Effects of Cooling Rate on 6.5% Silicon Steel Ordering

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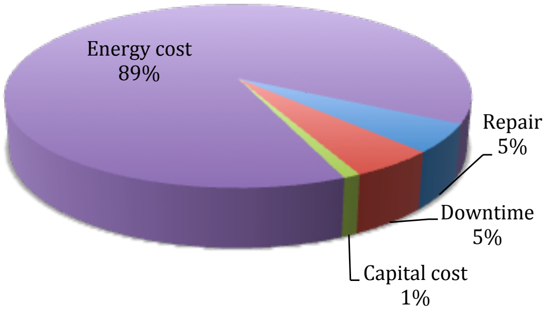
Outline

- Background
  - Overview of soft magnetic materials
  - Why 6.5% Si steel
  - Approaches and challenges
- Melt-spun 6.5% Si steel approach
  - Experimental setup and method
- Effects of cooling rates on 6.5% Fe-Si physical properties
  - Actual cooling rates
  - TEM phase fraction
  - Physical properties
    - Mechanical, magnetic, electrical
- Discussion

Cost is a top priority for electric motor industry

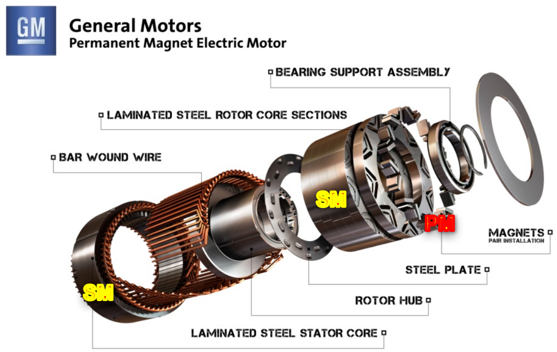
- Reducing capital costs is the most important consideration driving customers' decision, because people who build the plant is not the people who operate it
- 91% reported that all motor purchase decisions were made at the plant level.
- 8% included efficiency in their specifications for the motor to be purchased
- Customers most often use the size of the failed motor being replaced as a key factor in selecting the size of the new motor.
- The energy saving due to higher efficiency may command a small premium if there is any.

- *A motor is competitive if it has higher efficiency while maintaining competitive price*

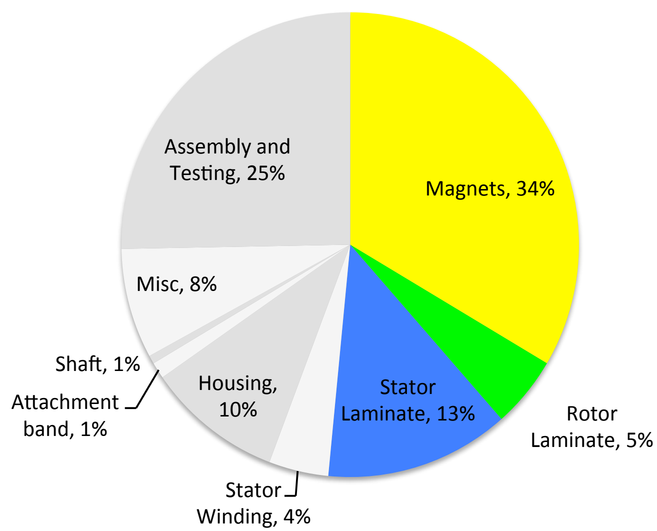


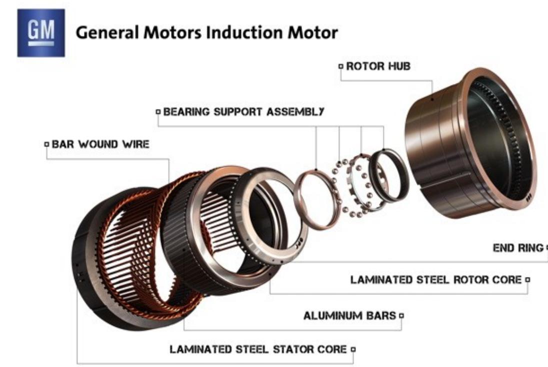
[2] Paul Waide and Conrad U. Brunner, "Energy-efficiency policy opportunities for electric motor-driven systems", International Energy Agency
[3] Premium Efficiency Motor Selection and Application Guide, A Handbook for Industry, DoE, EERE, Advanced Manufacturing Office

Cost Breakdown of Electric Motors

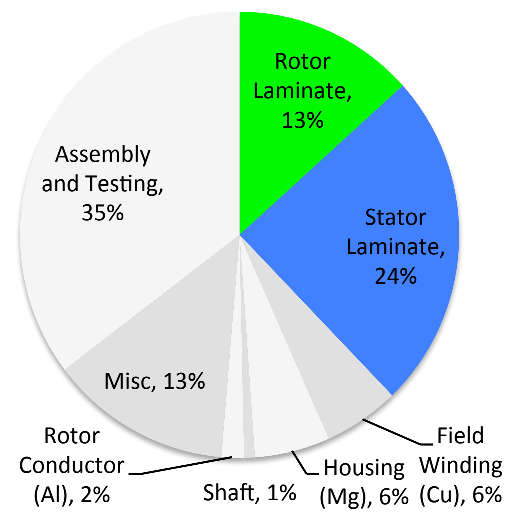


32kW PMM motor, $522





40kW Al Induction motor, $450

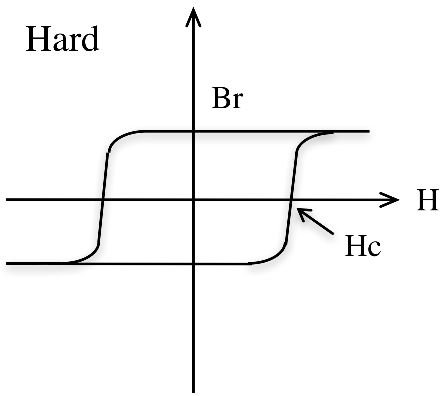


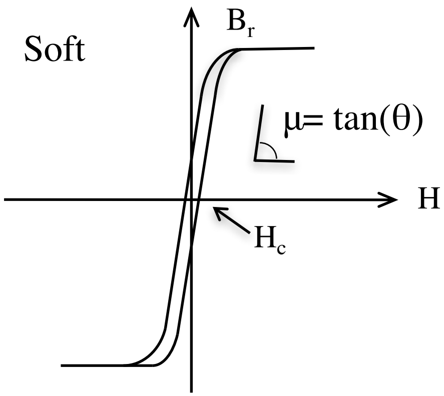
- Magnetic materials (PM+SM) account **>52%** of raw materials cost
- Labor accounts a significant fraction, but not much room to reduce

- Magnetics (laminate) account 37% of raw materials cost
- IM is more labor intensive than PMM, less efficient, bigger in size, and require more expensive/complex drives electronics, but IM is cheaper and free of REE

REF: Evaluation of Electric Vehicle Production and Operating Costs by R.M. Cuenca, L.L. Gaines, and A.D. Vyas Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Nov-99

Basics of magnetic materials





- Coercivity (Hc): the field required to demagnetize magnet
- Remanent magnetization (Br): the remaining magnetization when applied field is reduced to zero
- Permeability (μ): the ratio of magnetization vs applied field

Ideal hard magnetic materials:

- High coercivity, Hc > 20 kOe
- High magnetization, Br > 1.4 T
- High energy product, BHmax > 50 MGOe
- Small temperature dependence

Ideal soft magnetic materials:

- Low coercivity, Hc < 0.1 Oe
- High resistivity, ρ > 1000 μΩ-cm
- High magnetization, Br > 2 T
- High permeability, μ > 10^5

Commercial Soft Magnetic Materials

Type	Materials	Bs (T)	Hc (A/m)	$10^3\mu_r$ 1 kHz	R ($\mu\Omega$-cm)	λ (ppm)	$W_{1.5/50}$ (W/kg)	$W_{10/400}$ (W/kg)	Ref
Crystalline	Electrical Steel, 0.2mm, NGO, 3.2% Si	2	26	15	57	8	0.7-1.2	11	[1,5]
	Electrical Steel, 0.2mm, NGO, 6.5% Si	1.6	45	19	82	0.01	0.6	8.1	[1,2]
	Molypermalloy, 0.5mm, Ni78Fe17Mo5	0.65-0.82	0.25-0.64	100-800	60	2-3	0.07	0.3	[3,4]
	Hiperco 50, Fe49Co49V2	2.4	16-400	5-50	27	60	4	10	[4]
Nano-crystalline	FINEMET, $Fe_{73.5}Si_{13.5}Nb_3B_6Cu_1$	1.2	0.5-1.4	80	110	0-2	--	1.1	[4-6]
	NANOPERM, $Fe_{88}B_4Zr_7Cu_1$	1.5-1.6	2.4-4.5	48	56	~0	--	3	[4-6]
	HITPERM, $(FeCo)_{44}Zr_7B_4Cu_1$	1.6-2.0	80-200	1-10	120	36	--	20	[4-6]
Amorphous	Metglas, Fe78Si9B13	1.54	3	2.1	135	27	0.7	2-5	[7]
	Metglas 2650CO, $Fe_{67}Co_{18}B_{14}Si_1$	1.8	3.5	50	123	35	0.3	3	[4,8]
Ferrite	Ferrite, MnZnFeO	0.36-0.5	10-100	0.5-10	10^7-10^8	5	--	--	[4]
	Ferrite, NiZnFeO	0.25-0.42	14-1600	0.01-1	10^{11}	-20	--	--	[4]

Fe-3.2%Si steel offers the most attractive cost/performance ratio (raw materials ~$2.8/kg, stamped laminate ~$4.7/kg)

REF
[1] http://www.jfe-steel.co.jp/en/products/electrical/supercore/jnex/04.html
[2] H. Haiji, K. Okada, T. Hiratani, M. Abe, M. Ninomiya, J. MMM, 160 (1996) 109-114
[3] G. Herzer, Ch. 3. Nanocrystalline soft magnetic alloys, Handbook of Magnetic Materials, V.10, 1997
[4] O. Gutfleisch, M. Willard, E. Bruck, C. Chen, S.G. Sankar, J.P. Liu, Advanced Mats. (2011), 23, 821-842
[5] M. A. Willard, D.E. Laughlin, M.E. McHenry, D. Thoma, K. Sickafus, J.O.Cross, V.G. Harris, J. Appl. Phys. Vo. 84 (1998), 6773-6777
[6] M. McHenry, M. Willard, D. Laughlin, Prog. Mats Sci, 44 (1999(, 291-433
[7] A. Makino, IEEE Trans. Mag. (2012) V. 48, 1331-1335
[8] [illegible] Introduction to Magnetism and Magnetic Materials, Chapman and Hall, London (1990).

Q:

How much does a 12-ounce can of soda weigh?

A:

It weighs at least 368.7 grams (aluminum can ~13.7 grams; 12 ounces of soda ~355 grams).

If you pay a $ at vending machine, that is $2.7/kg for the can of soda.

We can’t lower our labor cost…

We can’t reduce raw materials cost…

What can we do?

We can go for higher frequency

A 100 kW motor at 50 Hz with 90% efficiency would deliver 200 kW when running at 100 Hz. [1]

Higher frequency will lead to higher power density, smaller size, less raw materials, thus lower cost

- Increasing *f* increases RPM, HP
- Increasing # of poles increases power density (due to shorted end winding & back iron) but it also increases *f*.

$$HP = \frac{Torque \times RPM}{5252}$$

$$RPM = \frac{120 f}{\# P}$$

[1]: Beckley, Philip. *Electrical steels for rotating machines*. No. 37. IET, 2002.

However, higher frequency leads to higher loss and lower efficiency

A 100 kW motor at 50 Hz with 90% efficiency would deliver 200 kW when running at 100 Hz, but efficiency would decrease to 80%. [1]

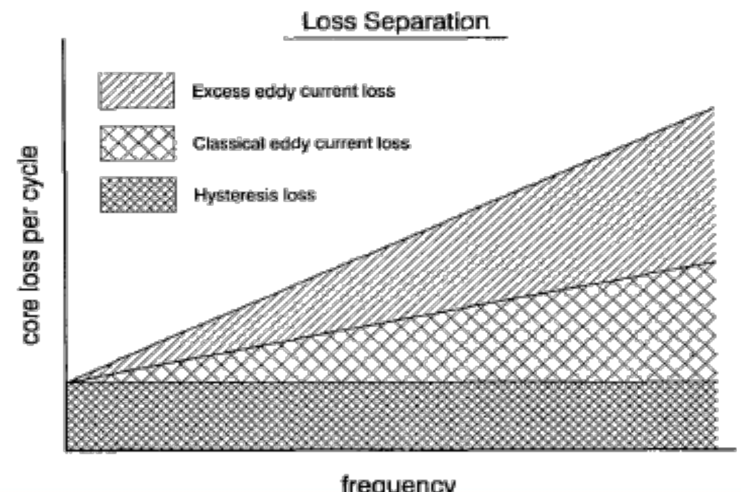
Ref: Beckley, Philip. *Electrical steels for rotating machines*. No. 37. IET, 2002.

Losses

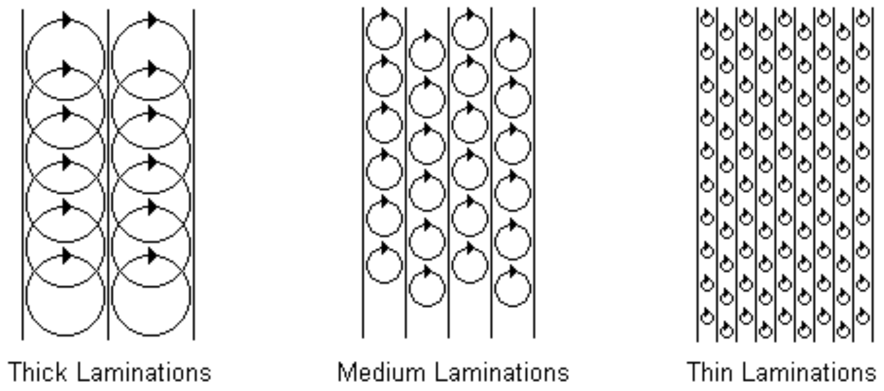
- Copper
- Core
  - Hysteresis: $P_{Hys} = k_{Hys} B^2 f$
  - Eddy Current: $P_{Eddy} = k_{Eddy} B^2 f^2$
  - Excess: $P_{Excess} = k_{Excess} B^{1.5} f$
- Mechanical
- Stray

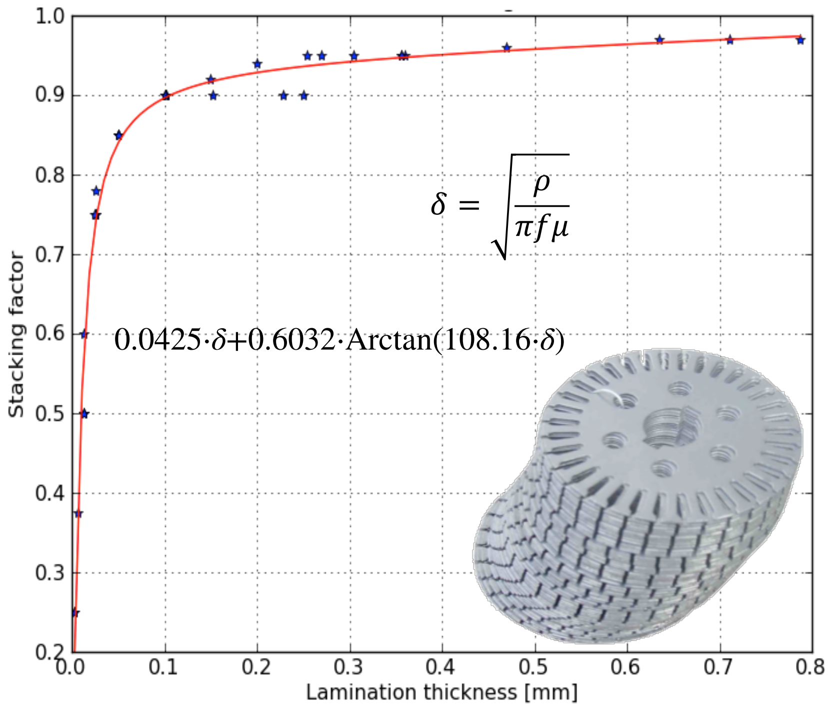
- To improve machine power density without compromising efficiency, it requires SM with
  - Higher Resistivity
  - Lower Hysteresis
  - Higher flux density
  - Maintaining mechanical properties

Total losses per cycle vs. Frequency



Thinner laminate reduces eddy current, increase excitation frequency:





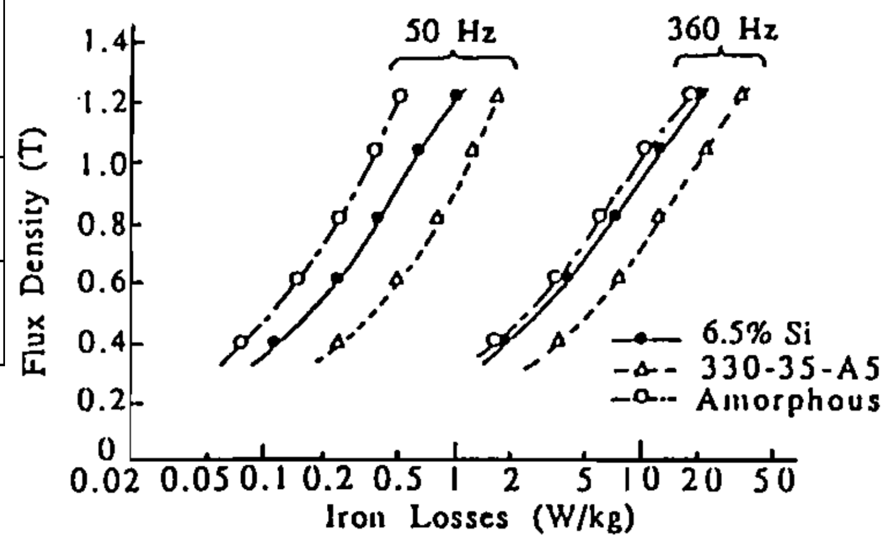
- Skin depth is due to the circulating eddy currents (arising from a changing H field) cancelling the current flow in the center of a conductor and reinforcing it in the skin.
- Thinner laminate allows higher frequency

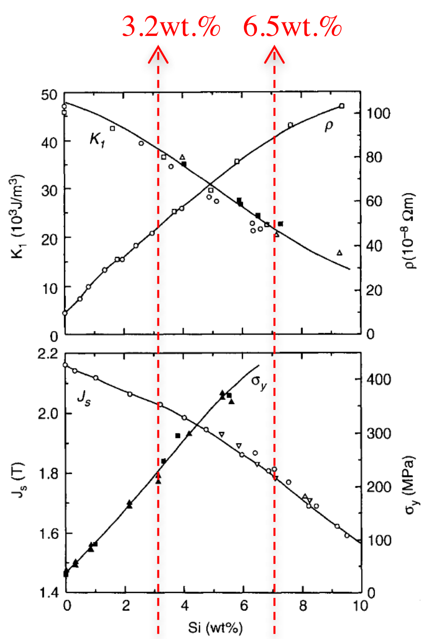
However, thinner laminate increase laminate fabrication cost, and reduce stacking factor.

With the thickness of laminate at its practical limit, go for a higher frequency is beneficial only if a new soft magnetic material with higher e-resistivity and lower coercivity is cheaply available

High Si content electrical steel promises more efficient motors

FeSi steels	Saturation Magnetization (T)	DC Max relative permeability	Electric resistance (μΩ-cm)	Magnetostriction (ppm)	Core loss W10/400 (W/kg)
3.2% Si	1.96	18,000	52	7.8	14.4
6.5% Si	1.8	23,000	82	0.1	5.7

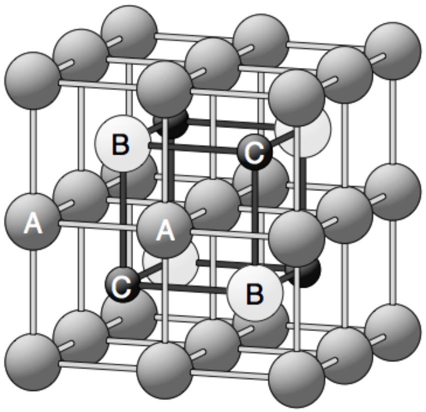




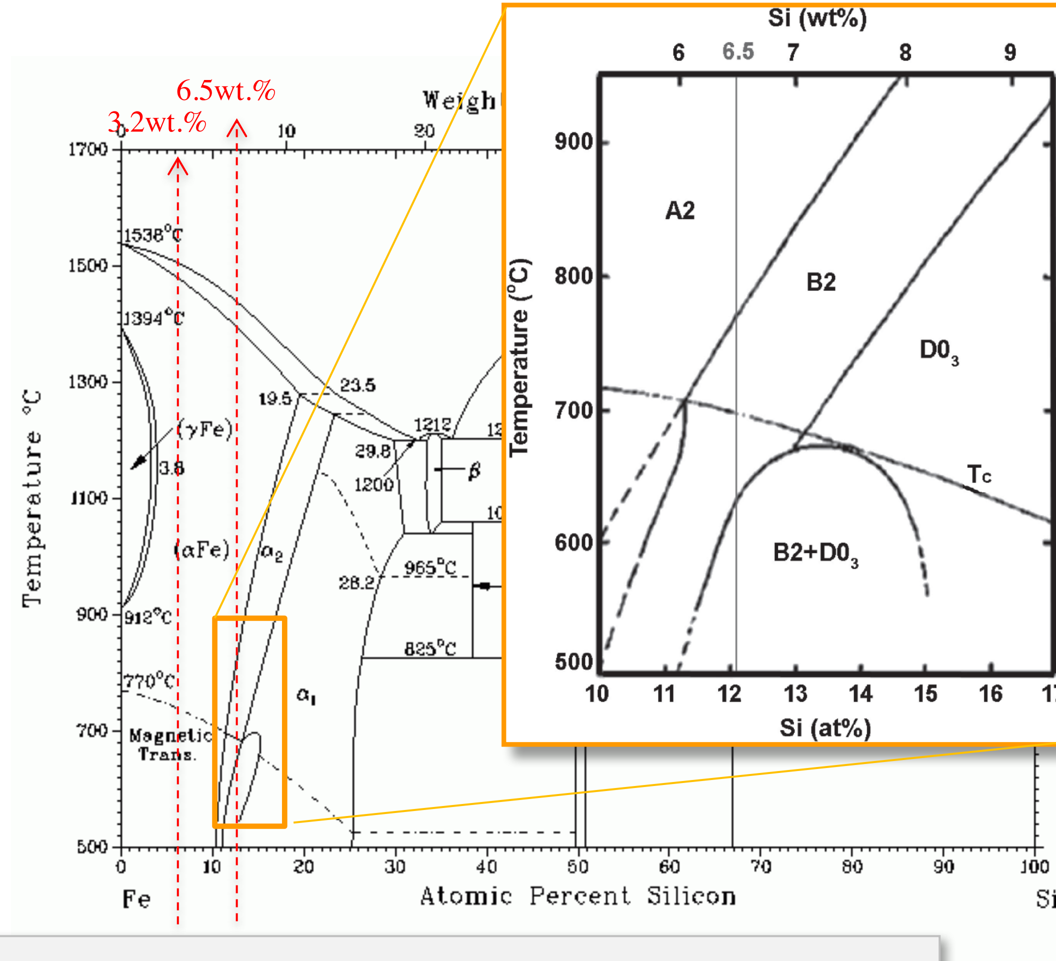
- Increasing Si wt.% improves magnetic/electric properties (6.5% Si is the optimum, lower Eddy current, smaller hysteresis loss, near zero noise
- Less heat, less demand on cooling system, higher carrier frequency, higher power density, smaller size

[1] **Characterization and Measurement of Magnetic Materials (Electromagnetism)** January 5, 2005 by Fausto Fiorillo, ISBN-13: 978-0122572517
[2] JFE-STEEL, http://www.jfe-steel.co.jp/en/products/electrical/supercore/jnex/03.html
[3] M. Mochizuhi, S. Hibino, F. Ishibashi, Elec. Machine Powr Syst. (1994) 22:1, 17-29

However, 6.5% Si steel is brittle

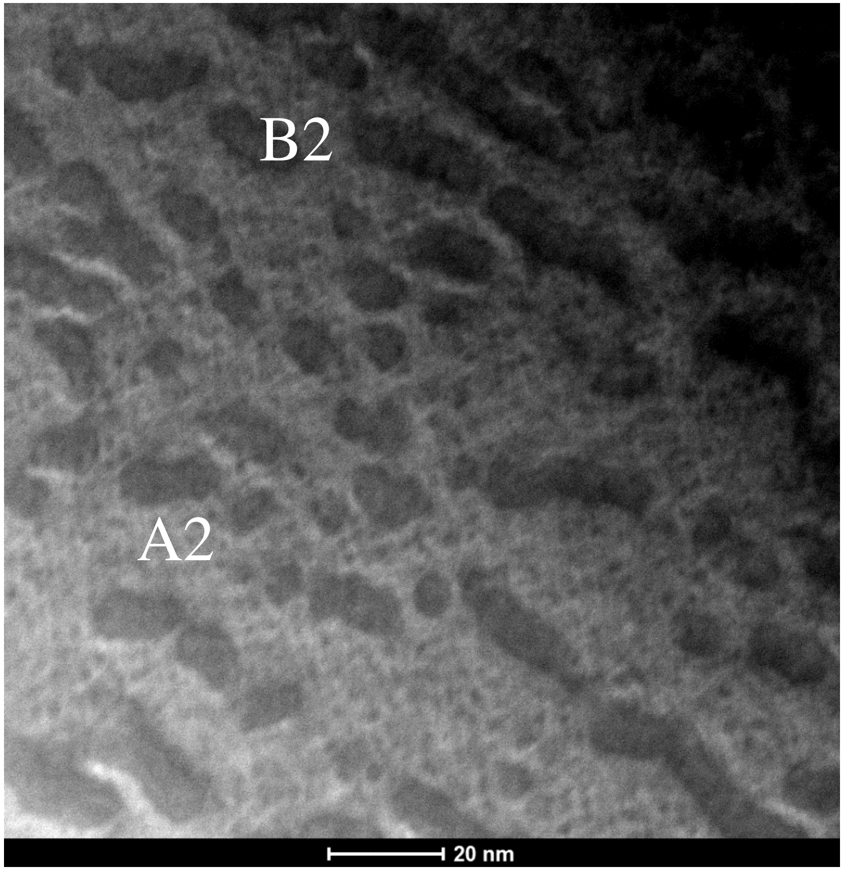


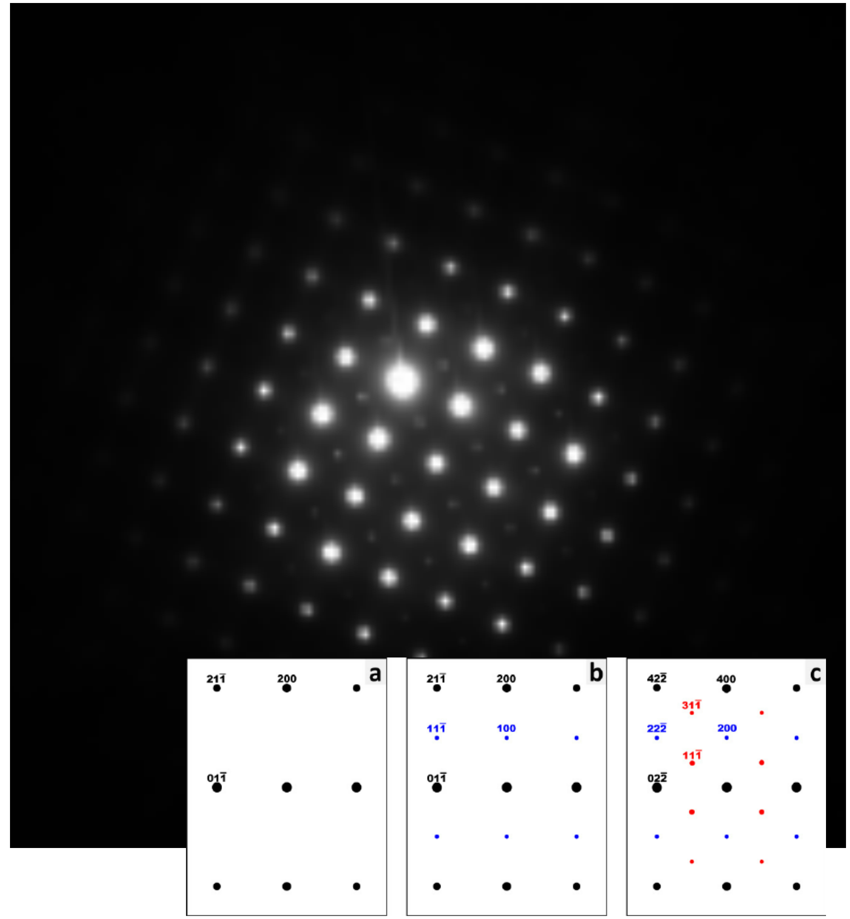
Fe (A)	Fe (B)	Si (C)
α- FeSi	A2	All sites are randomly occupied by Fe or Si
α_2- FeSi	B2	C, B sites are randomly occupied by Fe or Si
α_1- FeSi	$D0_3$	C sites are randomly occupied by Fe or Si



The heterogeneous formation of α-FeSi and $Fe_3Si(\alpha_1)$ ordered phases is responsible for severe materials embrittlement.

The B2/$D0_3$ phases in 6.5% Si steel





HAADF STEM image and [100] diffraction pattern. The A2 phase has less Si compared with B2 phase, as a result, A2 is brighter than B2 in the STEM image

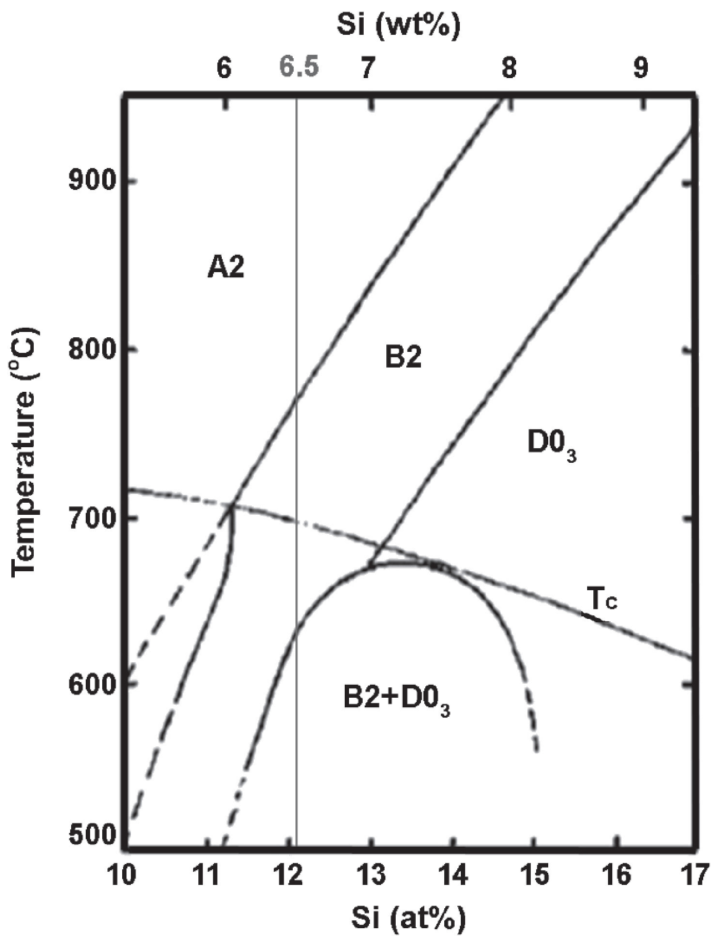
The questions are

1. What are the effects of B2/$D0_3$ phases on mechanical, electrical, and magnetic properties ?

2. Can we manipulate these phases?

3. If so, what are the consequences?

Effect of cooling rate on B2/$D0_3$ phases formation



Rapid cooling is expected to

- Suppress the formation of $D0_3$ phases, and
- Reduce B2 phase fraction

Experimental methods

- Sample preparation:
  - Melt spin method is used to prepare Fe-6.5%Si ribbons
  - Wheel speed is used to achieve various solidification rates
- Characterization methods:
  - IR thermal camera: solidification rate
  - VSM: magnetic properties
  - 4 point probe and wire: electrical resistivity
  - Hardness, tensile/compression: mechanical properties
  - XRD, SEM, TEM: microstructures

Solidification rates

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Imaging Dynamic Instabilities in Melt Spinning

TMS Spring Meeting
February 19, 2002

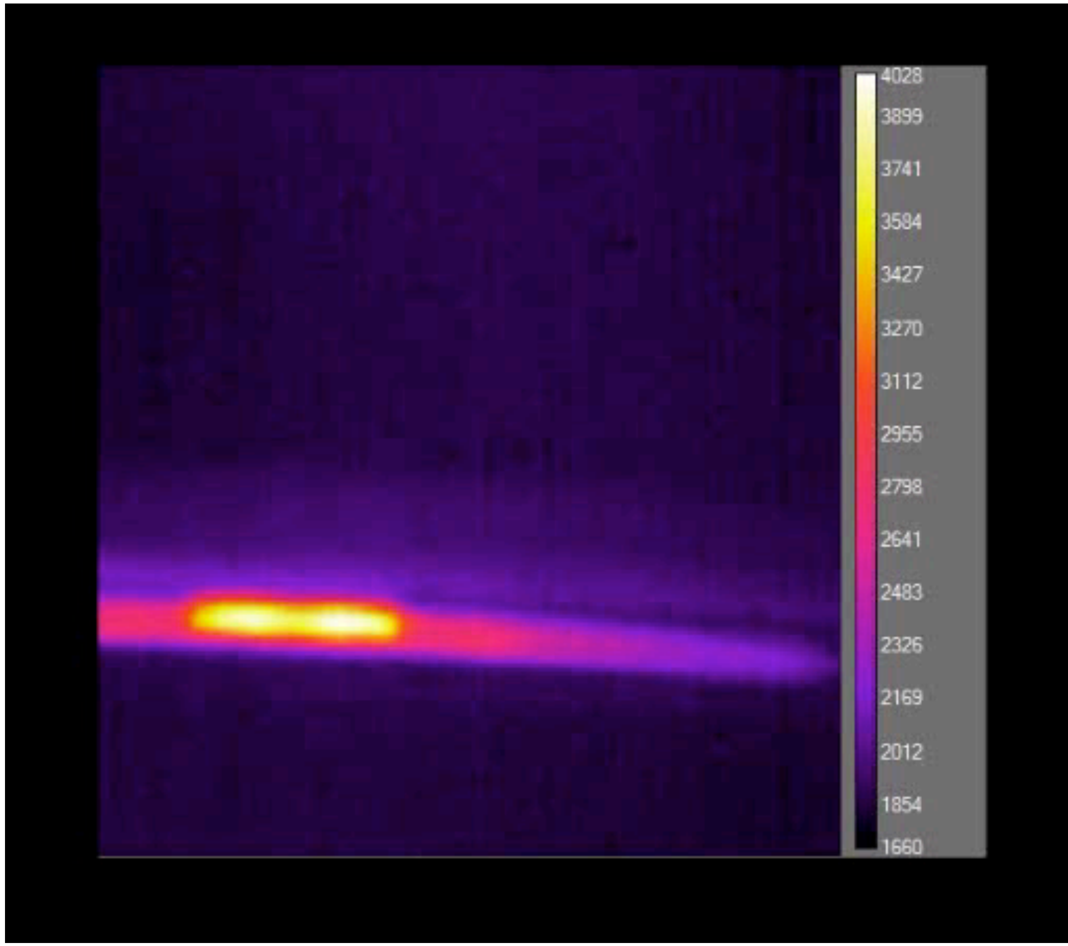
M.J. Kramer, R. E. Napolitano, H. Meco, M. Sawka, B. Kappes, K.W. Dennis and R.W. McCallum

Metal and Ceramic Sciences Program, Ames Laboratory (USDOE) and *Department of Materials Science and Engineering, ISU

U.S. Dept. of Energy, Division of Materials Sciences, Office of Basic Energy Sciences under contract No. W-7405-ENG-82 at Ames Laboratory. Additional support through the Processing Science Initiative, Materials Preparation Center, a USDOE user facility.

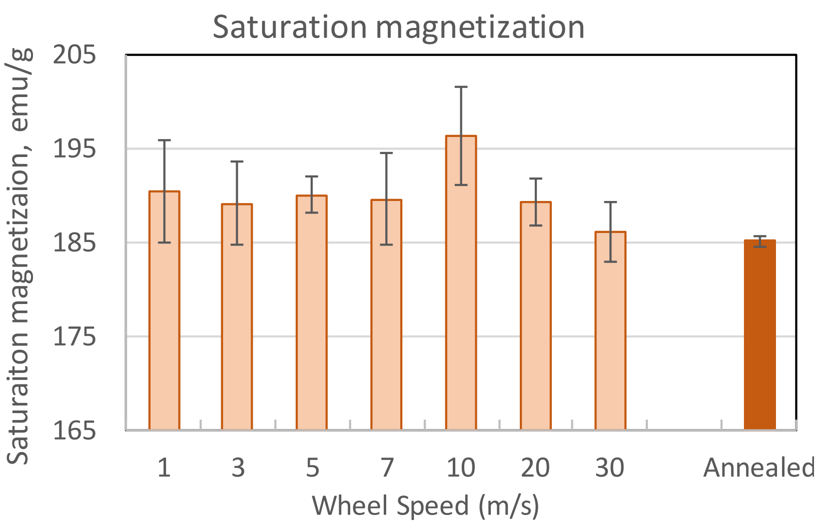
1

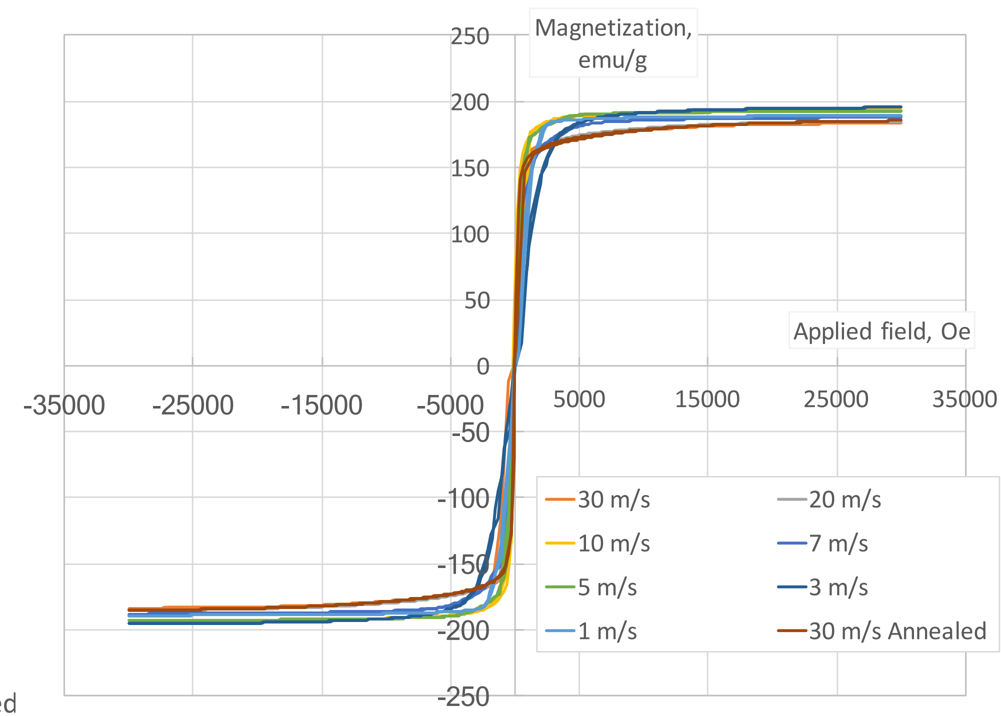
Solidification rate



Magnetic properties (saturation magnetization)

- Quantum Design Versalab VSM was used to measure saturation magnetization
- 5 samples per wheel speed were measured for error bar

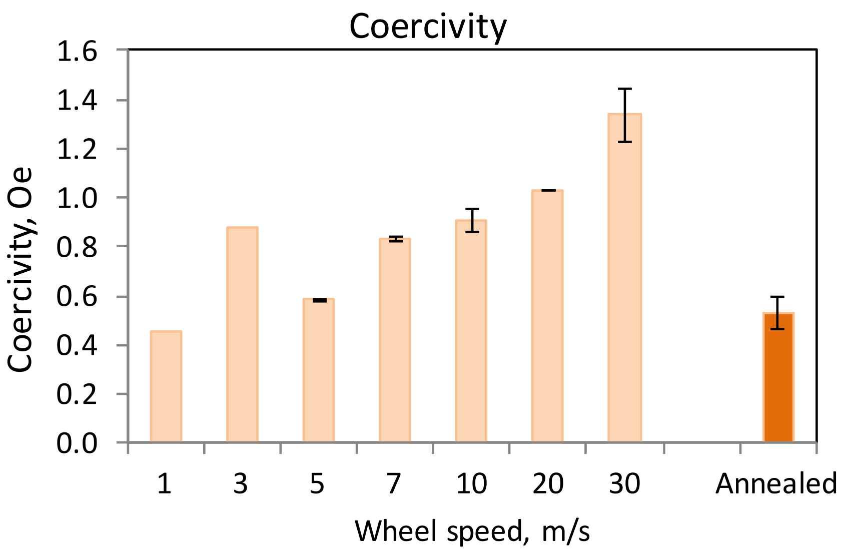


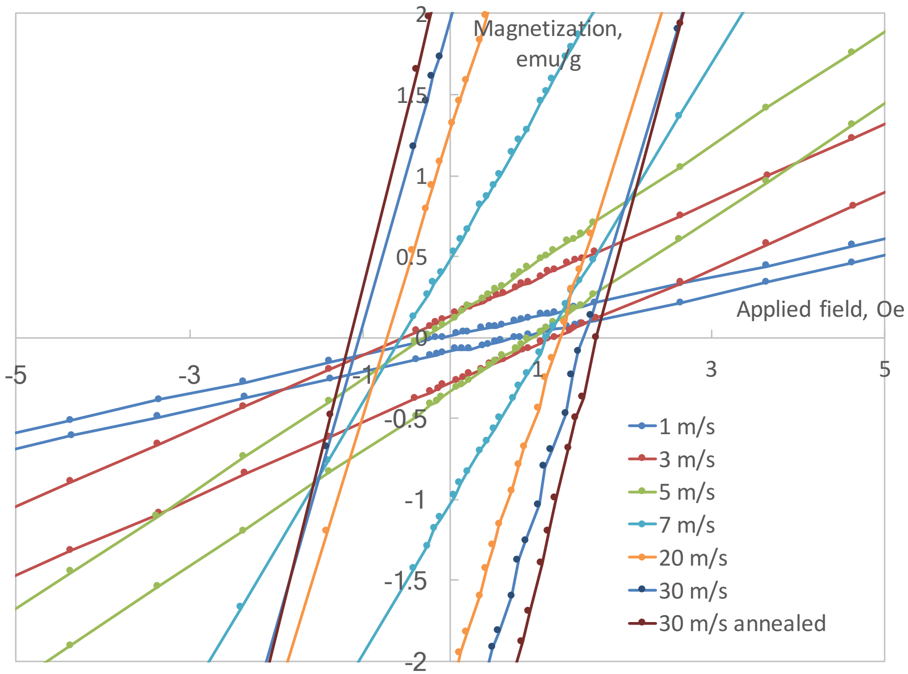


Ms decreases with increasing wheel speed, except the 10 m/s sample

Magnetic properties (coercivity)

- Microsense VSM was used to measure coercivity
- 2-5 samples per wheel speed were measured for error bar

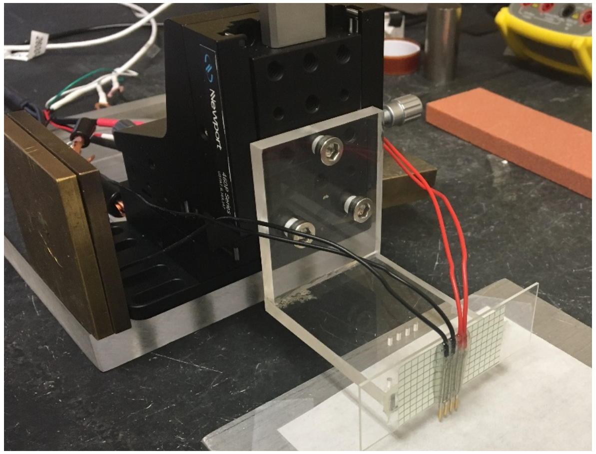


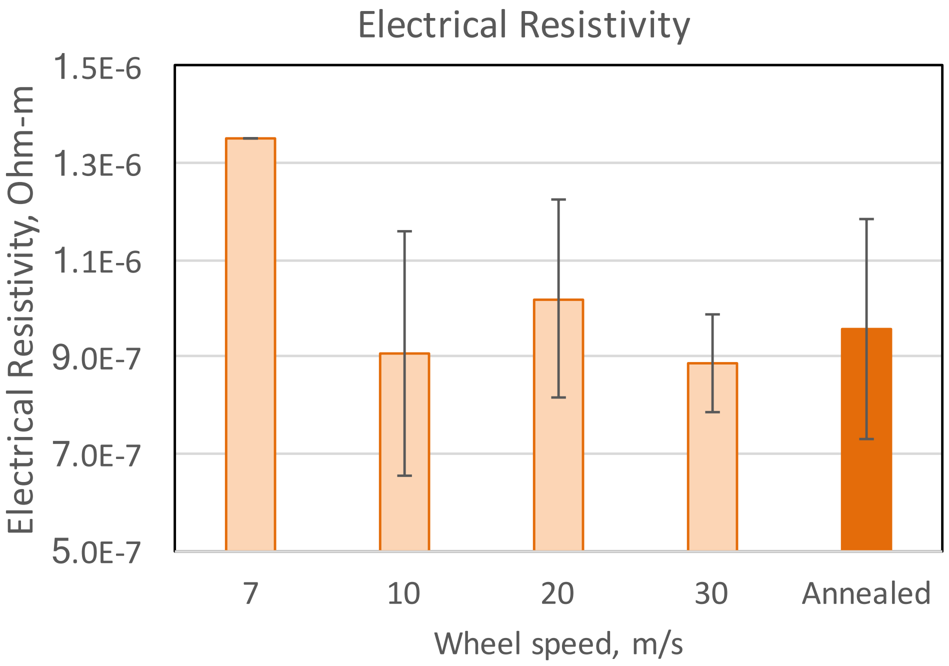


Ms decreases with increasing wheel speed, except the 10 m/s sample

Electrical resistivity

- 4 point probe method was used
- The method is calibrated using a copper foil (measured 1.71 E-8 Ω/m, theoretical 1.68 E-8 Ω/m)

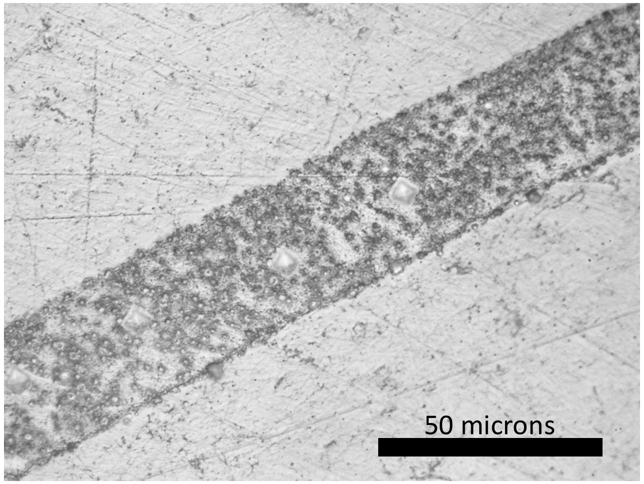


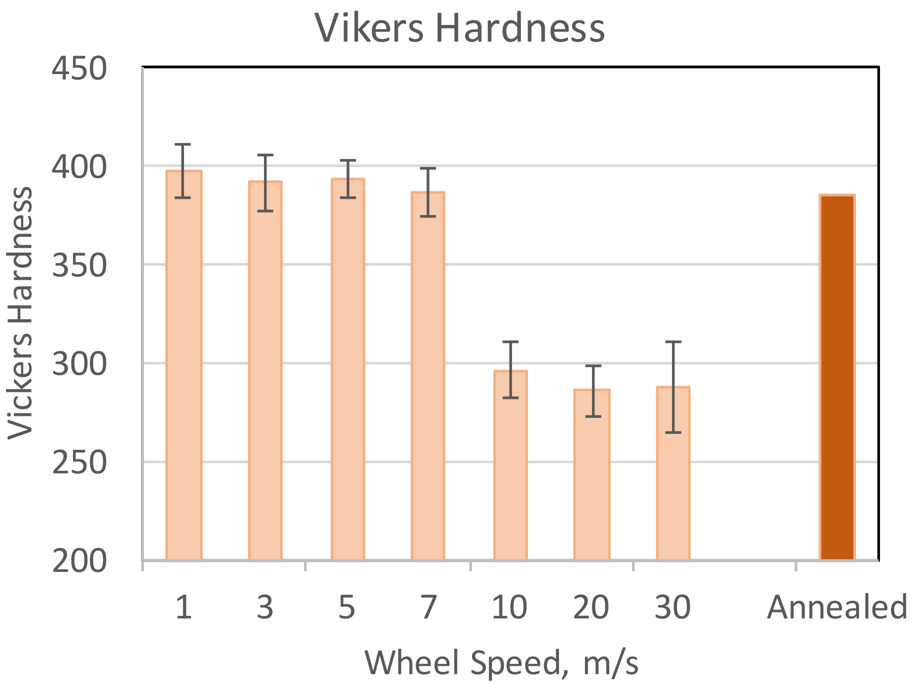


While no clear trend is observed, annealing shows signs of impact

Mechanical properties: hardness

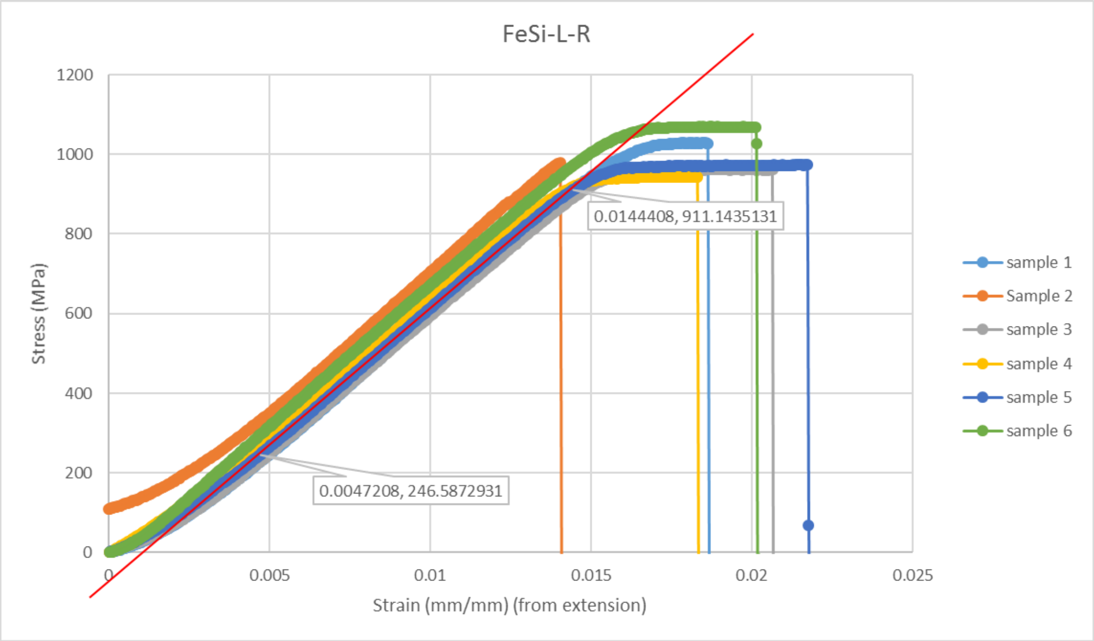
- Micro hardness indenter was used to measure Vicker hardness
- 3 samples per wheel speed (except 1 m/s), and 10 locations per sample





The critical wheel speed is between 7 and 10 m/s.

Mechanical properties: tensile (30 m/s)



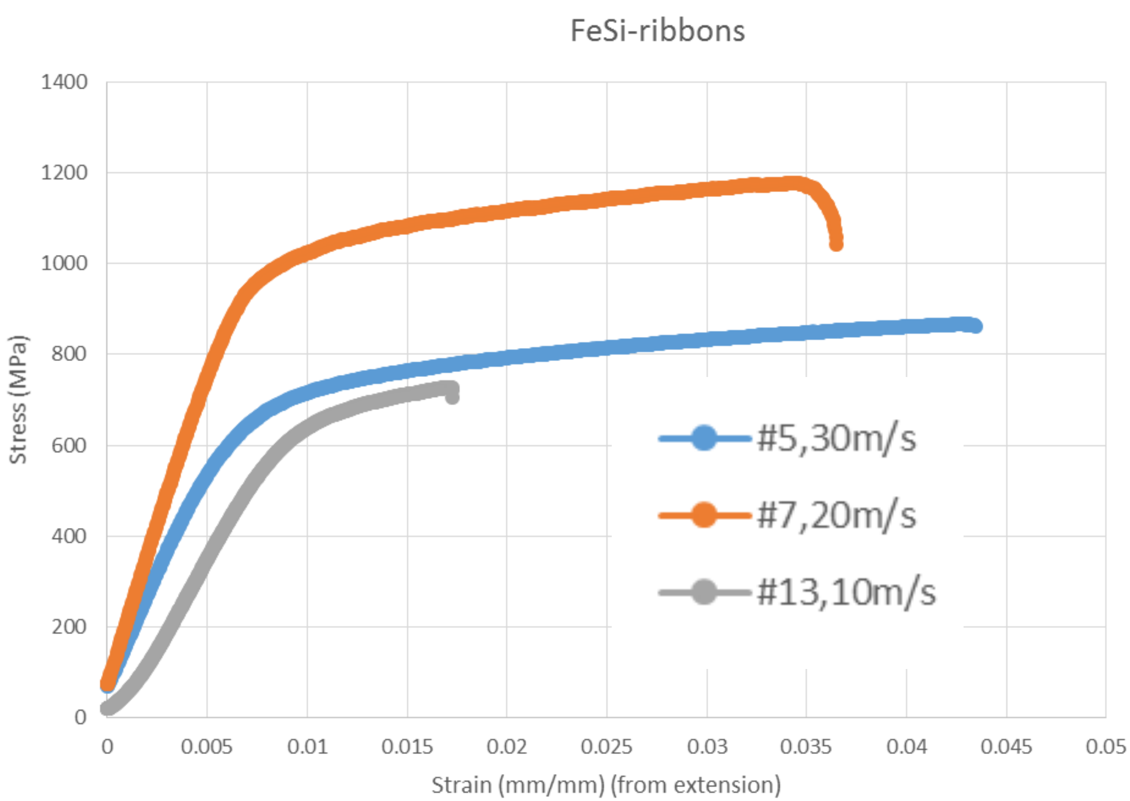
- Specimens were cut into ASTM D638-14 standard. Edges were grounded down with 1200 grit sand paper.
- Tests were done using Instron 3369 with 30KN load cell, 0.01 mm/s extension rate.
- Strain was measured using grip separation. For some tests, clip on extensometer was used to measure the true strain.

specimen number		s1	s2	s3	s4	s5	s6	average	STD
ultimate tensile strength	Mpa	1029.23	978.40	962.77	944.32	974.41	1070.31	996.21	52.12
elongation % in 25mm	extension	1.87	1.41	2.07	1.84	2.18	2.02	2.00	0.14
elongation % in 25mm	extensometer	0.62		0.91	0.78	1.02		0.83	0.17
Break in gauge?		yes	no	yes	yes	yes	yes		
Extensometer on?		yes	yes	yes	yes	yes	no		
comment		s2 excluded in all calculations.							

Typical values for steel:

- modulus: Structural ASTM-A36 steel: 200 GPa, AK steel oriented M6 silicon steel 124 GPa parallel, 200 GPa Transverse
- Ultimate tensile strength: Structural ASTM-A36 steel: 400–550 Mpa, AK steel M15 (2.7 Si%): 490 MPa
- Elongation: AK steel M15 (2.7 Si%): 23 % in 50mm.

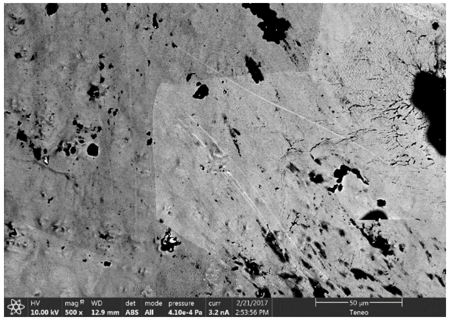
Mechanical properties: tensile (10, 20, 30 m/s)

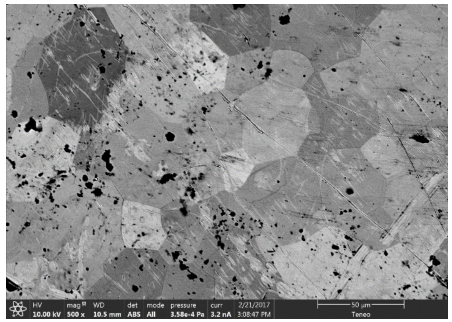


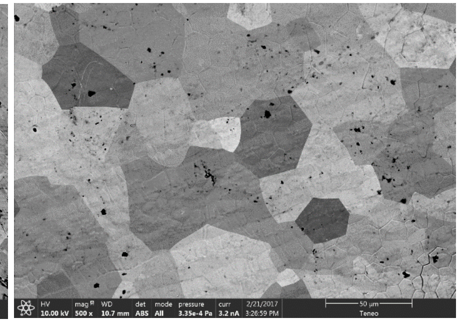
Sample	30 m/s	20 m/s	10 m/s
UTS (Mpa)	867	1177	755
Elongation %	4.53	3.65	2.25
Elastic modulus (GPa)	96.7	137	77.3
Average thickness (um)	29	35	50
Gauge Length (mm)	12.17	6.48	8.07

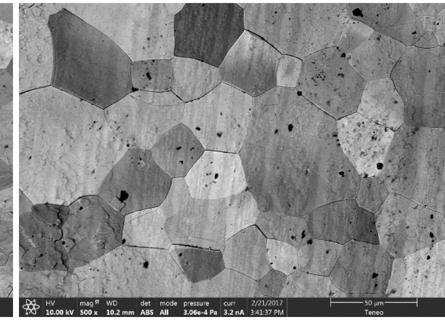
From 30m/s to 20m/s, a trend of specimens being less ductile is observed.

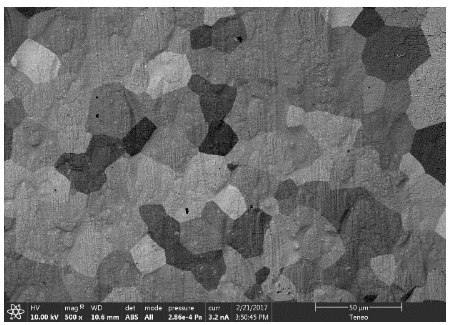
Microstructure: grain sizes (500X, BEC)

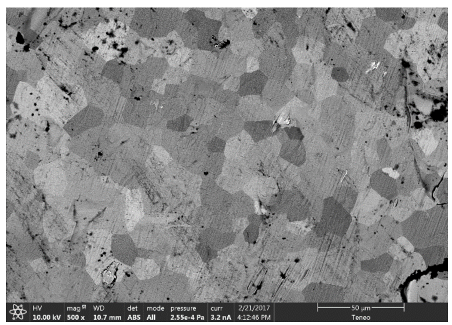

1m/s

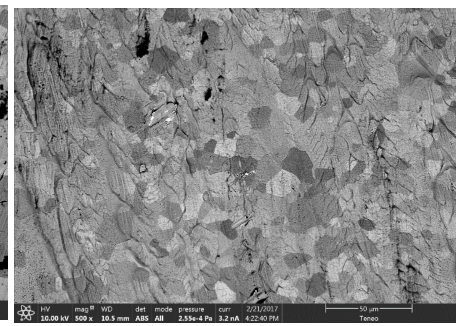

3m/s

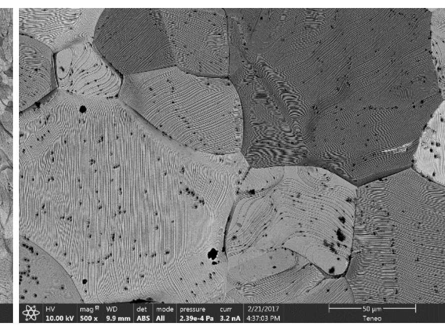

5m/s


7m/s


10m/s

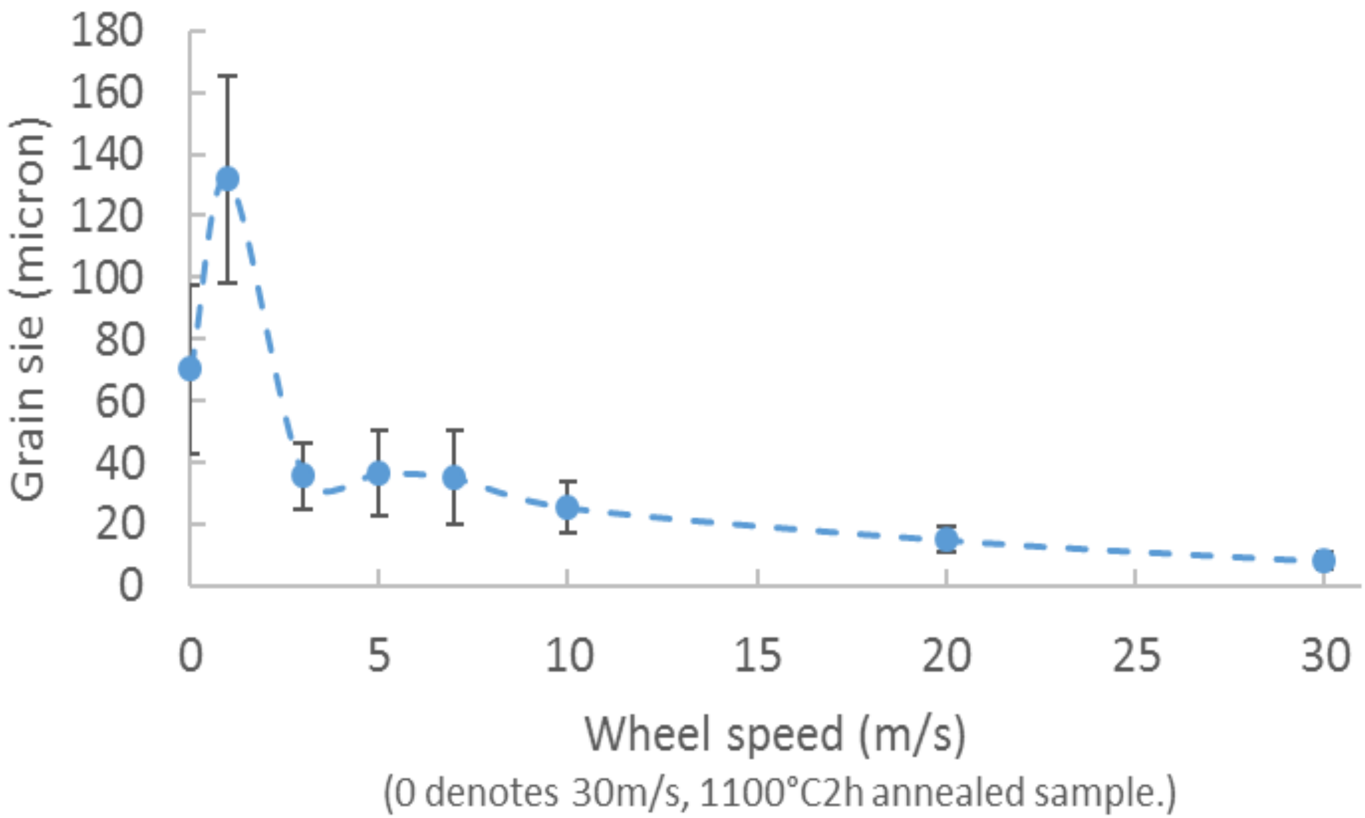

20m/s


30m/s


30m/s, 1100°C2h

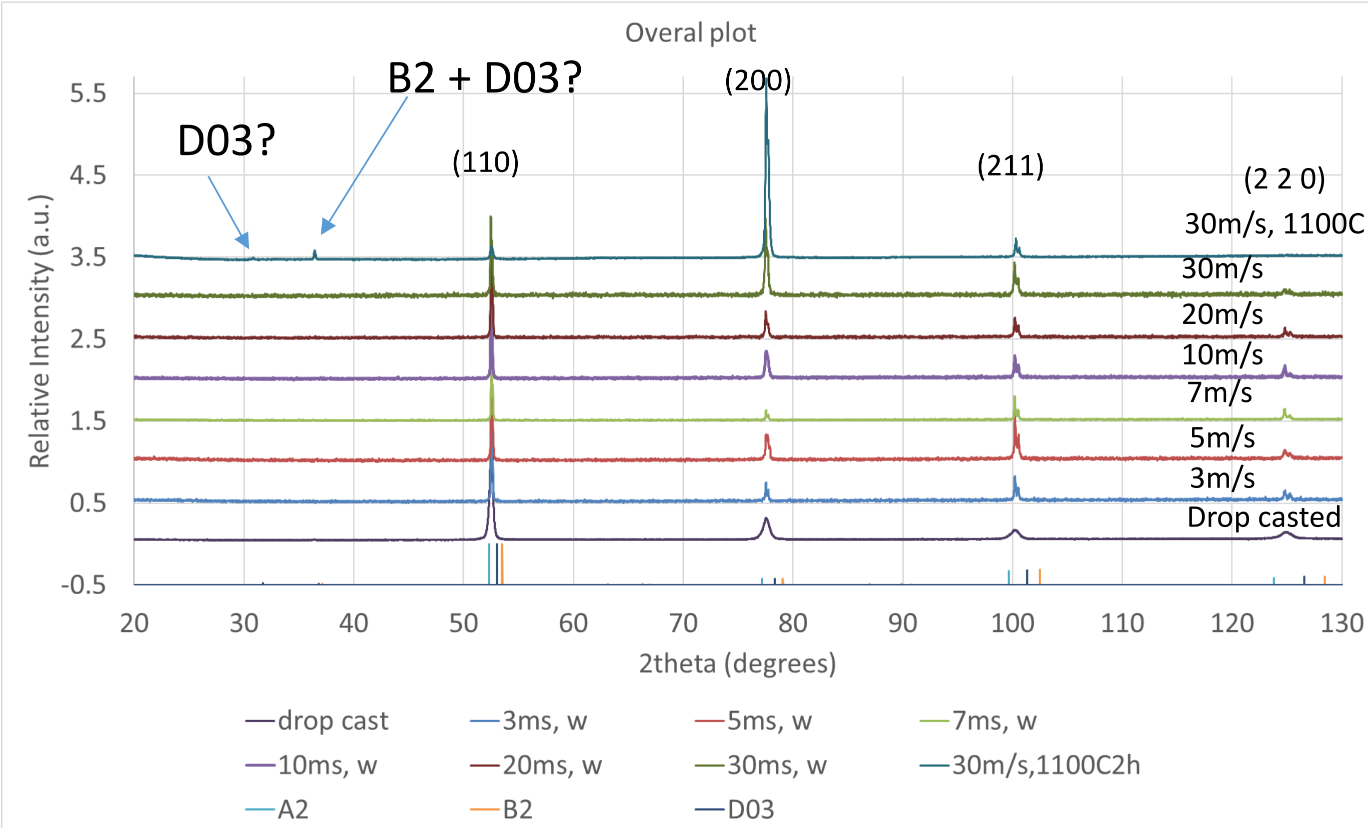
- All SEM taken on wheel side of the samples, samples were not polished.
- Backscattered images showed to reveal grain contrast.

Grain sizes



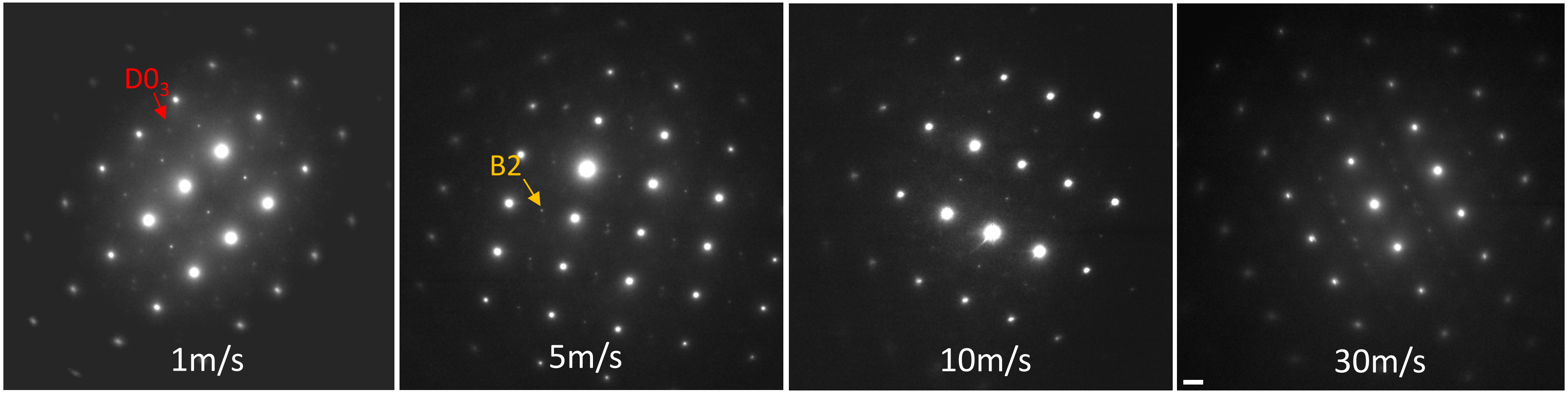
- Intercept method was used for grain size measurement. 15 grains were measured on the line for grain size analyze. 5 grains were used on 1m/s sample due to limited grains in view.
- Critical wheel speed is about 10 m/s

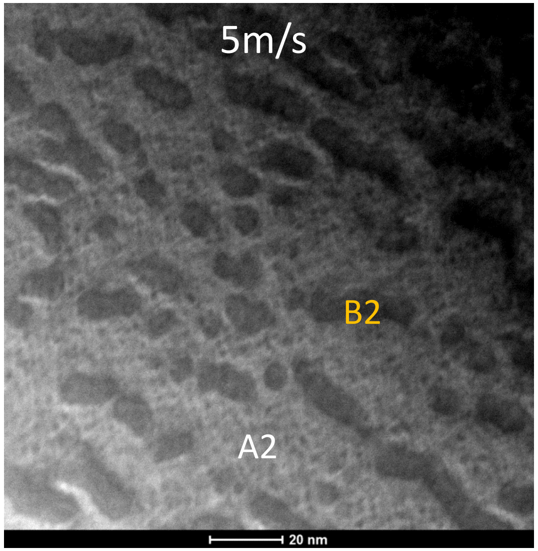
Microstructures: XRD

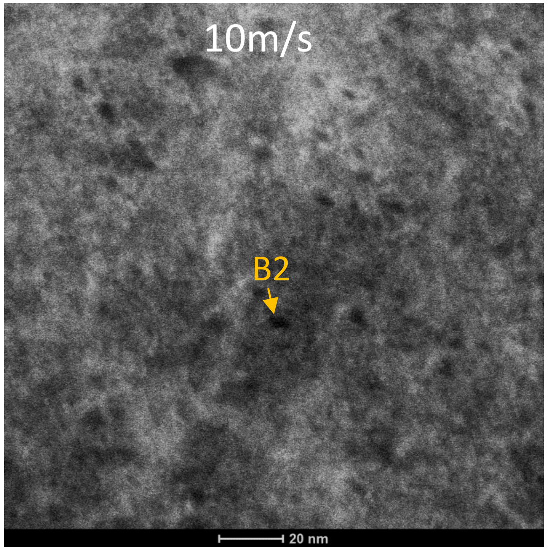


- All ribbons revealed only A2 phase.
- Major peaks of B2 and $D0_3$ overlap with A2. Peaks between 30-40° for B2 and $D0_3$ do not overlap with A2, but only somewhat visible for the long annealed sample.

Microstructure: TEM







Decrease of B2 and $D0_3$ phase volume fraction with increasing wheel speed. The $D0_3$ phase is only observed in the 1m/s sample.

Discussion

- Rapid cooling may reduce B2 phase formation, suppress $D0_3$ phase formation, reduce grain size
- Rapid cooling may increase mechanical properties
- Higher cooling rate may
  - Lower saturation magnetization
  - Increase coercivity
  - Not have clear impact on electrical resistivity

Acknowledgement

This material is based upon a grant by the Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), under Award Number DE-EE0007794*.

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