

Fabrication of high-performance HREE-free hot-deformed Nd-Fe-B magnets

*Ryosuke Goto, Fumiaki Kihara, Takashi Oikawa, Hiroshi Miyawaki

Corporate Research & Development Center,
Daido Steel Co., Ltd.



Background: About us

Company name	<i>Daido Steel Co., Ltd.</i>
Head office location	Nagoya, Japan
Founded	August 19 th , 1916
Number of employees	12,054 (consolidated) 3,347 (non-consolidated)
Net sales	FY2024: JPY 574.945 billion (consolidated) JPY 385.260 billion (non-consolidated) Approx. USD3.9 billion USD2.6 billion
Common stock	JPY 37,172 million



Anisotropic hot-deformed magnet (Nd-Fe-B)

Features

- Heavy Rare Earth Free
- High heat resistance
- Radially oriented

- Ring shape
- Plate / Arc shape

Application

Traction motors of HEV
EPS, AC servo

Isotropic Bonded magnet (Nd-Fe-B, Sm-Fe-N)

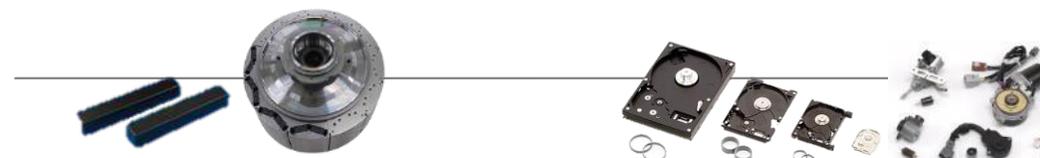
Features

- Free-form
- Various sub-assemblies

- Compression molding
- Injection molding

Application

HDD motor
Sensors for automobile



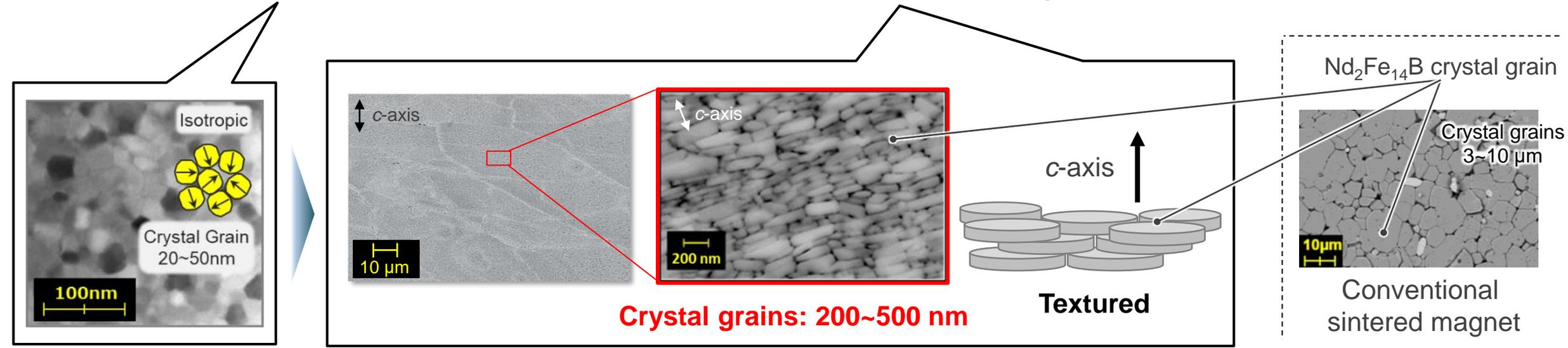
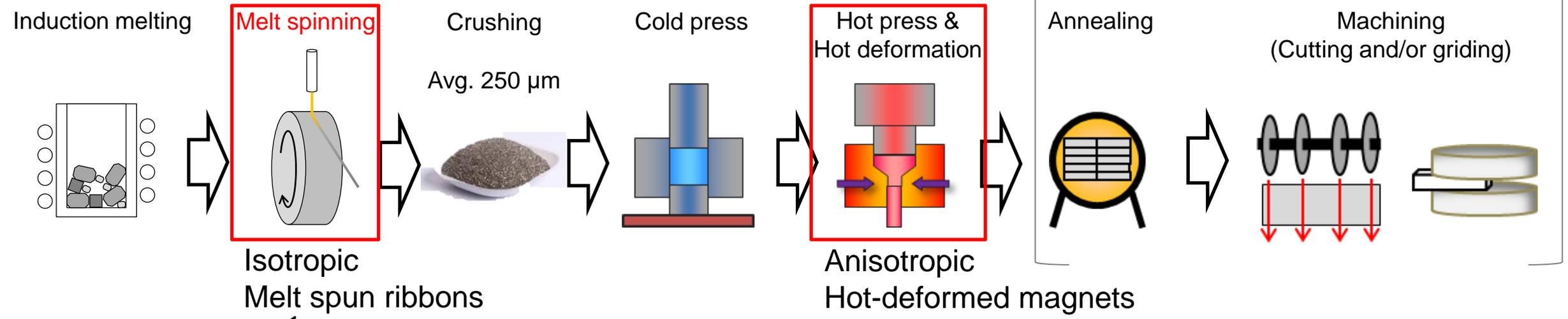
<https://www.daido.co.jp/en/>

Segment	Share of net sales
Specialty steels	38 %
High-performance materials & Magnetic materials	35 %
Parts for automobile & Industrial equipment	18 %
Engineering	4 %

Background: Hot-deformed magnets

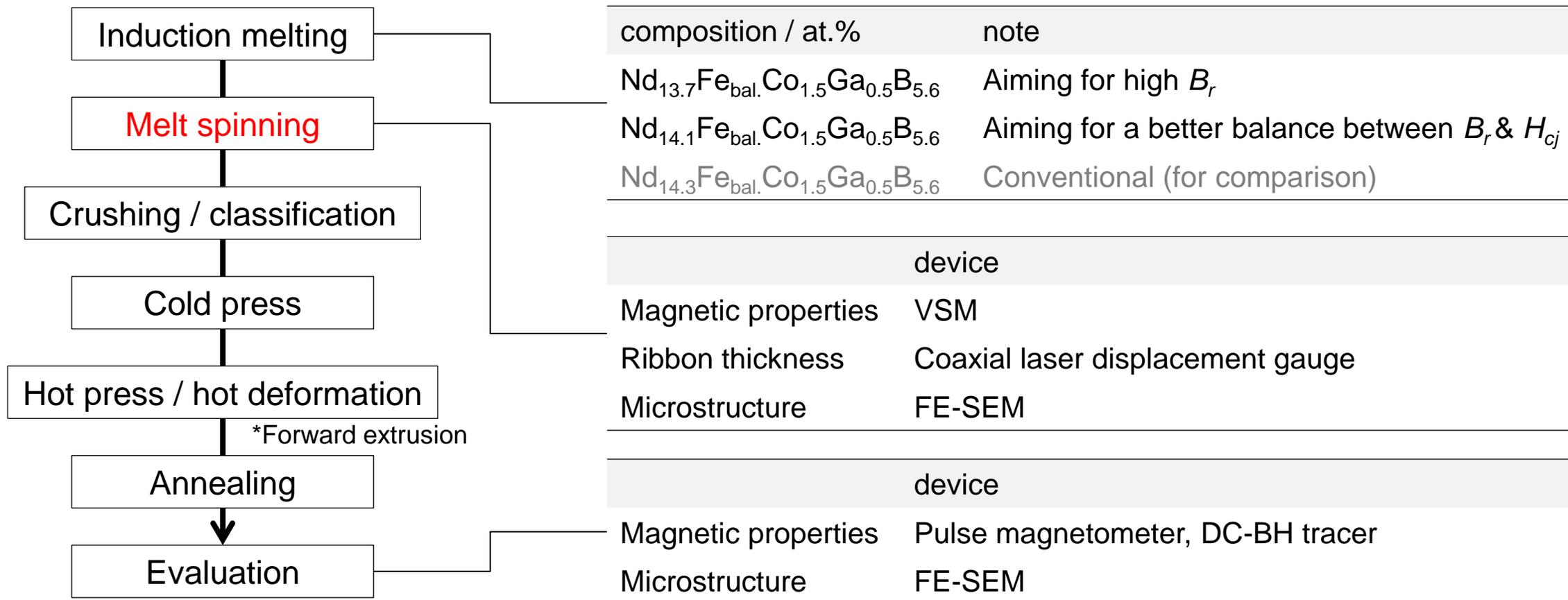
✓ Melt spinning and hot press / hot deformation processes are critical to the performance of the magnets.

Production process of hot-deformed magnets



Objective and Experimental procedure

✓ Improve magnetic properties of hot-deformed magnets without heavy rare earth elements.



Experiments: Optimization of melt spinning process

✓ Nozzle diameter (d_n), wheel speed (u) and differential pressure (ΔP) were optimized.

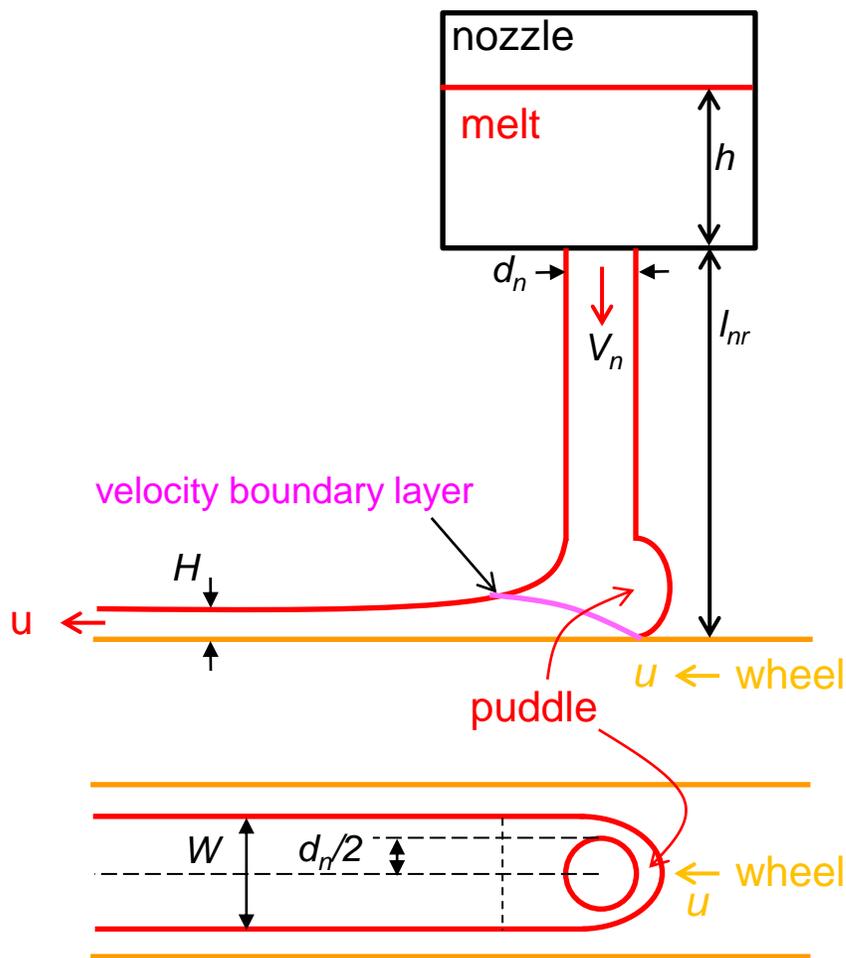


Fig . Schematic image of melt spinning

From flow balance conservation,

$$Q = H \cdot W \cdot u \quad \dots (1)$$

where, melt flow rate Q [m^3/s] is
(Cross-sectional area of orifice, A) \times (Velocity of melt, V_n)

$$Q = A \cdot V_n = \frac{\pi d_n^2}{4} \cdot V_n \quad \dots (2)$$

$$V_n = c_v \sqrt{\frac{2\Delta P}{\rho} + 2gh} \quad \dots (3)$$

From equation (1) and (2), Thickness of ribbon H is

$$H = \frac{\pi d_n^2}{4uW} c_v \sqrt{\frac{2\Delta P}{\rho} + 2gh} \quad \dots (4)$$

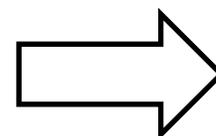
- Q : melt flow rate (m^3/s)
- H : thickness of ribbon (m)
- W : width of ribbon (m)
- u : wheel speed (m/s)
- A : cross-sectional area of orifice (m^2)
- V_n : velocity of melt (m/s)
- d_n : nozzle diameter (m)
- c_v : velocity constant (-)
- ΔP : differential pressure (Pa)
- ρ : melt density (kg/m^3)
- g : gravitational acceleration (m/s^2)
- h : height of melt surface (m)

[2] K. Miyazawa and T. Choh, *J. Japan Inst. Metals*, **47**, 8 (1983), pp. 717-723

Results: Magnetic properties of Nd-Fe-B melt spun ribbons

✓ Quenching state was changed by melt spinning conditions

- **Optimized** : finer and more homogeneous grains
- **Over quenched** : Partially amorphous
- **Under quenched** : Coarse grains



Thickness and its deviation can be controlled by optimized melt spinning

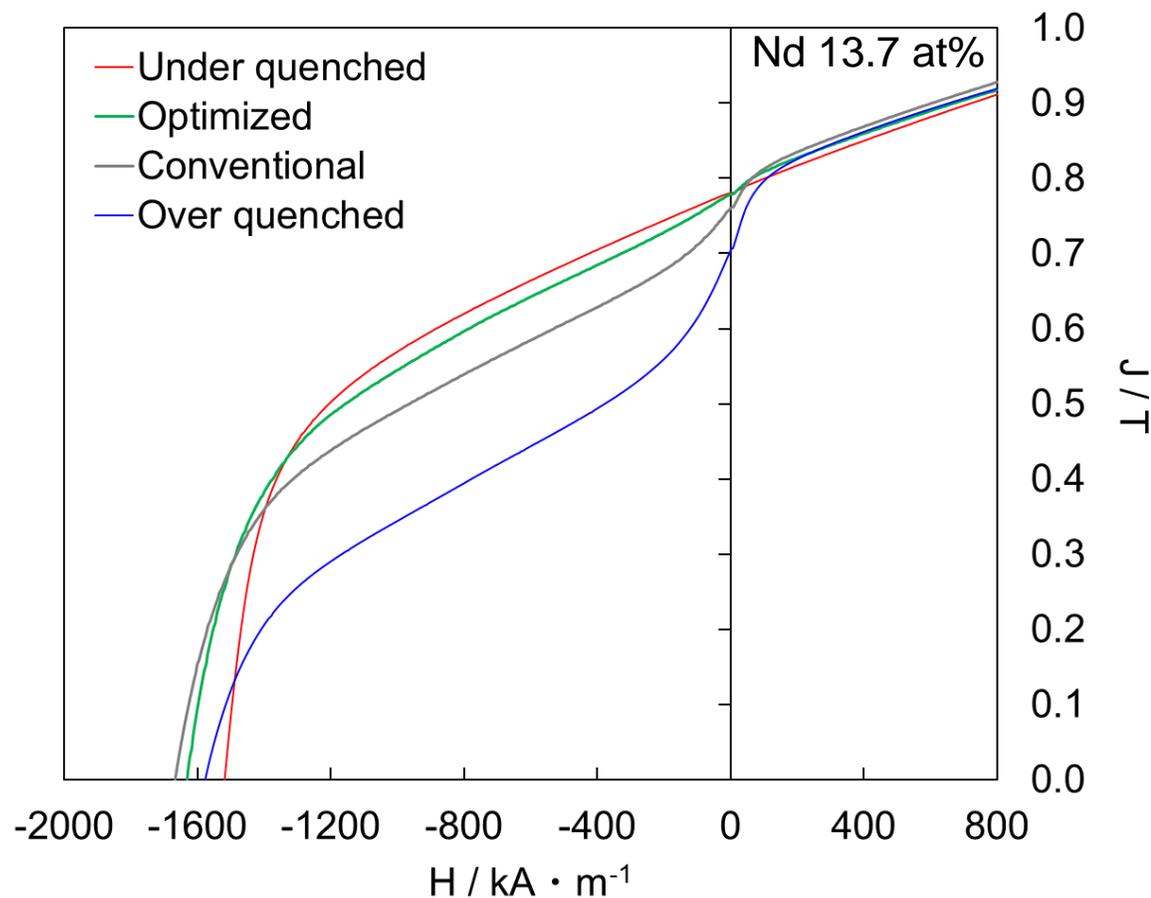


Fig . Demagnetization curves of melt spun ribbons

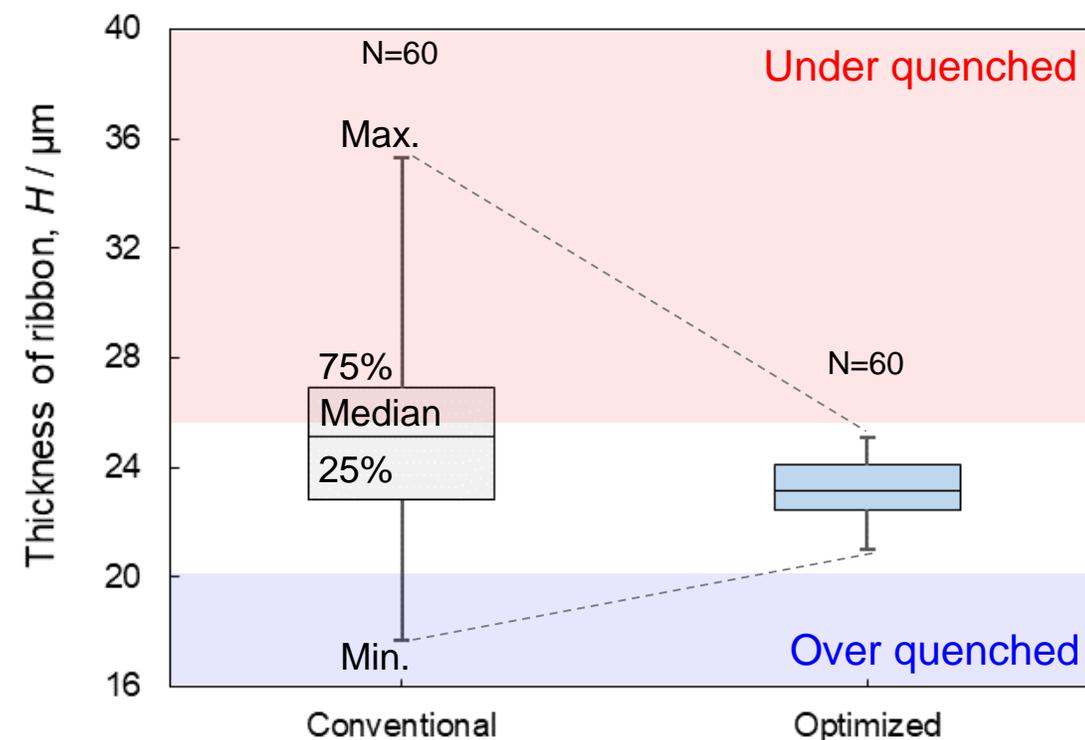
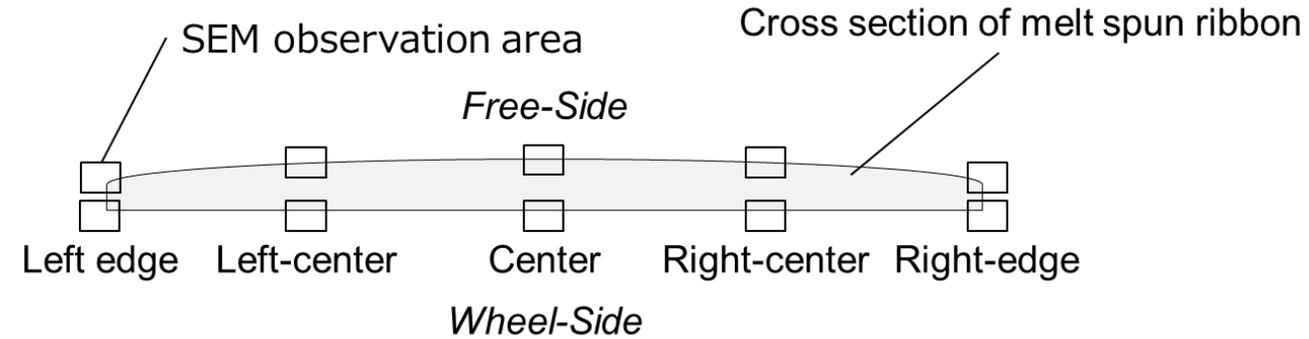


Fig .Thickness of melt spun ribbons

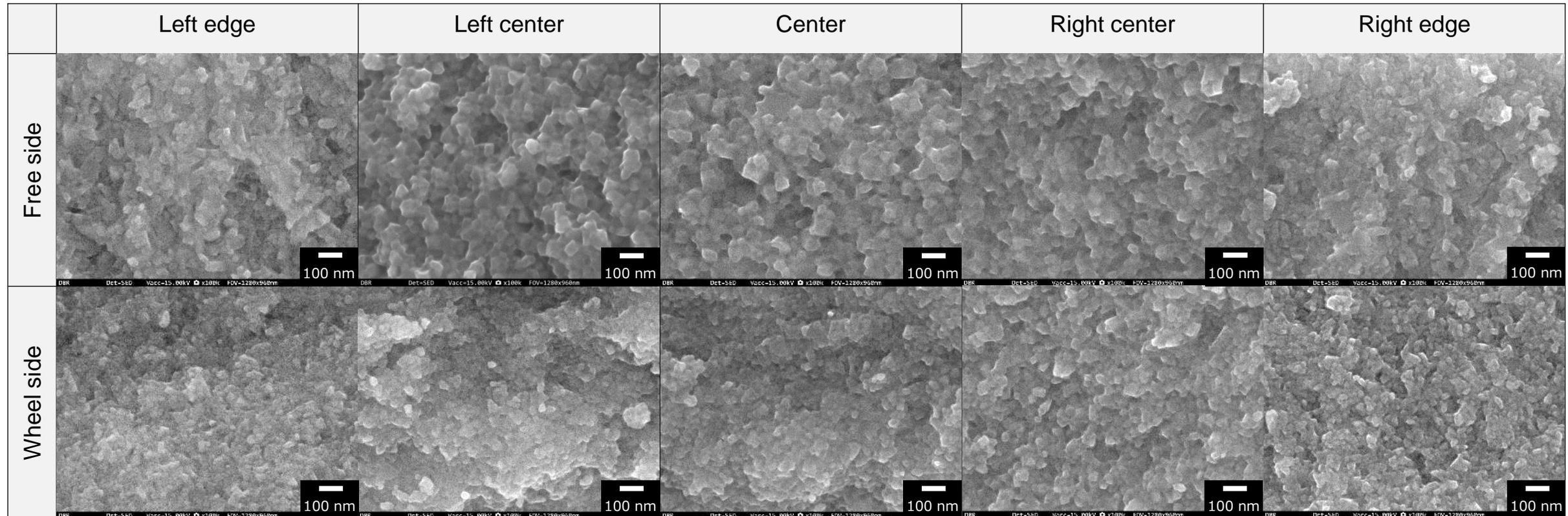
Results: Microstructure of Nd-Fe-B melt spun ribbons

Grain size measurement of melt spun ribbons

- ✓ Photos of 10 positions in fractured surface
- ✓ Grain identification by CNN (U-Net)
- ✓ Calculate the circle equivalent diameter of grains

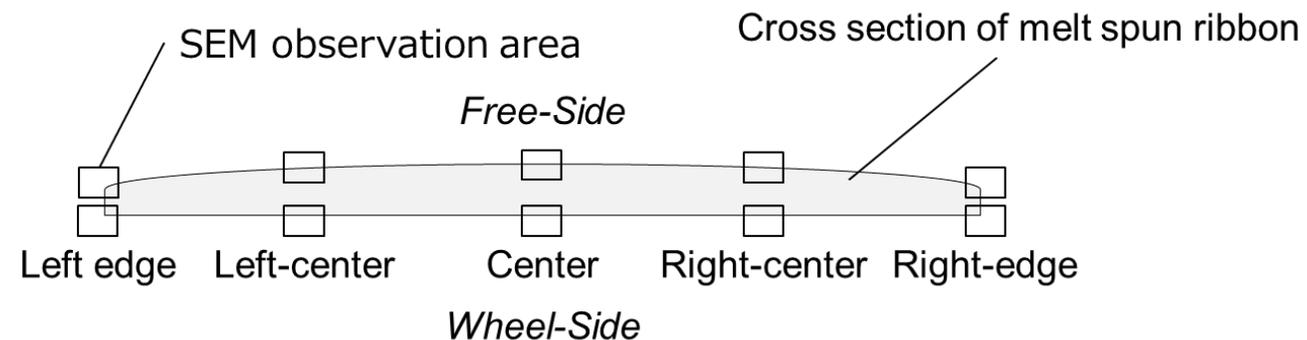


Conventional

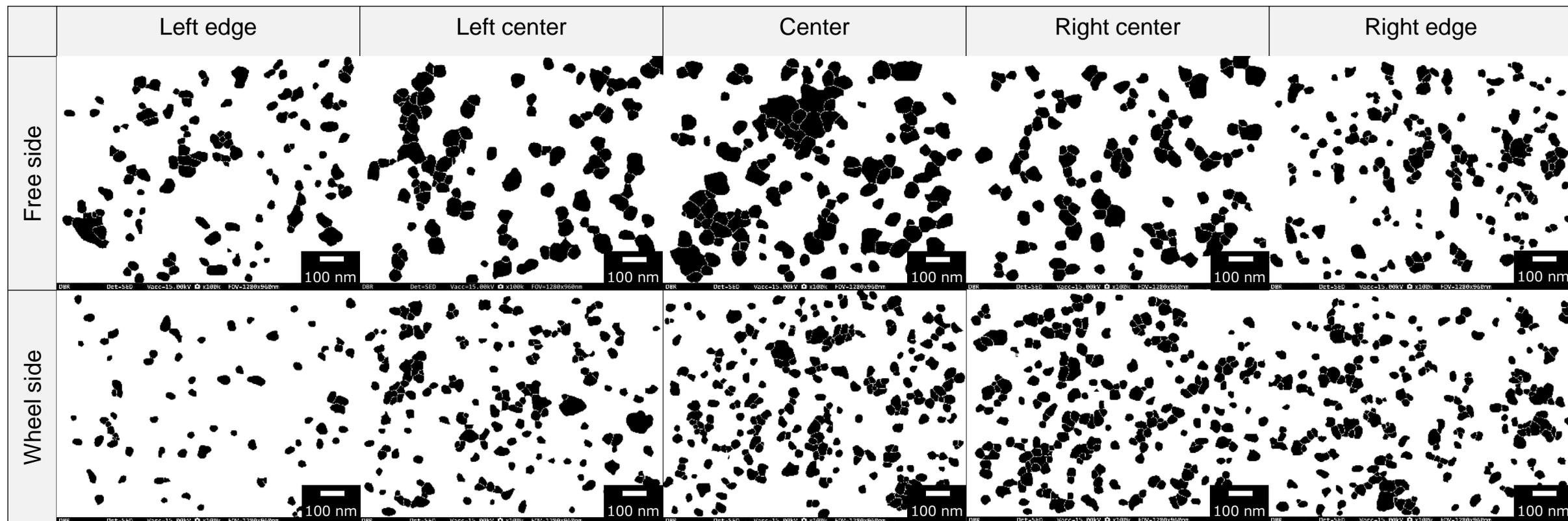


Grain size measurement of melt spun ribbons

- ✓ Photos of 10 positions in fractured surface
- ✓ Grain identification by CNN (U-Net)
- ✓ Calculate the circle equivalent diameter of grains



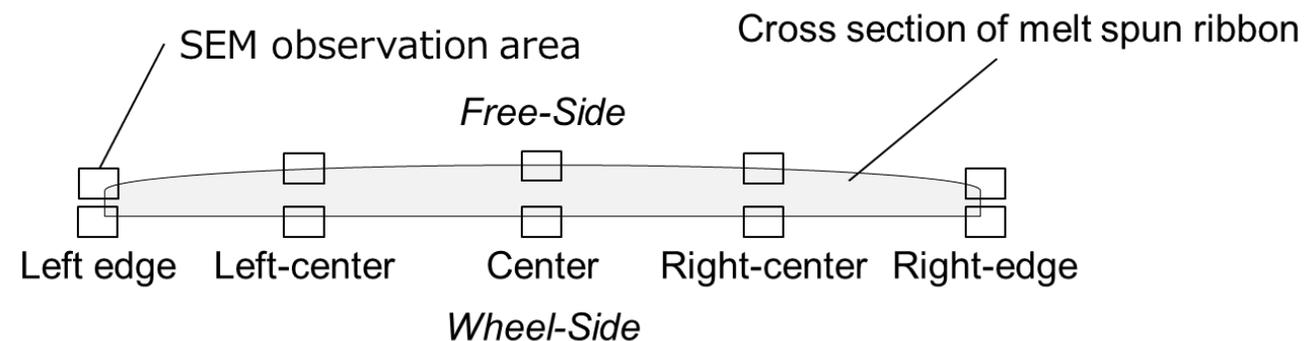
Conventional



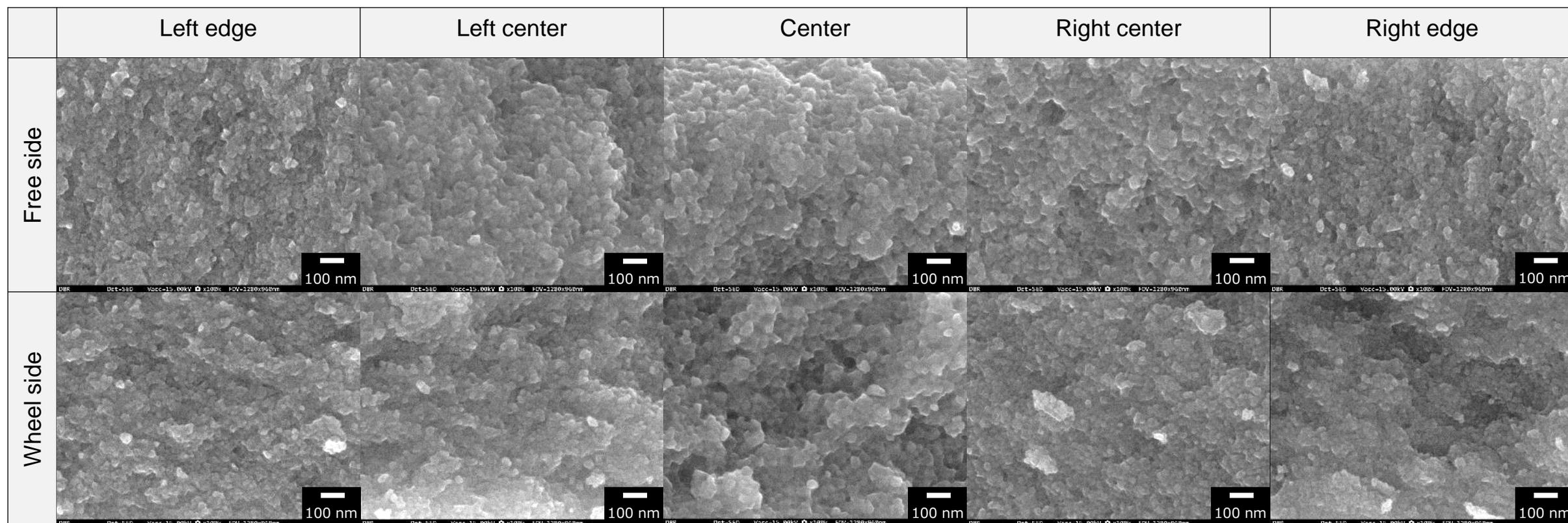
Results: Microstructure of Nd-Fe-B melt spun ribbons

Grain size measurement of melt spun ribbons

- ✓ Photos of 10 positions in fractured surface
- ✓ Grain identification by CNN (U-Net)
- ✓ Calculate the circle equivalent diameter of grains



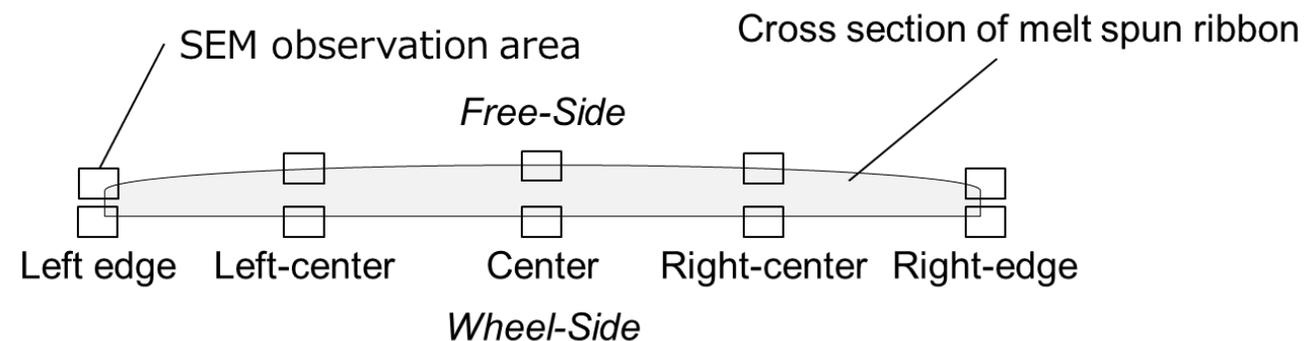
Optimized



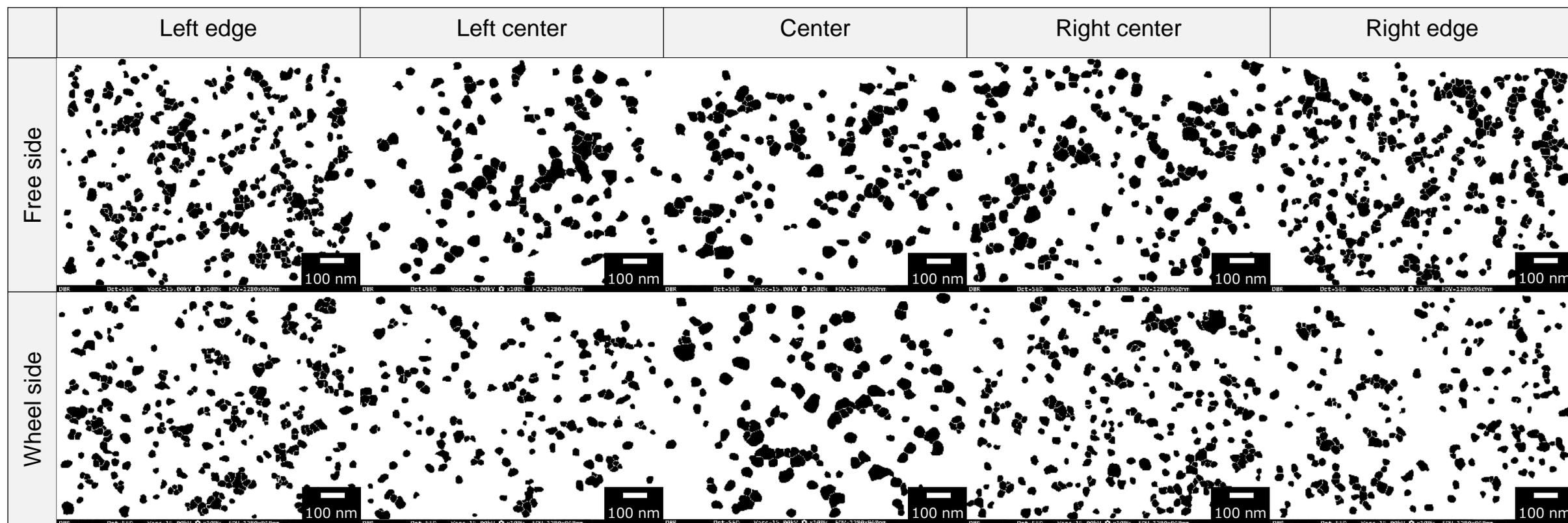
Results: Microstructure of Nd-Fe-B melt spun ribbons

Grain size measurement of melt spun ribbons

- ✓ Photos of 10 positions in fractured surface
- ✓ Grain identification by CNN (U-Net)
- ✓ Calculate the circle equivalent diameter of grains



Optimized



Results: Microstructure of Nd-Fe-B melt spun ribbons

- ✓ The grain size was finer on both the wheel and free side of the optimized ribbon.
- ✓ Average grain size of the ribbons was 45nm in conventional ribbons, and 37 nm in optimized one.

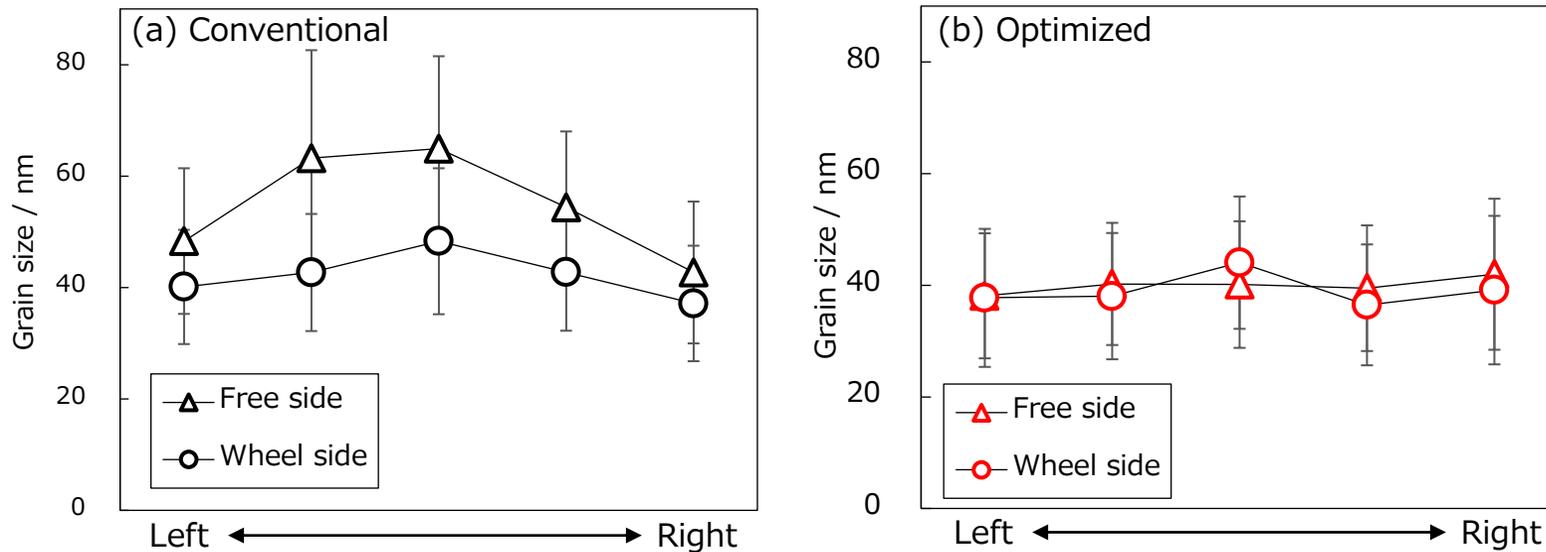


Fig . Grain size of melt spun ribbons (a) conventional and (b) optimized ribbon

Table. Average grains size of melt spun ribbons

	Conventional	Optimized
Average grain size	45 nm	37 nm
Standard deviation, σ	15.1	11.8

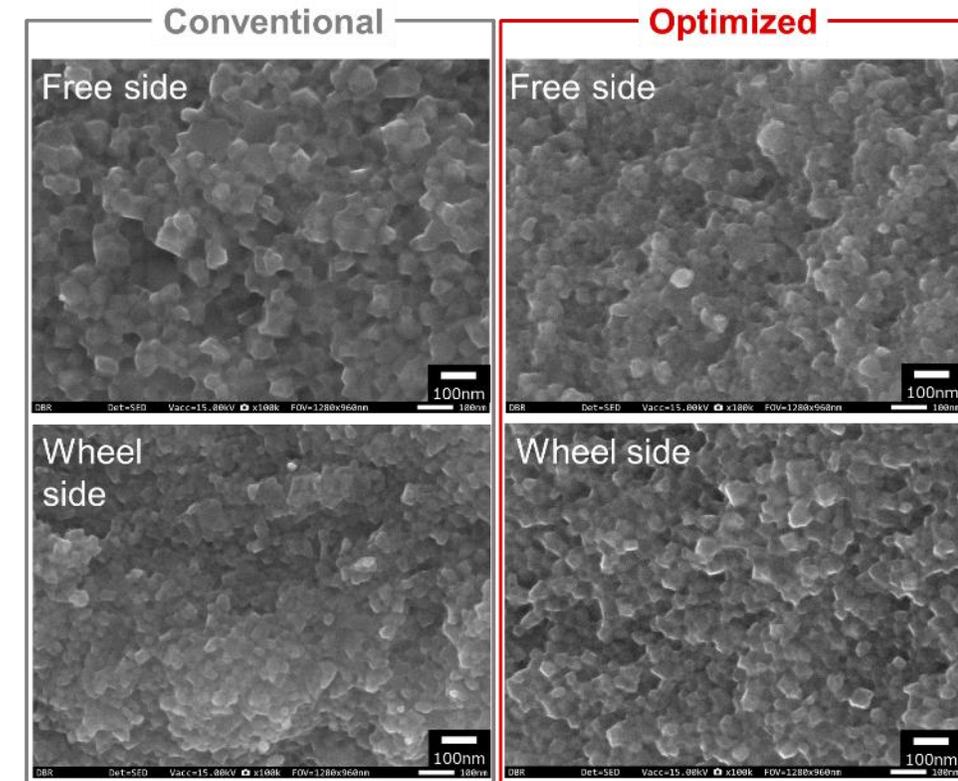


Fig. SEM images of fractured surface of melt spun ribbons (center)

Results: Magnetic properties of hot-deformed Nd-Fe-B magnets

- ✓ Optimized hot-deformed magnets show a good temperature coefficient of coercivity β .
- ✓ Remanence +6% or Coercivity +14% due to the optimization of melt spinning.

Nd -1.0 wt.%

Nd -0.4 wt.%

$$\beta = \frac{H_{cj}(23^\circ\text{C}) - H_{cj}(150^\circ\text{C})}{(23^\circ\text{C} - 150^\circ\text{C})} \times \frac{100}{H_{cj}(23^\circ\text{C})}$$

		Hcj [kA/m]		β [%/K]
		23	150	150
Hot-deformed HRE Free		1725	720	-0.458
Sintered	w/ Dy	1873	648	-0.515
	w/ Tb	1935	668	-0.516

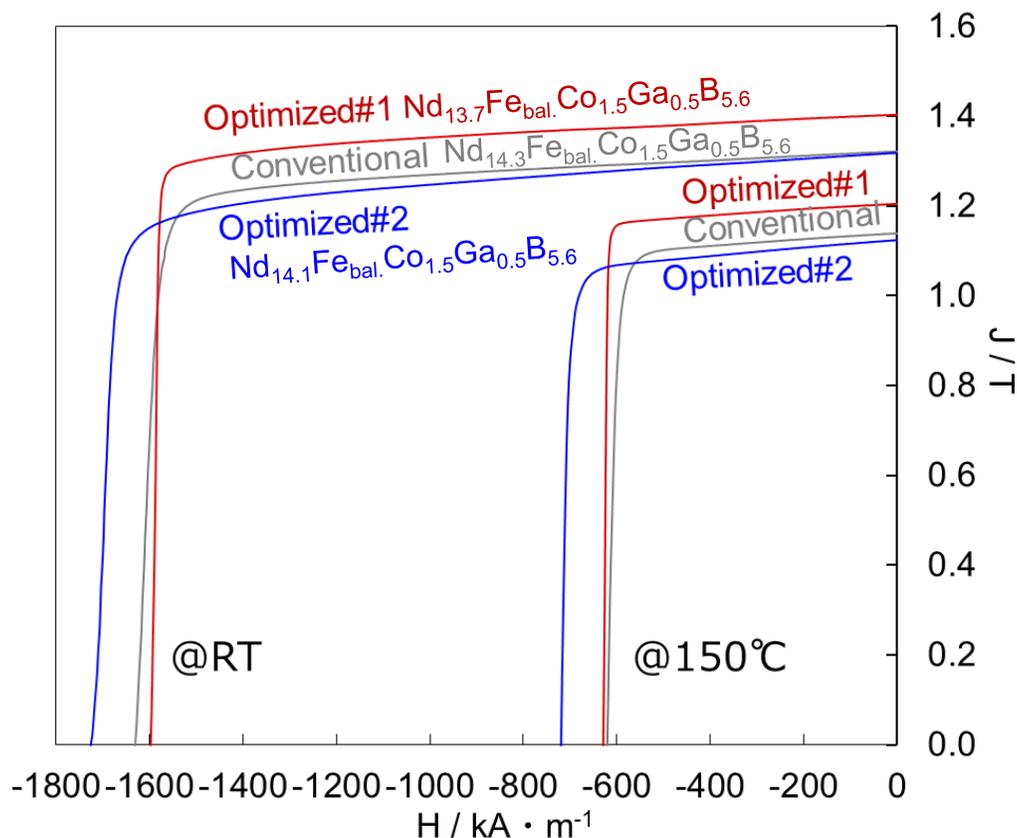


Fig. Demagnetization curves of Nd-Fe-B hot-deformed magnets

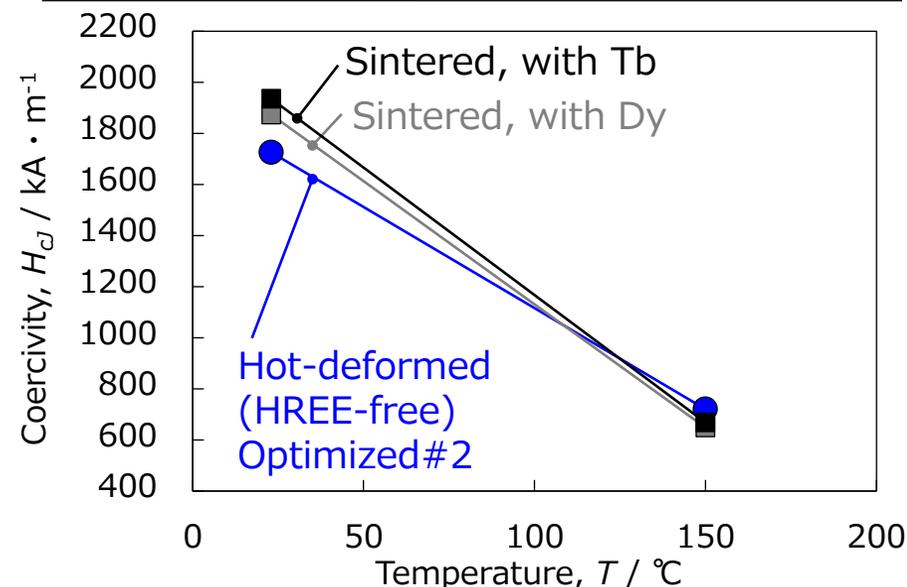


Fig. Temperature dependence of coercivity

Results: Magnetic properties of hot-deformed Nd-Fe-B magnets

- ✓ Optimized hot-deformed magnets show a good temperature coefficient of coercivity β .
- ✓ Remanence +6% or Coercivity +14% due to the optimization of melt spinning.

Nd -1.0 wt.%

Nd -0.4 wt.%

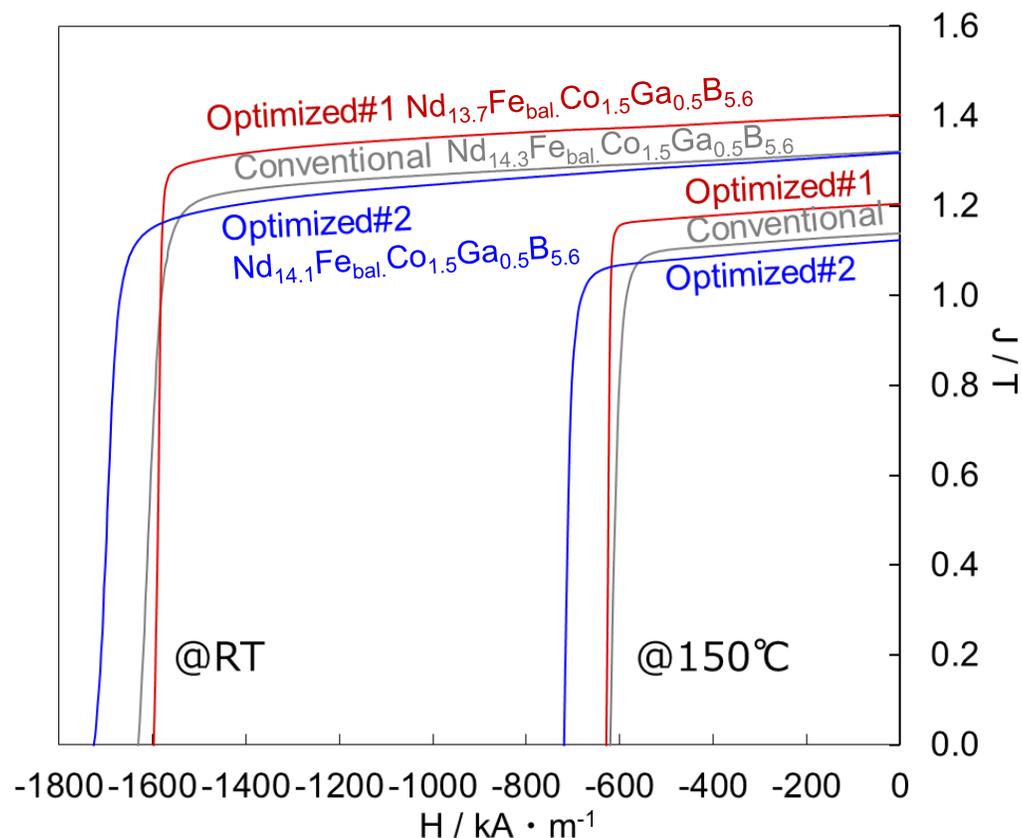


Fig. Demagnetization curves of Nd-Fe-B hot-deformed magnets

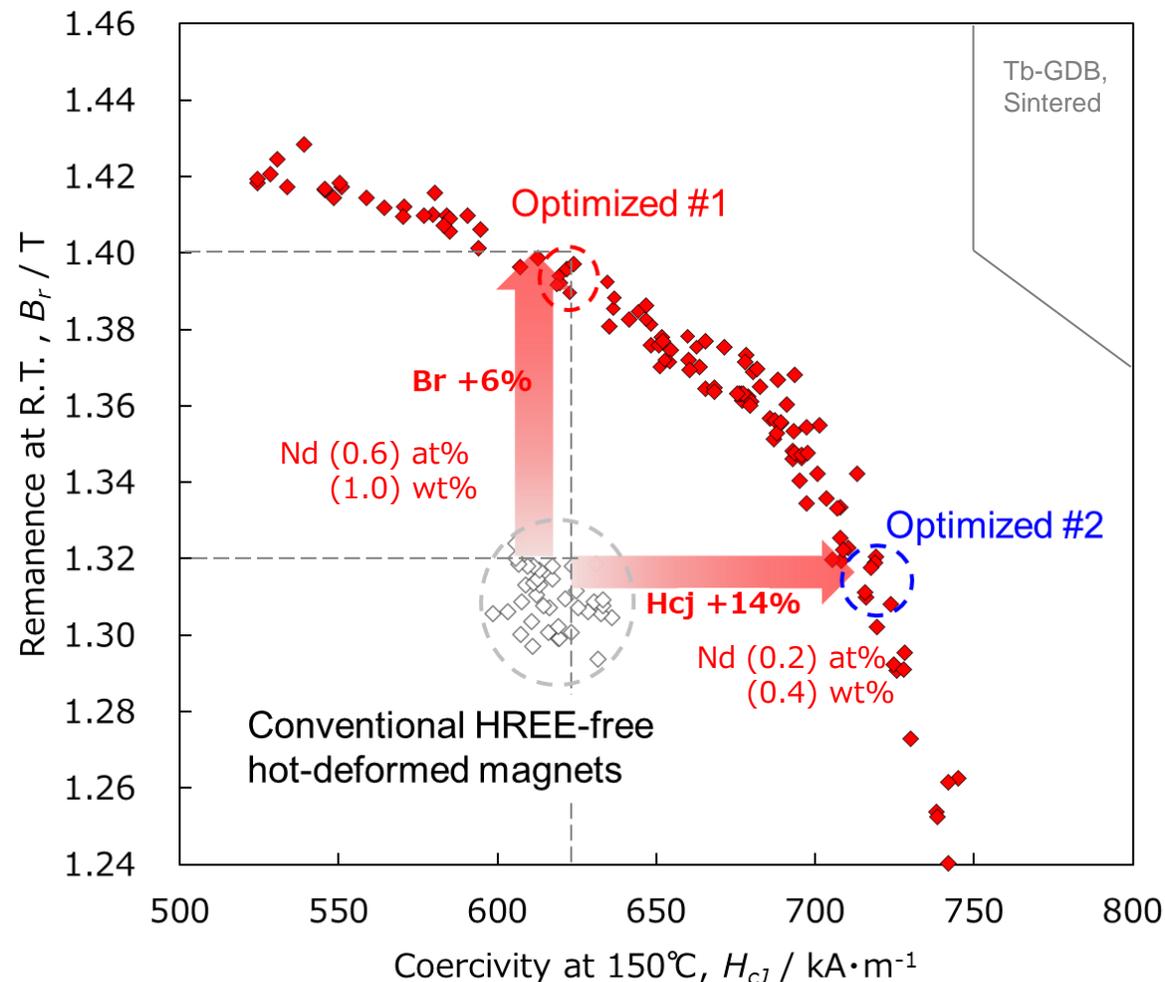
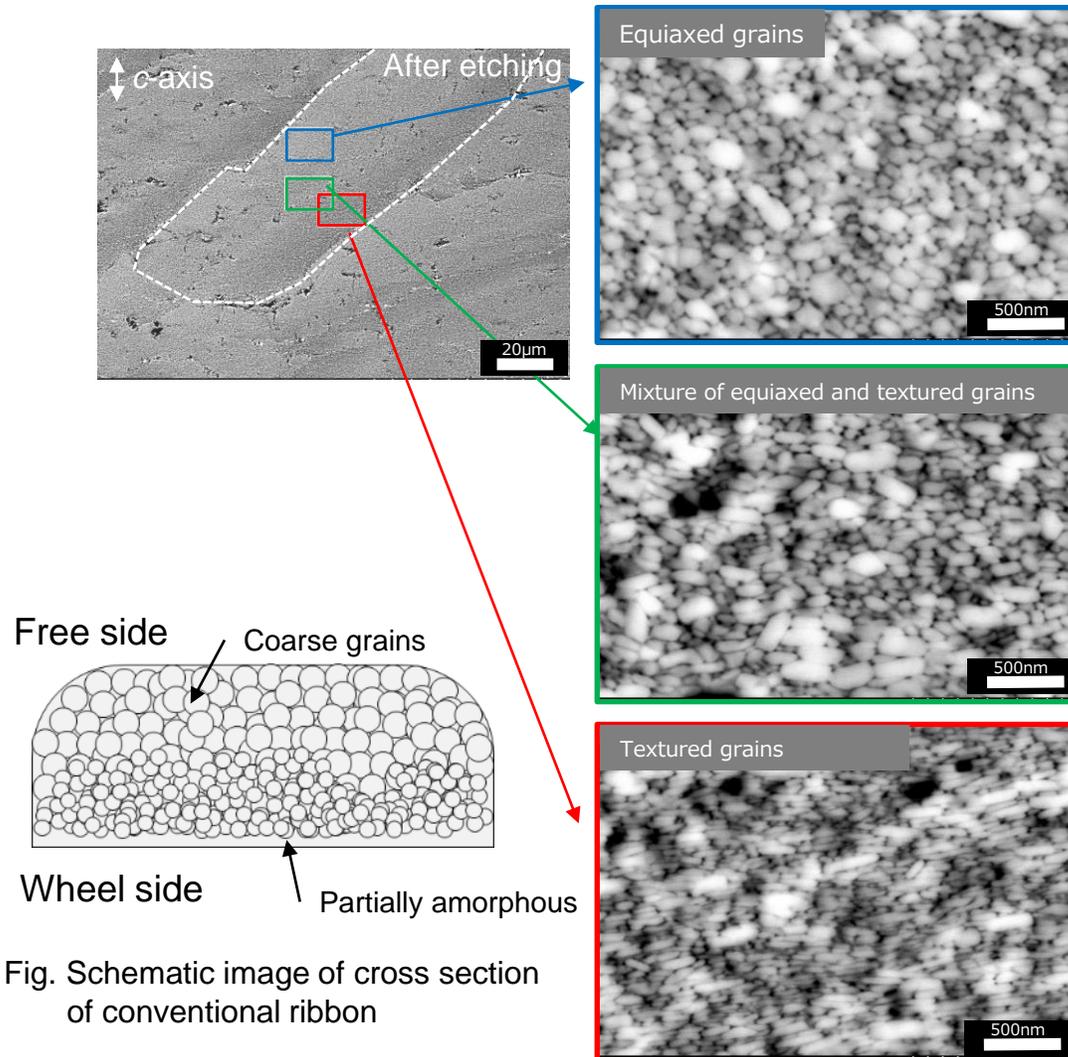


Fig. Magnetic property map of Nd-Fe-B hot-deformed magnets

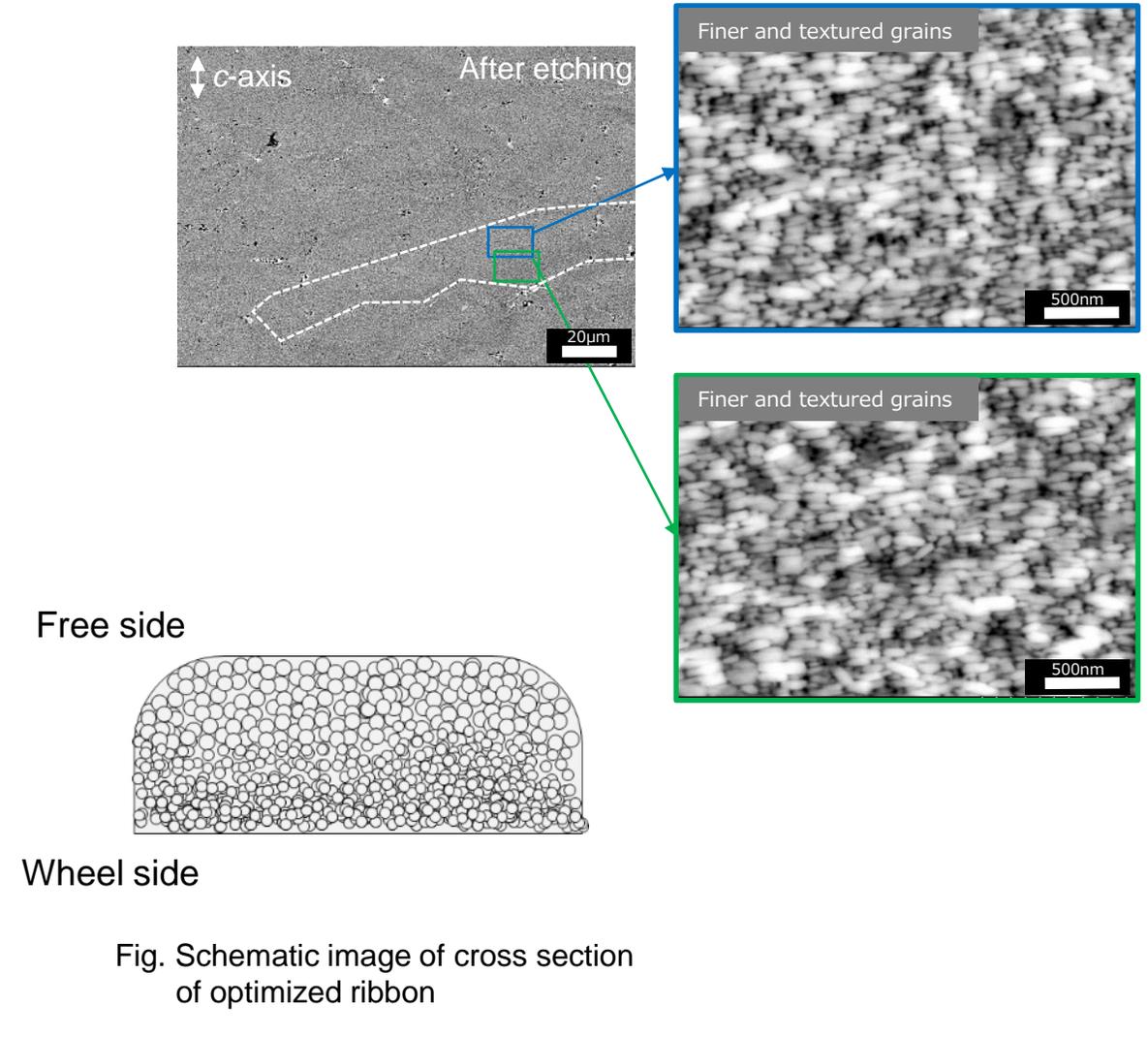
Results: Microstructure of hot-deformed Nd-Fe-B magnets

✓ Optimized hot-deformed magnets have a finer and more textured grains than the conventional one.

Conventional



Optimized



- High-performance hot-deformed magnets without Heavy Rare Earth Elements were obtained by optimization of melt spinning process.
- Although the RE content is low, hot deformed magnets with higher performance than conventional ones were obtained.

Remanence +6% and Nd can be reduced by 1.0 wt.%
or Coercivity +14% and Nd can be reduced by 0.4 wt.%

Thank you for your attention !