Materials for magnets & measurements - I

Lecture I, Mon Nov 27

- Introduction and bibliography
- Magnetic properties of materials: types of magnetic behaviour
- Families and behaviour of magnetic materials

Lecture II, Tue Nov 28

- Materials for magnets: structural, cryogenics, vacuum
- Non-magnetic materials, phase transformations and measurements

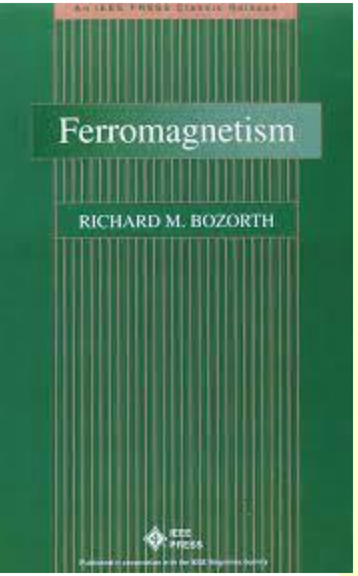
CAS course on "Normal- and Superconducting Magnets", 19/11 – 02/12/2023, St. Pölten, Austria

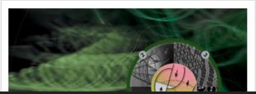
Stefano Sgobba

Engineering Department

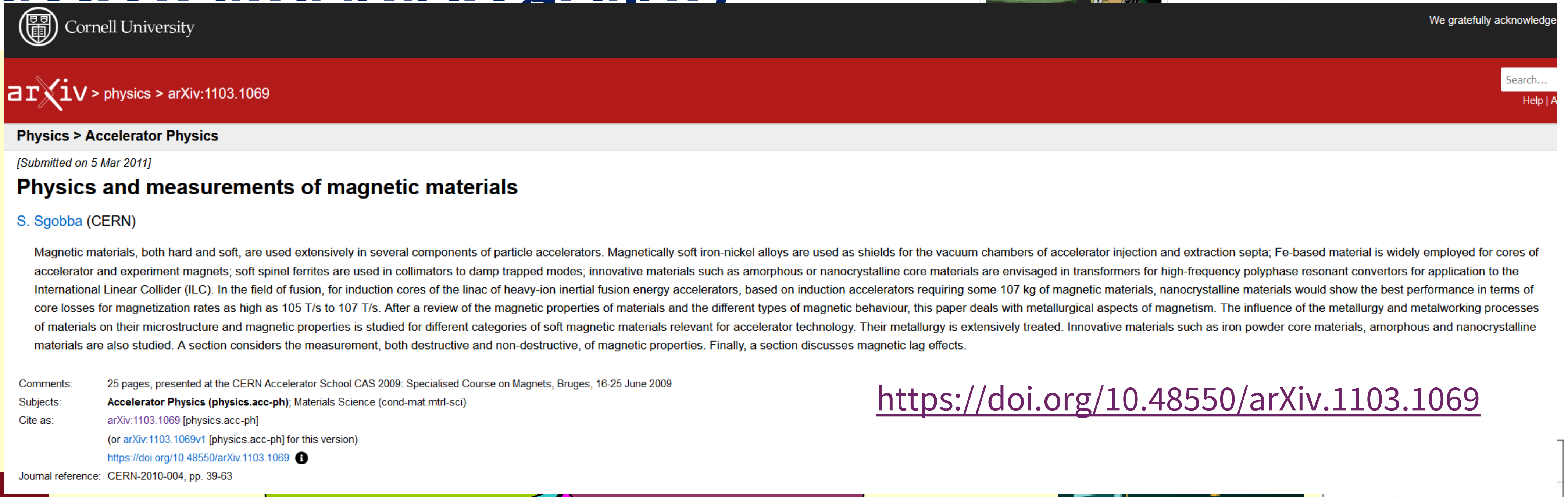
Copyright statement and speaker's release for video publishing

Introduction and bibliography





Handbook of Magnetism and Advanced Magnetic Materials, 5 Volume Set



Physics > Accelerator Physics

[Submitted on 5 Mar 2011]

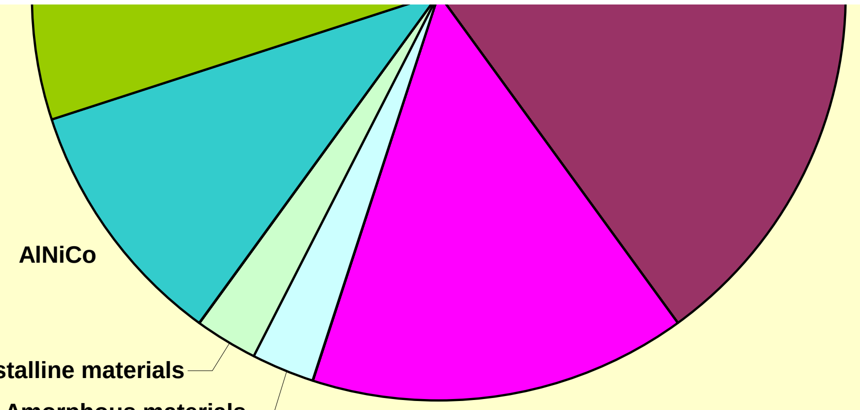
Physics and measurements of magnetic materials

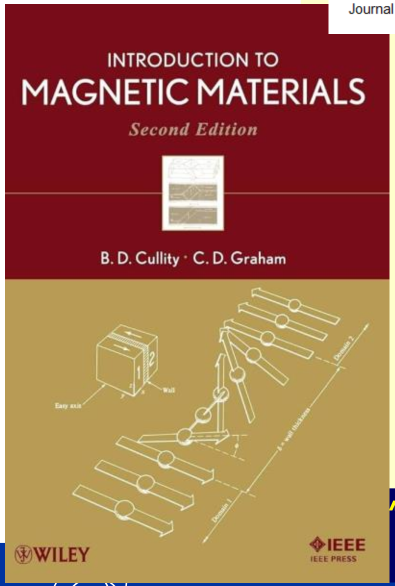
S. Sgobba (CERN)

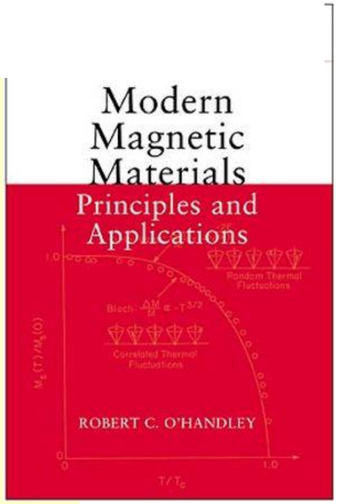
Magnetic materials, both hard and soft, are used extensively in several components of particle accelerators. Magnetically soft iron-nickel alloys are used as shields for the vacuum chambers of accelerator injection and extraction septa; Fe-based material is widely employed for cores of accelerator and experiment magnets; soft spinel ferrites are used in collimators to damp trapped modes; innovative materials such as amorphous or nanocrystalline core materials are envisaged in transformers for high-frequency polyphase resonant convertors for application to the International Linear Collider (ILC). In the field of fusion, for induction cores of the linac of heavy-ion inertial fusion energy accelerators, based on induction accelerators requiring some 107 kg of magnetic materials, nanocrystalline materials would show the best performance in terms of core losses for magnetization rates as high as 105 T/s to 107 T/s. After a review of the magnetic properties of materials and the different types of magnetic behaviour, this paper deals with metallurgical aspects of magnetism. The influence of the metallurgy and metalworking processes of materials on their microstructure and magnetic properties is studied for different categories of soft magnetic materials relevant for accelerator technology. Their metallurgy is extensively treated. Innovative materials such as iron powder core materials, amorphous and nanocrystalline materials are also studied. A section considers the measurement, both destructive and non-destructive, of magnetic properties. Finally, a section discusses magnetic lag effects.

Comments:	25 pages, presented at the CERN Accelerator School CAS 2009: Specialised Course on Magnets, Bruges, 16-25 June 2009
Subjects:	**Accelerator Physics (physics.acc-ph)**; Materials Science (cond-mat.mtrl-sci)
Cite as:	arXiv:1103.1069 [physics.acc-ph]
	(or arXiv:1103.1069v1 [physics.acc-ph] for this version)
	https://doi.org/10.48550/arXiv.1103.1069
Journal reference:	CERN-2010-004, pp. 39-63

https://doi.org/10.48550/arXiv.1103.1069







B.D. Cullity, C.D. Graham, Introduction to Magnetic Materials, 2nd ed., Wiley (2009)

Materials and Special-Purpose Metals, American Society for Metals, Metals Park, Ohio (1980)

Magnetic properties of materials

1. **Some general definitions**

2. **Types of magnetic behaviour**

    a. diamagnetism
    b. paramagnetism
    c. ferromagnetism
    d. antiferromagnetism
    e. [ferrimagnetism]
    f. [spin glasses…]

3. **Families and behaviour of magnetic and non-magnetic materials**

    a. materials for magnetic applications (with point 2.c)
    b. non-magnetic materials (point 2.b and 2.d)

4. **Phase transformations and their influence on magnetic behaviour (→28/11)**

Magnetic properties of materials

- Focused on temperature range of interest for magnet construction
- Focused on materials of technological interest
- Non-magnetic and structural materials and specific risks covered (examples issued from CERN and ITER applications)
- Applied and technological approach
- SI units used

Magnetic properties of materials, some definitions

- **Flux density, magnetic induction B (T)**
- **Permeability μ ($H \cdot m^{-1}$)**
- **Magnetic field strength H ($A \cdot m^{-1}$)**

$$B = \mu \cdot H$$

- **Magnetization M ($A \cdot m^{-1}$)**

$$B = \mu_0 \cdot (H + M)$$

- **Permeability of free space μ_0 ($H \cdot m^{-1}$)**
- **Susceptibility κ (dimensionless) $= M/H$**

Magnetic properties of materials, some definitions

- From above equations
  - $\mu = \mu_0 \cdot (1 + \kappa)$
- Relative permeability defined as
  - $\mu_r = \mu / \mu_0 = 1 + \kappa$
- and frequently encountered in discussions of ferromagnetic materials
- μ, μ_r, κ are properties of materials

Magnetic properties of materials, some definitions

SI units exclusively used

Table 6.1 Units for magnetic properties.

Property	cgs emu Symbol	cgs emu Units	Conversion Factor, C [a]	mks SI Symbol	mks SI Units
Flux density, magnetic induction	B	gauss (G)	10^{-4}	B	tesla (T) [b]
Flux	ϕ	maxwell (Mx)	10^{-8}	ϕ	weber (Wb)
Magnetic field strength, magnetizing force	H	oersted (Oe) [c]	$10^{3}/4\pi$	H	$A\cdot m^{-1}$ [d]
(Volume) magnetization	M	$emu\cdot cm^{-3}$ [e]	10^{3}	M [f]	$A\cdot m^{-1}$
(Volume) magnetization	$4\pi M$	gauss (G)	$10^{3}/4\pi$	M	$A\cdot m^{-1}$
(Mass) magnetization	σ, M	$emu\cdot g^{-1}$	1	σ, M	$A\cdot m^{2}\cdot kg^{-1}$
(Volume) susceptibility	χ	dimensionless $emu\cdot cm^{-3}\cdot Oe^{-1}$ $emu\cdot cm^{-3}$	4π	κ	dimensionless
(Mass) susceptibility	χ_{ρ}	$cm^{3}\cdot g^{-1}$ $emu\cdot g^{-1}\cdot Oe^{-1}$ $emu\cdot g^{-1}$	$4\pi \times 10^{-3}$	κ_{ρ}	$m^{3}\cdot kg^{-1}$
(Molar) susceptibility	χ_{mol}	$cm^{3}\cdot mol^{-1}$ $emu\cdot g^{-1}\cdot mol^{-1}\cdot Oe^{-1}$ $emu\cdot mol^{-1}$	$4\pi \times 10^{-6}$	κ_{mol}	$m^{3}\cdot mol^{-1}$
Magnetic moment	m	$erg\cdot Oe^{-1}$, $erg\cdot G^{-1}$	10^{-3}	m	$A\cdot m^{2}$, $J\cdot T^{-1}$
Permeability	μ	dimensionless	$4\pi \times 10^{-7}$	μ	$henry\cdot m^{-1}$ $(H\cdot m^{-1})$ [g]
Relative permeability	—	—	1	μ_r	dimensionless

[a] Multiply a number in cgs emu system by C to convert it to mks SI.
[b] $T = Wb\cdot m^{-2} = V\cdot s\cdot m^{-2}$.
[c] Dimensionally, 1 Oe = 1 G.
[d] Often expressed as ampere-turn$\cdot m^{-1}$.
[e] The designation "emu" is not a unit. Sometimes substitution of "$erg\cdot Oe^{-1}$" or "$erg\cdot G^{-1}$" will yield correct units.
[f] Often called intensity of magnetization, I, or magnetic polarization, J. It is the magnetic moment per unit volume.
[g] $H\cdot m^{-1} = Wb\cdot A^{-1}\cdot m^{-1}$.

R.P. Reed, A.F. Clark (1983)

Magnetic properties of materials, some general definitions

- **The basic natural unit for magnetism is the "Bohr magneton"**

$$\mu_B = e \cdot h / 4\pi \cdot m_e = 9.274 \cdot 10^{-24}\ A \cdot m^2$$

- **Three sources of the magnetic force of a free atom (Kittel):**
  a. The spin with which electrons are endowed
  b. Their orbital angular momentum about the nucleus
  c. The change in orbital moment induced by an applied magnetic field

  - a and b give paramagnetic contributions to the magnetisation
  - c gives a diamagnetic contribution

Magnetic properties of materials

TS Department-Metallurgy and Metrology
CERN/TS/MME/MM/GJ/30-10-2008 *EDMS 976034*

CERN — European Organization for Nuclear Research

TS/MME-MM
Section de Métallurgie et Métrologie/ *Metallurgy and Metrology section*
Rapport expérimental / *Investigation report*

Domaine / Field: ., *prélèvement écran faisceau QBQI-24R3*	*Date: 30-10-2008*	*N° EDMS / EDMS Nr.: 976034*
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…ement de poussières magnétiques dans l'écran …t à l'aide d'un aimant permanent)

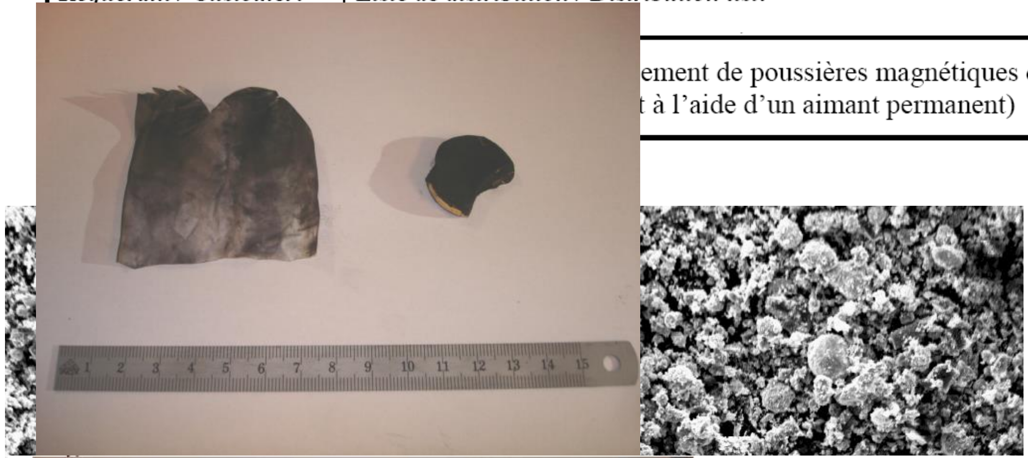


Figure 3

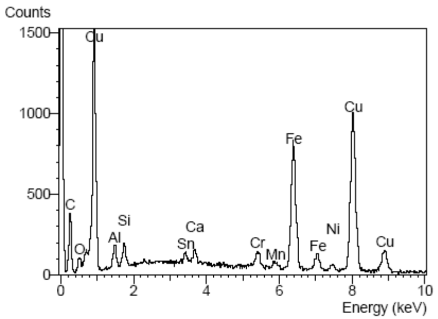


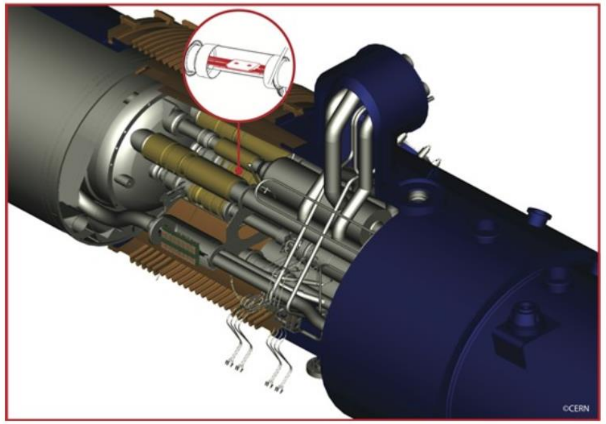
Figure 7: analyse sur particule voir Fig. 5 (flèche rouge):
C – O – Al – Si – Sn - Ca – Cr – Mn – **Fe** – Ni - **Cu**

Elmt	Spect. Type	Element %	Atomic %
Al K		2.13	4.61
Si K		1.89	3.93
Ca K		0.74	1.07
Cr K		2.09	2.35
Mn K		[illegible]	0.95
Fe K		24.45	25.58
Ni K		2.02	2.01
Cu K		63.47	58.36
Sn L		[illegible]	1.15
Total		100.00	100.00

CERN releases analysis of LHC incident

16 OCTOBER, 2008

Geneva, 16 October 2008. Investigations at CERN following a large helium leak into sector 3-4 of the Large Hadron Collider (LHC) tunnel have confirmed that cause of the incident was a faulty electrical connection between two of the accelerator's magnets. This resulted in mechanical damage and release of helium from the magnet cold mass into the tunnel.



Damage of the LHC magnets in sector 3-4 of the LHC, provoked by the incident which happened on 19 September 2008 (Image: CERN)

Magnetic properties of materials

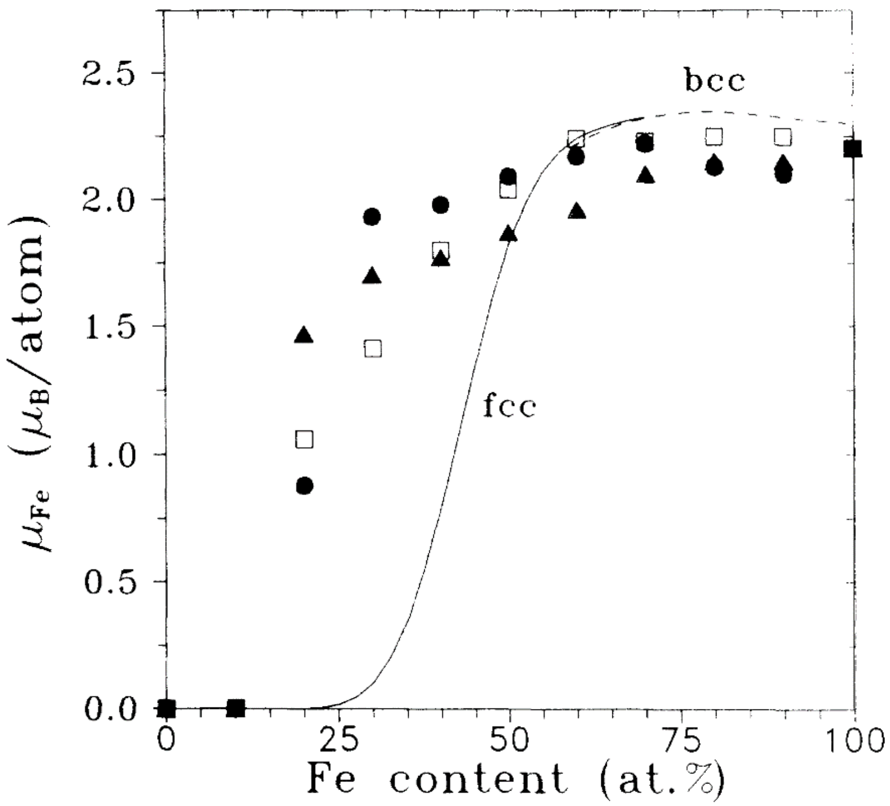


FIG. 5. Magnetic moment per Fe atom (μ_{Fe}) for bcc (dashed lines) and fcc (solid lines) Fe_xCu_{100-x} as a function of Fe content. Symbols denote experimental data (black dots from Ref. 2, triangles from Ref. 4, and squares from Ref. 6).

PHYSICAL REVIEW B VOLUME 50, NUMBER 2 1 JULY 1994-II

Ferromagnetism in FeCu metastable alloys

P. A. Serena and N. García
Grupo de Física de Sistemas Pequeños, Consejo Superior de Investigaciones Científicas, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain
(Received 7 February 1994)

TABLE I. Magnetization of bcc and fcc Fe_xCu_{100-x} metastables alloys as a function of the Fe content. Nonmagnetic phases are labeled N.M.

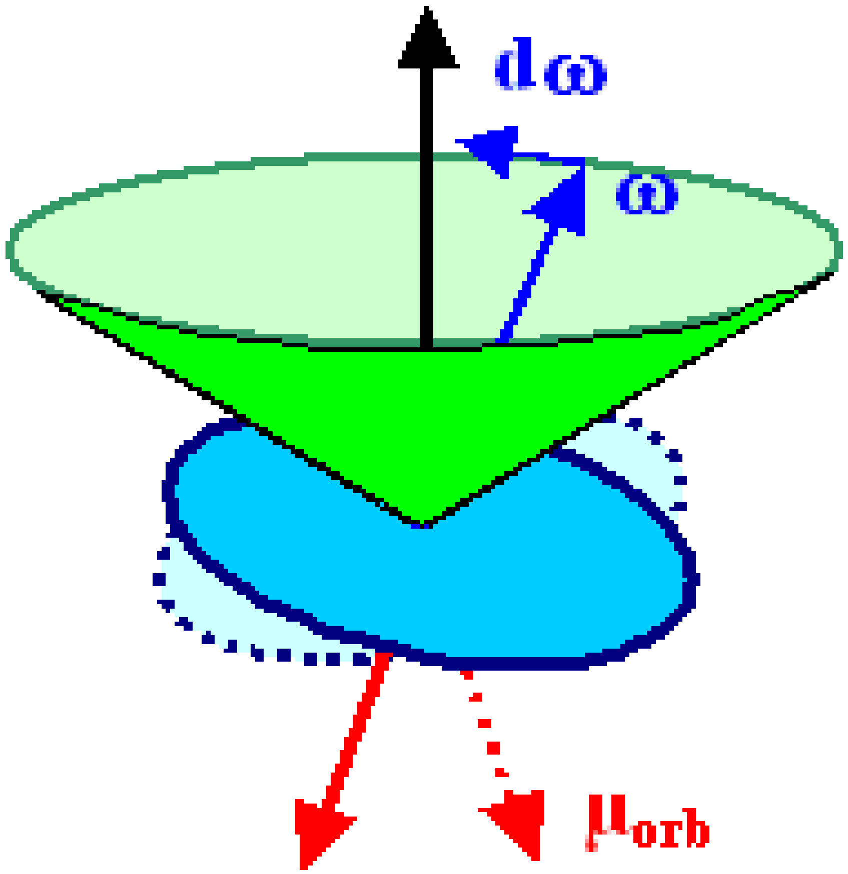
	Magnetic moment per Fe atom (μ_B)	
Fe content at. %	bcc	fcc
0	N.M.	N.M.
25	N.M.	N.M.
50	2.10	2.18
75	2.32	2.30
100	2.30	2.42

Magnetic properties of materials

Types of magnetic behaviour, <u>diamagnetism</u>

Features:

1) Materials with a negative magnetic susceptibility are called diamagnetics,
2) due to shielding currents giving a moment that opposes the applied field and is proportional to it
3) it is constant, negative and small ($\kappa \cong 10^{-6}$)



The response of an orbiting electron to a changing magnetic field is a precession of the orbit, i.e. the polar vector describing the orbit now moves in a circle around the magnetic field vector H

Magnetic properties of materials, diamagnetism

R.P. Reed, A.F. Clark (1983)

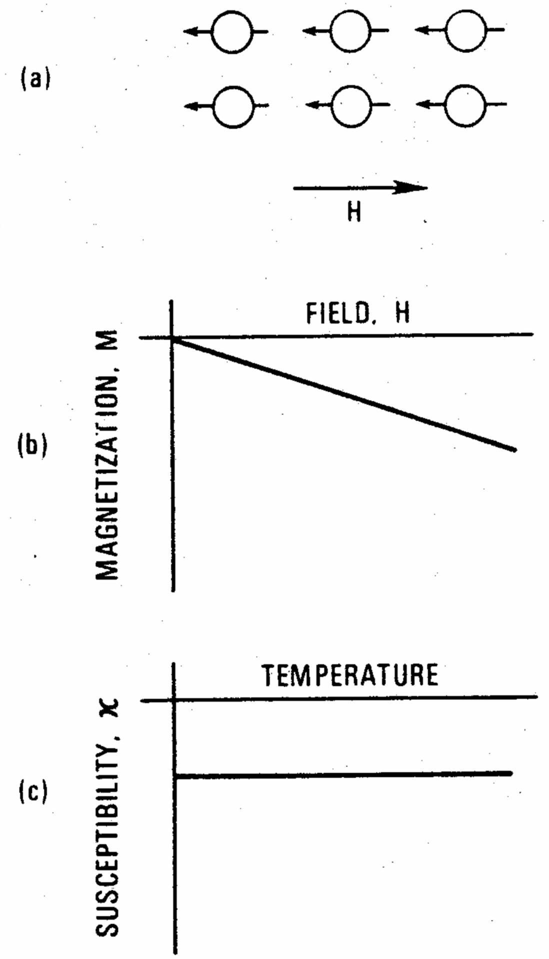


Figure 6.1 (a) Diamagnetic alignment of atomic magnetic moments. (b) Magnetization vs. field for a diamagnet. (c) Susceptibility vs. temperature for a diamagnet.

The minus sign arises from the fact that the effect of a changing magnetic fields will be opposing the cause in accordance with Lenz's law.

"Changing" magnetic fields, because there is no way to bring matter into a magnetic field without changing it - either be switching it on or by moving the material into the field.

Induced currents are of the type that persist even when the field is no longer changing

Occurs in atoms and superconductors (perfect diamagnetism for certain SC, κ = -1)

Even in a normal metal there is a diamagnetic contribution from conduction electrons

Magnetic properties of materials, diamagnetism

R.P. Reed, A.F. Clark (1983)

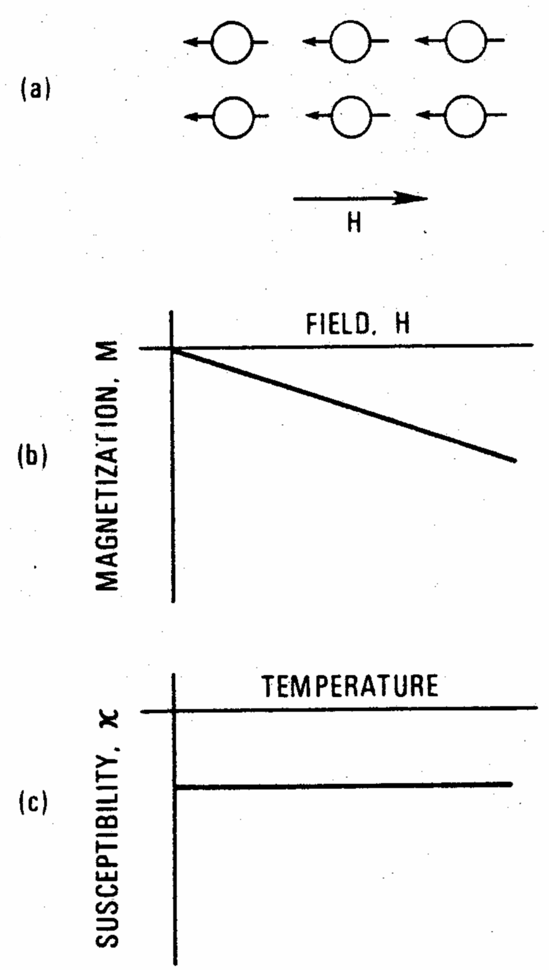


Figure 6.1 (a) Diamagnetic alignment of atomic magnetic moments. (b) Magnetization vs. field for a diamagnet. (c) Susceptibility vs. temperature for a diamagnet.

- **Copper representative of diamagnetic materials of technical importance**
- **T-dependent contributions are attributed to Fe impurities**
- **Most specimens show a significant decrease of their diamagnetism at low T**
- **Less negative susceptibility in the figure**
- **Contamination during the wiredrawing process?**

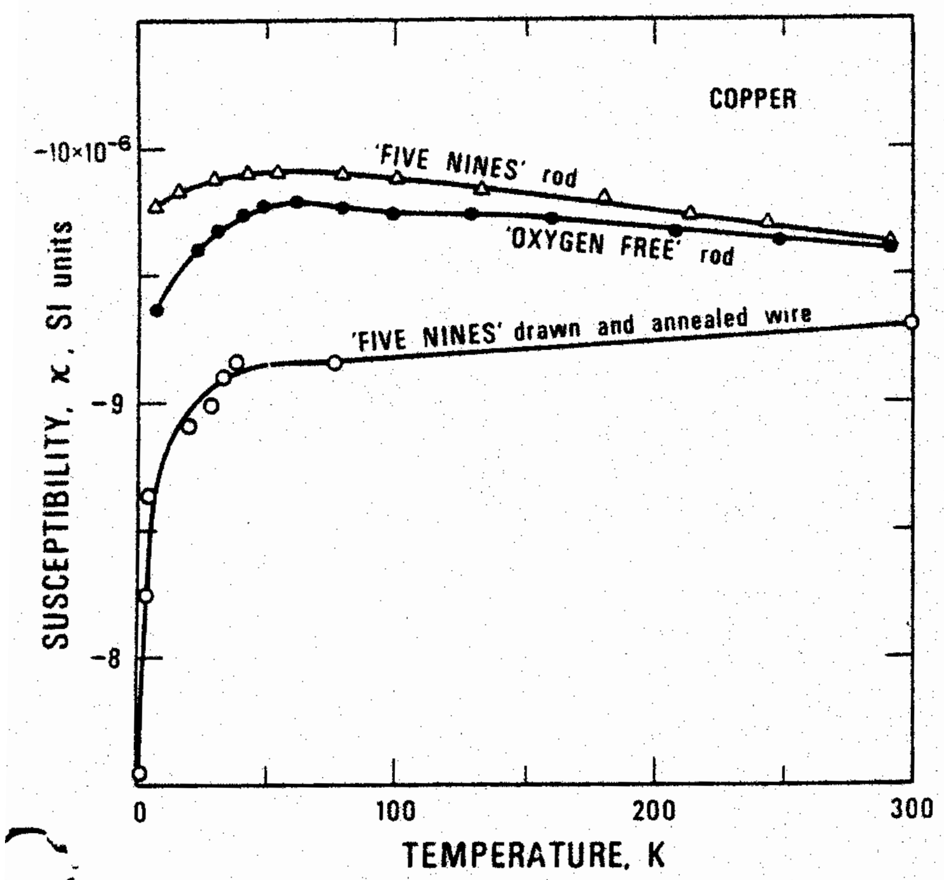


Figure 6.2 Magnetic susceptibility of diamagnetic copper as a function of temperature. △, ● — Hurd (1966); ○ — Bowers (1956).

Magnetic properties of materials, diamagnetism

- **In most applications diamagnetism not a serious concern**
- **Susceptibility small**
- **Important for some sensitive measurements**

Magnetic properties of materials, diamagnetism

United States Pater

Fletcher et al.

[57] ABST

The present invention pro
separating a gas-liquid mi
critical cryogenic helium v
ducting magnet at low g
orbit, permitting conserva
tended service life of the s

National Aeronautics and Space Administration
Goddard Space Flight Center

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Astrophysics Science Division | Sciences and Expl

BESS

*B*alloon-borne *E*xperiment with *S*uperconducting *S*pectrometer

gnets M in a
experiments
encountered
magnetic and

f a substance

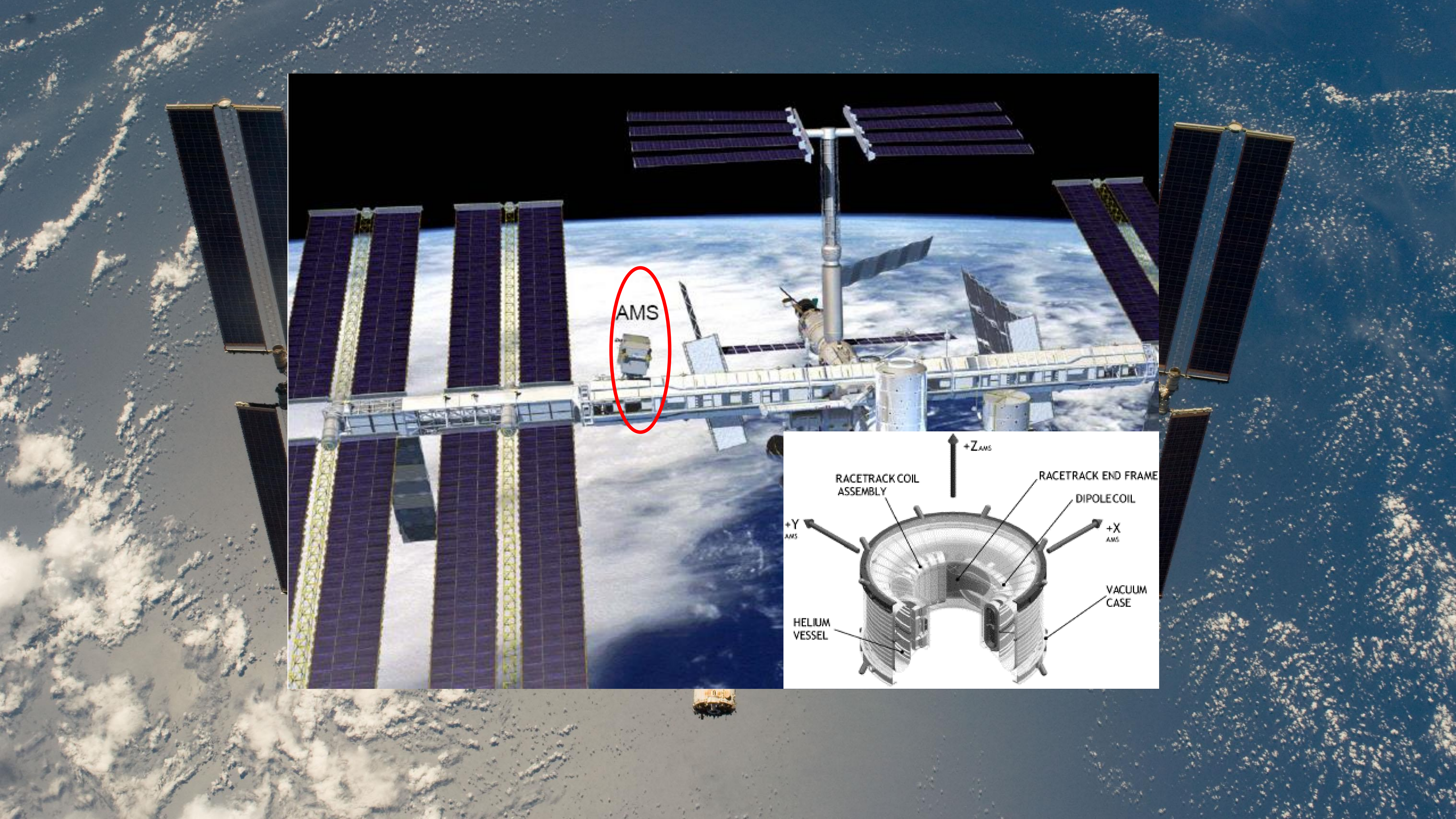
For helium χ_m
Typical values
atellite coil M
nagnetic body
vicinity of the

$F = 330$ dynes/gram.

This force corresponds to about one-third the acceleration of gravity at the earth's surface.

In normal laboratory situations a very moderate liquid helium level, for example about 1 centimeter, has sufficient head to maintain contact with the magnet. However, in an orbiting satellite the only forces acting to keep the liquid helium in contact with the coils M are surface tension and accelerations of the spacecraft. For such a coil, surface tension and diamagnetism become comparable for distances from the magnet larger than about 100 cm.

"An interesting situation has been observed in orbital flights of SC magnets where diamagnetic liquid He is forced away from the high-field regions of the magnet, no doubt much to the consternation of the experimenters" (Fickett and Goldfarb, 1980)


AMS
+Z AMS
RACETRACK COIL ASSEMBLY
RACETRACK END FRAME
DIPOLE COIL
+Y AMS
+X AMS
VACUUM CASE
HELIUM VESSEL

Magnetic properties of materials, diamagnetism

ALPHA MAGNETIC SPECTROMETER (AMS) EXPERIMENT UTILIZATION PLAN FOR EXPLORATION MAGNET DEVELOPMENT

Revision: Preliminary Draft

March 24, 2005

National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

The absence of gravity modifies the behavior of the superfluid helium, allowing some of the smaller influences such as diamagnetism and film flow to become significant. The response of the cryogenic system to disturbances and changes may therefore be different in space from those observed on the ground. Measurements in space could therefore yield valuable information on:

- The effect of magnetic field on diamagnetic liquid helium;

Magnetic properties of materials, paramagnetism

- **Due to unpaired electron spin moments in a material**
- **Atoms, molecules, lattice defects, possessing an odd number of electrons for which the total spin cannot be zero**
- **Metals**

Magnetic properties of materials, paramagnetism

- **Aligned in the direction of an applied magnetic field**
- **Result in an increased magnetization of the material**
- **Is generally linear with field, gives a positive susceptibility**

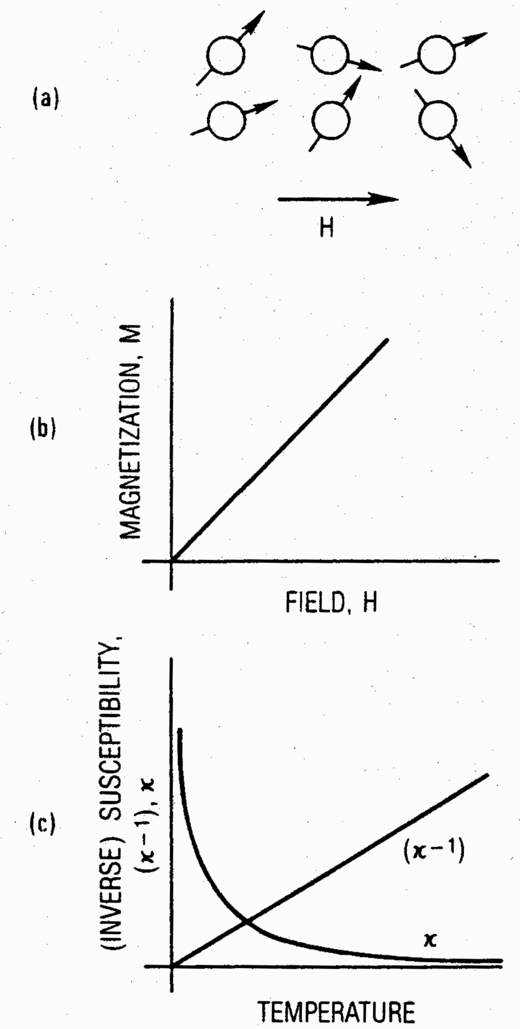


Figure 6.3 (a) Paramagnetic alignment of atomic magnetic moments. (b) Magnetization vs. field for a paramagnet. (c) Susceptibility and reciprocal susceptibility vs. temperature for a paramagnet.

R.P. Reed, A.F. Clark (1983)

Magnetic properties of materials, paramagnetism

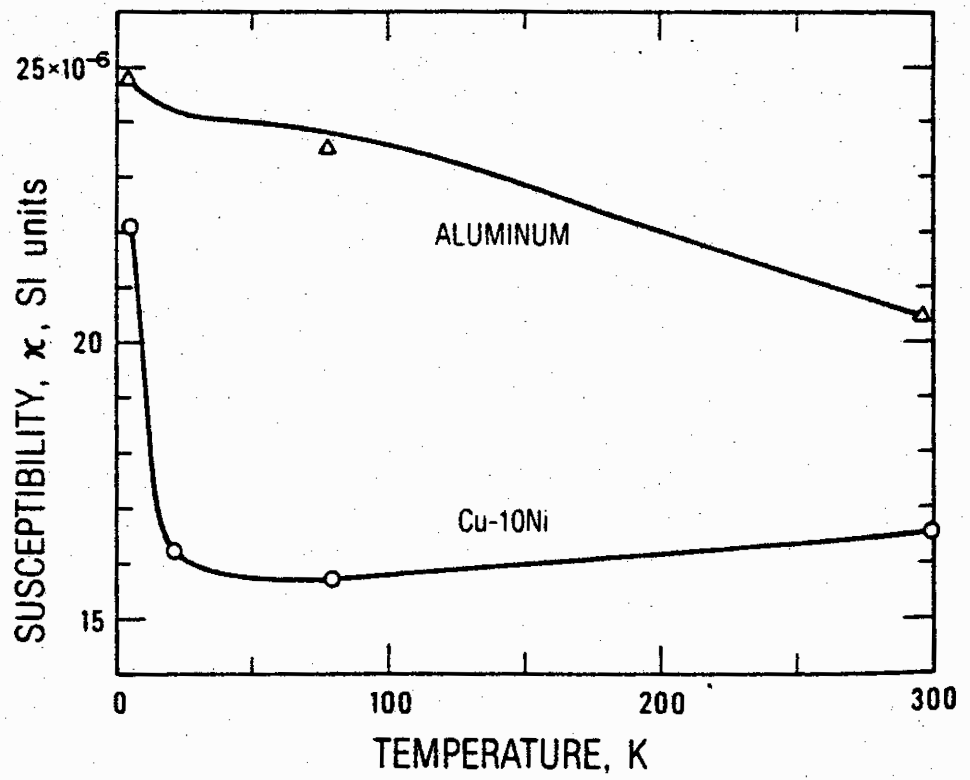
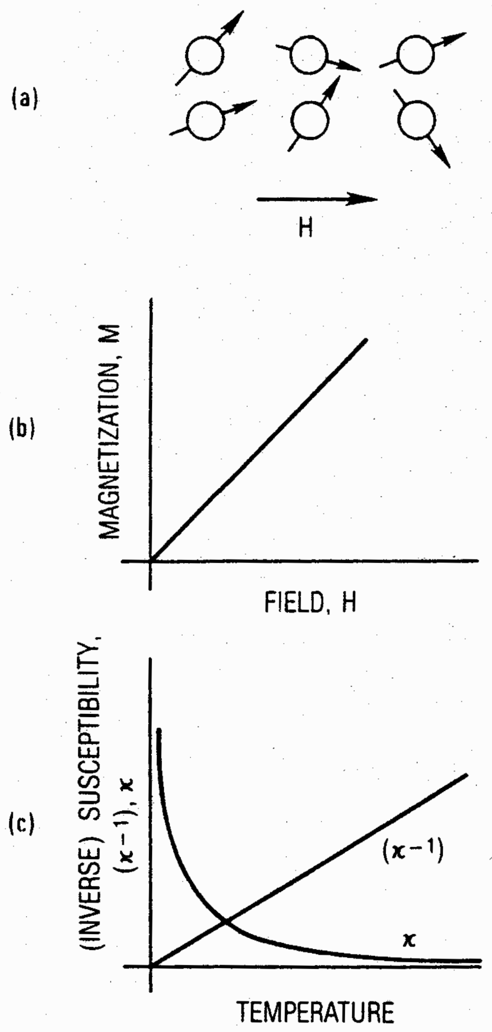


Figure 6.4 Magnetic susceptibility of relatively well-behaved paramagnetic metals. Δ — Fickett (1976); ○ — Pugh and Ryan (1958). Solid curve for aluminum representing about 30 points from graphical data of Cooper and Miljak (1976).

R.P. Reed, A.F. Clark (1983)

Different types of temperature dependences:

1) Non-ferromagnetic materials, small κ nearly T-independent, (Pauli paramagnetism due to conduction electrons)



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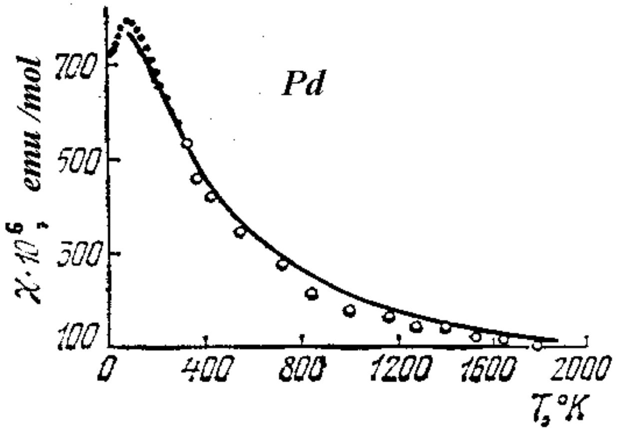
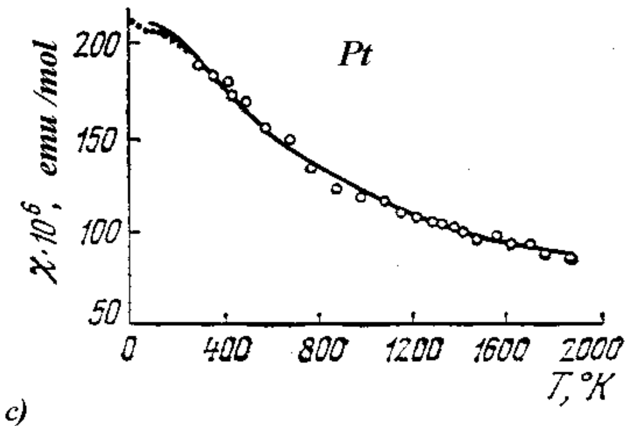
R.P. Reed, A.F. Clark (1983)

Magnetic properties of materials, paramagnetism

2) Transition metals (unfilled inner shells), quite large κ, increases generally with decreasing T (Pd, Pt, see V.Y. Irkhin and Y.P. Irkhin)





c)

SI reported values of κ ≅ $7.2 \cdot 10^{-4}$ at RT and κ ≅ $12 \cdot 10^{-4}$ for Pd (Nagasawa, 1970)

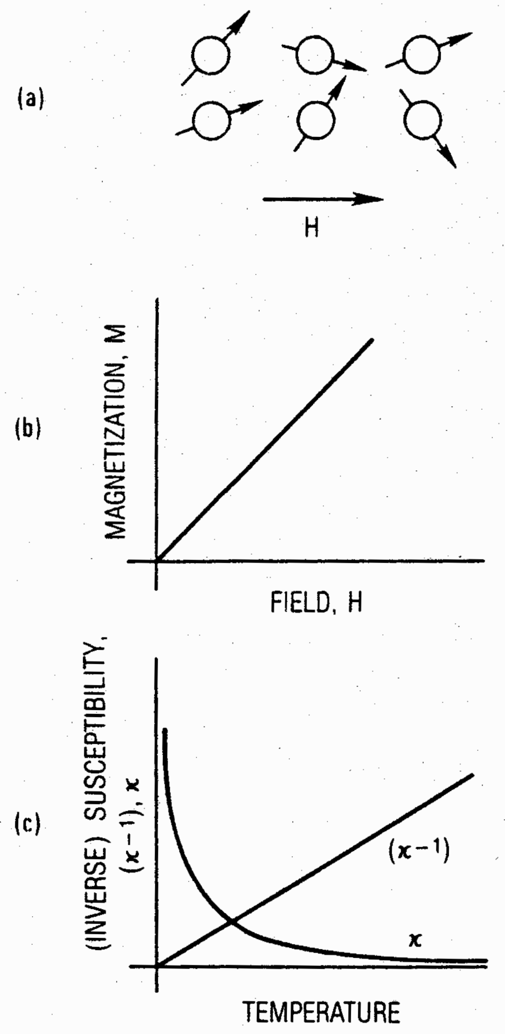


Figure 6.3 (a) Paramagnetic alignment of atomic magnetic moments. (b) Magnetization vs. field for a paramagnet. (c) Susceptibility and reciprocal susceptibility vs. temperature for a paramagnet.

R.P. Reed, A.F. Clark (1983)

Magnetic properties of materials, paramagnetism

Kittel (1986)

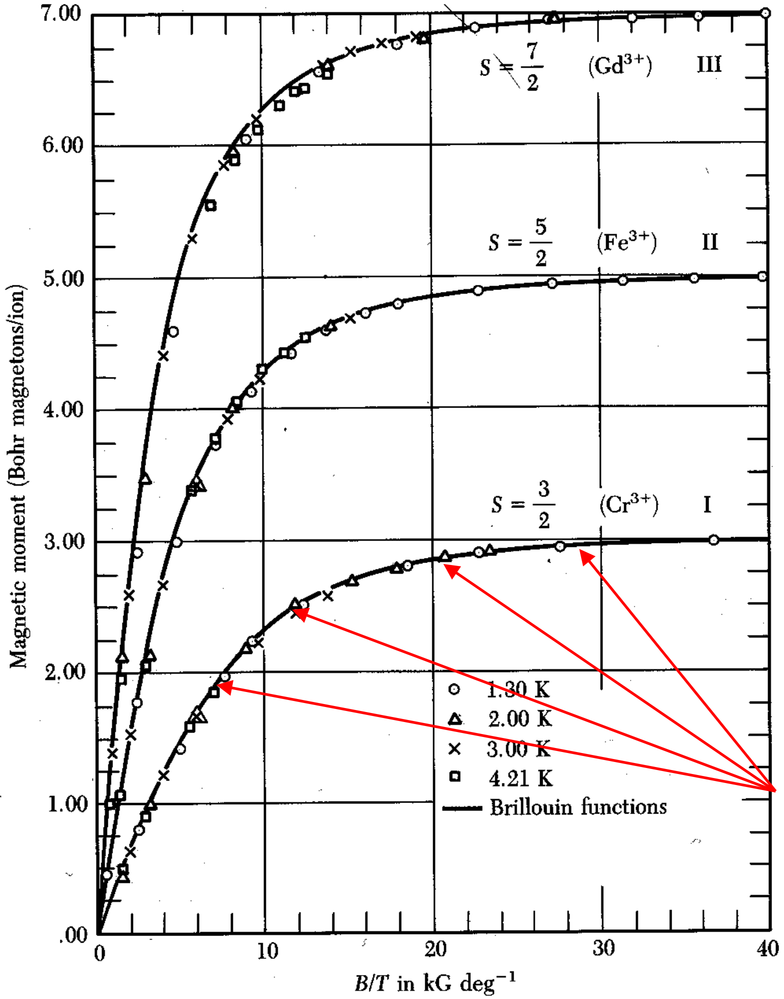
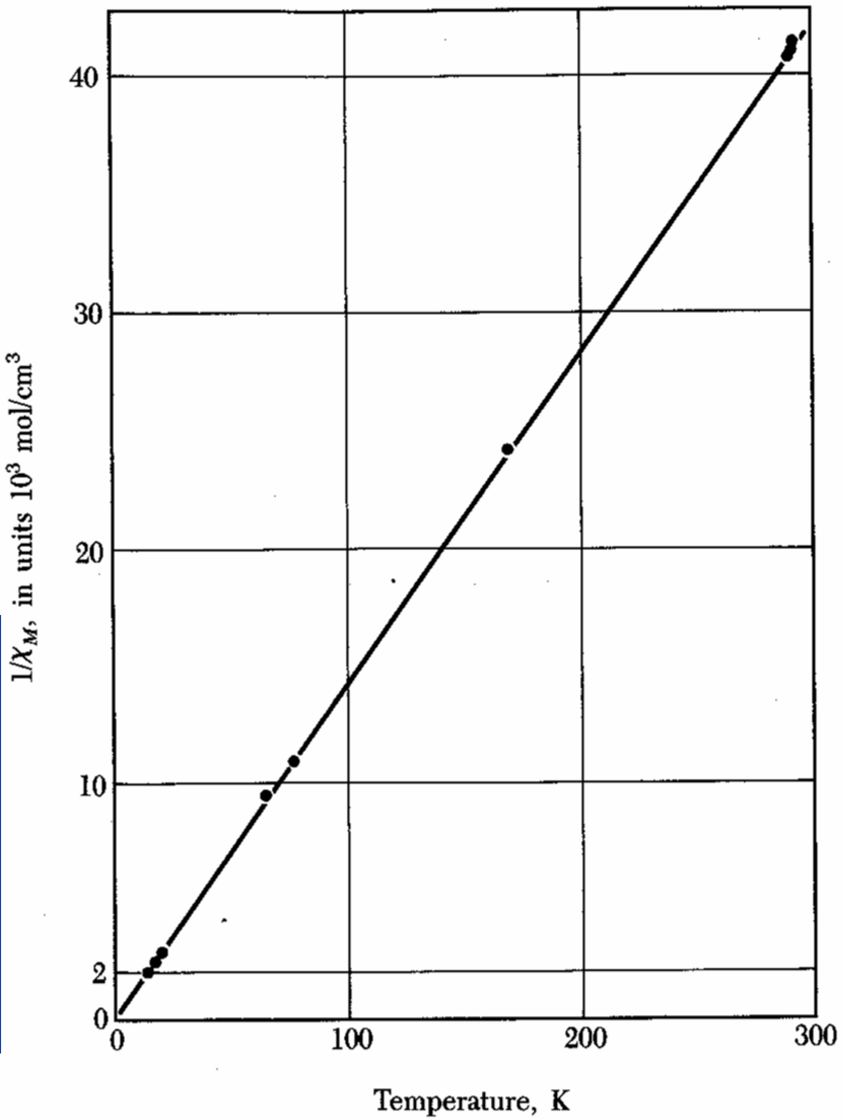


Figure 4 Plot of magnetic moment *versus* B/T for spherical samples of (I) potassium chromium alum, (II) ferric ammonium alum, and (III) gadolinium sulfate octahydrate. Over 99.5% magnetic saturation is achieved at 1.3 K and about 50,000 gauss. (After W. E. Henry.)

3) Some metal ions, κ = C/T, strongly T-dependent, C is a constant determined by the ionic density

At low temperatures and high fields magnetization may approach saturation, thus κ becomes field dependent



Plot of $1/\chi$ *vs* T for a gadolinium salt, $Gd(C_2H_5SO_4)_3 \cdot 9H_2O$. The straight line is the (After L. C. Jackson and H. Kamerlingh Onnes.)

Magnetic properties of materials, paramagnetism

- Same « Langevin type » paramagnetism for ferromagnetic and antiferromagnetic materials above a critical temperature
- This temperature is the one above which their spontaneous magnetization breaks down
- This behaviour is expressed by the Curie-Weiss law, $\kappa = C/(T-\theta)$ (examples follow)

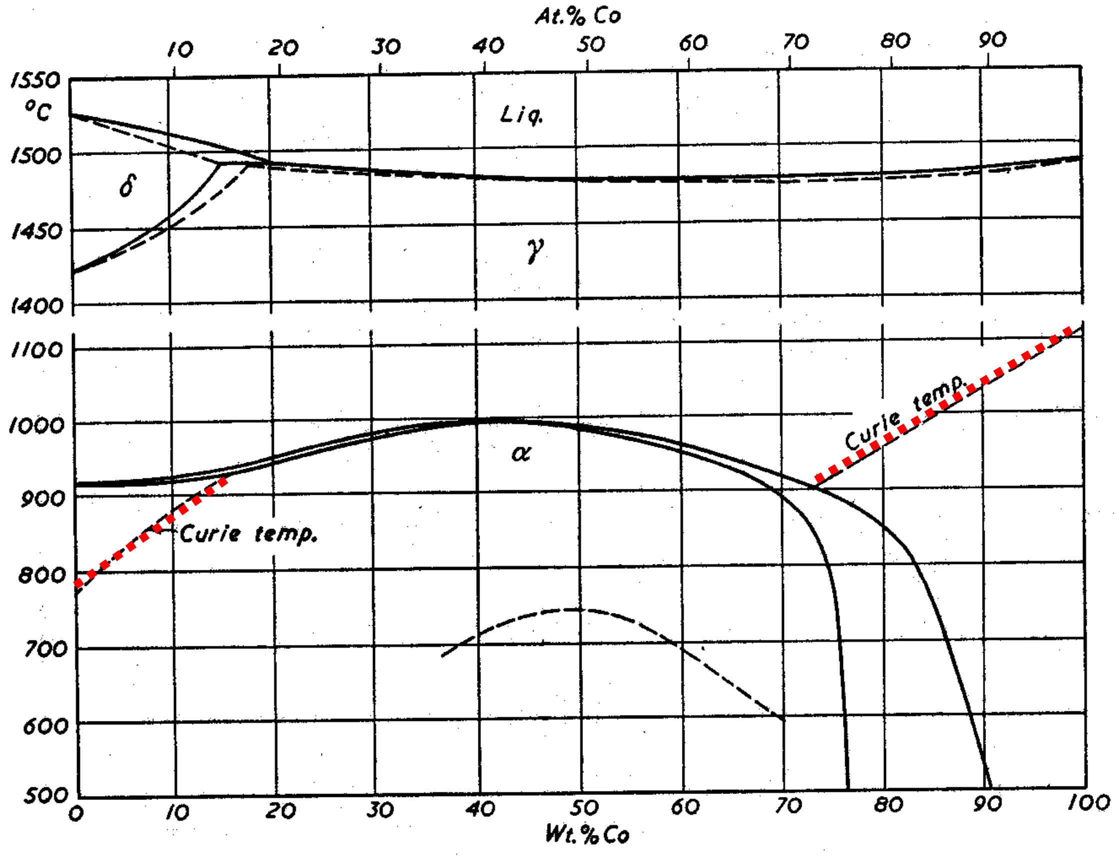
Magnetic properties of materials, ferromagnetism

Interaction of atomic spin moments with each other

Occurs in certain instances

To produce:

- Ferromagnetism
- Antiferromagnetism
- Ferrimagnetism



Co–Fe

Smithells Metals Ref. Books, 1967

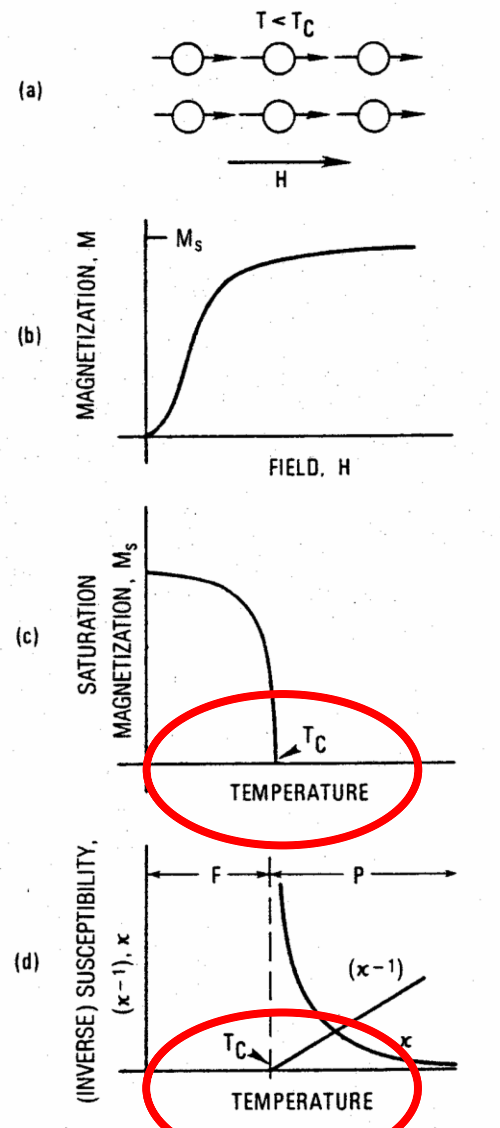


Figure 6.5 (a) Ferromagnetic alignment of atomic magnetic moments. (b) Magnetization vs. temperature showing saturation magnetization, M_S. (c) Saturation magnetization vs. temperature below the Curie temperature, T_C. (d) Susceptibility and reciprocal susceptibility vs. temperature above the Curie temperature, T_C, showing ferromagnetic (F) and paramagnetic (P) intervals.

R.P. Reed, A.F. Clark (1983)

Magnetic properties of materials, ferromagnetism

Particular care with Ni-basis superalloys for non-magnetic application at very low T!

Incoloy 800
32.5Ni-21Cr-46Fe

Commercial Names

Trade name. Incoloy 800
UNS number. N08800

Magnetic Properties

Magnetic permeability. Annealed material, 1.0092 at a field strength of 15.9 kA/m
Curie temperature. −115 °C (−175 °F)

From ASM Handbook

Magnetic properties of materials, ferromagnetism

- Large field dependent permeability

- Magnetisation often persists after application and removal of a magnetic field

  - T_C Fe = 1043 K
  - T_C Ni = 631 K
  - T_C Co = 1394 K

- Ferrous alloys of high interest for magnet applications

Magnetic properties of materials, ferromagnetism

Features (Bozorth, 1951)

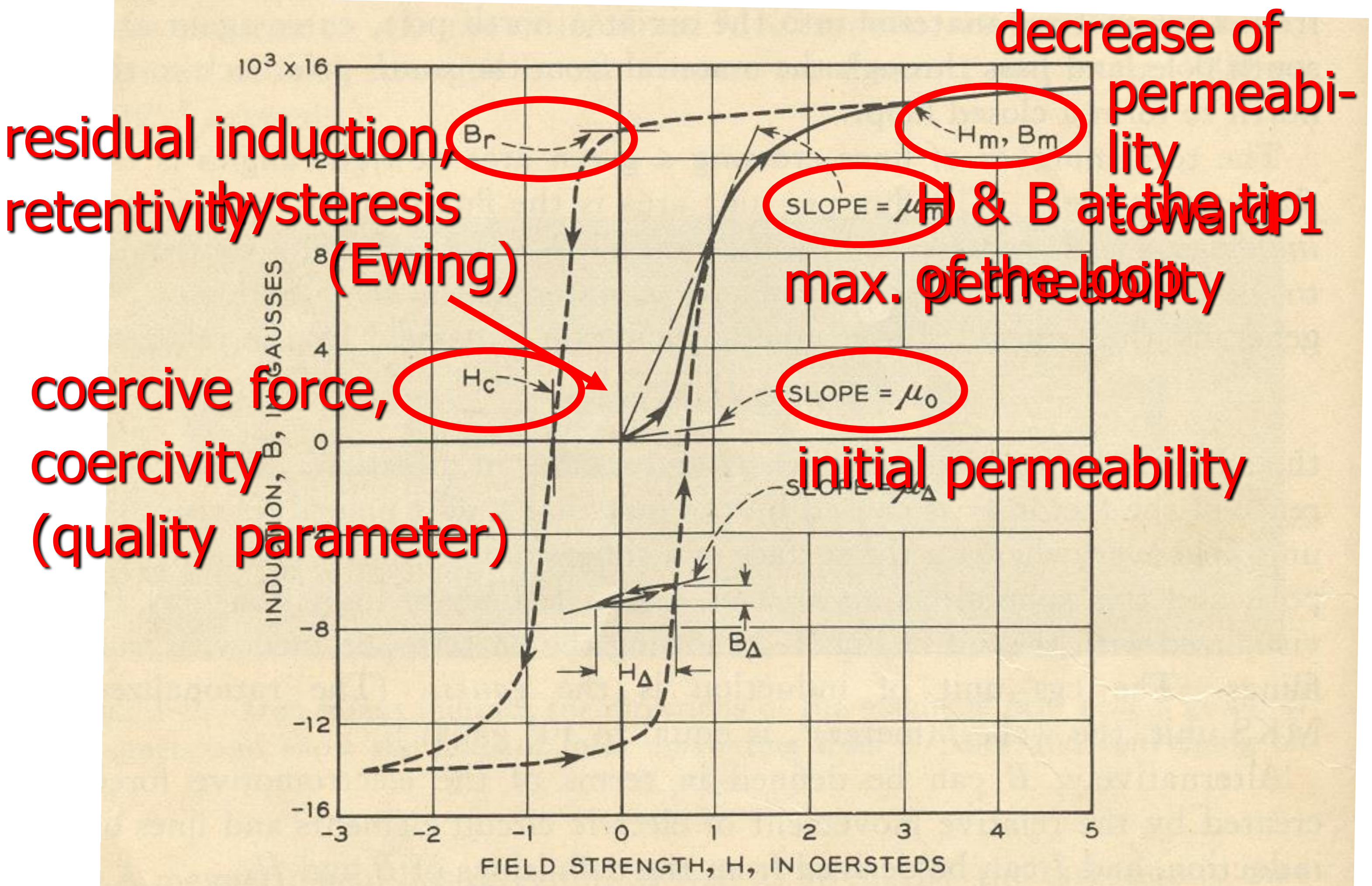
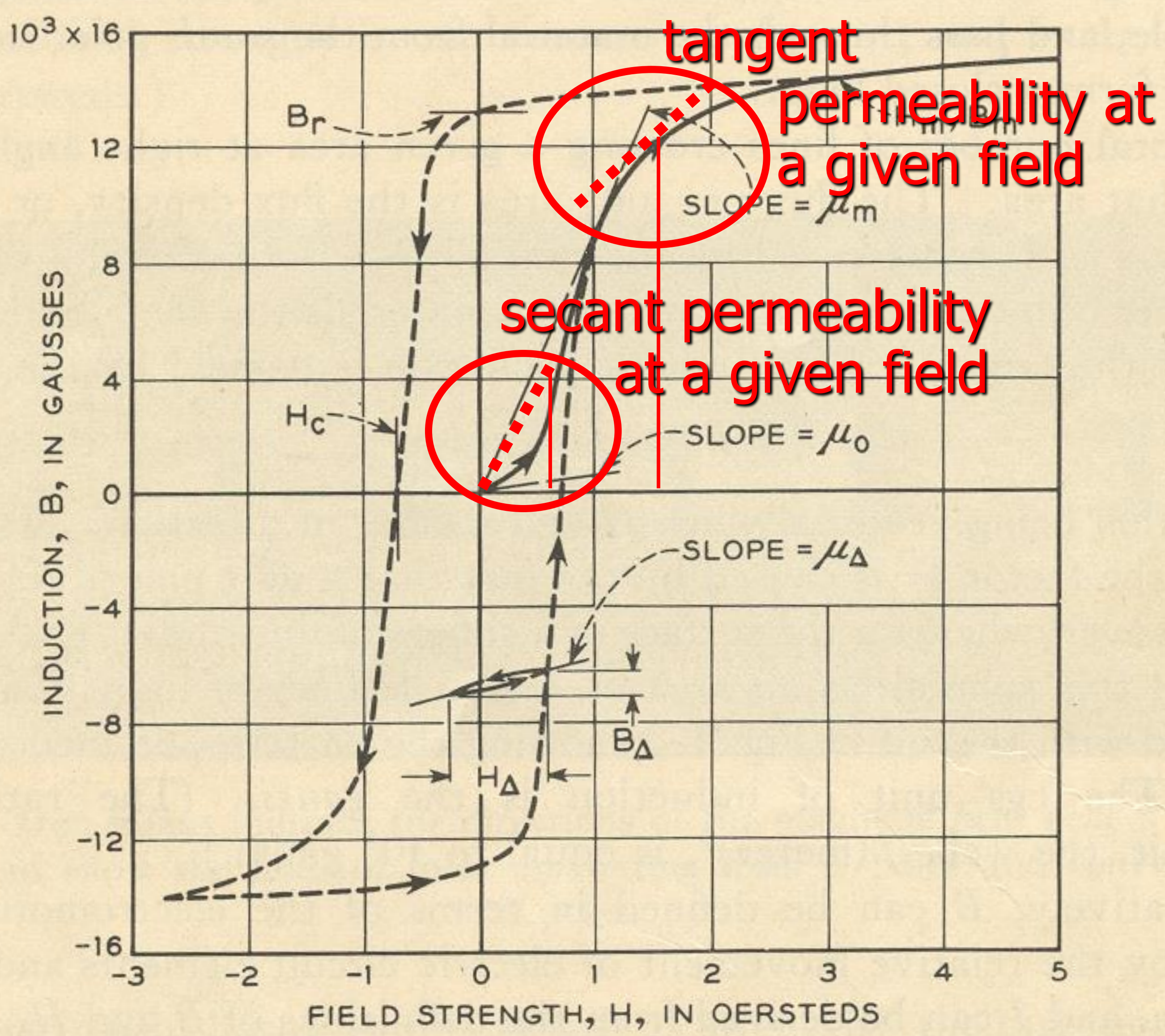


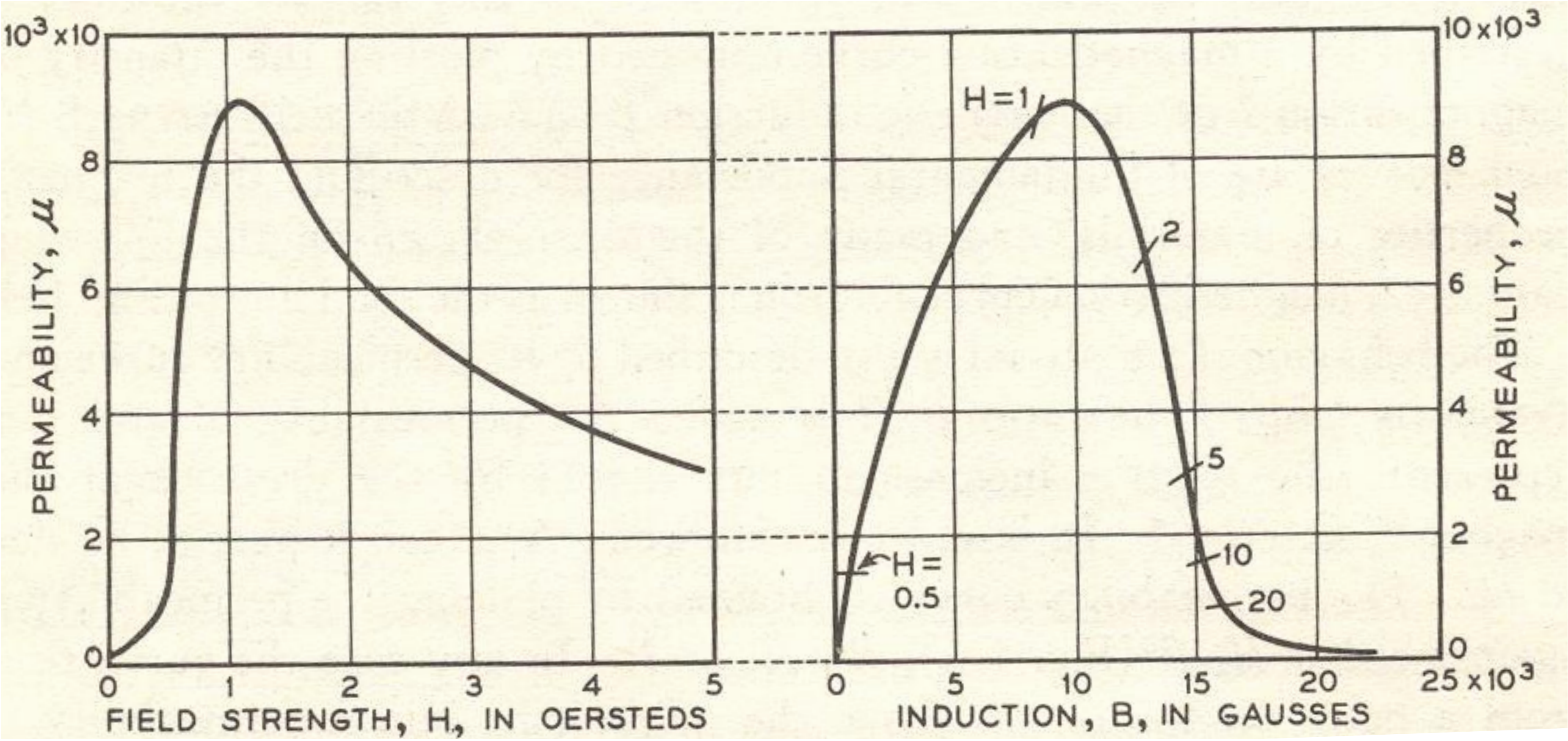
FIG. 1–4. Magnetization curve (solid) and hysteresis loop (dotted). Some important magnetic quantities are illustrated.

Magnetic properties of materials, ferromagnetism



1–4. Magnetization curve (solid) and hysteresis loop (dotted). Some im-

Magnetic properties of materials, ferromagnetism



Magnetic properties of materials, ferromagnetism

- T_C and saturation magnetization are insensitive to material structure

- All other properties are significantly affected by the physical and metallurgical state of the material:

  cold working, subsequent annealing…

- Anisotropy effects (texture) can occur (rolled steel)

Magnetic properties of materials, irons and steels

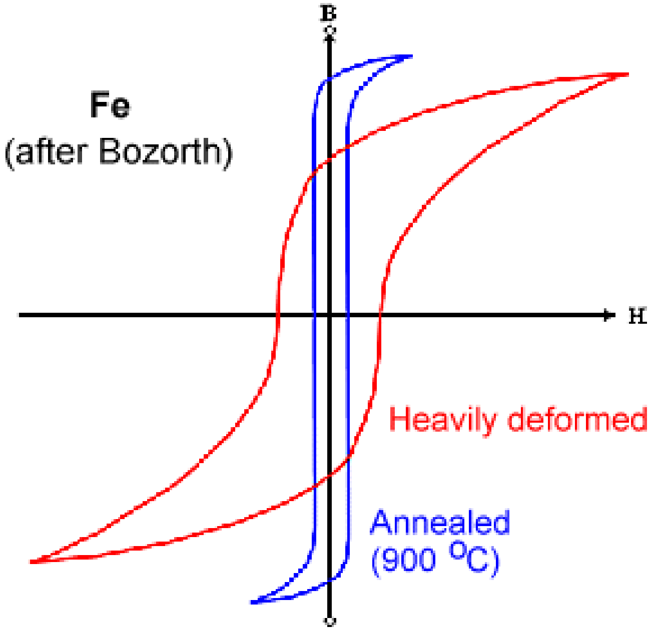
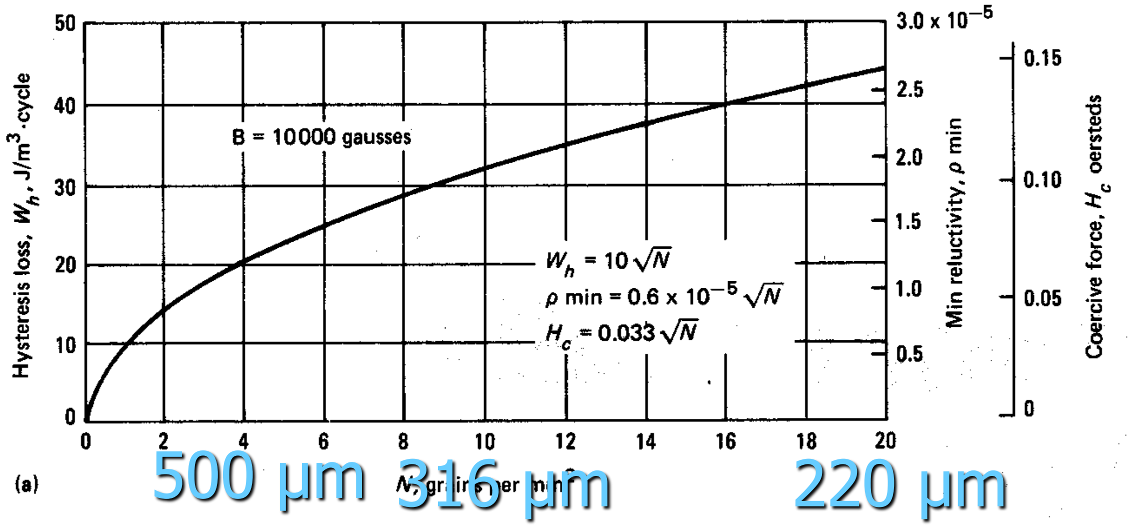
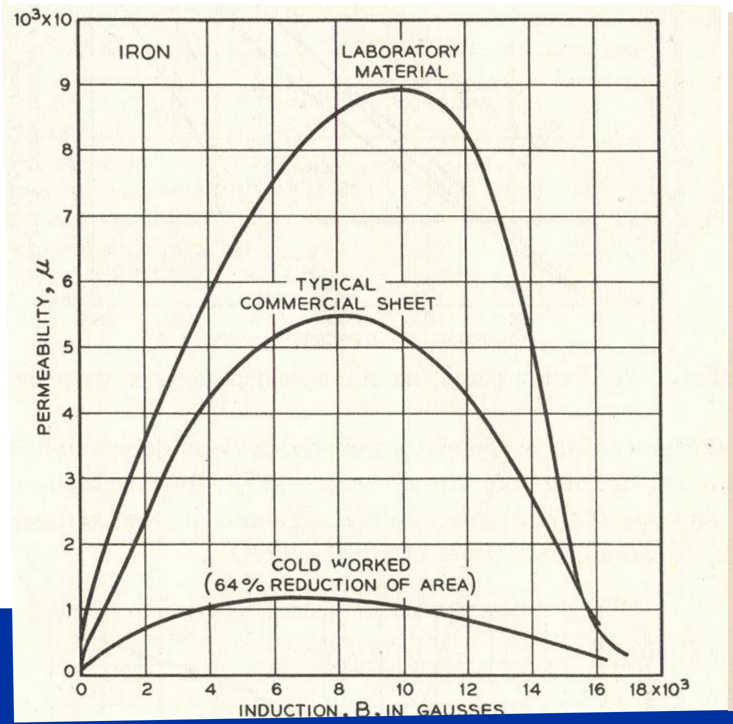


Fig. 2 Effect of grain size on magnetic properties of pure iron and silicon iron





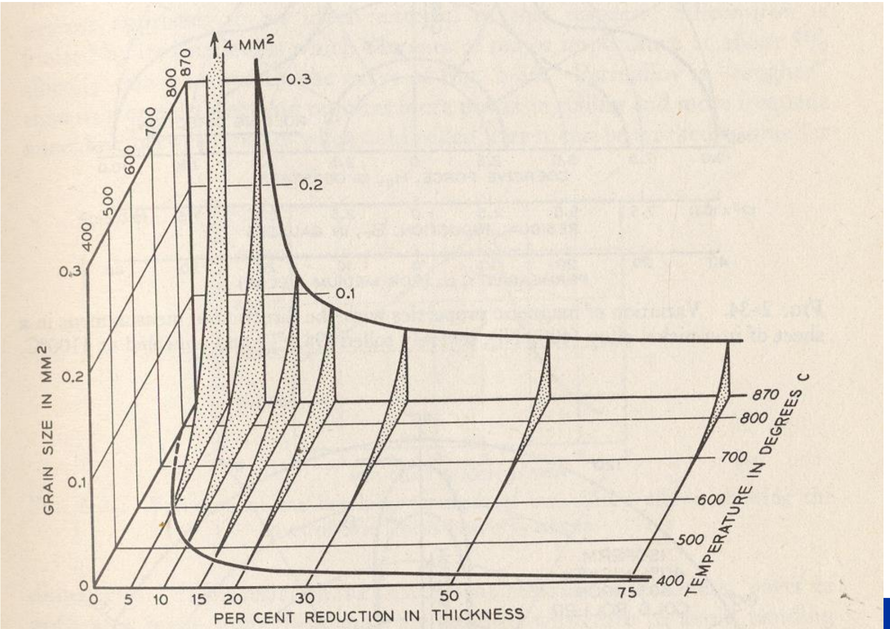


Fig. 2–33. Dependence of the grain size of iron on the amount of deformation and on the temperature of anneal.

Magnetic properties of materials, irons and steels

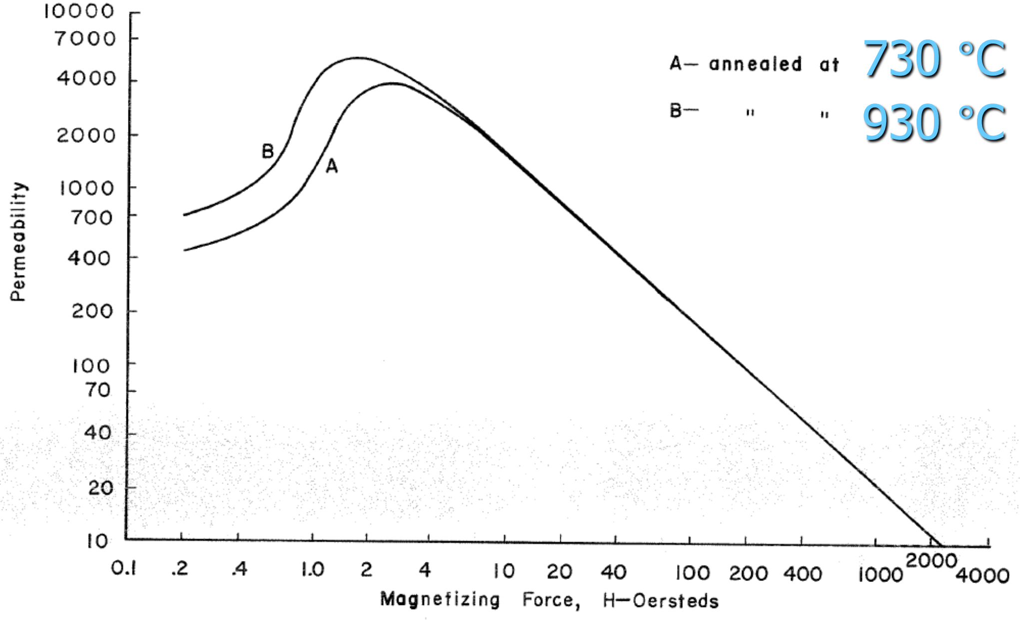


FIG. 2. Permeability of Armco Magnetic Ingot Iron.

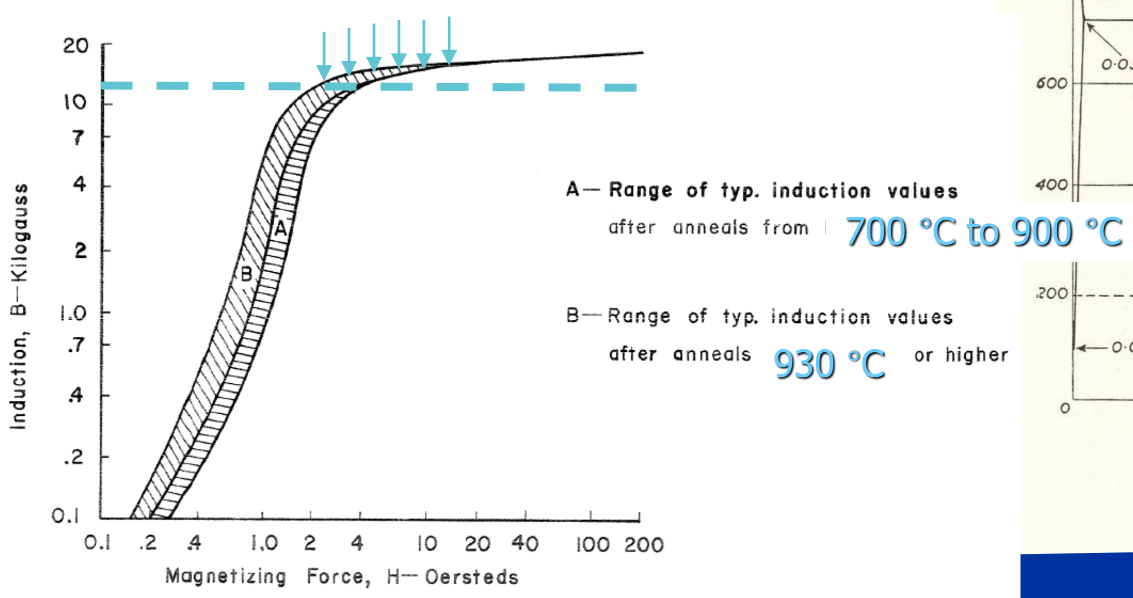
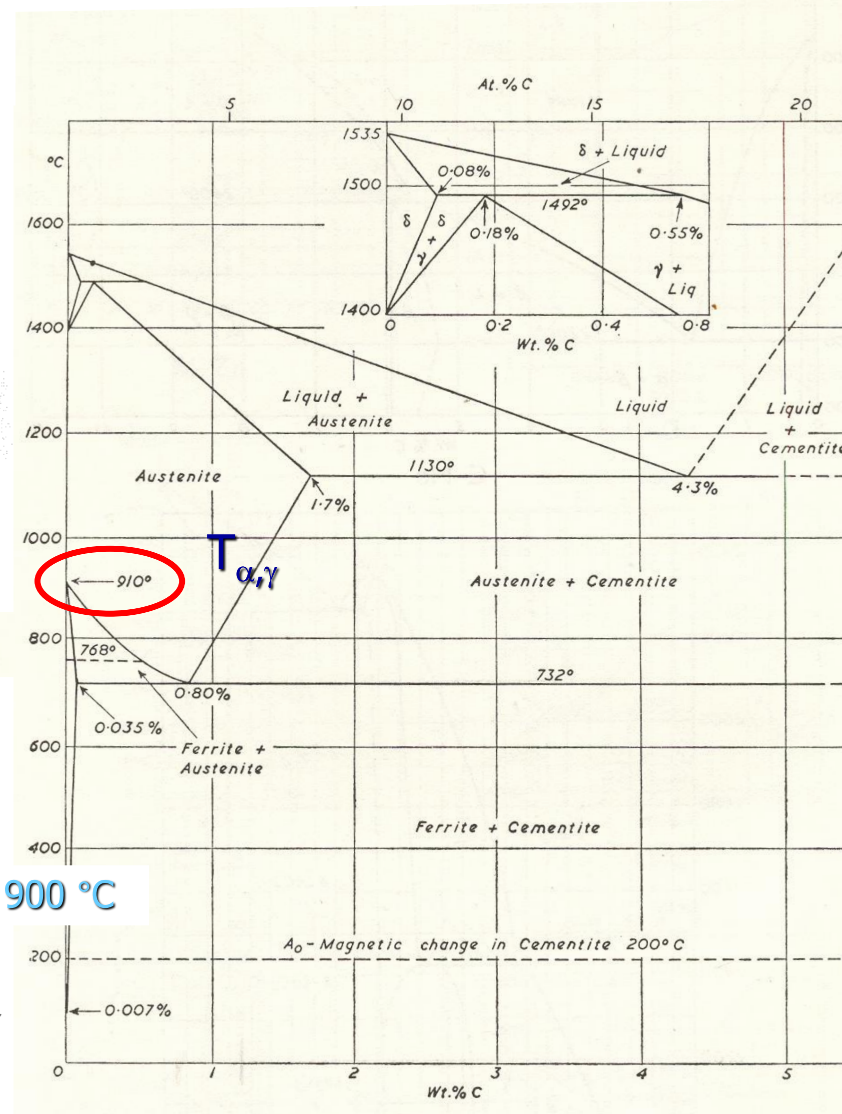


FIG. 3. Typical medium and low induction values for annealed Armco Magnetic Ingot Iron.



C–Fe

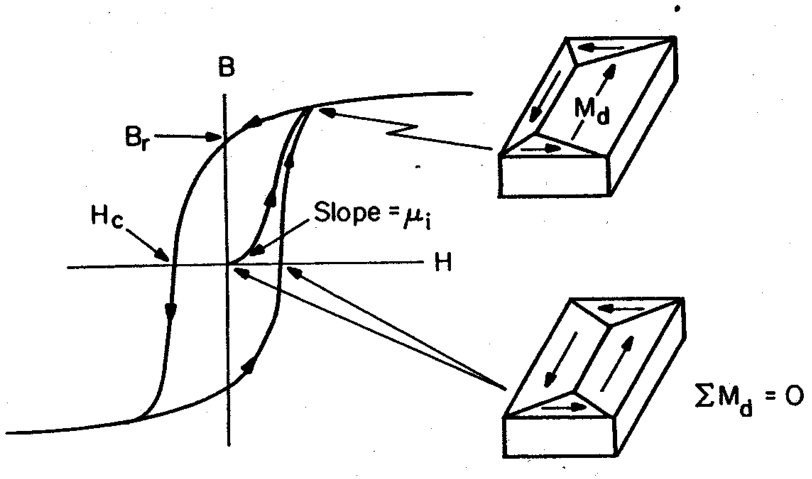
Magnetic properties of materials, ferromagnetism

Soft ferromagnets

- Easily magnetised and demagnetised (transformer cores, ferrite cores, shielding of magnetic fields)
- Usually metals
- Narrow hysteresis loops (low values of H_c)
- High permeabilities
- Low eddy-current loss from electric currents induced by flux changes
- High magnetic saturation inductions

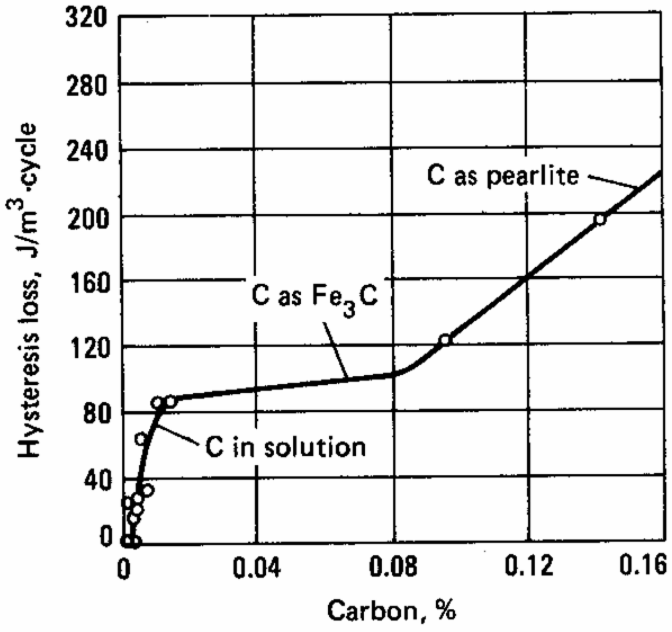
Magnetic properties of materials, ferromagnetism

- C, S, N, O are deleterious to fm properties
- They distort the lattice and even in small amounts (ppm) may greatly interfere with easy movements of magnetic domains
- C in excess of 30 ppm in pure Fe cause excess solute to precipitate in GB



Fiorillo, 2007

Fig. 1 Relationship between carbon content and hysteresis loss for unalloyed iron



Induction B = 1 tesla (10 000 gausses).

ASM Metals Handbook, 9th. ed

Magnetic proper

JOURNAL OF APPLIED PHYSICS VOLUME 37, NUMBER 7 JUNE 1966

Comparison of the Thermal Conductivity, Electrical Resistivity, and Seebeck Coefficient of a High-Purity Iron and an Armco Iron to 1000°C*

W. Fulkerson, J. P. Moore, and D. L. McElroy
Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received 6 December 1965)

Iron referred to as "high purity" when total concentration of impurities (mainly C, N, O, P, S, Si and Al) does not exceed a few hundred ppm

Otherwise Low Carbon Steel or Non-alloyed Steel

Very pure Fe ⇒ high electrical conductivity ⇒ unsuitable for AC applications

Table I. Chemical analysis[a] of high-purity iron, ORNL Armco iron, and BMI Armco iron.

Element	Concentration (at.%)×10³ High-purity iron	ORNL Armco iron	BMI Armco iron
Al	0.21–2.1	<105	<0.4
Ca	0.14–1.4		
Cr		<54	<0.9
Cu	0.09–0.9	90	0.09–0.9
Mn		51	1–10
Mo		<29	<6
Ni	0.95–9.5	95	1–10
Si	2.0 –20	<40	0.2–2
Ti		<12	<1.1
V		<22	<1.1
C	14	61	75
P	2.0	11	16
S	5.2	40	51
H_2	<5.6	<5.6	95
O_2	8.8	304	210
N_2	2.0	20	328
Totals:			
Minimum including oxygen	40.99	672	777
Minimum without oxygen	32.19	368	567
Maximum including oxygen	71.50	940	807
Maximum without oxygen	62.7	636	597

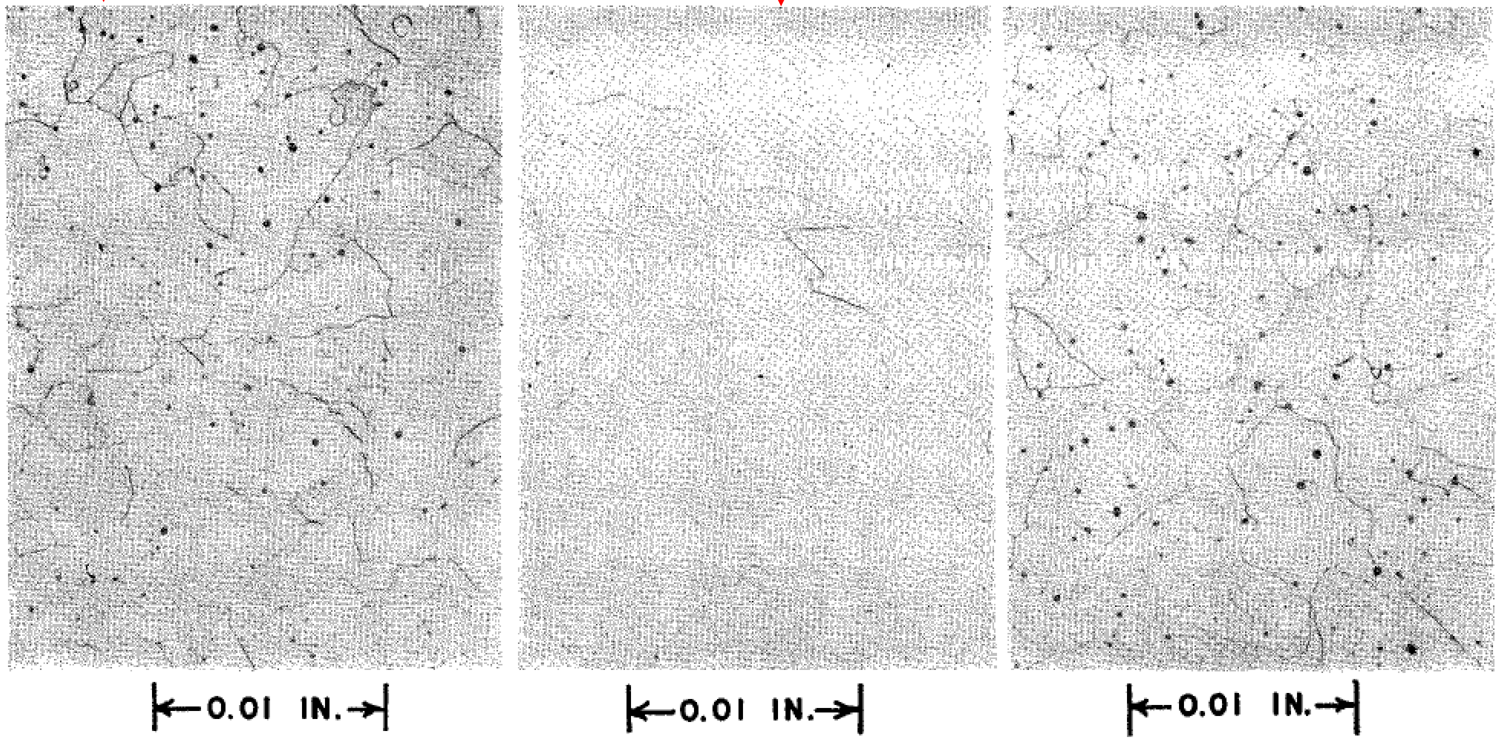
[a] Al, Ca, Cr, Cu, Mn, Mo, Ni, Si, Ti, V analyzed by emission spectroscopy (semiquantitative); C, P, S, H_2, O_2, N_2 analyzed by quantitative analysis.

Magnetic properties of materials, irons and steels

TABLE IV. Smoothed values of the resistivity ($\mu\Omega\cdot$cm) of Armco irons and high-purity irons as reported by several sources.[a]

Temperature (°C)	Armco iron ORNL[b]	Armco iron ORNL[c]	Armco iron NPL[d]	Armco iron NRC[e]	High-purity iron ORNL[f]	High-purity iron USS[g]
−269	1.02(5.0)[h]	0.96(6.8)[h]			0.40(6.1)[h]	
−195.7	1.74(14)	1.47(11)			1.01(17)	
−79.1	6.19(9)	5.95(11)			5.31(10)	
0	9.97	9.64	10.0	10.4	9.04	8.63
50	12.72	12.36	12.5		11.72	11.37
100	15.81	15.45	15.6	15.6	14.70	14.46
150	19.21	18.85	19.1		18.06	17.86
200	23.00	22.65	23.1	23.0	21.84	21.60
250	27.29	26.95	27.1		26.10	25.85
300	32.05	31.71	31.3	32.1	30.72	30.55
350	37.15	36.81	36.5		35.90	35.55
400	42.84	42.51	42.0	43.1	41.51	41.13
450	49.04					
500	55.63					
550	62.88					
600	70.66					
650	78.95					
700	88.02					
750	98.64					
800	107.61					
850	111.74					
900	114.69					
910	115.19					
920	114.96					
950	116.15					
1000	117.95					
$\rho_{300}/\rho_{4.2}$	11.0					

[a] In each column, the first entry
[b] Armco iron specimen machine
[c] Armco iron specimen machine annealed state of the iron.
[d] Values were calculated from d
[e] Values were calculated from da
[f] ORNL high-purity iron specin
[g] Values calculated from data re communication with Dr. Arajs.
[h] Numbers in parentheses after



(a) (b) (c)

FIG. 1. Microstructure of (a) ORNL Armco iron, (b) ORNL high-purity iron, and (c) BMI Armco iron. (×200). The ORNL Armco iron and BMI Armco iron specimens were etched with a solution of 2% nitric acid in ethyl alcohol. The high-purity iron was first electrolytically polished and then etched with a solution consisting of 3.2% picric acid and 0.4% nitric acid in ethyl alcohol.

Magnetic properties of materials, irons and steels

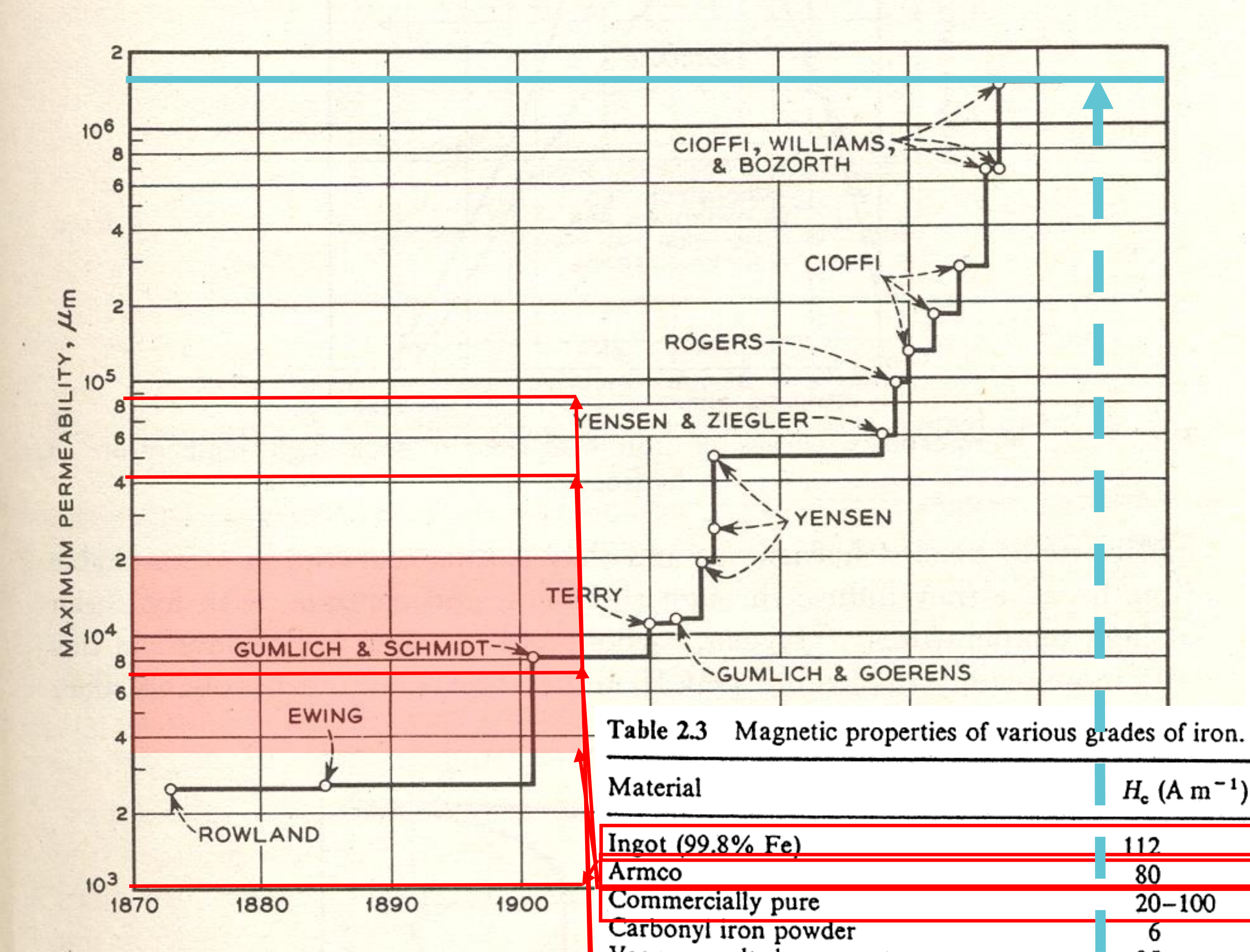


FIG. 3–10. Highest values of maximu[m] ...
y...

Table 2.3 Magnetic properties of various grades of iron.

Material	H_c (A m^{-1})	μ_i (μ_0)	μ_{max} (μ_0)
Ingot (99.8% Fe)	112	10	1 000
Armco	80	200	7 000
Commercially pure	20–100	200–500	3 500–20 000
Carbonyl iron powder	6	3 000	20 000
Vacuum-melted	25	—	21 000
Electrolytic	7	1 000	26 000
Electrolytic annealed	18	—	41 500
Vacuum-smelted and hydrogen-annealed	3	—	88 400
Purified Armco (99.95% Fe)	4	10 000	227 000
Vacuum-annealed	—	14 000	280 000
Single-crystal	—	—	680 000
Single-crystal, magnetically annealed	12	—	1 430 000

Saturation magnetic polarization $J_s = 2.15$ T at 20°C, except for ingot with $J_s = 2.05$ T.

Magnetic properties of materials, irons and steels

Low C steels

TABLE 2.2 Typical impurities and their concentrations (wt ppm) in several grades of iron and in low-carbon steel

Iron type	C	N	O	Mn	P	S	Si	Cu	Ni
ARMCO	150	20	150	280	50	250	30	150	
Electrolytic	40	100	100	15	20	30	30	40	10
H_2 treated	30	10	30	280	40	<30			
Zone refined	7	<10	2	0.5	<0.1	0.2		1.5	0.50
Low-carbon steel	50–1000	30–200	20–100	5×10^3	200–1000	50–300	10^3–10^4	100	

F. Fiorillo, Measurement and Characterization of Magnetic Materials, Elsevier-Academic Press, Amsterdam (2004)

Low-Carbon Steels

For many applications that require less than superior magnetic properties, low-carbon steels (type 1010, for example) are used. Frequently, higher-than-normal phosphorus and manganese contents are used to increase electrical resistivity. Such steels are not purchased to magnetic specifications.

ASM Metals Handbook Ninth Edition, Vol. 3

Magnetic properties of materials, irons and steels

Table 11 Direct-current magnetic properties of relay steels and alloys after annealing

Metal	Magnetizing force, H_{max} from B = 10 000	H_c, coercive force(a), oersteds	B_r, kilogausses from B = 10 000	Permeability, μ Initial	Permeability, μ Maximum	Flux density at max permeability, kilogausses	Saturation induction, kilogausses	Resistivity, μΩ·cm
Low-carbon iron and steel								
Low-carbon iron.	2.0 to 5.8	0.80 to 1.70	7.0 to 8.5	200(b) 500 to 1000(c)	2 200 to 5 500	6.4 to 7.5	21.5	10
1010 steel	3.0	1.00 to 2.00	8.4	200(b)	3 800	7.5	21.0	12

U.S.A. — Baustähle — Aciers de construction — Structural and constructional steels

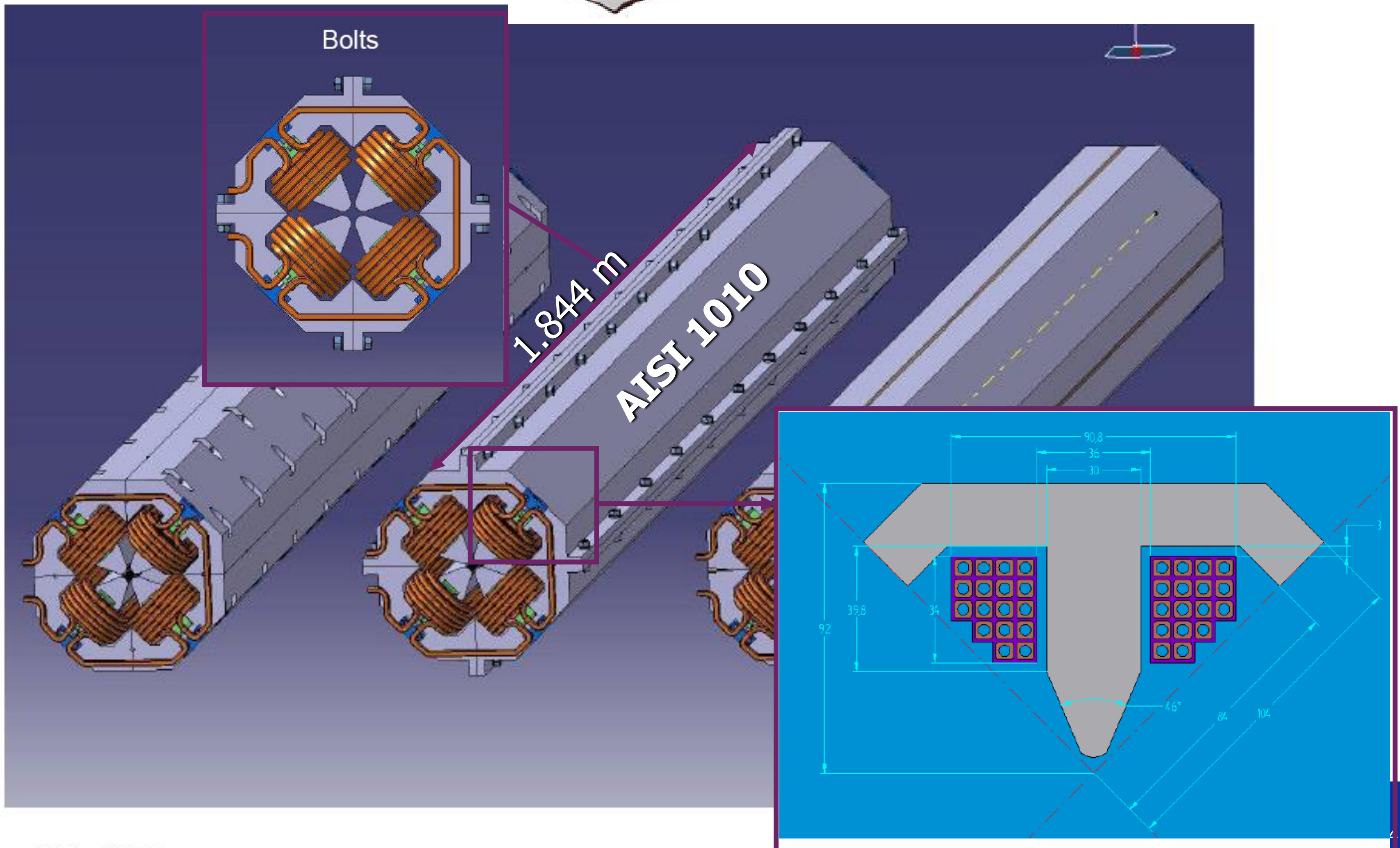
No.	US-Norm / Norme / Standard SAE	AISI	Unified Numbering System UNS	C %	Si %	Mn %	P ≤ %	S ≤ %	Cr %	Mo %	Ni %	Sonstige / Autres – Others %	WNr. / No. du mat. / Mat. no.
1	J 403 (1995)	Kohlenstoffstähle (nur anwendbar für Halbzeug zum Schmieden, warmgewalzte und kalt nachgearbeitete Stäbe, Drähte und nahtlose Rohre – Aciers au carbone (applicable seulement pour demi-produits pour forgeage, barres l.à.c. et usiné à froid, fil, tubes sans soudure – Carbon steels (applicable only for semifinished products for forgings, hot rolled and cold finished bars, wire rods, seamless tubing											
2	1005	1005	G10050	≤ 0,06	a; b	≤ 0,35	0,030	0,050	–	–	–	–	1.0314
3	1006	1006	G10060	≤ 0,08	a; b	0,25–0,40	0,030	0,050	–	–	–	–	1.0313
4	1008	1008	G10080	≤ 0,10	a; b	0,30–0,50	0,030	0,050	–	–	–	–	1.0204/1.0330/1.0318/ 1.0211/1.0212
5	1010	1010	G10100	0,08–0,13	a; b	0,30–0,60	0,030	0,050	–	–	–	–	1.1121/1.0301/1.0308/1.0032
6	1012	1012	G10120	0,10–0,15	a; b	0,30–0,60	0,030	0,050	–	–	–	–	–
7	1015	1015	G10150	0,13–0,18	a; b	0,30–0,60	0,030	0,050	–	–	–	–	1.1141/1.0413/1.0037
8	1016	1016	G10160	0,13–0,18	a; b	0,60–0,90	0,030	0,050	–	–	–	–	–
9	1017	1017	G10170	0,15–0,20	a; b	0,30–0,60	0,030	0,050	–	–	–	–	1.1141
10	1018	1018	G10180	0,15–0,20	a; b	0,60–0,90	0,030	0,050	–	–	–	–	–

Magnetic properties of materials, irons and steels

CLIC Main Beam

CLIC Main Beam Quadrupole (V4, T.Zickler)

Aperture radius: 5.00 mm
Integrated gradient: 70 (170, 270, 370) Tm/m
Nominal gradient: 200.1 T/m
Iron length: 344 (1844) mm
Magnetic length: 349 (1849) mm
Total length: 414.7 (1914.7) mm
Magnet width: 192 mm
Magnet height: 192 mm
Magnet weight: 109.3 (393.3) kg

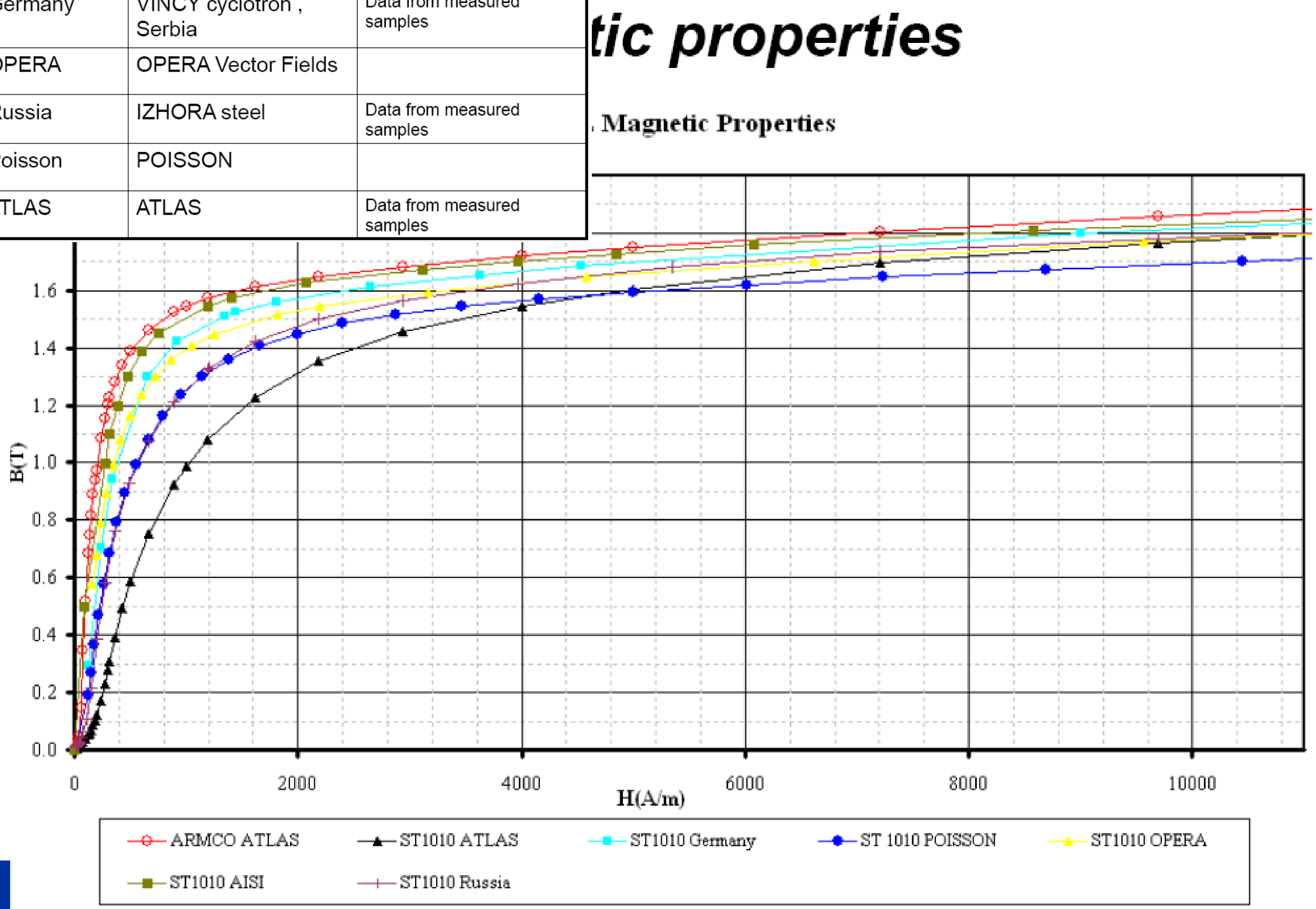


(Courtesy of A.Vorozhtsov)

M. Modena, 27 April 2009

Magnetic properties of materials, irons and steels

Type of steel	source	comments
ARMCO ATLAS	ATLAS	Data from measured samples
ST1010 AISI	AISI	
ST1010 Germany	VINCY cyclotron , Serbia	Data from measured samples
ST1010 OPERA	OPERA Vector Fields	
ST1010 Russia	IZHORA steel	Data from measured samples
ST1010 Poisson	POISSON	
ST1010 ATLAS	ATLAS	Data from measured samples



(Courtesy of A.Vorozhtsov)

Magnetic properties of materials, irons and steels

Magnetic ageing

Group Code.: SL-MS
EDMS No.: 115684

SL Division Project

Technical Specification of the Low Carbon Steel for the MBG and QTG Magnets of the CNGS Project

3.1.1.3 Ageing

The steel supply shall be entirely stable with respect to time in both coercivity and permeability. Since the operating temperature of the magnet cores is expected to vary in the range 27 °C - 45 °C, the stability of the magnetic properties refers to many years of operation in this temperature range. The ageing properties of the steel sheets will be evaluated by re-measuring the coercivity after 100 hours of accelerated ageing at 150 °C on samples taken throughout the whole production. The coercivity values of the aged samples shall not exceed those measured before the treatment by more than 10%. The accelerated ageing and the subsequent measurements are to be carried out by the steel producer at least twice for every melt.

Fiorillo, 2004

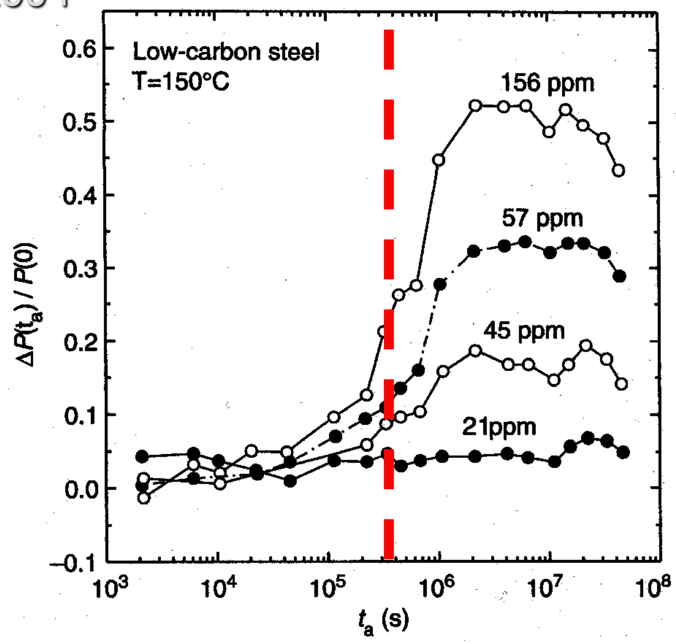


FIGURE 2.5 Relative increase of power losses ($f = 50$ Hz, $J_p = 1.5$ T) in a low carbon steel lamination (Si = 0.3 wt%) after aging at 150 °C up to 600 days [2.17 Different curves refer to different C concentrations, ranging between 156 an 21 ppm.

Magnetic properties of materials, irons and steels

... by final purification under pure hydrogen:

$Fe + C + 2H_2 = Fe + CH_4$

Oxygen, Sulfur, Nitrogen ⇒ H_2O, H_2S, NH_3

TABLE 5

Maximum permeability of Armco iron with different degrees of purification, effected by heat treatment in pure hydrogen at 1475°C for the times indicated (P. P. Cioffi). Analyses from R. F. Mehl (private communication).

Time of Treatment (hours)	μ_m	Composition (%)					
		C	S	O	N	Mn	P
0	7 000	0.012	0.018	0.030	0.0018	0.030	0.004
1	16 000	.005	.010	.003	.0004	...	...
3	30 000	.005	.006	.003	.0003	...	...
7	70 000	.003	...	.003	.0001	...	...
18	227 000	.005	< .003	.003	.0001	.028	.004
Precision of analysis:		.001	.002	.002	.0001	...	...

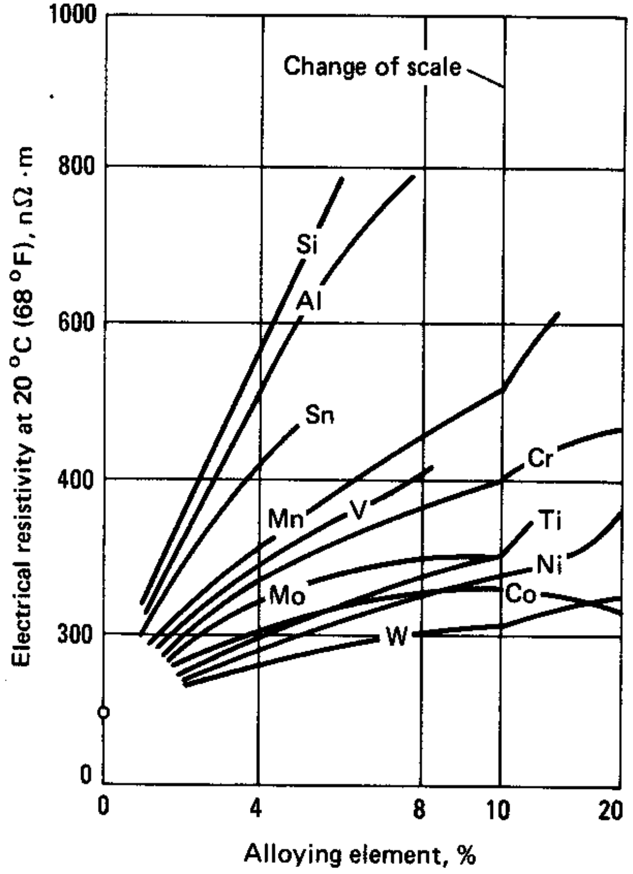
Magnetic properties of materials, non-oriented electrical steels

- Pure Fe very soft but requires special handling
- Used extensively in dc applications
- Low electrical resistivity makes unsuitable for ac circuits

  $\Rightarrow$ FeSi alloys

- Grain growth can be promoted
- Saturation induction reduced by all alloying elements except Co

Fig. 3 Effect of alloying elements on electrical resistivity of iron



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Magnetic properties of materials, non-oriented electrical steels

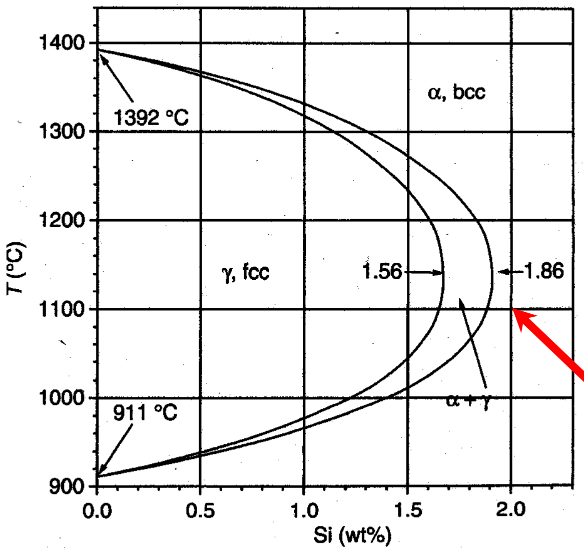

FIGURE 2.7 Fe–Si phase diagram: the γ loop.

Fe-Si alloys accidentally discovered by Hadfield (1882), 1.5 % Si

Magnetic properties reported in 1900

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903

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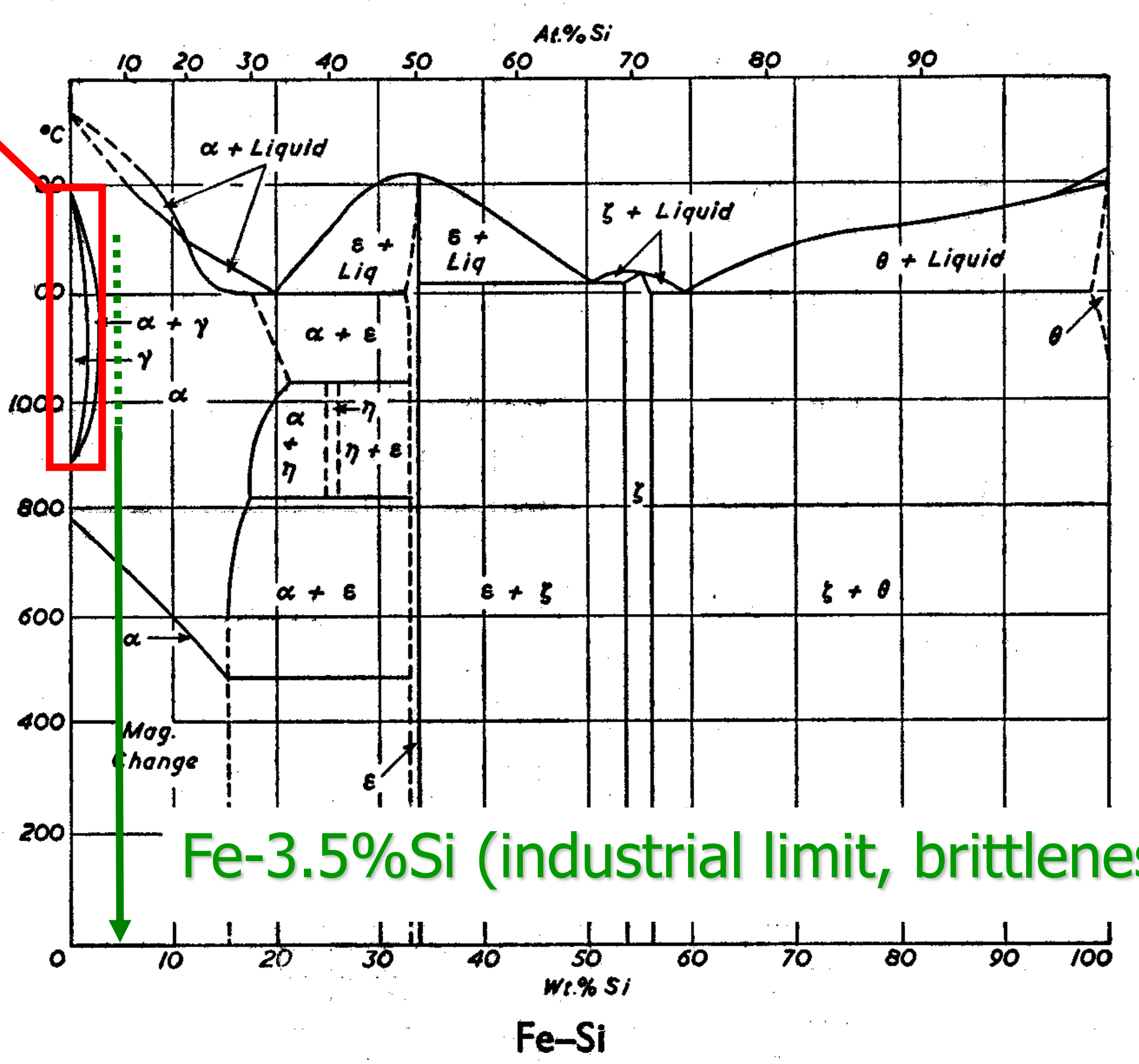


Fe-3.5%Si (industrial limit, brittleness)

Magnetic properties of materials, non-oriented electrical steels

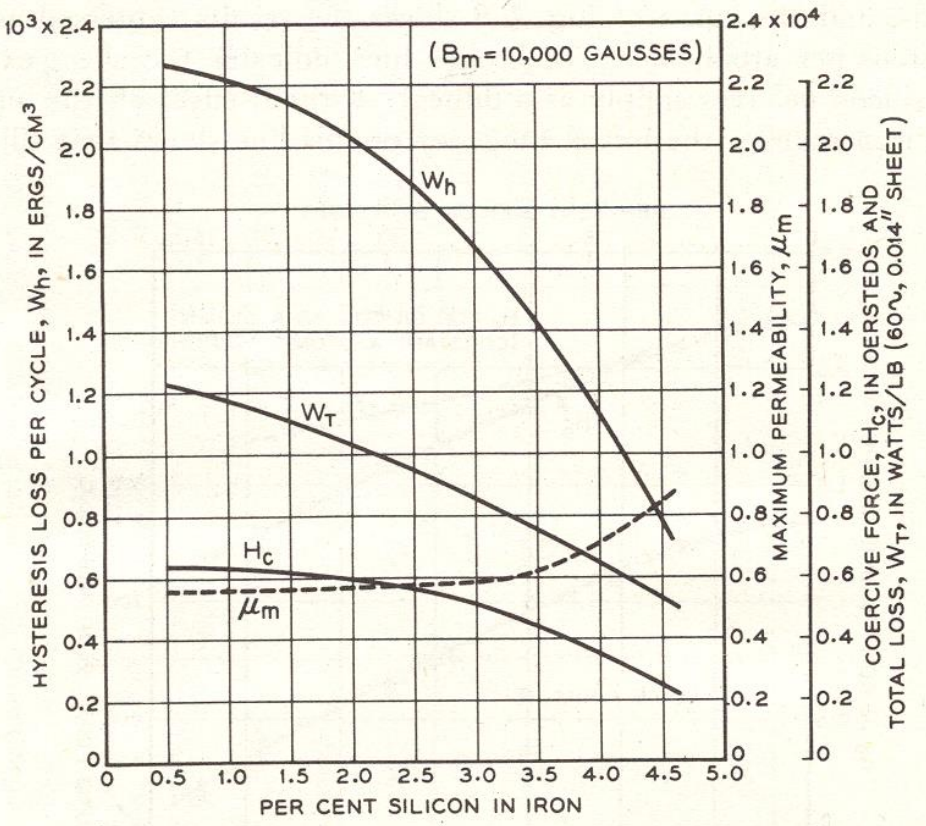


Fig. 4–10. Some magnetic properties of hot-rolled commercial silicon-iron sheet. Some of the change with composition is due to the higher annealing temperature of the material having higher silicon contents.

Advantages:

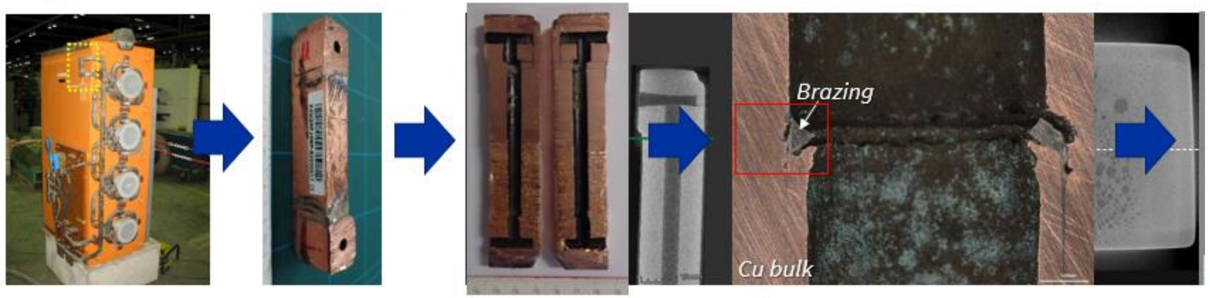
- Increase in permeability
- Decrease in hysteresis loss
- Eddy current loss decrease due to higher resistivity (Al and Mn added as well)
- No ageing (due to Al ⇒ AlN)

Magnetic properties of materials, non-oriented electrical steels

Magnetic properties of materi steels

Analysed samples & method

All the conducts under study correspond to Cu based sections mostly brazed with Sil-Fos (**self-**
with Ag and P)



Analysed samples

No-leaking samples extracted from different PSB locations

Quadrupoles/ Dipoles/ Bending Magnets

After different service time

From 2 weeks to 50 years

Common cooling circuit of demineralized water

Equivalent for all accelerators circuits

Samples examina

Non-destructive test by comp

Selection of the cutting planes

Dry cutting to access the inr

Inspection and chemical an

Metallurgical preparation (poli

Examination of the brazec

Common effort from TE-MSC, HSE-RP, EN-CV, EN-MME and TE-VSC to ensure the **appropriate proc**

2023-06-14 Subtask-2: Analysis and understanding of the failure modes - A.T. Perez, S. Sgobba - EN-MME-MM

PS Booster magnets Task Force day, 14/06/2023

A. Bartkowska & S. Sgobba

Materials Technical Specification
EN-MME

21.08.2023

Technical Sheet
EDMS N°: 2930603

Technical sheet for the supply of cold rolled non-oriented fully processed electrical steel sheets or strip for the PSB quadrupole magnets

REQUIREMENTS	
Normative references	EN 10106, EN 10251, IEC 60404-2, EN 10342, EN 10204
Steel grade and dimensions	M700-100A (1.0894) accordingly to EN 10106 • 1±0.02 mm x 1670 mm x 600 mm (final exact dimensions will be reconfirmed by the blanking company) • Minimum stacking factor (0.98) and other geometric and technological properties, tolerances and inspection procedures as per EN 10106
Manufacturing process	Cold rolled and delivered in sheets (strip may be an option). The steel shall be delivered fully processed. Material shall be supplied with trimmed edges.
Structure and composition	Non-oriented. Indicative composition 2.3 % Si, 0.2% Mn, specification on magnetic properties prevails on composition.
Magnetic properties	Coercive force: target value H_c = 35 ± 3.5 A/m, for cycles up to 1.5 T. Relative permeability μ_r: B (T) | = | 0.1 | 0.3 | 0.6 | 1.0 | 1.2 μ_r | ≥ | 3300 | 5500 | 6500 | 4500 | 2500 The above values are provided as target values. Max. deviations $\Delta\mu_r/\mu_r$ of ±15% are allowed. The properties specified by EN 10106 should also be respected.
	...roviding surface insulation resistance, ...y. Coating should be according to the ...he EC-5 and the product should be

Type of magnet	Composition	Total sales
Hard	Ferrite 56%, Sm-Co 10%, Nd-Fe-B 26%, Alnico, etc. 8%	$5 billion
Semihard	Particulate media 65%, thin films 35%	$15 billion
Soft	Electrical steels 86%, ferrites 12%, amorphous 2%	$8 billion

Table 1. Estimate of the world market for magnetic materials in 1997.

256 t of electrical steel

Magnetic properties of materials, FeNi alloys

Low Ni (50 %), lower μ, high saturation (1.6 T)

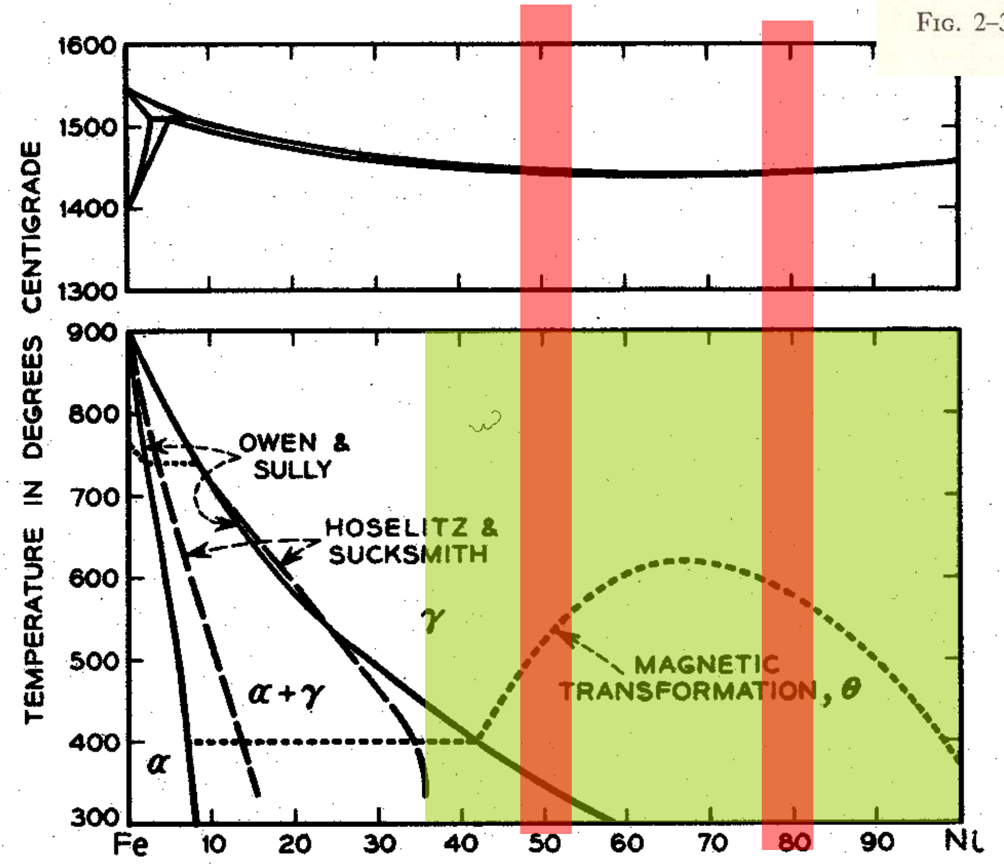


FIG. 5–1.

High Ni (79 %), high μ, low saturation (0.8 T)

From Bozorth, Ferromagnetism, 1951

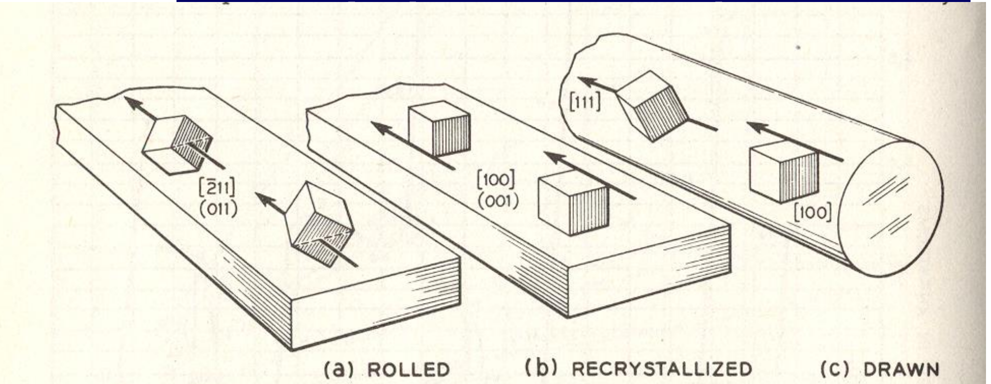
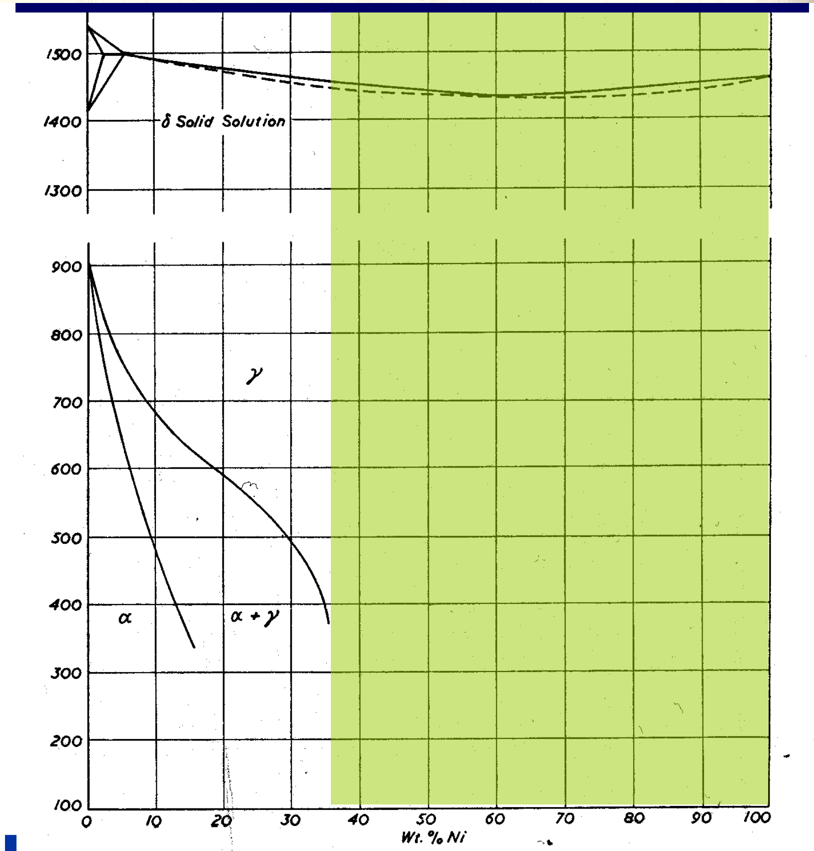


FIG. 2–32. The preferred orientations of crystals in nickel sheet and wire after fabrication and after recrystallization.



Fe–Ni

From Smithells, Metals Handbook

Magnetic properties of materials, FeNi alloys

F. Fiorillo, 2004

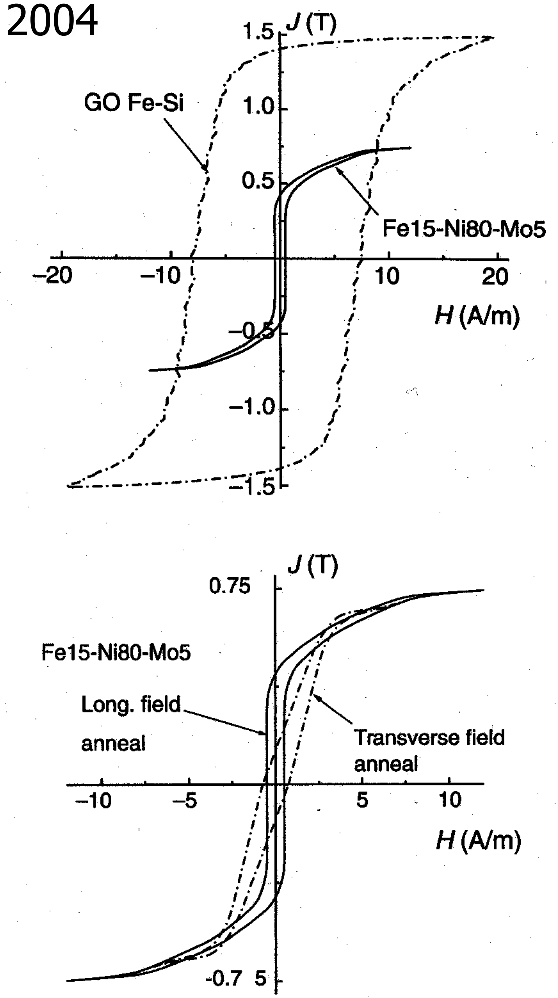
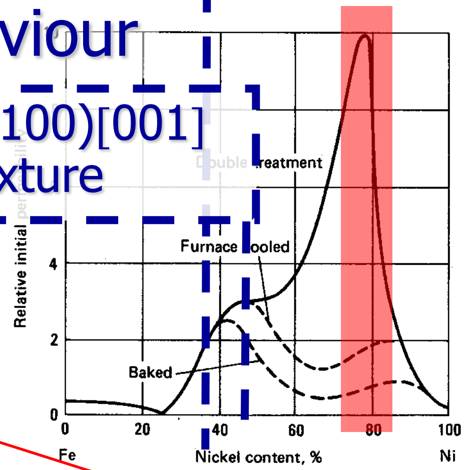


FIGURE 2.19 (a) DC hysteresis loops in GO Fe–(3 wt%)Si laminations and in permalloy (Fe15–Ni80–Mo5) tapes. (b) Loop shearing in permalloy by means of annealing under a transverse saturating magnetic field.

Fig. 13 Relative initial permeability at 2 mT (20 gausses) for Fe-Ni alloys given various heat treatments

Invar behaviour

Strong (100)[001] texture



Treatments were as follows: furnace cooled—1 h at 900 to 950 °C (1650 to 1740 °F), cooled at 100 °C/h (180 °F/h); baked—furnace cooled plus 20 h at 450 °C (840 °F); double treatment—furnace cooled plus 1 h at 600 °C (1110 °F) and cooled at 1500 °C/min (2700 °F/min).

Magnetic properties of materials, FeNi alloys

CERN
CH-1211 Geneva 23
Switzerland

the
Large
Hadron
Collider
project

LHC Project Document No.
LHC-VCRS-ES-0001 rev 1.0

CERN Div./Group or Supplier/Contractor Document No.
AT/VAC

EDMS Document No.
405734

Date: 2004-05-12

Functional specification

VACUUM CHAMBERS FOR THE CIRCULATING BEAMS IN THE LHC INJECTION AND EXTRACTION SEPTA

Magnetic properties of materials, FeNi alloys

CERN	Groupe Logistique Section Standardisation	

A.J. Mager, Magnetic Shields, IEEE Trans. on Magnetics, **6** (1970) 67

N° de codification CERN	SCEM : 39.74.60.059.9
Désignation	*TUBE EN MUMETAL® 77 Ni-5Cu-4Mo-Fe POUR CHAMBRES SPECIALES LSS*

CARACTERISTIQUES	
Matière	Mumetal® 77Ni-5Cu-4Mo-Fe
Dimensions et tolérances	Diamètre ext. = 59.80 mm ± 0.15 mm, diamètre in 58 mm, épaisseur = 0.90 mm ± 0.09 mm, ovalisati 0.4 mm, tolérance sur diamètre moyen = ± 0.2 mn tolérance sur rectitude ≤ 1 mm sur 2.5 m. Longueur 5100 mm -0/+10 mm[1].
Quantités	La quantité minimale à produire est de 69 longu de 5100 mm avec une tolérance -0+10%.
Documents applicables	Soudure : EN 288-3, EN 1435, ISO 5817 Niveau B (qualité à garantir en qualification et fabrication). Matière de base : IEC 404.4, EN 10204.
Etat de livraison	Les tubes seront livrés à l'état roulé-soudé ce nécessitera un traitement thermique de restaur des propriétés magnétiques à effectuer au Cl Dans le cas de perte des tolérances dimensionr due au traitement thermique, notamment ovalisation et flèche, un calibrage (redressage) effectué par le fournisseur. Absence d'oxydation sur le cordon fondu.
Caractéristiques indicatives de la matière de base à l'état roulé-soudé, avant traitement thermique final	Etat de la matière de base : adouci. Perméabilité initiale ≡ 1000, maximale ≡ 10000, champ à saturation ≡ 0.77 T.
Contrôles	100 % visuel, dimensionnel et RX (ce dernier sur soudure). Acceptation : dimensionnel selon cette fiche technique, RX et visuel selon EN 288-3 (ainsi qu'EN 1435 pour RX) et ISO 5817 Niveau B. Une coupe macro-micro d'échantillon suiveur par jour de production sera effectuée (acceptation selon EN 288-3 et ISO 5817 Niveau B).
Caractéristiques garanties après traitement thermique de restauration	Perméabilité initiale ≥ 60000, maximale ≥ 120000, champ à saturation ≥ 0.77 T.

[1] Une surlongueur opportune pour l'éventuel calibrage (redressage) en rectitude et en ovalisation après traitement thermique de restauration des propriétés magnétiques à effectuer au CERN devra être prévue par le fournisseur sur le tube roulé-soudé fourni au CERN.

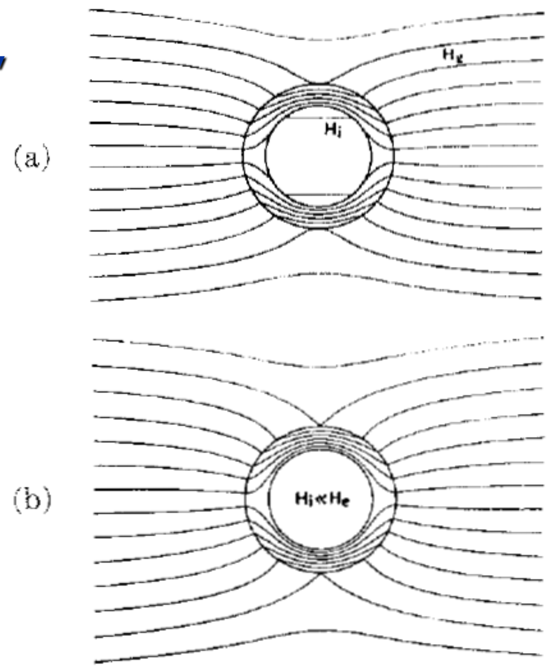


Fig. 1. Calculated field distribution for cylinders with ratio of inner to outer diameter of $D_i/D_o = 0.7$ in field transverse to axis; H_e, external field, H_i, field in the interior of the shield. (a) For a permeability of $\mu = 20$. (b) For a very high permeability.

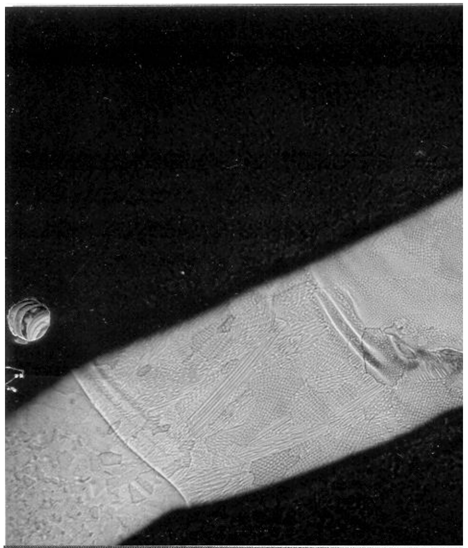
$$S_T = \tfrac{1}{4}\mu(1 - D_i^2/D_o^2) + 1 = (\mu d/D_o)(D_m/D_o) + 1,$$

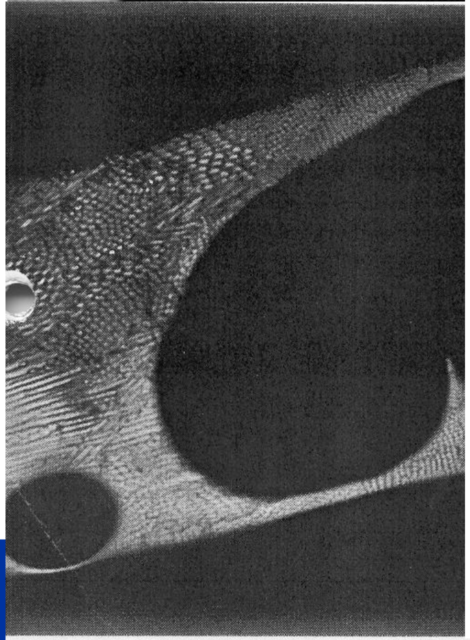
cylindrical shell (transverse field).

⇒Inforce field lines of an external perturbing field H_{ext} through the magnetic material

⇒Weakens the H_{int} field

Magnetic properties of materials, FeNi alloys

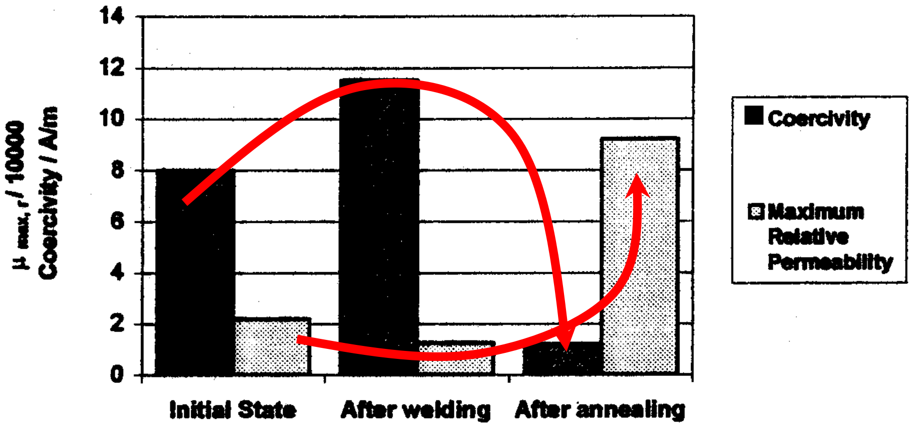




Report n. 98/10/06 **Att. 4, page 1 of 1**

Testing of magnetic properties and relative results

Graph, Table:	**Summary of the evolution of the measured magnetic properties on the Mumetal rings.**
Material:	**Mumetal**
Samples ID:	**ring 1, ring 2**
Density:	**8.6**
Weight before welding:	**ring (1&2) – 28.98 g**
Weight after welding:	**ring 1 – 14.47 g**
	ring 2 – 14.42 g
Permeameter:	**90 turns used for excitation**
	180 turns used for detection



Note: The properties of the initial state were measured on the two rings coupled. After the TIG welding, they were measured on both rings together and on each one separately. Since the measured values of the magnetic properties were reproducible between ring 1 and ring 2, further operations and measurements were performed only on one ring (ring 1).

Magnetic properties of materials, Fe-Ni vs. Fe-Co

Table 7 Typical magnetic properties for various Fe-Ni and Fe-Co alloys

Material	Nominal composition(a)	Typical anneal(b)	Permeability At B=20	Permeability Max	Saturation induction, gausses	Coercivity, H_c, oersteds	Retentivity, B_r, gausses
45 Permalloy	45Ni	1920 °F	2 500	30 000	16 000	0.20	8000
		H_2, 2150 °F	4 000	50 000	16 000	0.06	8000
4750 alloy	47-50Ni	H_2, 2050 °F	4 000	50 000	16 000	0.07	8000
Carpenter 49 alloy	47-50Ni	H_2, 2050 °F	4 000	50 000	16 000	0.07	8000
Conpernik	50Ni	...	1 500	2 000	16 000	...	...
Orthonol	50Ni(c)	H_2, 1825 °F	...	60 000	15 600	0.20	14500
78 Permalloy	78Ni	1920 °F	8 000	100 000	10 700	0.05	6000
4-79 Moly Permalloy	79Ni, 4Mo	2000 °F, Q	20 000	100 000	8 700	0.03	5000
Hymu 80	79Ni, 4Mo	2000 °F, Q	[illegible]	[illegible]	…700	0.05	5000
Supermalloy	79Ni, 5Mo	H_2, 2375 °F, Q	[illegible]	[illegible]	…000	[illegible]	[illegible]
Mumetal	77Ni, 5Cu, 2.75Cr	2050 °F	[illegible]	[illegible]	…500	[illegible]	[illegible]
Permendur	50Co	1470 °F	800	5 000	24 500	2.00	14000
2V Permendur	49Co, 2V	1470 °F	800	8 000	24 000	1.2	14000
Hiperco 2.7	37Co, 0.6Cr	...	650	10 000	24 200	[illegible]	[illegible]
Supermendur	49Co, 2V	...	...	60 000	24 000	[illegible]	[illegible]
2-81 Moly Permalloy powder	81Ni, 2Mo	1200 °F	125	130	...	[illegible]	[illegible]
Carbonyl iron powder	...	...	60	150	...	[illegible]	[illegible]

(a) Remainder iron plus deoxidizer. (b) H_2, annealed in hydrogen; Q, quenched or controlled cooled. (c) Grain oriented.

Up to 1300 °C

Tc = 980 °C

Volume reduction

On-board high speed generators for spacecrafts and aircraftes

Magnetic properties of materials, perm

Rare earths (hard magnetic)

Permanent magnet materials:
→ Materials of high coercivity

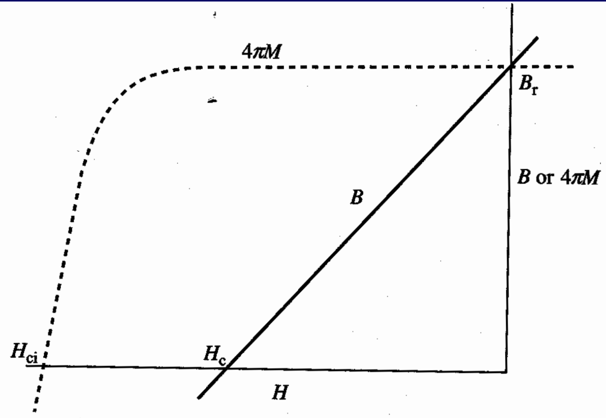


Fig. 14.7 Demagnetizing behavior of a high H_{ci} permanent magnet. The magnetization is unchanged by negative fields less than H_c, so $H_c = B_r$ (in cgs units).

"Ideal" return curve of a permanent magnet (Cullity and Graham, ibid)

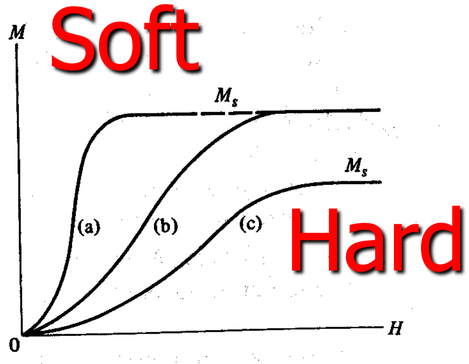


Fig. 1.14 Magnetization curves of different materials.

B.D. Cullity, C.D. Graham, Introduction to Magnetic Materials, 2nd ed., Wiley (2009)

F. Fiorillo, ibid.

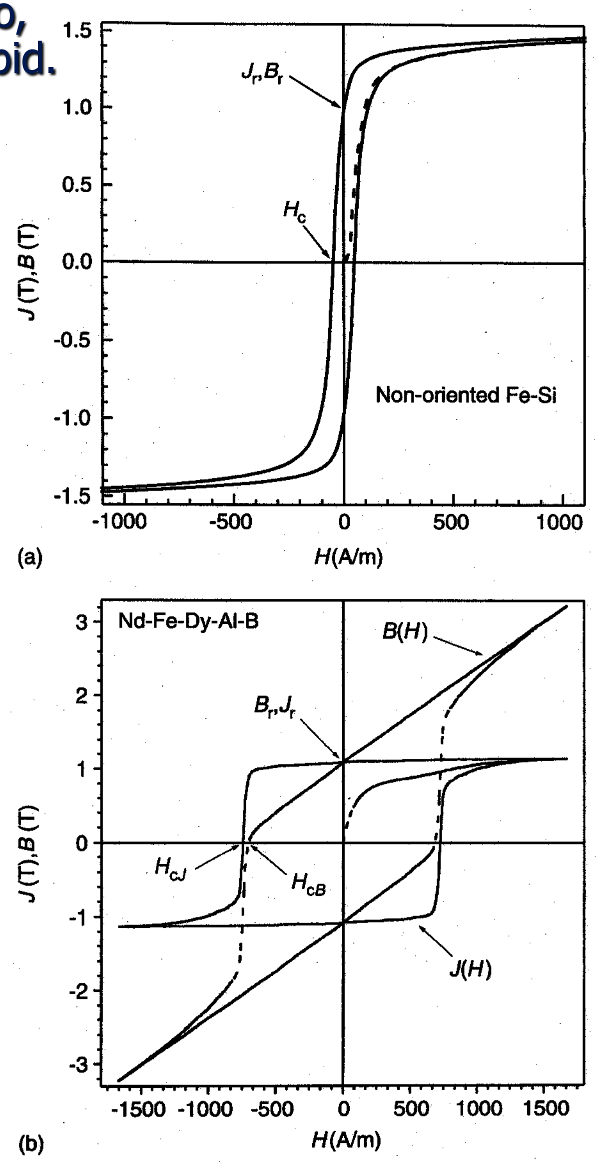


FIGURE 1.7 Examples of hysteresis loops in soft and hard magnets. In the soft Fe–Si laminations, there is no detectable difference between the $B(H)$ and $J(H)$ curves for magnetizations and fields of technical interest. The difference is instead apparent in permanent magnets. It leads to two different definitions of coercive field: H_{cB} is the field required to bring the induction to zero value starting from the saturated state and H_{cJ} is required to reduce to zero the polarization J (i.e. magnetization M). It is always $H_{cJ} > H_{cB}$ (courtesy of E. Patroi).

Magnetic properties of materials, permanent magnets

F. Fiorillo, Characterization and Measurement of Magnetic Materials, Elsevier, 2004

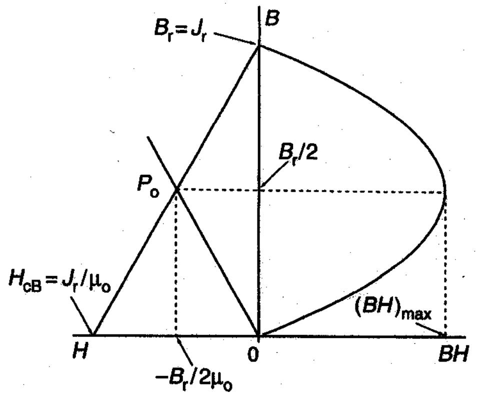


FIGURE 3.3 Return curve and energy product in an ideal permanent magnet. If the material is brought to the saturated state ($J_r = J_s$), the maximum theoretical energy product $(BH)_{max} = J_s^2/4\mu_0$ is attained at the working point P_0.

(BH)max parameter of merit
→ attained at Br/2

Magnetic properties of materials, permanent magnets

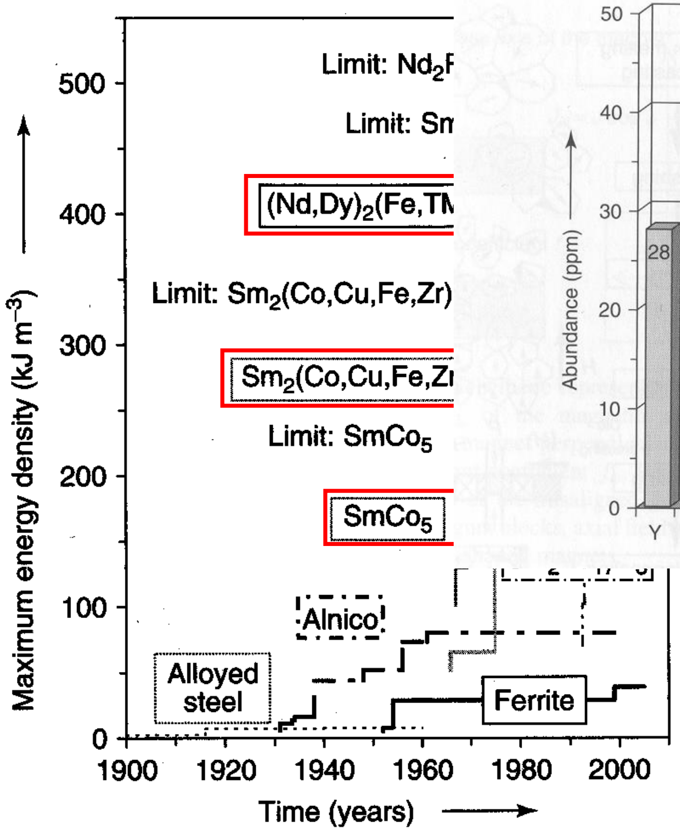
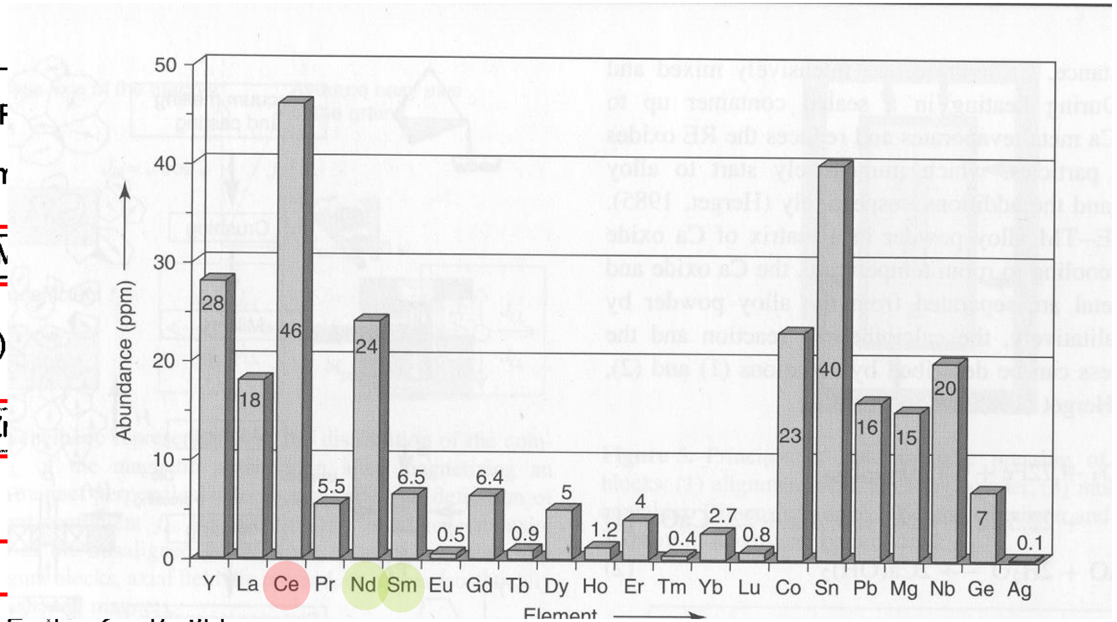


Figure 1. Progress in the maximum energy density of permanent magnets. For RE–TM magnet materials, the theoretical limits are indicated.



W. Rodewald, Rare-earth Transition-metal Magnets, in: Handbook of Magnetism and Advanced Magnetic Materials, vol. 4, Wiley (2007)

Rare Earth (RE) alloys:

Ce the most abundant, but limited use

Technological families:

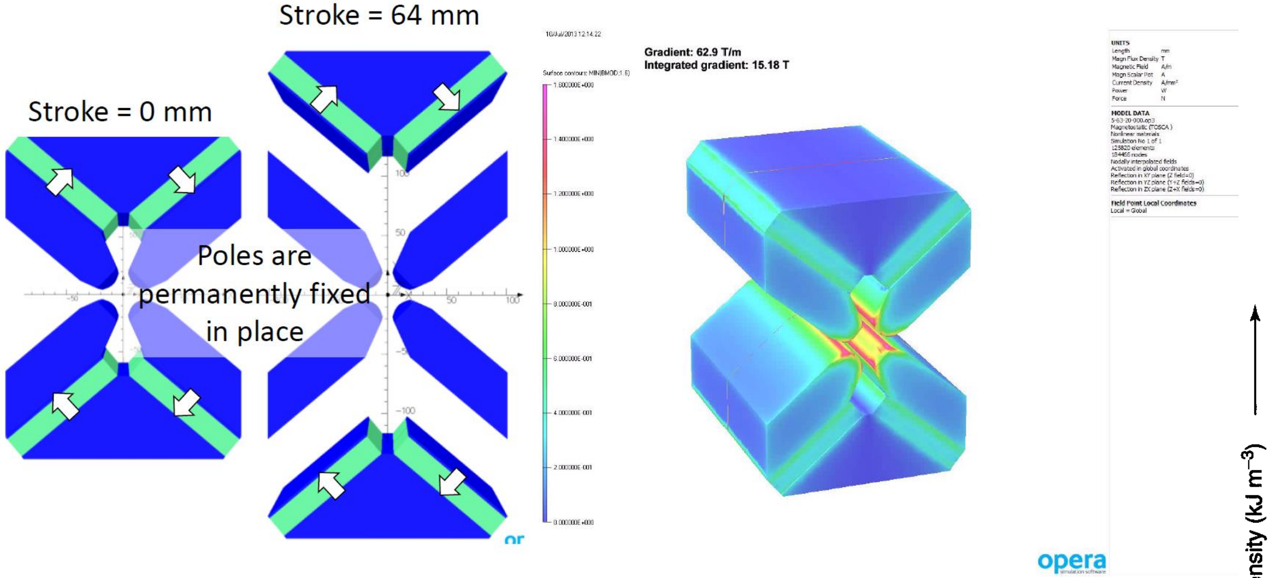
- $SmCo_5$
- "Sm_2Co_{17}"
- "NdFeB"

Magnetic properties of materials, permanent magnets

High Energy Quad Design

- **NdFeB** magnets with **B_r = 1.37 T** (VACODYM 764 TP)
- 4 permanent magnet blocks each 18 x 100 x 230 mm

- Max gradient = **60.4 T/m** (stroke = 0 mm)
- Min gradient = **15.0 T/m** (stroke = 64 mm)
- Pole gap = 27.2 mm
- Field quality = ±0.1% over 23 mm



Jim Clarke et al., "The Application of Variable Strength Permanent Magnet Dipoles and Quadrupoles", CLIC Workshop 2016, CERN

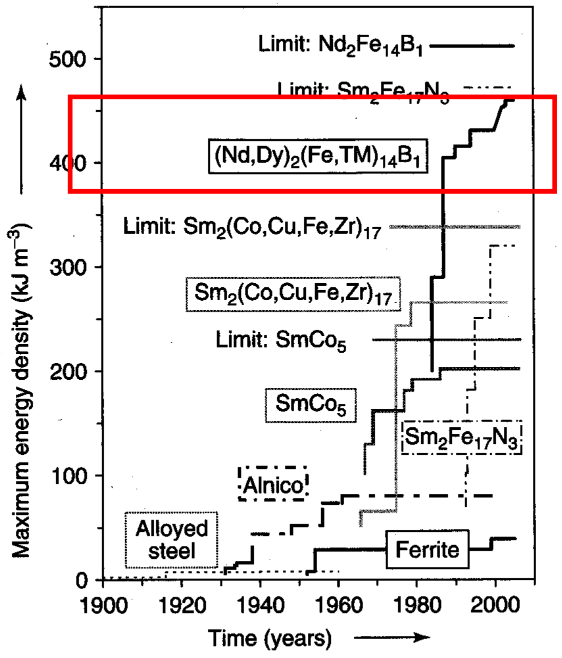


Figure 1. Progress in the maximum energy density of permanent magnets. For RE–TM magnet materials, the theoretical limits are indicated.

Magnetic properties of materials, antiferromagnetism

Antiparallel arrangement of magnetic moments

Zero net magnetic moment for the material

Cr, Mn and "non magnetic" steels are antiferromagnetic

Exists below a critical temperature (Néel or antiferromagnetic transition temperature T_{af})

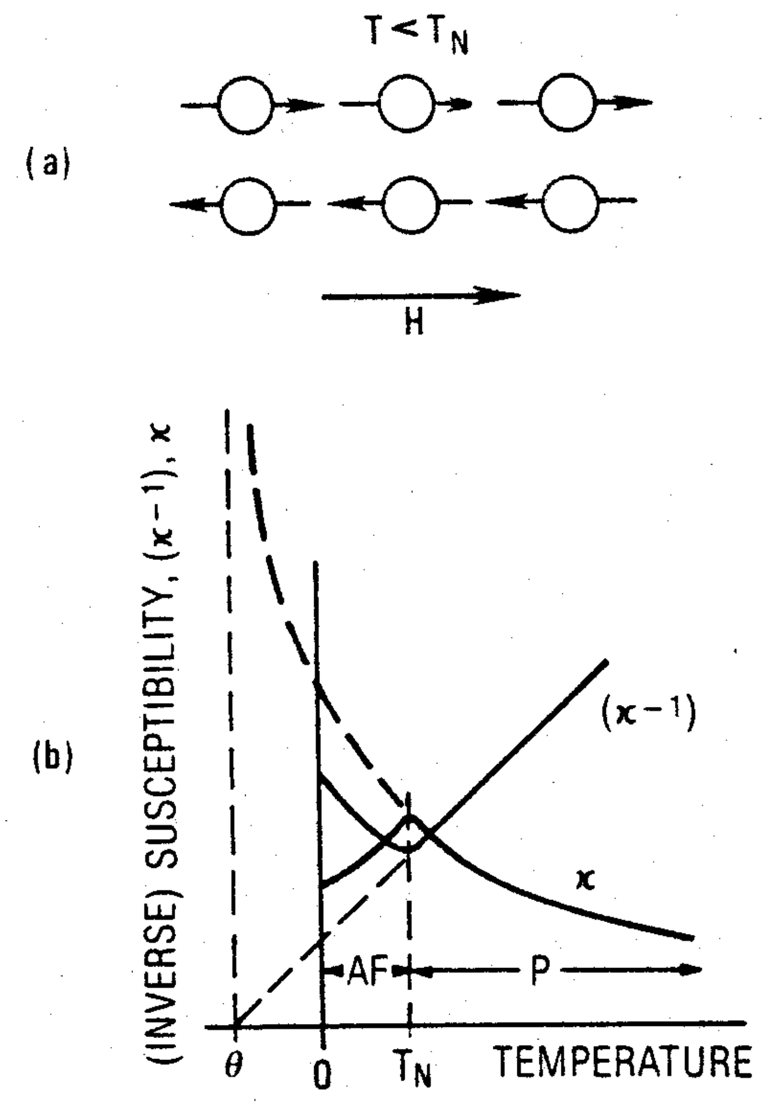
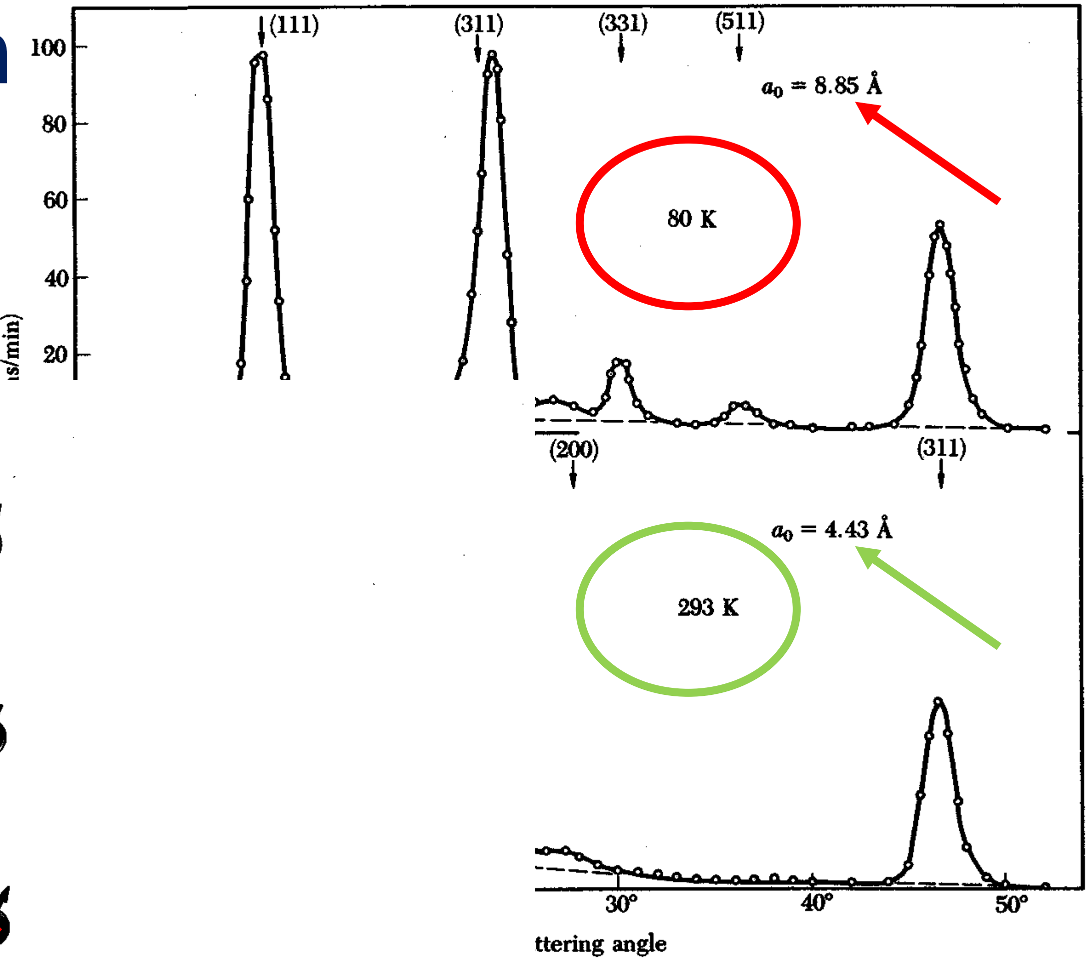


Figure 6.8 (a) Antiferromagnetic alignment of atomic magnetic moments. (b) Susceptibility and reciprocal susceptibility vs. temperature showing antiferromagnetic (AF) and paramagnetic (P) intervals.

R.P. Reed, A.F. Clark (1983)

Magnetic properties of materials, antiferromagnetism



ow and above the spin-ordering temperature
). Wollan. The reflection indices are based on
At the higher temperature the Mn^{2+} ions are

Kittel (1986)

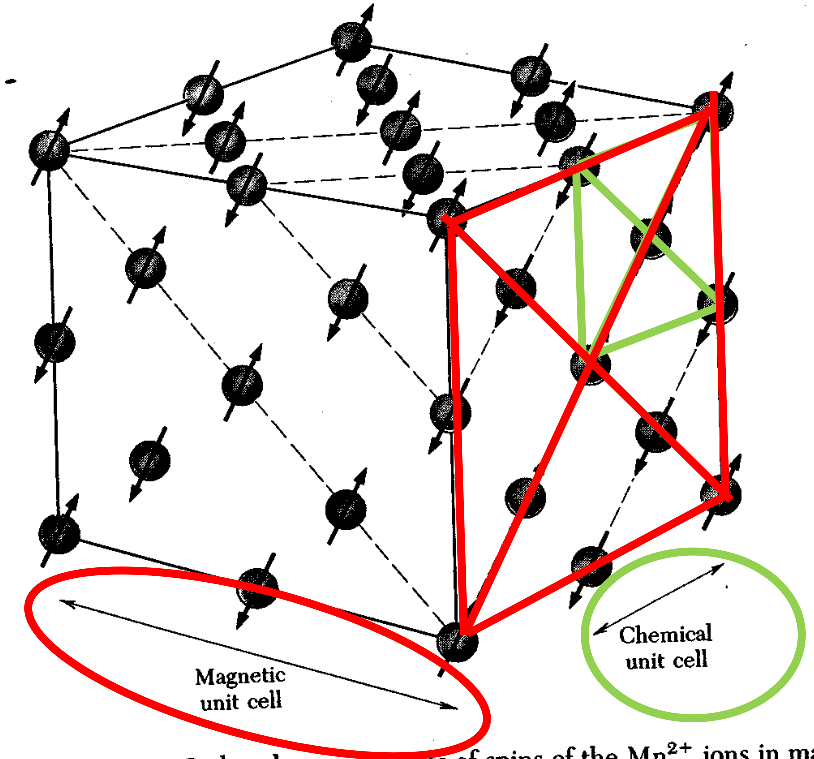


Figure 21 Ordered arrangements of spins of the Mn^{2+} ions in manganese oxide, MnO, as determined by neutron diffraction. The O^{2-} ions are not shown.

Magnetic properties of materials, antiferromagnetism

- **Neutrons are sensitive to the magnetic moment of electrons (interaction of their magnetic moments)**
- **X-rays are not**
- **Several other physical properties have discontinuities at T_{af}**

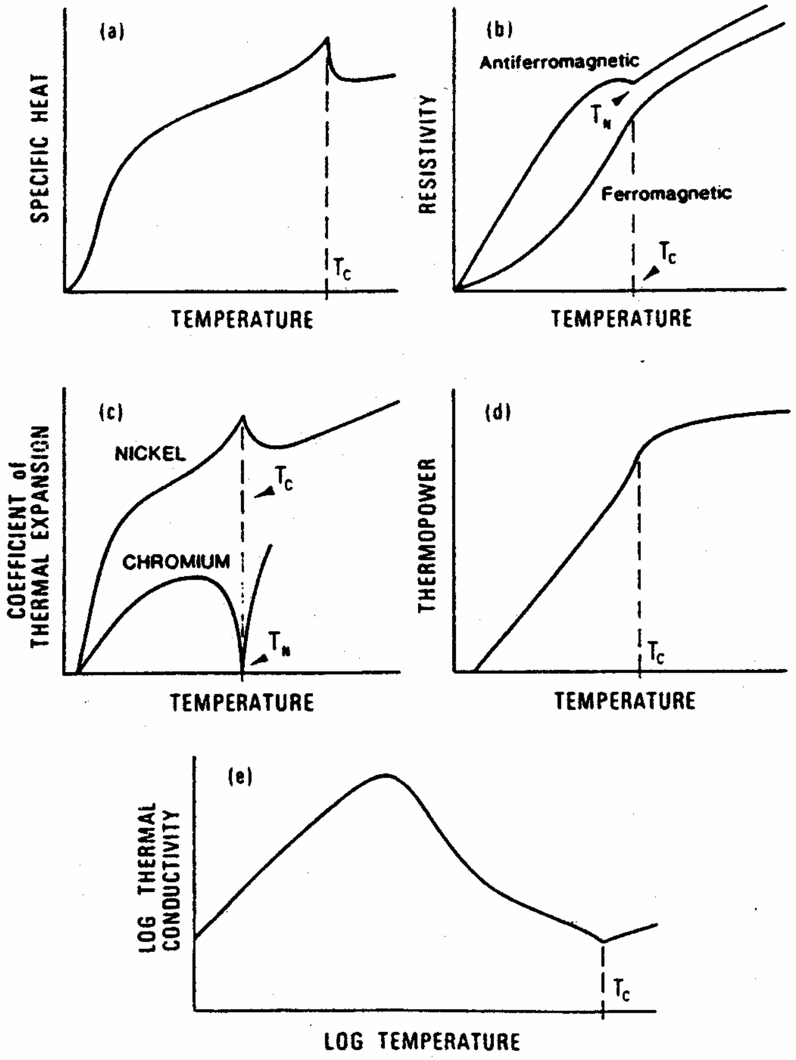


Figure 6.16 The effect of ferro- and antiferromagnetic transitions on a number of material properties.

R.P. Reed, A.F. Clark (1983)

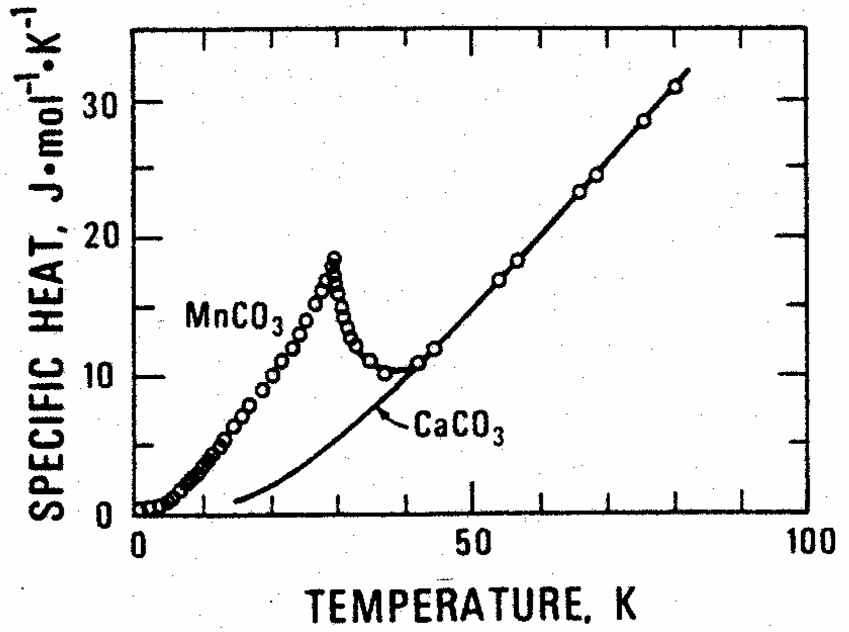
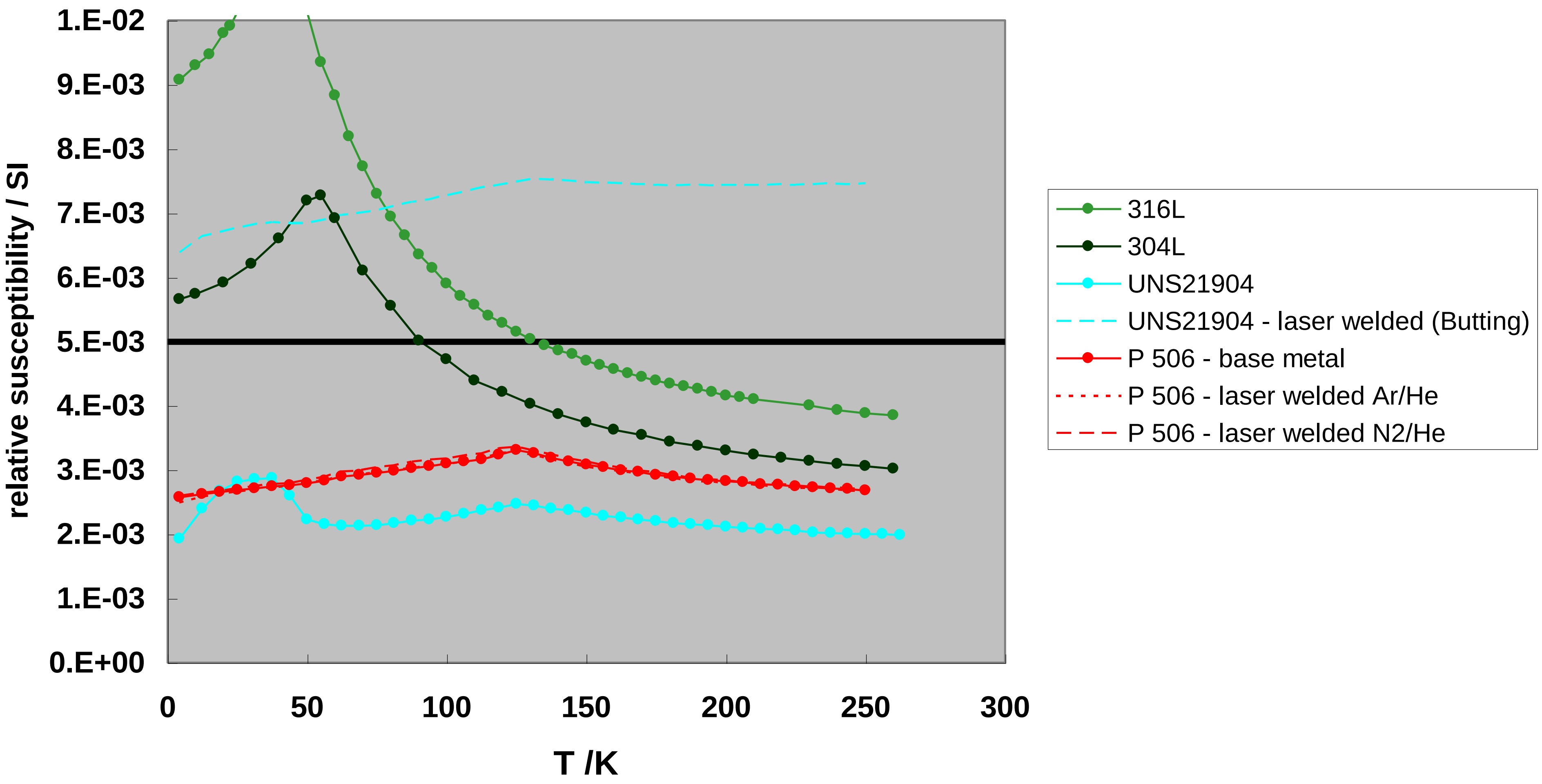


Figure 2.9 Specific heats of $MnCO_3$ and $CaCO_3$ (Kalinkina, 1963) illustrate the general effect of a magnetic transition. The Néel temperature for $MnCO_3$ is 29.4 K.

Magnetic properties of materials, antiferromagnetism



S. Sgobba, G. Hochörtler, A New Non-Magnetic Stainless Steel for Very Low Temperature Applications, Proceedings of the International Congress Stainless Steel 1999: Science and Market, Chia Laguna (I), 6-9 June 1999, Vol. 2, p. 391-401

Magnetic properties of materials, summary

Type	Dependence of *M* on *H*	Dependence of κ or μ on *T*	Magnitude of κ	Magnetic Remanence	Example of Material
Diamagnetism	Linear	Independent[a]	Small (<0)	None	Cu, organic compounds
					…rconductors
					…low critical

Type	Material	At $T \cong 295$ K[a]	References and Comments

Type	Material	At $T \cong 295$ K[a]	At $T = 4.2$ K[a]	References and Comments
Diamagnetic	Cu	$\kappa = -9.3 \times 10^{-6}$	$\kappa = -9.4 \times 10^{-6}$	Fickett (1976); very pure Cu
	Nb	Paramagnetic	$\kappa = -1$	Superconductor below 9 K
Paramagnetic	Al	$\kappa = 2.0 \times 10^{-5}$	$\kappa = 2.5 \times 10^{-5}$	Fickett (1976)
	Ce	$\kappa = 1.6 \times 10^{-3}$	$\kappa = 23 \times 10^{-3}$	Edelstein (1968)
	Potassium–chrome–alum[b]	$\kappa = 1.6 \times 10^{-3}$	$\kappa = 32 \times 10^{-4}$ [c]	DeHaas and Gorter (1930)
	Fe–22Cr–13Ni–5Mn stainless steel	$\kappa = 2.1 \times 10^{-3}$	Antiferromagnetic	Ledbetter and Collings (1979)
Ferromagnetic	Low-carbon steel	$\mu_r = 5250$ (max.)	$\mu_r = 4900$ (max.)	McInturff and Claus (1970a)
	Si steel (1.8% Si)	$\mu_r = 6250$ (max.)	$\mu_r = 9700$ (max.)	McInturff and Claus (1970a)
Ferrimagnetic	Fe_3O_4	$\mu_r \geq 5.3$	$\mu_r \geq 5.5$	Jacobs (1959) – 4 K; Nagata (1961) – RT Assumes saturation at 0.11 MA·m^{-1} (1.4 kOe)
Antiferromagnetic	Fe–22Cr–13Ni–5Mn stainless steel	Paramagnetic	$\kappa = 6.0 \times 10^{-3}$	Ledbetter and Collings (1979)

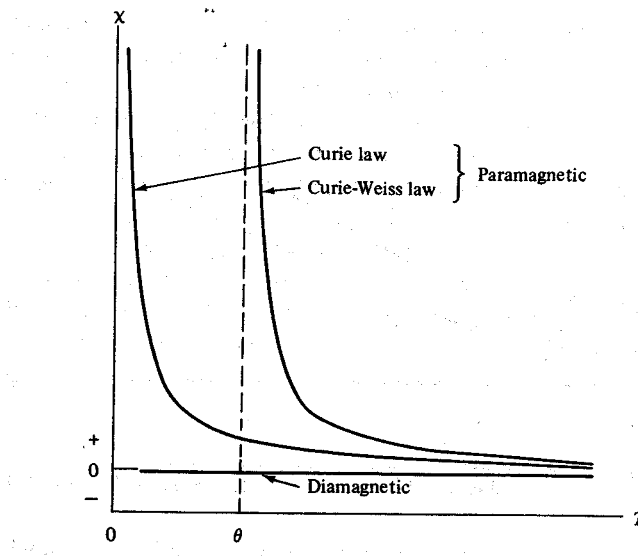
[a] Si units
[b] $Cr_2(SO_4)_3 \cdot K_2SO_4 \cdot 24H_2O$
[c] $T = 14$ K

R.P. Reed, A.F. Clark (1983)

Spare slides

Magnetic properties of materials, ferromagnetism

- Systematic measurements reported by P. Curie in 1895
- Susceptibility for paramagnets ⇒ $\kappa_p = C/T$ (Curie law)
- Weiss (J. Phys. **6** (1907) 66) postulated interaction of elementary moments (⇒ molecular field)
- Fictitious internal field postulated
- $H_e = \lambda M$ *(λ, molecular field constant)*
- Total magn. $M = \kappa_p(H_a+H_e) = C/T\,(H_a+\lambda M)$
- $\kappa = M/H_a = C/(T-C\lambda)$, $T_c = C\lambda$



Variation of mass susceptibility with absolute temperature for para- and diamagnetics.

B.D. Cullity, C.D. Graham, Introduction to Magnetic ... 2nd ed., Wiley (2009)

⇒ 1) T_c connected to the "mean" or "molecular field constant"

⇒ 2) Theory is consistent with existence of spontaneous magnetisation at T_c and below

Magnetic properties of materials, ferromagnetism

As a rule of thumb:

In general b.c.c. ferrous phases are ferromagnetic, f.c.c. are not

Phases, not alloys (see austenitic stainless steels)!

Magnetic properties of materials, irons and steels

Properties affected by the T and t of annealing, and by cooling rate

Latter especially critical in the 900 °C to 800 °C range due to γ⇒α transformation

If $T_{\alpha,\gamma}$ is exceeded, cooling rate slow, approx. 5 °C/min

Higher max. μ is obtained by exceeding $T_{\alpha,\gamma}$ than by not allowing the material to transform to γ at all

Hence, for high μ_{max} an anneal at 925-1000 °C with cooling < 5 °C/min recommended

For high permeability at B ≥ 1.2 T, advisable to anneal at max 800 °C and to cool slowly (Armco steel Co., 1943)

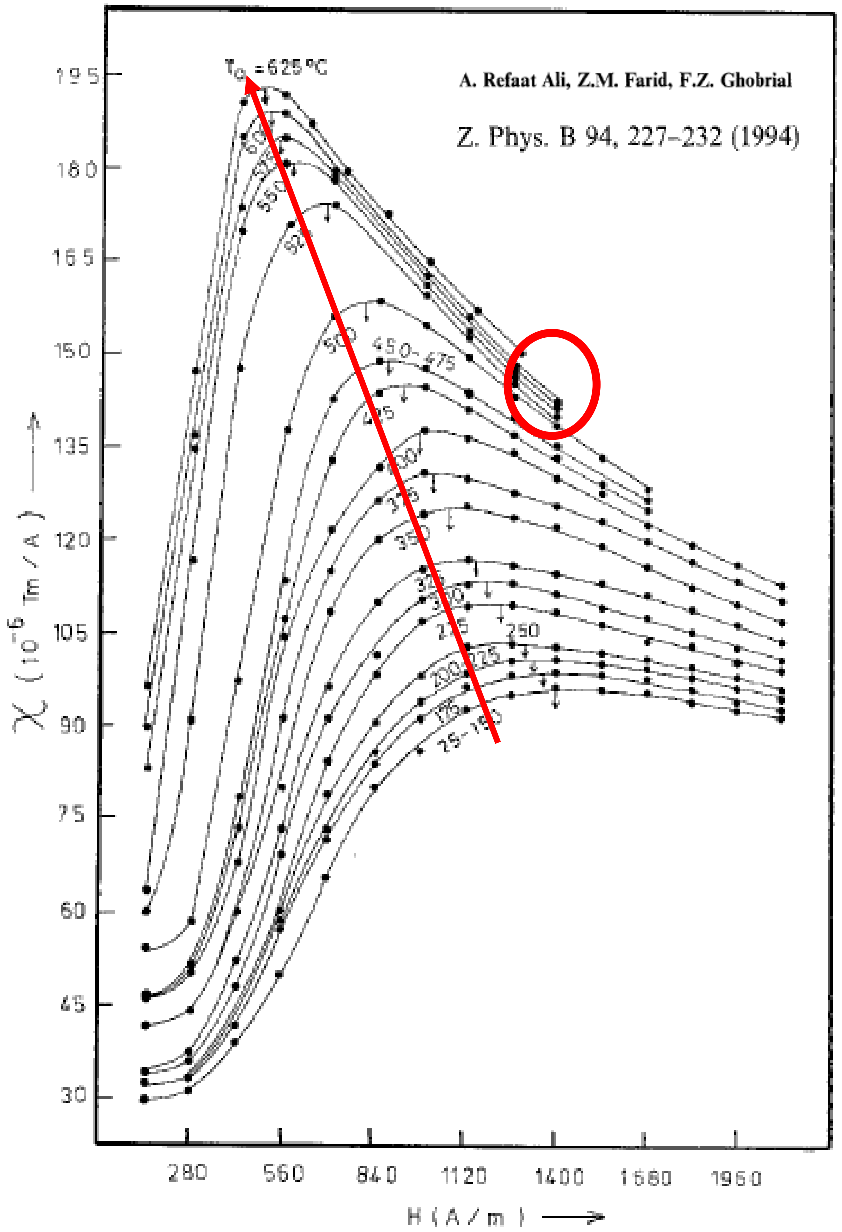


Fig. 1. Effect of annealing temperature of the dependence of the magnetic susceptibility (χ) on the magnetic field (H) of heavily cold-worked Fe-0.006 wt.% C, t_a = 15 min

Magnetic properties of materials, FeNi alloys

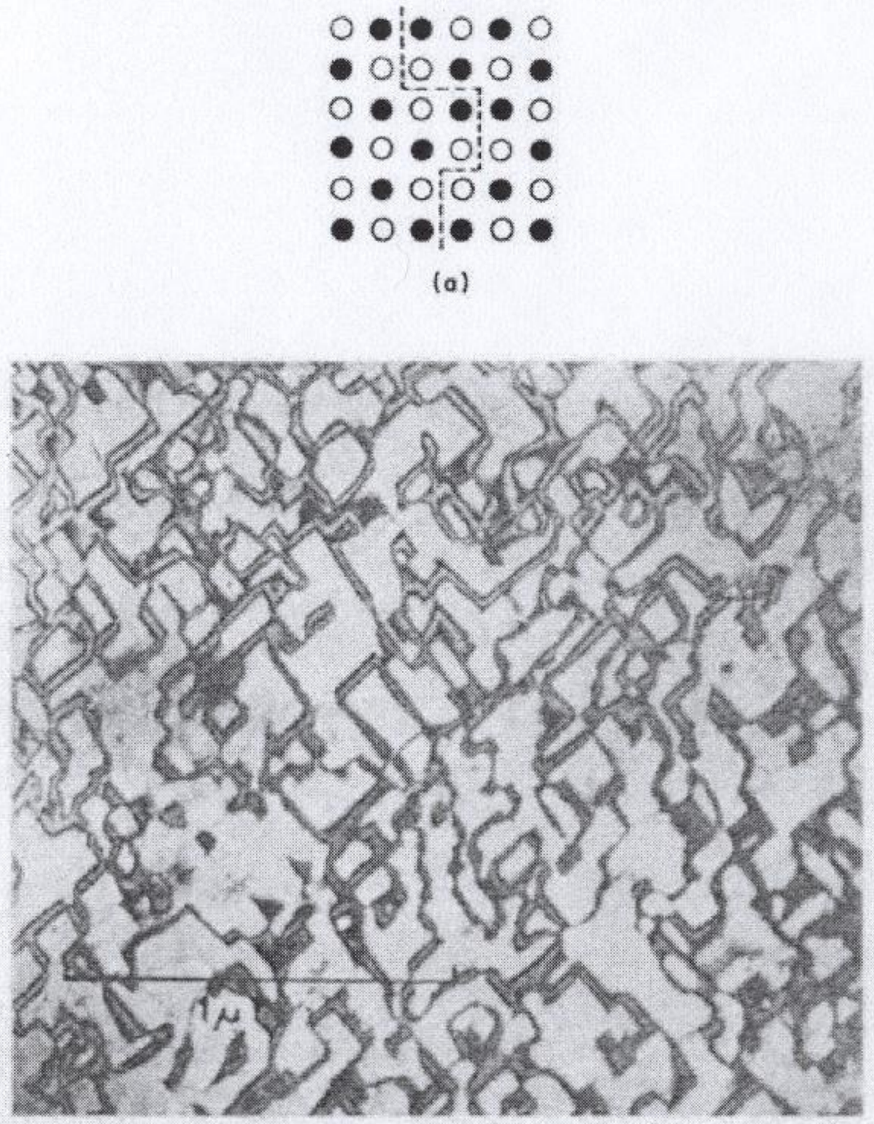


Fig. 5.54. Antiphase domain boundaries characterizing short-range order. (a) A two-dimensional diagram showing the like-atom pairs across the boundary and (b) electron microscopy evidence ((b) Fisher and Marcinkowski [1960]).

"Directional-order" theory (Néel, Taniguchi and Yamamoto, Chikazumi and Oomura)

Any solid solution which is not completely ordered contains some pairs of nearest neighbor like atoms

At T≤ Tc, but high enough for diffusion to occur, like-atom pairs tend to be aligned in the direction of the local magnetization.

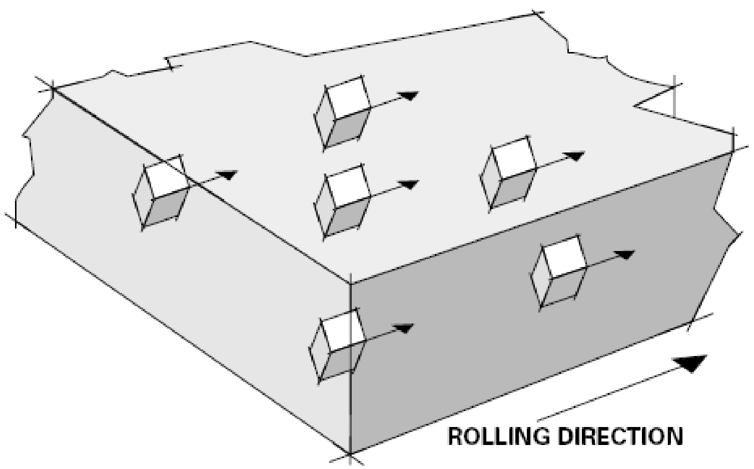
When the temperature drops so low that diffusion can no longer occur at an appreciable rate, the like-atom pairs are frozen in place, and produce a uniaxial anisotropy in the material.

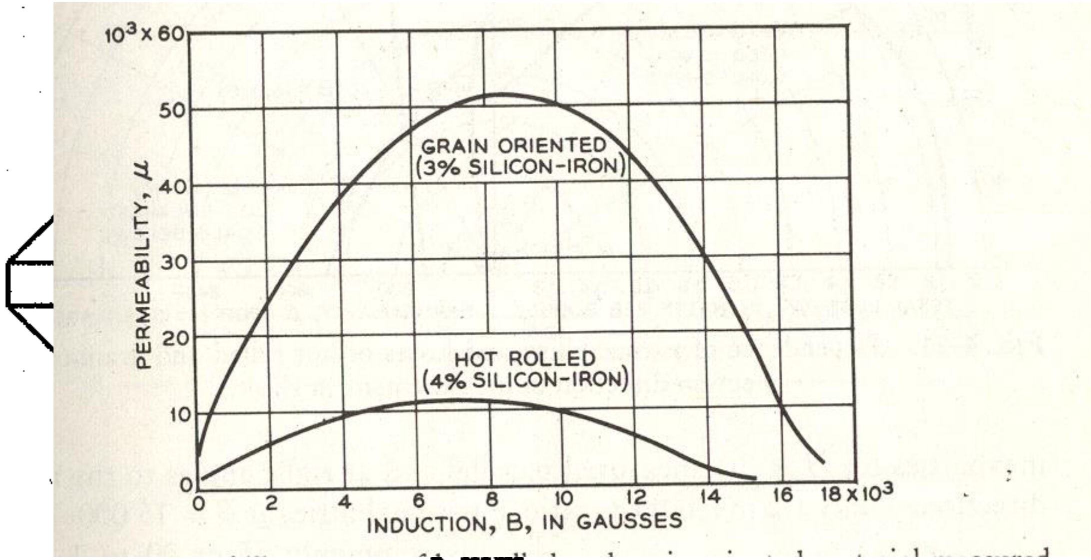
[Gordon and Sery, IEEE Trans. Nuclear Science, vol. NS-I 1, pp. 105-110 (1964)]

Magnetic properties of materials, oriented electrical steels

"Goss" (1934-37) texture (110)[001]

Courtesy of A+K Steel





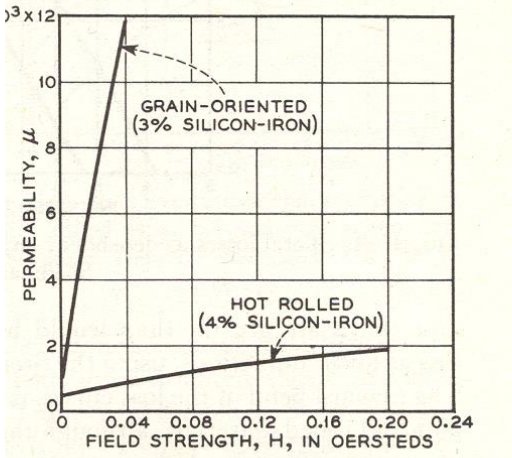


FIG. 4-13. Permeability in low fields, showing non-linear relation.

Fe single crystals exhibit

1. minimum coercivity
2. maximum permeability

when magnetized along one of the <001> axes

Magnetic properties of materials, oriented electrical steels

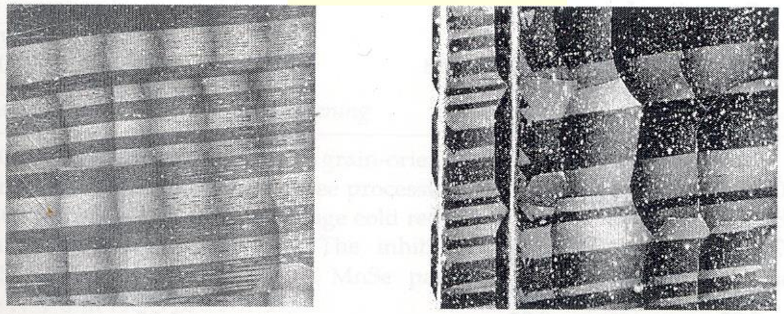


FIGURE 2.11 Domains in HGO Fe–Si laminations. They are oriented along the [001] axis and tend to multiply upon scribing the sheet surface.

F. Fiorillo, Characterization and Measurement of Magnetic Materials, Elsevier, 2004

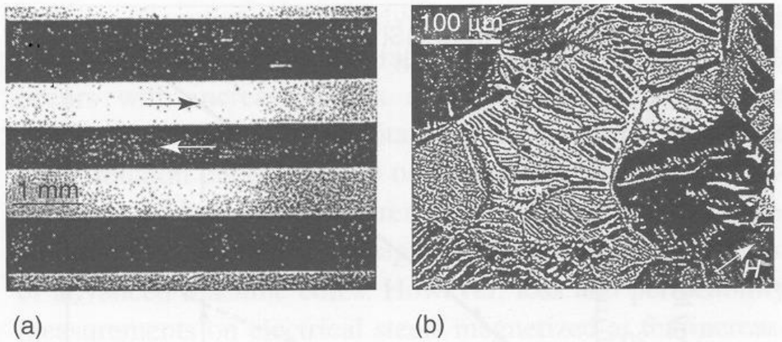


Figure 1. Typical static domain images in (a) grain-oriented and (b) nonoriented electrical steel. (Reproduced from Hubert *et al.*, 1998. With permission from Springer-Verlag GmbH. © 1998.)

A.J. Moses, in: Handbook of Magn. and Adv. Magn. Mat., Wiley, 2007

Texture + large grain size + low impurity content

1. coercive fields as low as 4-10 A/m
2. maximum permeability around 5 x 10^4

in GO alloys (10 x NGO)

1. Conventional GO (7° dispersion) – 80 % of the market – 1 M ton/y, 1500 M EUR/y
2. High permeability GO (3° dispersion)

of the [001] axes around RD