Low Loss Soft Magnetic Materials for Industrial Motor

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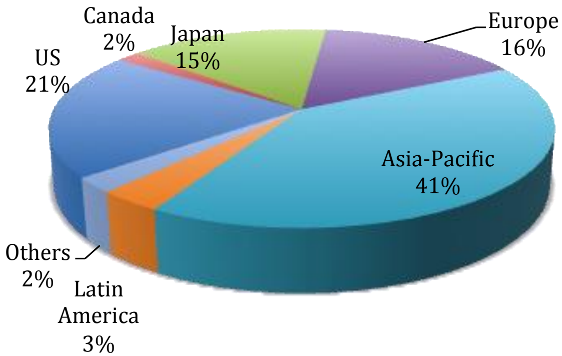
Impact of cost effective low-loss magnetics

Soft magnetic materials global market is $14B in 2010 [1]



Loss comparison of motors made of FeSi and amorphous motor (5.5 kW, 380 V, 50 Hz) [3]

Loss (W)	Amorphous Motor	Classical Motor
Core	5	28
Stator Winding	1119	1505
Rotor Winding	1140	1537
Total Losses	2265	3071

- A 1% increase in efficiency through advanced soft magnetic materials would realize 159 TWh energy savings

A successful development of cost effective soft magnet materials and manufacturing processes may

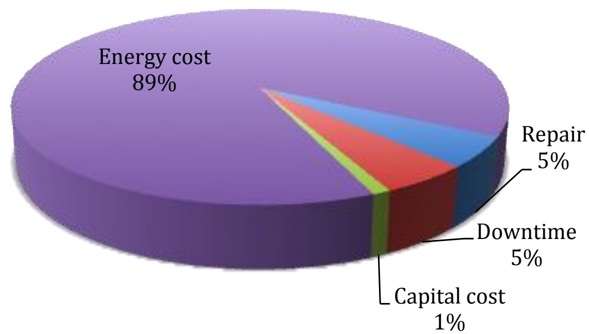
- Save energy and
- Increase U.S. share of global markets (soft magnets, motor, power electronics).

[1] Magnetic materials, A global strategic business report, MCP-1488, Global industry Analysts, Inc, Oct. 2010
[2] M. Komatsubara et al., Newly developed electrical steel for high frequency use, J. MMM. 2002, 242–245, p.212.

Priority of motor industry

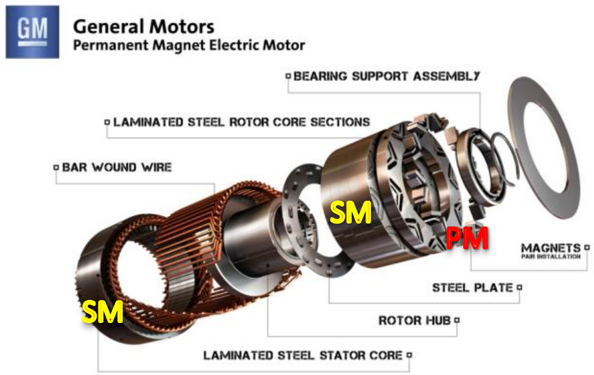
- 91% reported that all motor purchase decisions were made at the plant level.
- 8% included efficiency in their specifications for the motor to be purchased
- Customers most often use the size of the failed motor being replaced as a key factor in selecting the size of the new motor.
- Reducing capital costs is the most important consideration driving customers' decision
- The energy saving due to higher efficiency may command a small premium if there is any

- *Cost is more important than efficiency*
- *A motor is competitive if it has higher efficiency while maintaining competitive price*

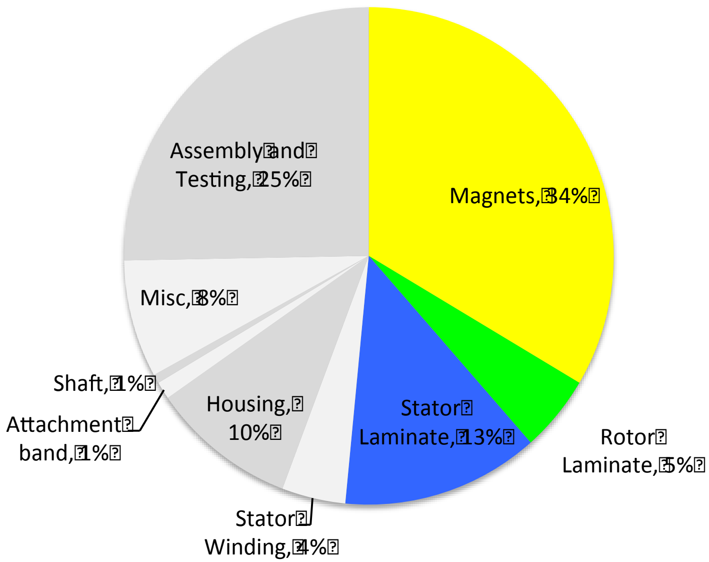


[1] United States Industrial Electric Motor Systems Market Opportunities Assessment, XENERGY, INC., Burlington, MA, 1998.
[2] Paul Waide and Conrad U. Brunner, "Energy-efficiency policy opportunities for electric motor-driven systems", International Energy Agency
[3] Premium Efficiency Motor Selection and Application Guide, A Handbook for Industry, DoE, EERE, Advanced Manufacturing Office

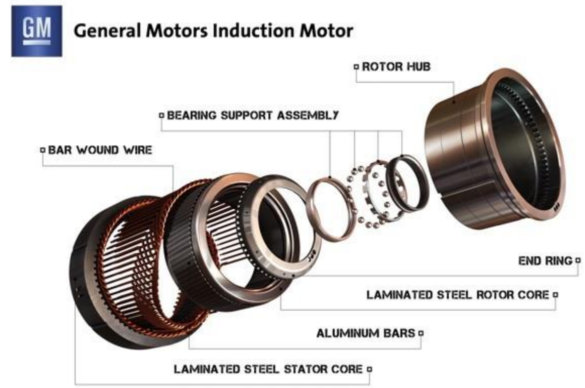
Cost Breakdown of PMM Motors



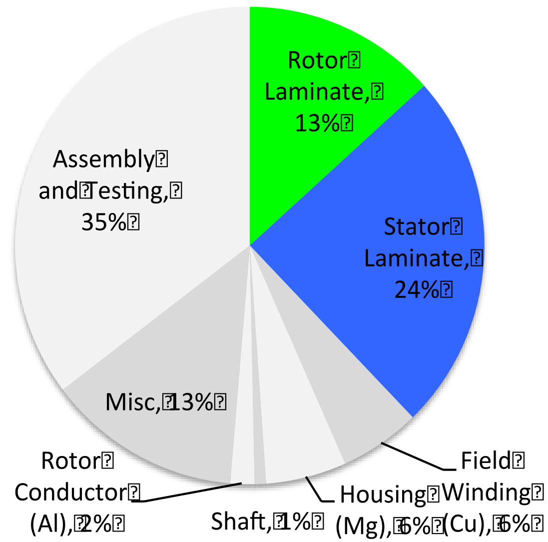
32kW PMM motor, $522



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



40kW Al Induction motor, $450



- Magnetic materials (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

Higher frequency, higher power density, smaller size, lower cost

$$RPM = \frac{120f}{\#P} \qquad HP = \frac{Torque \times RPM}{5252}$$

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

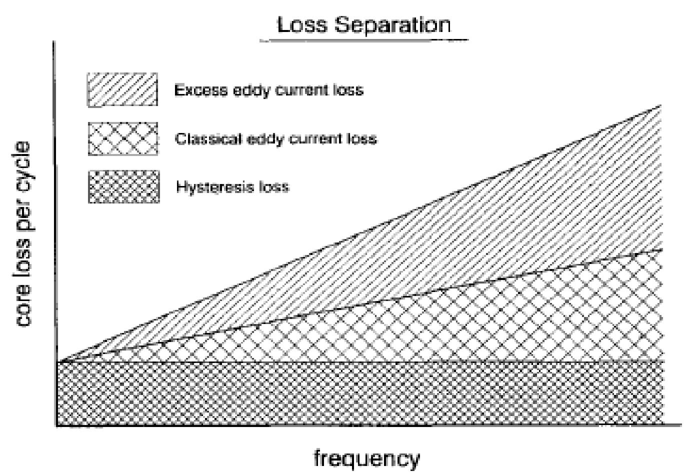
Losses

- 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

Higher *f* is beneficial only if new soft magnetic materials can keep the loss low

Total losses per cycle vs. Frequency



SOA Soft Magnetic Materials

Type	Materials	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)	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	1.4	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]

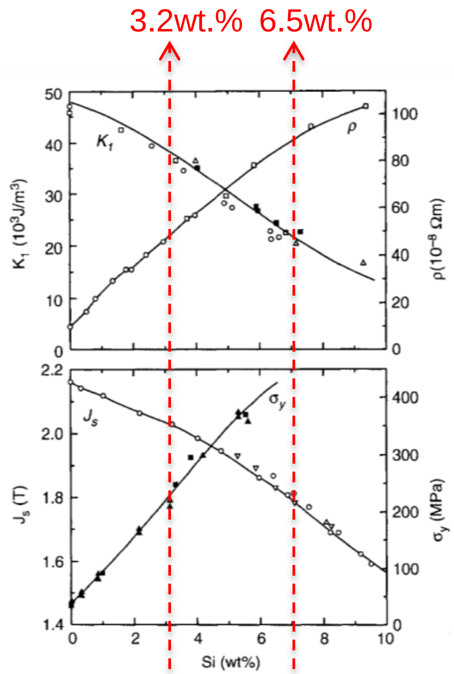
Fe-3.2%Si steel offers the most attractive cost/performance ratio

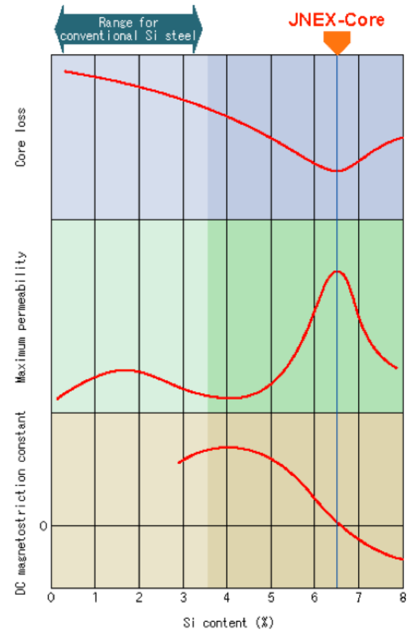
(raw materials $1.3/kg, stamped laminate $2.1/kg)

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] C. D. Jiles, Introduction to Magnetism and Magnetic Materials, Chapman and Hall, London (1990).

High Si content electrical steel promises more efficient motor

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

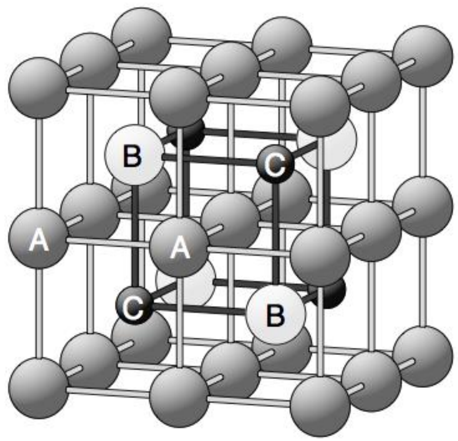




- Increasing Si wt.% improves magnetic/electric properties (6.5% Si is the optimum, lower Eddy current, smaller hysteresis loss, near zero noise
- Less heat, less demand on cooling system, higher carrier frequency, higher power density, smaller size

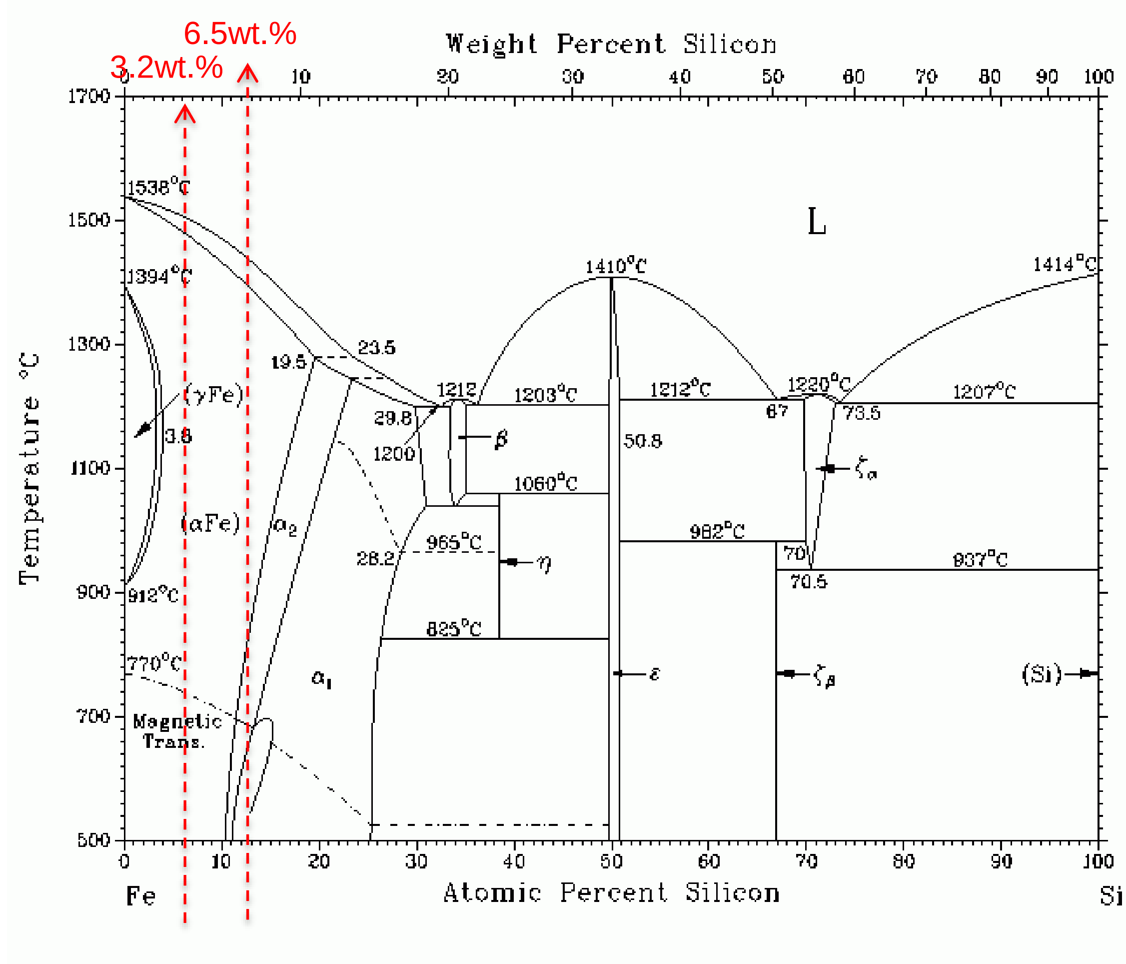
[1] **Characterization and Measurement of Magnetic Materials (Electromagnetism)** January 5, 2005 by Fausto Fiorillo, ISBN-13: 978-0122572517
[2] JFE-STEEL, http://www.jfe-steel.co.jp/en/products/electrical/supercore/jnex/03.html

Fe-Si alloys with >4% Si 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

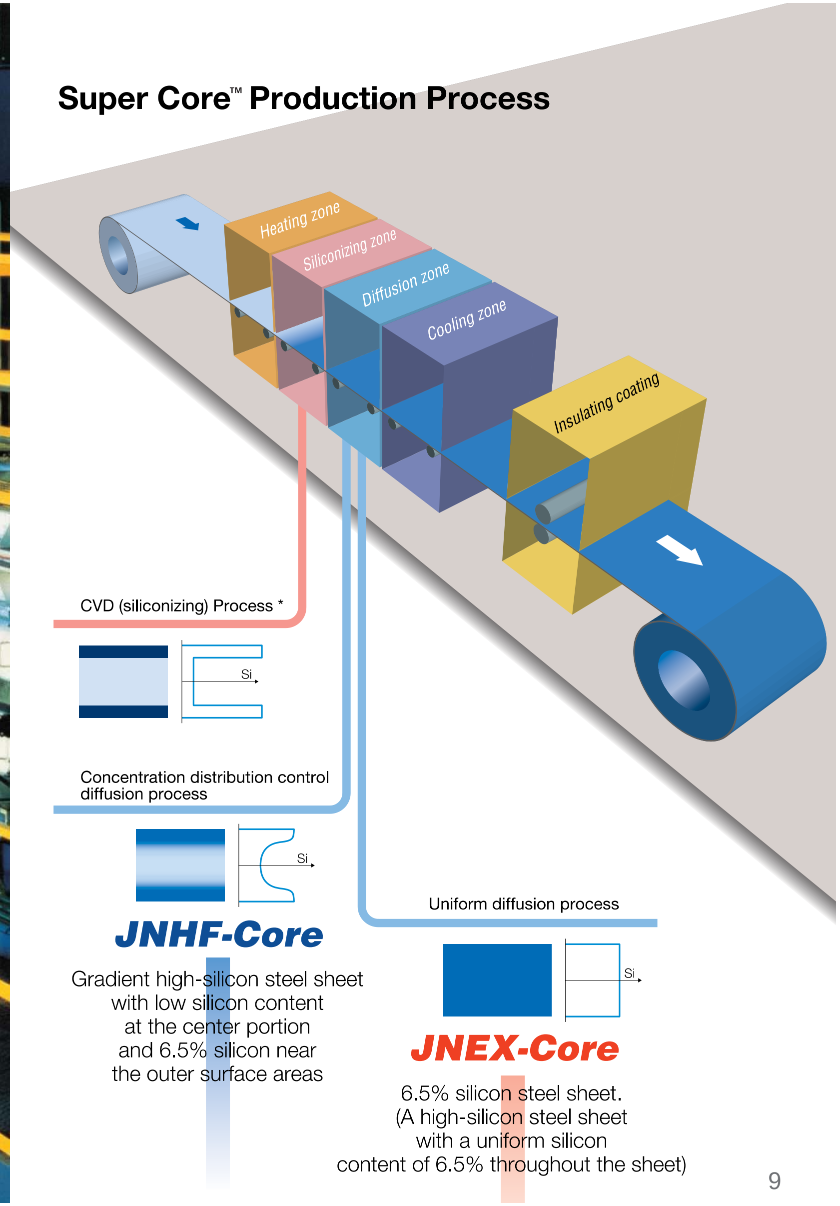


The heterogeneous formation of α-FeSi and $Fe_3Si(\alpha_1)$ ordered phases is responsible for severe materials embrittlement.

Commercial methods of manufacturing 6.5% Si steel

- CVD, PVD, or a hot dipping process followed by diffusion annealing
  - Pro: great mechanical and magnetic properties
  - Con: expensive, adverse impact to environment, thin thickness

Current methods of manufacturing 6.5% Si steel are expensive, and the product has limited applications



State-of-the-art researches on high Si steel

- Melt spinning
- Rapid solidification
- Hot/cold spray
- Direct powder rolling
- Thermal-mechanical process
  - Hot roll
  - Warm roll
  - Cold roll

Rapid Solidification

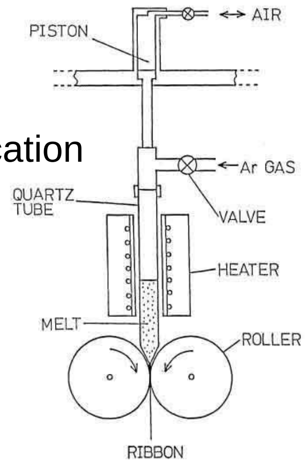


图 2-10 粉末直接轧制法生产高硅钢板[41]

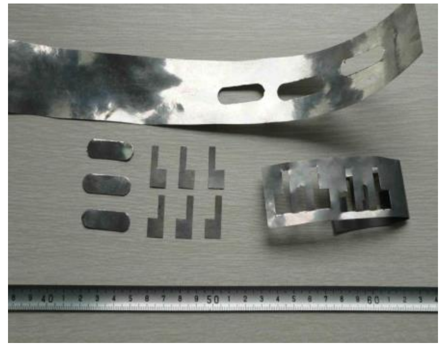
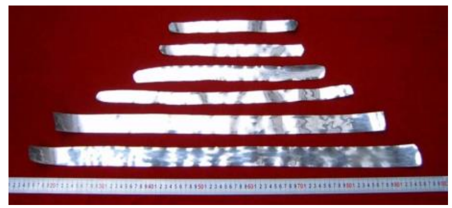


图 6-3 冲压 0.05mm 厚 Fe-6.5%Si 冷轧薄板



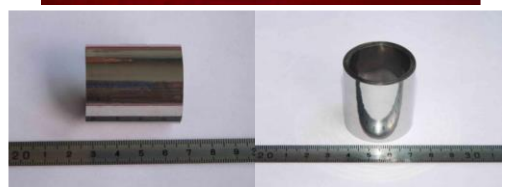


图 5-7 高硅钢冷轧板（卷）

Major progress was made in China through tailored cold-rolling process

- 0.05 to 0.5 mm 6.5%Si (with 500ppm B) sheet was successfully cold rolled and stamped
- Achieved the expected magnetic properties

Remaining challenges:

- Large ingot casting without micro-crack.
- Continuous cold rolling under tension without side cracks