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U.S. DEPARTMENT OF ENERGY

IOWA STATE UNIVERSITY

Design of high silicon steel for motors and electronics

Sandia Power Electronics and Energy Conversion Workshop 2023

Presentation Date: August 3rd, 2023

Presenter:

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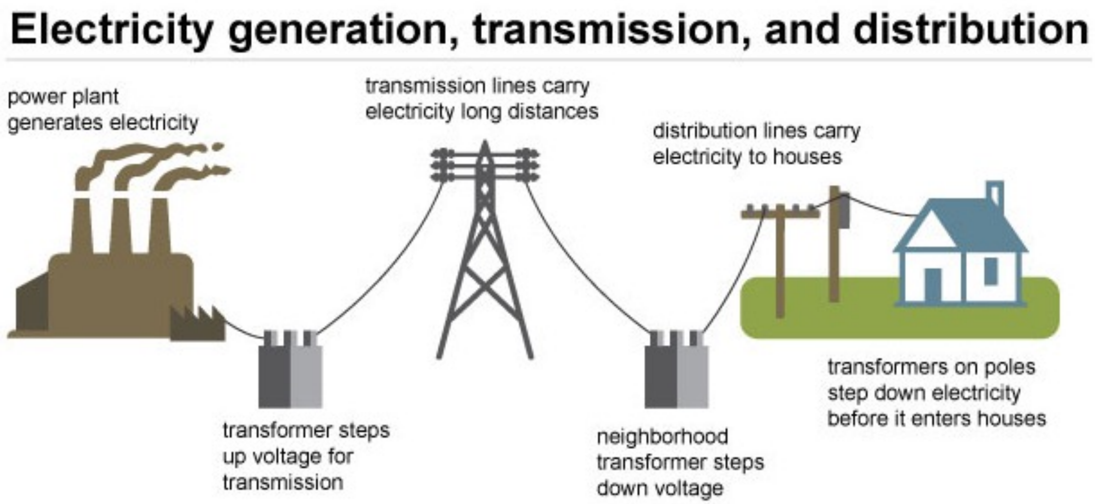
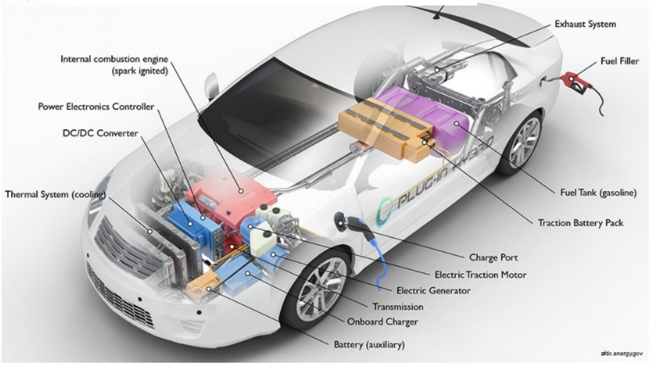
Soft magnet materials (SMMs) and clean energy





Applications of SMMs

Transformer cores

Electrical machines (motors and generators)

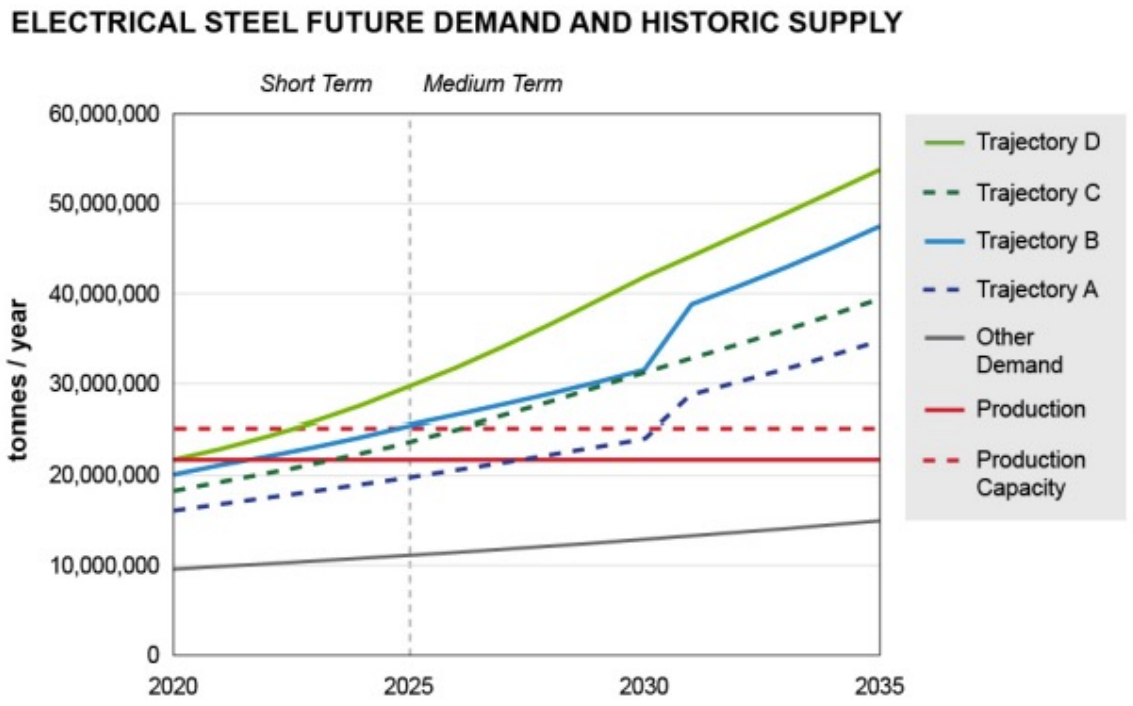
Inductor cores

Material	Application	Materials Intensity
Electrical steel	Vehicle motor	40-100 kg per vehicle
	Transformer	72,570 – 108,860 kg/unit of large power transformer
	Wind	1,360 – 4,810 kg/MW for onshore application 2,450 – 3,470 kg/MW for offshore application

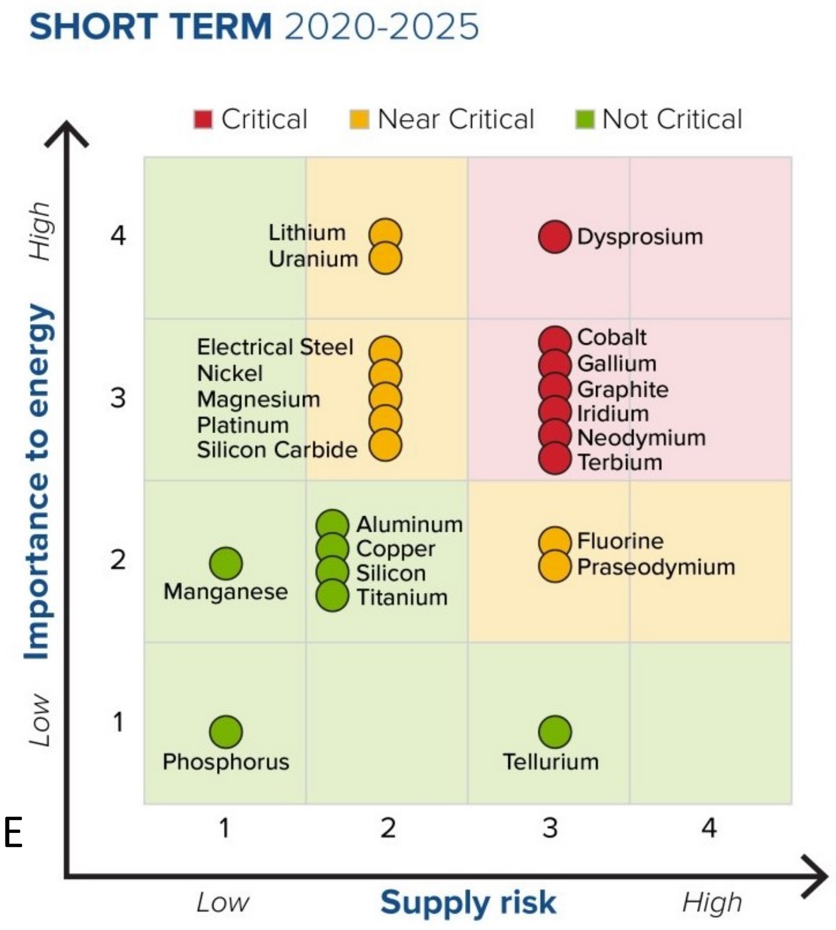
Ref: U.S. Department of Energy, Critical Materials Assessment 2023

- Soft magnetic materials are needed for transformers for the grid and motors in EV

SMMs are in great demand



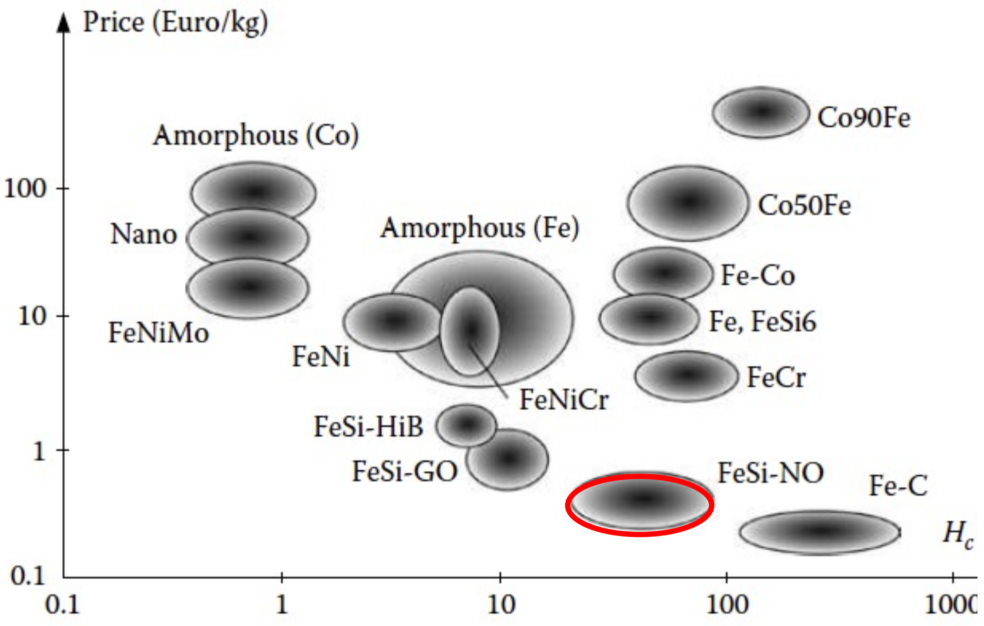
Ref: U.S. Department of Energy, Critical Materials Assessment 2023



Ref: U.S. Department of Energy, Critical Materials Assessment 2023

- Electrical steel has been identified as critical materials by US DOE
- Huge demand for soft magnetic materials

Cost and processing of SMMs



Multiple steps

Hot rolled up to 3% SiFe, 2–2.5 mm thick, ultra low carbon and sulfur — Hot roll

↓

Pickled to remove surface oxides, side trim — Scale removal

↓

Cold roll to intermediate gauge — Cold roll

↓

Annealing at about 800°C to recrystalize, coating — Anneal

↓

Cold roll to final thickness around 0.35 or 0.5 mm — Cold roll

↓

Side trim, slit, and coil up — Slit

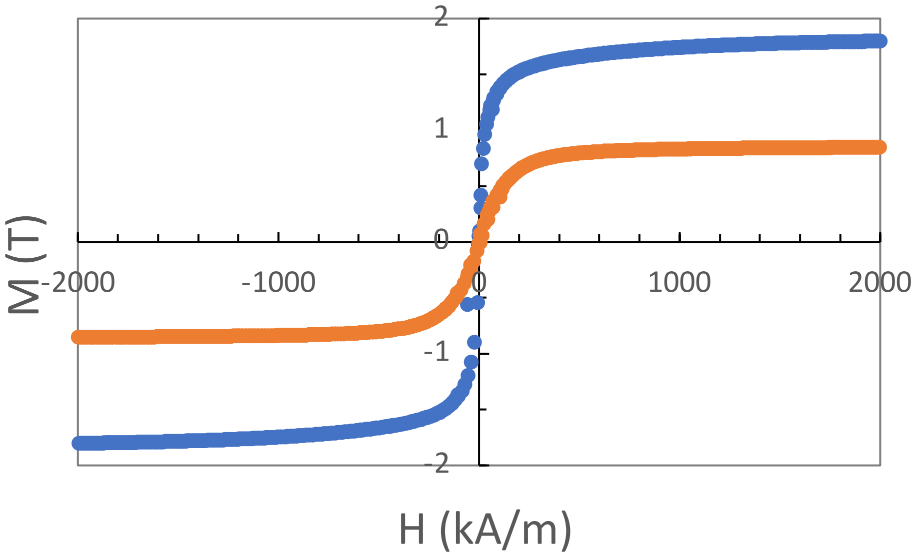
↓

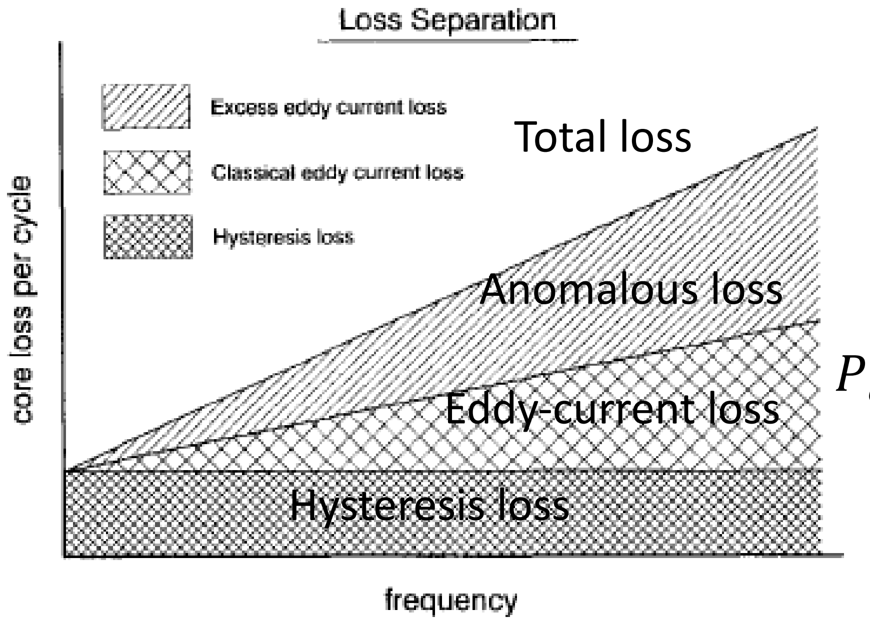
Final annealing at 800°C by customer after stamping — Anneal

Ref: Tumanski, S. *Handbook of magnetic measurements*. (CRC press, 2016).

- Both cost of raw materials and the cost of processing are important for soft magnetic materials

Power density and efficiency of SMMs





Flux density

Thickness

Frequency

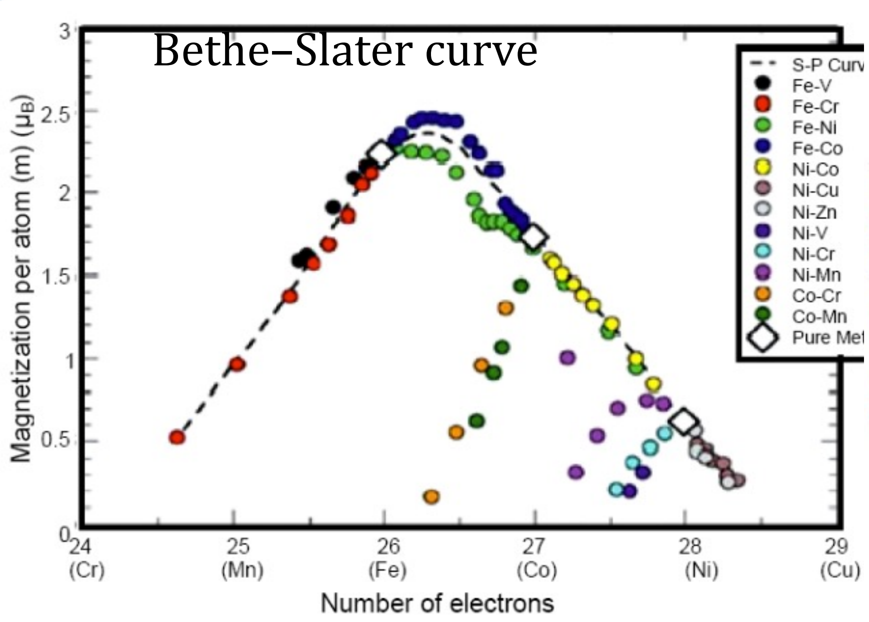
$$P_{eddy} = \frac{10^{-9}\pi^2 d^2 {B_0}^2 f^2}{6\rho}$$

Resistivity

- Higher saturation magnetization leads to high power density.
- Higher *f* increase power density, significantly reduces motor size.
- Higher *f* is beneficial only if new soft magnetic materials can keep the loss low.
- SMMs with high saturation and high resistivity are needed.

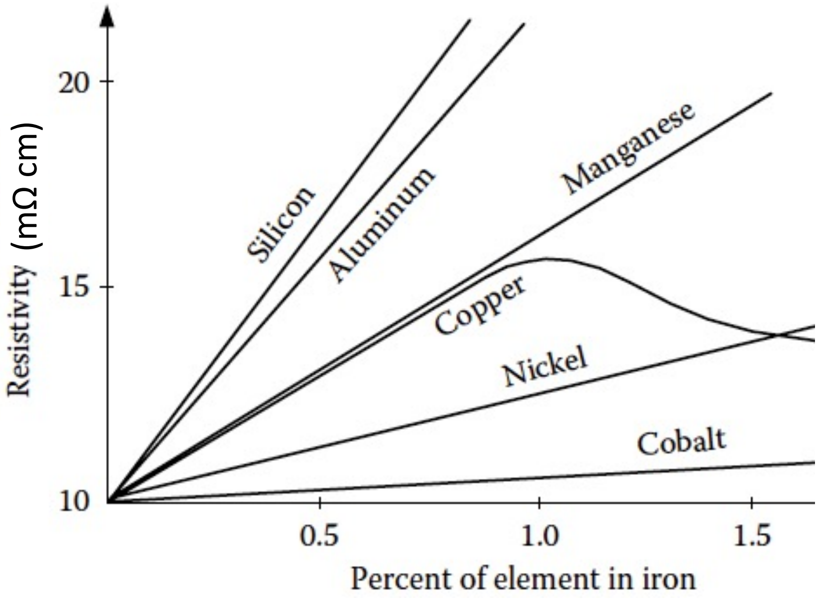
Aspects for designing of SMM

Saturation



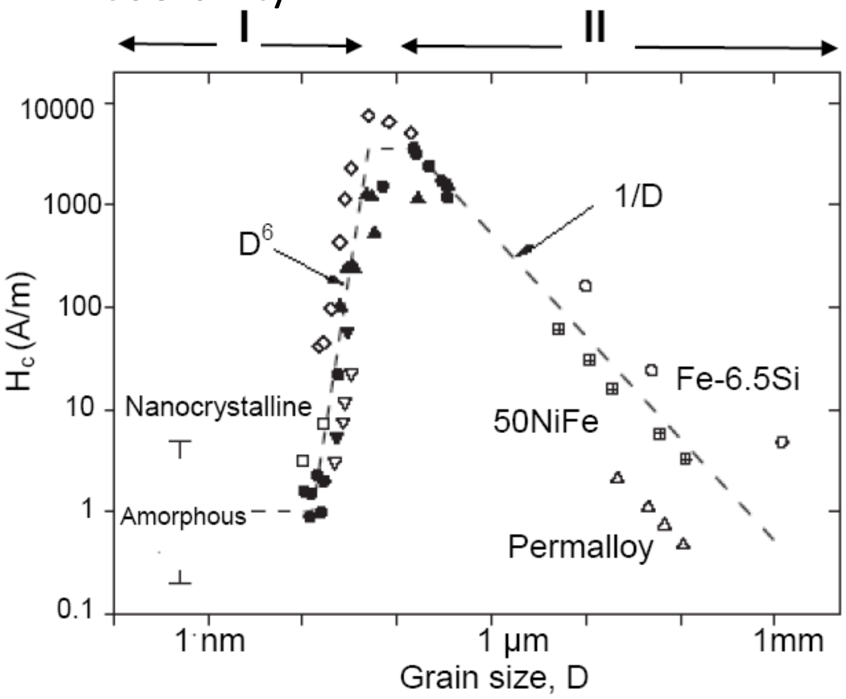
Ref: Roy et al. Alloy Development through Rapid Solidification for Soft Magnetic Application

Resistivity



Ref: Tumanski, S. Handbook of magnetic measurements. (CRC press, 2016).

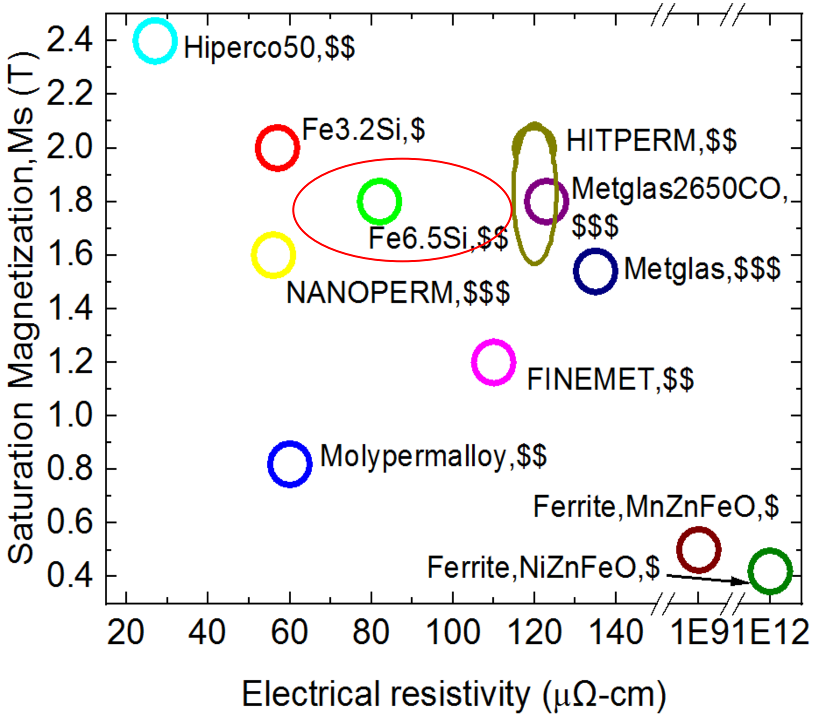
Coercivity



G.Herzer coercivity grain size relationship

- SMM can be designed through compositions and processing

Overview of SMM and high silicon steel

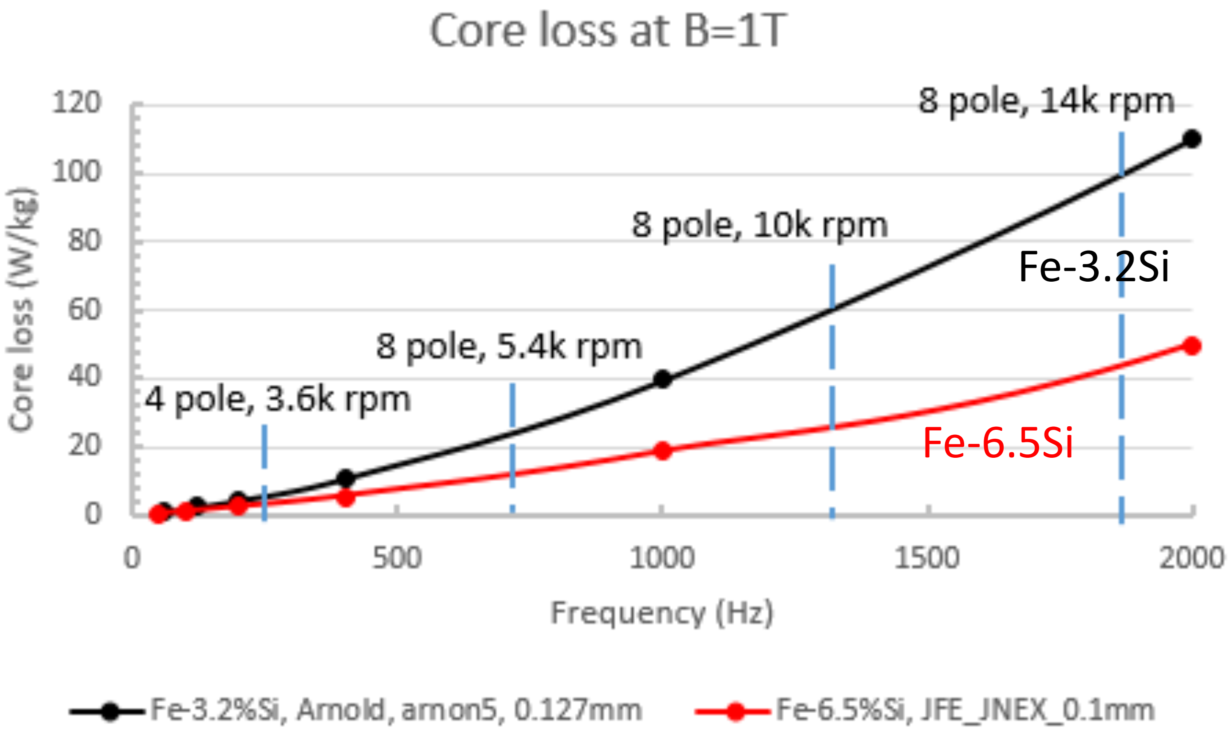


Materials ($$ additions)	Bs (T)	Hc (A/m)	$10^3\mu_r$ 1 kHz	R (μΩ-cm)	λ (ppm)	$W_{1.5/50}$ (W/kg)	$W_{10/400}$ (W/kg)
Electrical Steel, 0.2mm, NGO, 3.2% Si	2	26	15	57	8	0.7-1.2	11
Electrical Steel, 0.2mm, NGO, 6.5% Si	1.8	20	19	82	0.01	0.6	8.1
Molypermalloy, 0.5mm, Ni78Fe17Mo5	0.65-0.82	0.25-0.64	100-800	60	2-3	0.07	0.3
Hiperco 50, Fe49Co49V2	2.4	16-400	5-50	27	60	4	10
FINEMET, $Fe_{73.5}Si_{13.5}Nb_3B_6Cu_1$	1.2	0.5-1.4	80	110	0-2	--	1.1
NANOPERM, $Fe_{88}B_4Zr_7Cu_1$	1.5-1.6	2.4-4.5	48	56	~0	--	3
HITPERM, $(FeCo)_{44}Zr_7B_4Cu_1$	1.6-2.0	80-200	1-10	120	36	--	20
Metglas, Fe78Si9B13	1.54	3	2.1	135	27	0.7	2-5
Metglas 2650CO, $Fe_{67}Co_{18}B_{14}Si_1$	1.8	3.5	50	123	35	0.3	3

- Fe-3.2%Si steel offers the most attractive cost/performance ratio
- Fe-6.5%Si Electric steel offers both high flux density and high electric resistivity.
- Fe-6.5%Si offers lower eddy current, smaller hysteresis loss, nearly zero magnetostriction.

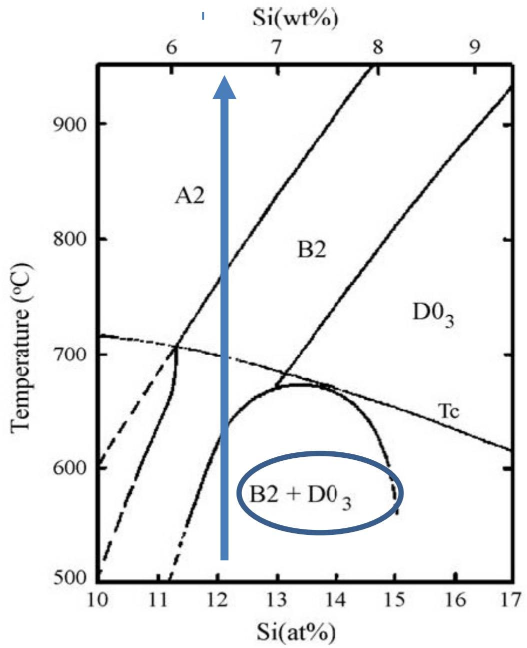
1. O. Gutfleisch et al. Advanced Mats. (2011), 23, 821-842
2. B.D. Cullty, Introduction to Magnetic Materials, John Wiley & Sons, (2009)
3. G. Ouyang et al, JMMM, 481, 234-250 (2019).

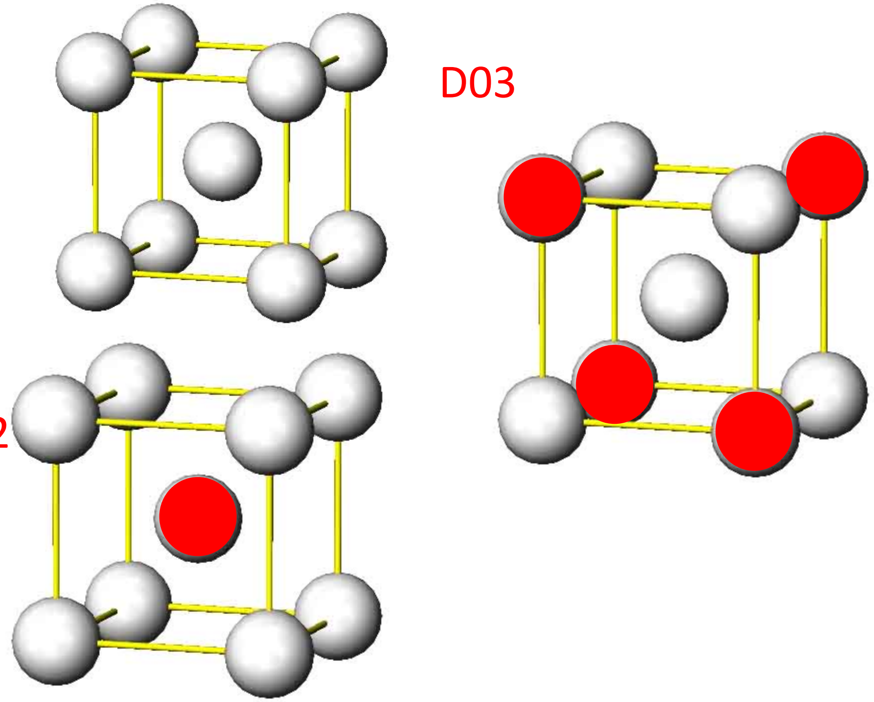
Comparison of Fe-6.5Si over Fe-3.2Si

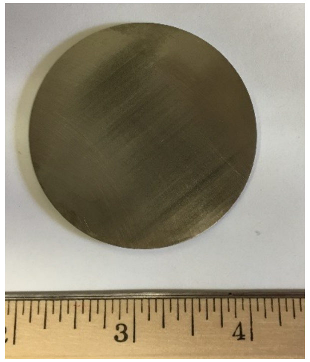


- Fe-6.5Si offers significant lower iron losses than Fe-3.2Si, especially at high frequencies

Challenges in Fe-6.5Si (ordering)

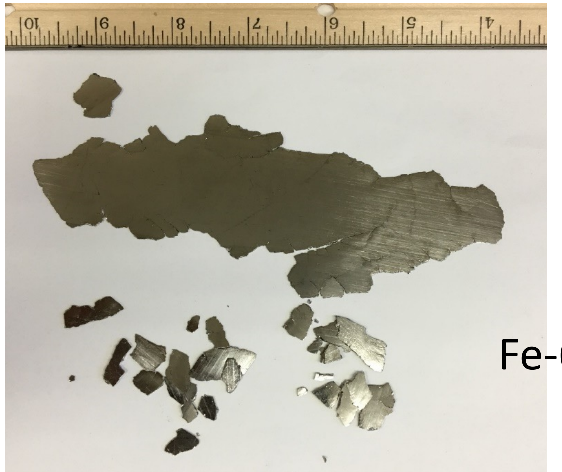






Fe-6.5Si

Cold roll



Fe-6.5Si

- Fe-6.5Si lies in the B2/$D0_3$ two phase region.
- B2 and $D0_3$ ordering results in brittleness. resulted from ordering of nearest neighbor and next-nearest-neighbor atoms.
- B2 and $D0_3$ ordering results in brittleness.
- Fe-6.5Si can not be cold rolled.

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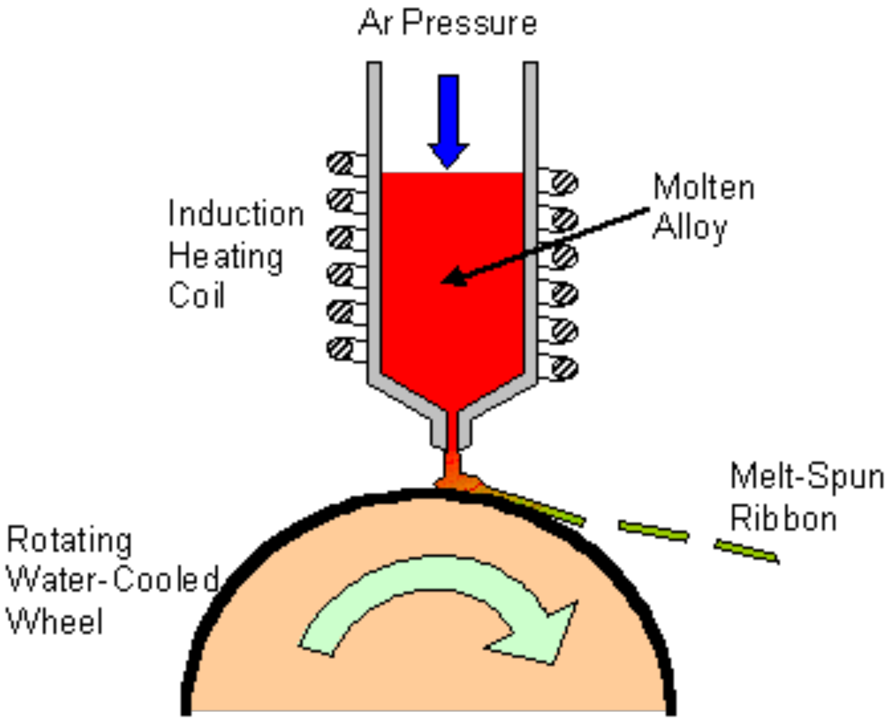
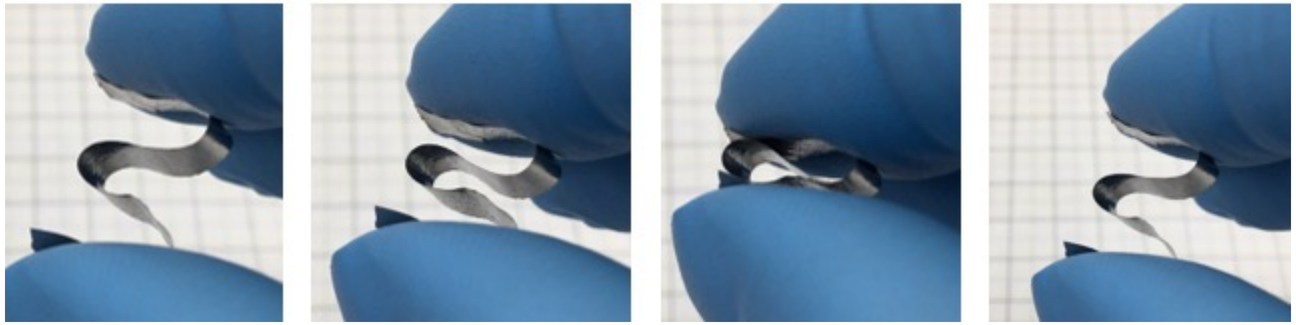
1. Shin et al. Materials Science and Engineering: A 2005;407:282.
2. Swann PR et al. Metal Science 1975;9:90.

Rapid solidification suppresses the ordering





Time lapse of a video

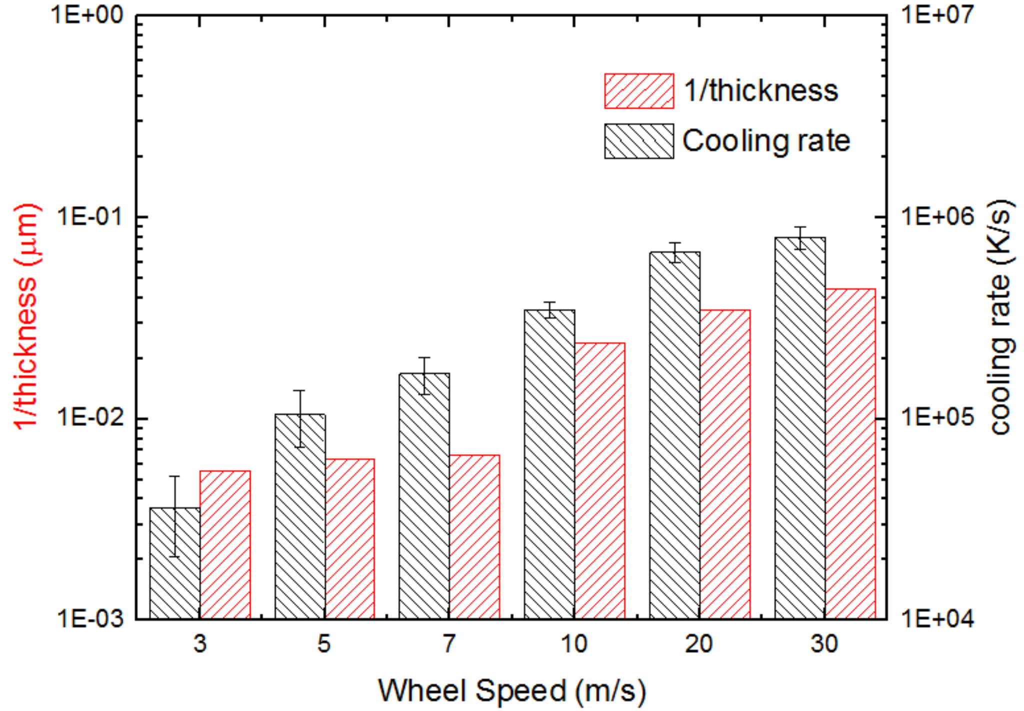
Heavy spur implies the material is too ductile

Rapid solidification of Fe-6.5Si bypasses the ordered phases resulting in ductility.

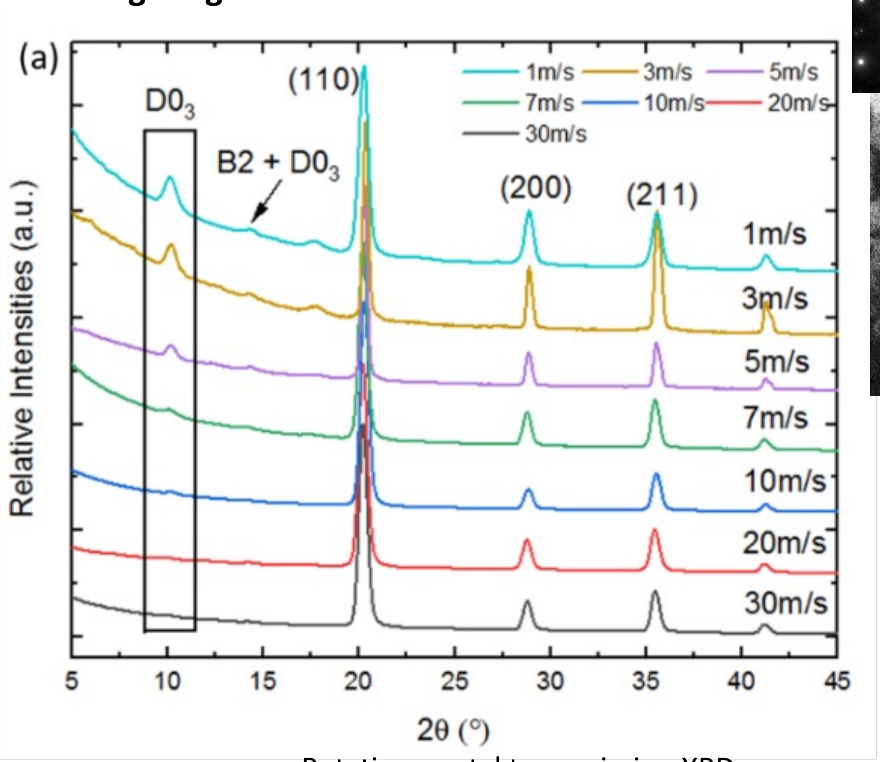
- **Can the property of Fe-6.5Si be adjusted by varying the cooling rate/wheel speed?**
- **How can we use rapid solidified Fe-6.5Si?**

Cooling rates and Fe-6.5Si ordering

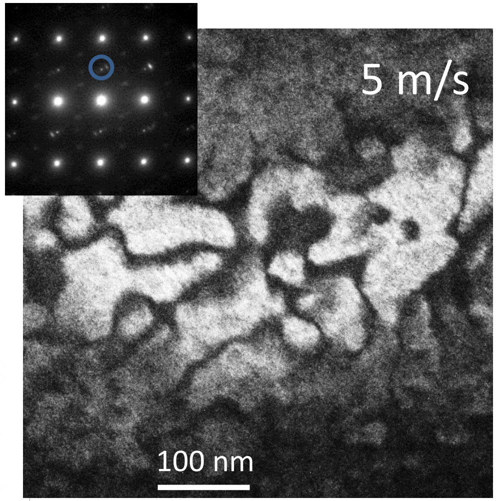
Tuning long range order through varying cooling rates

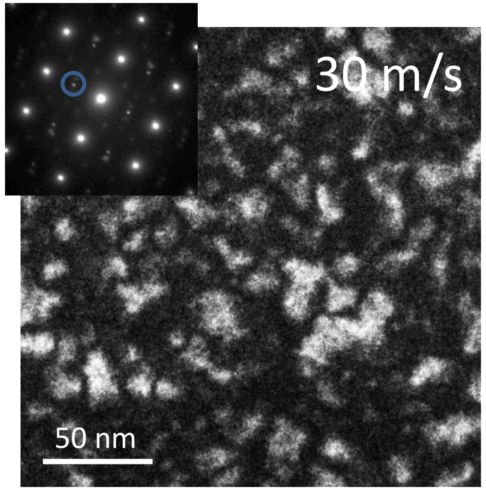


Long range order characterization



Rotating crystal transmission XRD

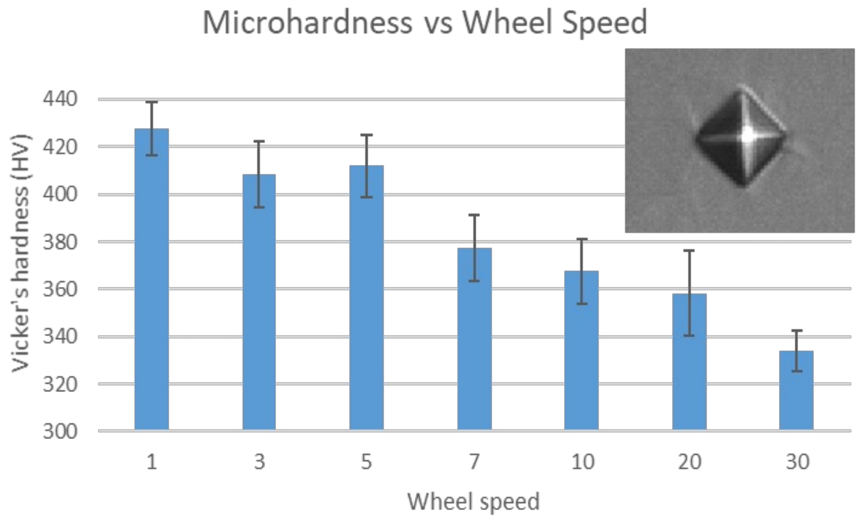




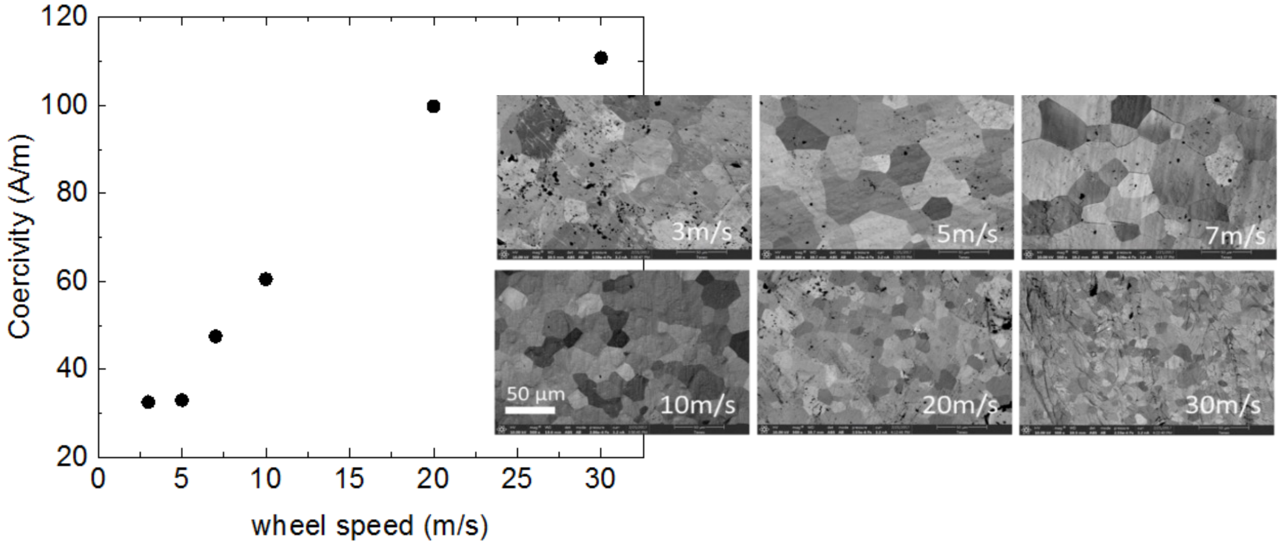
- Cooling rate and ribbon thickness effectively tuned by adjusting the wheel speed.
- Faster cooling results in lower degree of ordering of Fe-6.5Si and smaller ordered domain size.

1. G. Ouyang et al. Materials Characterization 158 (2019) 109973
2. G. Ouyang et al. Acta Materialia 205 (2021) 116575

Cooling rates and Fe-6.5Si physical properties



Faster cooling rate



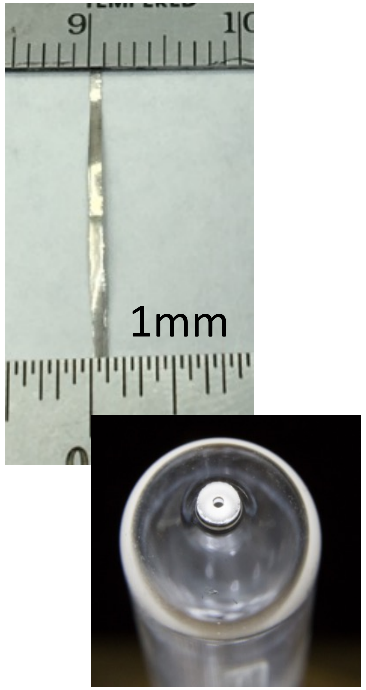
Faster cooling rate

- Ductile Fe-6.5Si ribbon beyond 7m/s due to lower degree of ordering.
- Coercivity is affected by different grain size on as spun Fe-6.5Si.

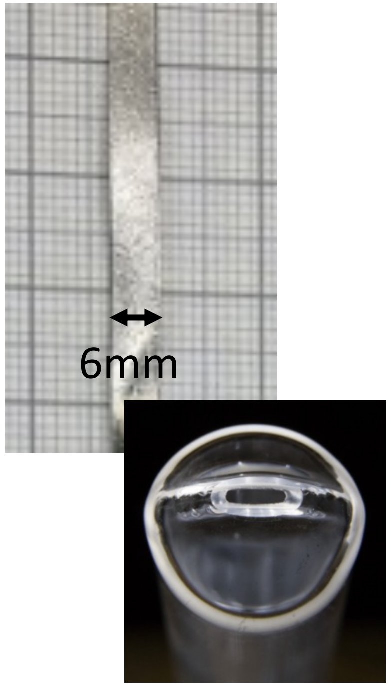
1. G. Ouyang et al. Acta Materialia 205 (2021) 116575

Fe-6.5Si ribbon/tape for tape wound cores

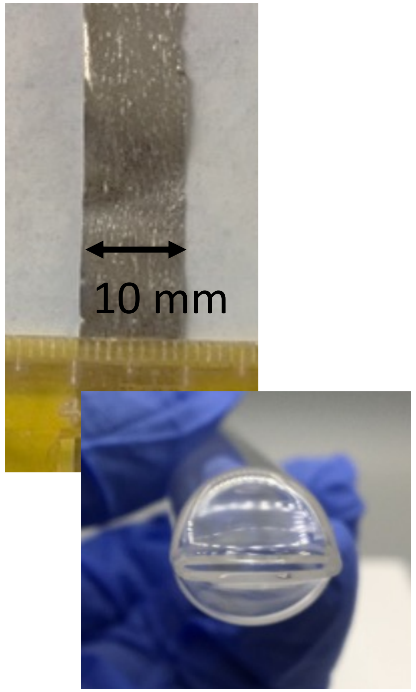
Fe-6.5Si



Fe-6.5Si

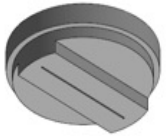


Fe-6.5Si



Fe-6.5Si

17 mm wide

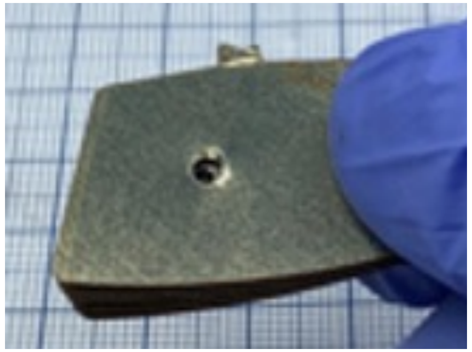


Tape wound cores

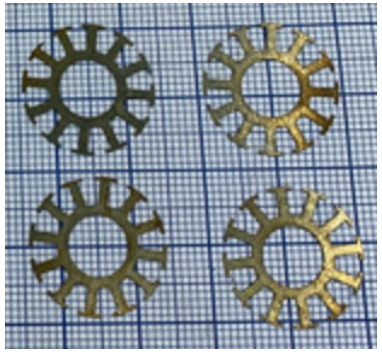
- Width of the ribbon increased from 1mm to 10mm.
- Consistently producing 6 mm wide 0.1mm thick Fe-6.5Si ribbons using small melt spinner.
- Currently working on further increase the width to 50mm.

Fe-6.5Si tape for motor laminates

Fe-6.5Si motor demon

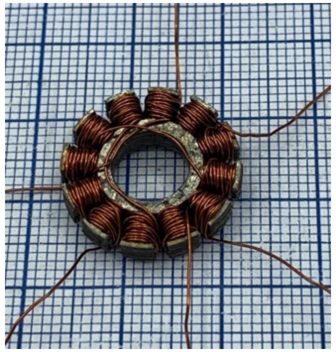


Fe-6.5Si



EDM

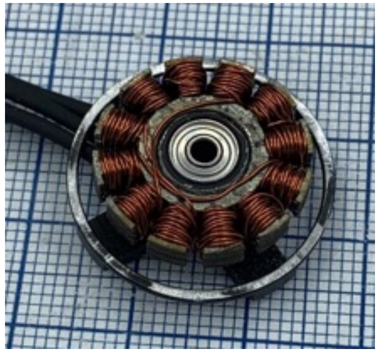
Laminating



Winding

30,000 RPM/zero load

Running with ESC

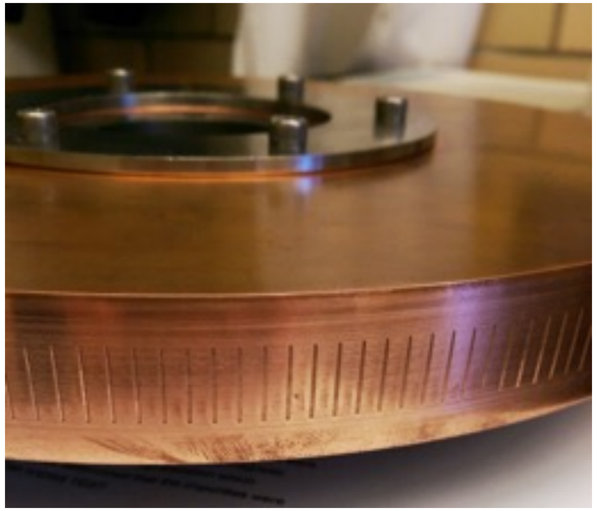


Stator

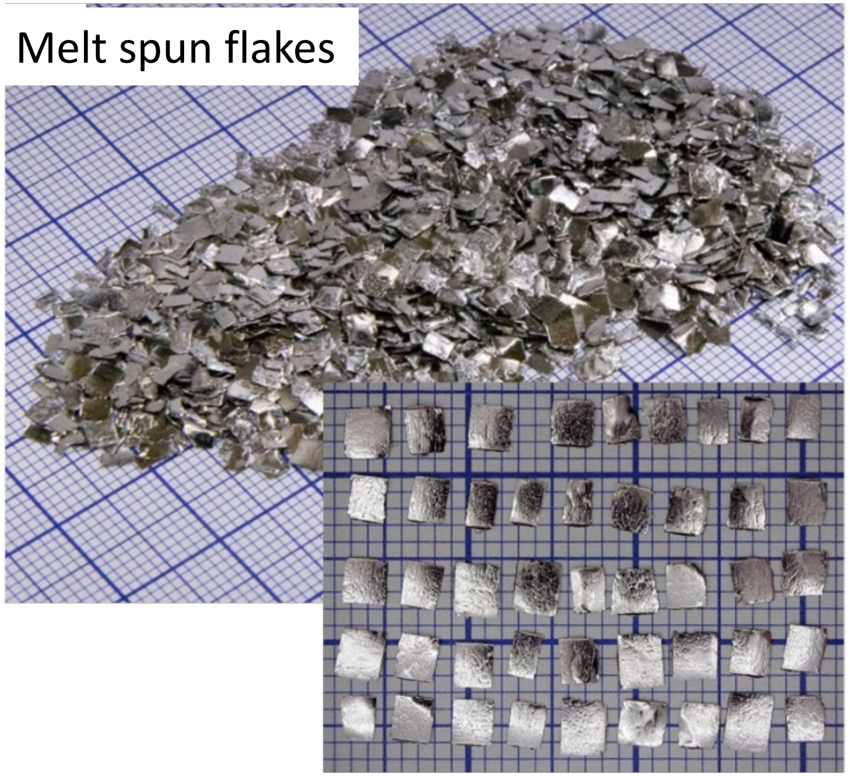
PM rotor

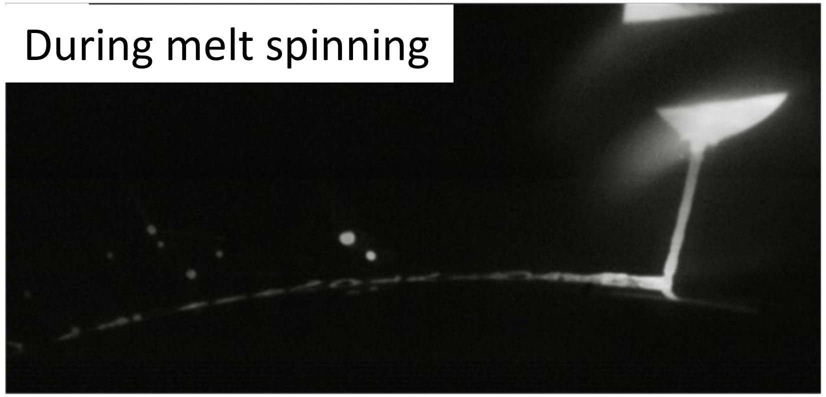
- Fe-6.5Si laminates/tapes can be machined for stator laminates for motors.

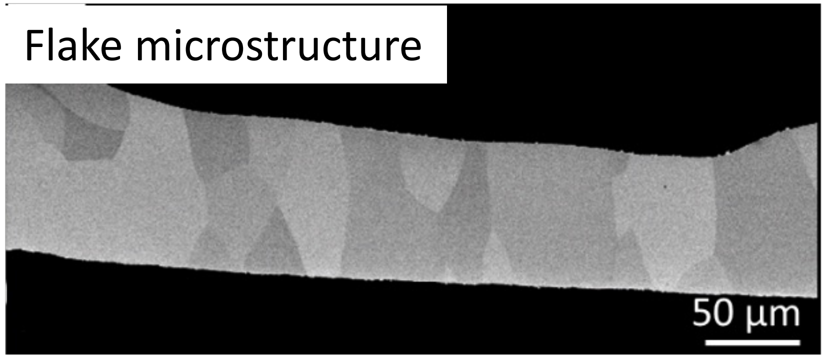
Fe-6.5Si flake production



Grooved wheel breaking continuous ribbon to flakes





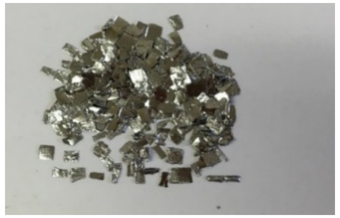


- Successful production of flakes ~0.1mm thickness, 1mm width and 2mm length.
- The waste can be used as raw material to melt spun more flakes, eliminating waste.

1. G. Ouyang et al. Acta Materialia 201 (2020) 209–216

Performance of flake-based Fe-6.5Si

Melt spun →



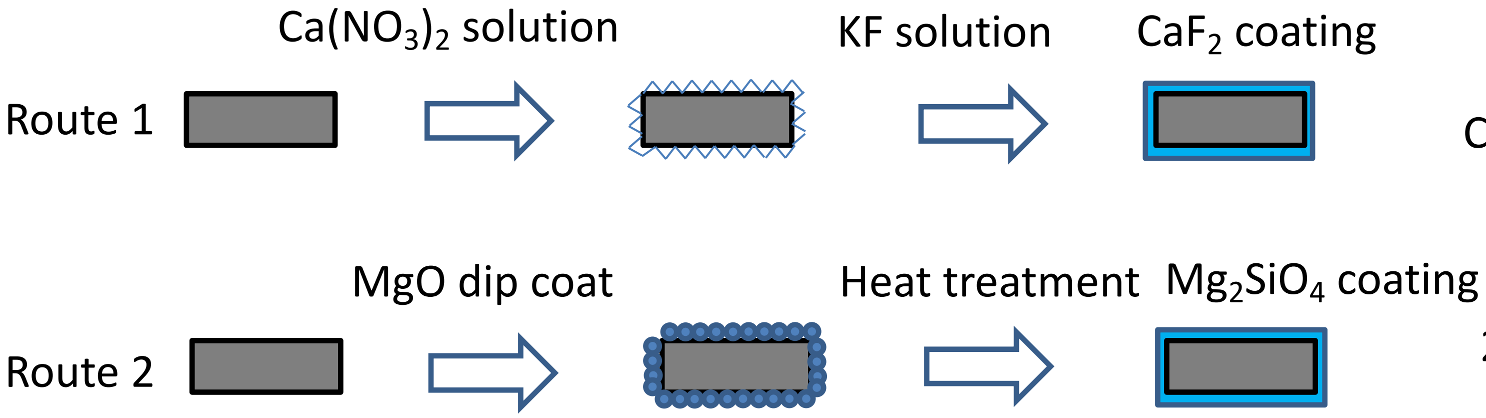
Hot press →

→ 1100°C2h annealing + Slice →

		Ameslab GO2P23	NO Si steel	Ameslab GO2P23	JNHF	Ameslab GO2P23	JNEX
		Fe-6.5Si	Fe-3.2Si	Fe-6.5Si	Gradient Fe-6.5Si	Fe-6.5Si	Fe-6.5Si
thickness	(mm)	0.33	0.35	0.2	0.2	0.1	0.1
W10/400	(W/kg)	10.8	14.4	7.2	14.5	6.1	5.7
W10/1k	(W/kg)	45.7	62.0	27.3	29.1	20.2	18.7
DC,μMax		28.7k	18.0k	28.4k	3.9K	25.8k	23.0k

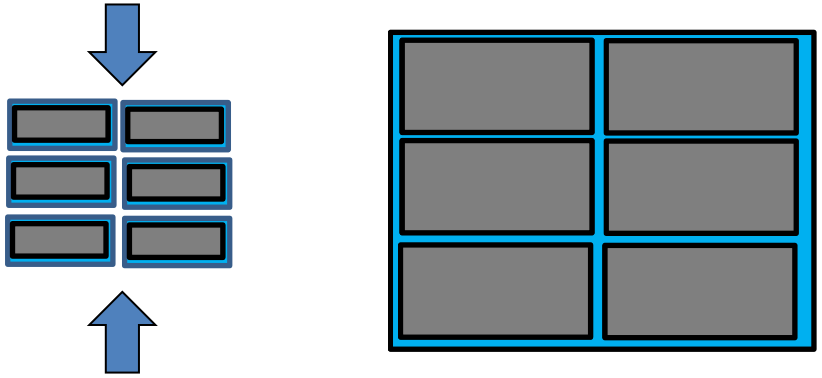
- The hot pressed sample suffered from poor AC magnetic properties (high iron loss).
- Fe-6.5Si has lower losses than the traditional Fe-3.2%Si with the same thickness.
- Our 0.2mm sample achieved record low iron loss at 400Hz and 1000Hz.
- Our 0.1mm sample has W10/400 of 6.1W/kg.

Flake lamination and assembly



$Ca(NO_3)_2 + 2KF \rightarrow CaF_2 + 2KNO_3$

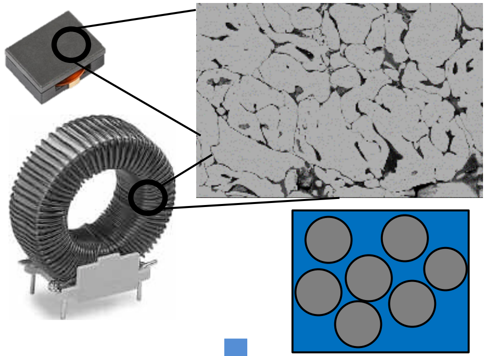
$2MgO + SiO_2 \rightarrow Mg_2SiO_4$



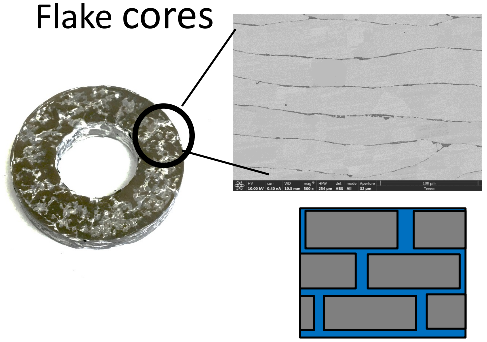
- Coating + Shaping
  - Solution coating of CaF2
  - Dip coat of MgO
  - MgO powder co pack anneal
  - Si-B powder co-pack cementation
  - Epoxy solution coat

The comparison of flake cores and powder core

Current state of the art:
Powder based cores



Flake cores



Flake core vs. powder core

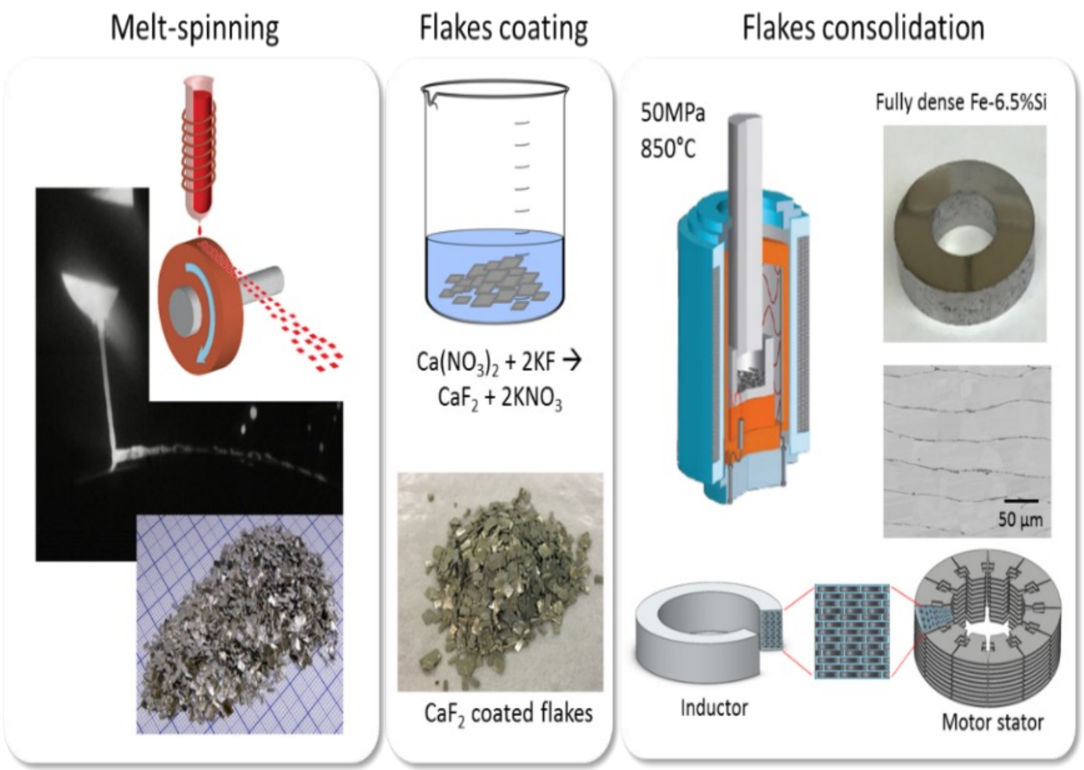
	AC/Iron Loss (W/kg)						DC		
Flux density	0.1T		0.2T		0.5T				
Frequency, Hz	Powder Core	Flake Core	Powder Core	Flake Core	Powder Core	Flake Core		Powder Core	Flake Core
50	0.14	0.05	0.48	0.18	2.33	0.87	B8, T	0.04	0.09
60	0.14	0.07	0.72	0.26	2.84	0.99	B15, T	0.07	0.16
100	0.32	0.12	1.19	0.43	4.87	1.83	B50, T	0.22	0.46
400	1.37	0.55	4.78	1.92	20.03	8.72	B80, T	0.34	0.64
1000	3.53	1.56	12.32	5.65	53.41	26.68	umax	35.90	86.75

Powder diameter = flake thickness; 5wt%epoxy binder

- Flake core shows improvement in magnetic properties than powder core.

Summary

- Significant demand for SMMs



Fe-6.5%Si

Low cost
High performance
No supply chain issue
Low carbon output processing

- Cooling rate determines Fe-6.5%Si properties.
- Fe-6.5%Si can be used as wide ribbon, flakes, and ribbons format.
- Fe-6.5%Si flakes enable near net shape processing, and good magnetic properties.

Questions: Gaoyuan Ouyang, gaoyuan@iastate.edu