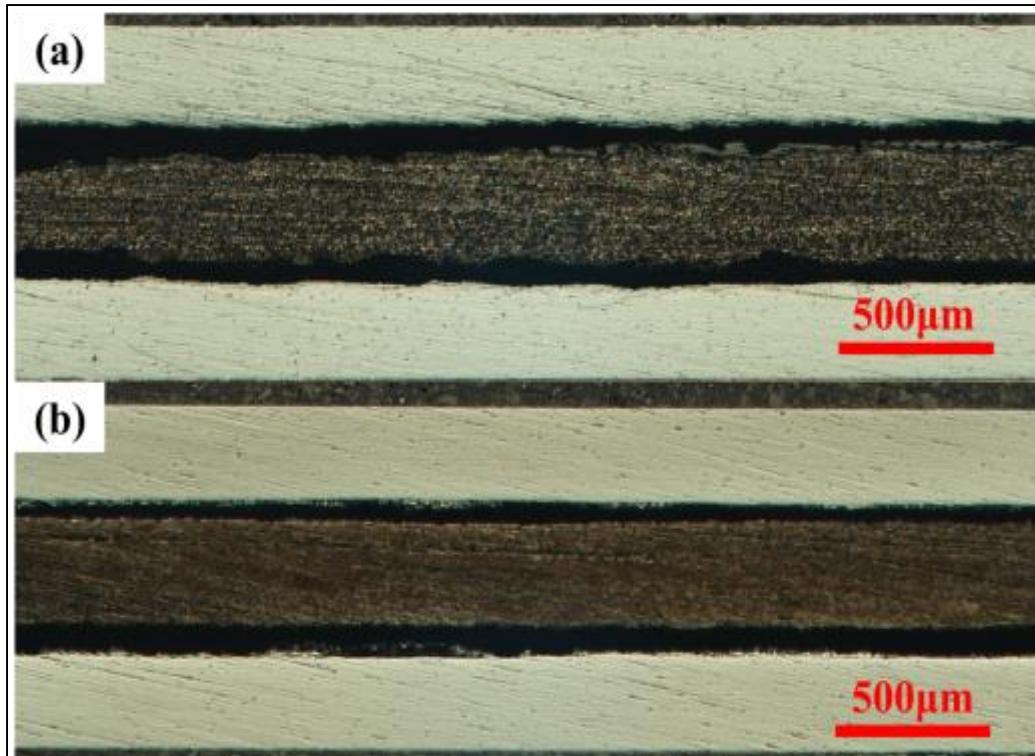


swa C24H12 700C rod17





Internal Mg diffusion(IMD) processed wires



Swaging

Groove rolling +
roller drawing