MAGNETIC PROPERTIES OF THE IRON LAMINATIONS FOR CBA MAGNETS*

M.J. Tannenbaum, A.K. Ghosh, K.E. Robins, and W.B. Sampson
Brookhaven National Laboratory, Upton, New York 11973

CONF-830311--93

BNL--32711

DE83 010457

Abstract

The required magnetic properties of the iron for CBA dipoles are for the most part the same as those for conventional accelerators, namely: low coercive force, high permeability at both low and high inductions, and high saturation induction. There are two main differences in the CBA application, 1) the iron is at 3.8°K, 2) the magnetic field in the iron can go as high as 6 Tesla, which is well above saturation. Measurements of the magnetization curves for CBA iron laminations at 300°K and 4.2°K are presented. The data are analyzed in terms of a simple model in which the variation in saturation induction can be separated from the low-field permeability variation. Tolerances on coercive force, permeability, and saturation induction are discussed.

Field Tolerances and Factors Which Control
The Magnetic Properties of Iron

The design tolerance on the reproducibility of magnetic properties of the iron is

$$\frac{\Delta B}{B_0} = 1.7 \times 10^{-4},$$

which is about 1/3 of the CBA central field tolerance. At injection (~0.4 Tesla) this is determined largely by variations in the coercive force. At 5 to 6 Tesla, however, it becomes a tolerance on the saturation induction (M_s)

Since the saturation induction is controlled by residual impurities, particularly carbon, the best material is nearly pure iron which has an M_s of 2.158 Tesla.^{1,2}

It turns out that the low field permeability (μ) and coercive force (H_c) are even more critically dependent on the carbon content than the saturation induction. This is the reason why conventional magnet steel can be used in CBA. According to Marcantonio² annealing for large grain growth gives a low coercive force and high permeability. However this can only be done reproducibly if the carbon content is below 0.005%.

Iron Specification Spec. No. 94

This specification is an attempt to balance the requirements of the project against standard industry practice. The 9000 tons of lamination steel for the full CBA Project represents only 0.4% to 0.6% of one week's steel production in the U.S. It is therefore rather significant that Spec. No. 94 has been accepted, with one exception to be discussed below, by the Middletown Works of the Eastern Steel Division of Armco, Inc., which supplied the lamination steel for most of the recent U.S. accelerators including FNAL, PEP, CESR, and NSLS.

The mechanical features of the specification will not be described except to note that the hardness and crown are critical to the precision of punching and

stacking. Also, the thickness of the material is limited because the carbon must diffuse to the surface in order to be removed by the decarburization process.

Specification No. 94 emphasizes the magnetic properties of the iron. The chemical analysis from the ladle is specified as tightly as the manufacturer will allow on the elements which are routinely analyzed; and it is emphasized that special effort should be made to control the impurities. The ladle analysis maxima are phosphorus, 0.03%; silicon, 0.05%; sulphur, 0.05%; manganese, 0.42%. The manganese is not an impurity, but is required in the alloy at a level of 0.35% to facilitate hot rolling of the ingots.¹ Carbon is specified at 0.10% maximum in the ladle, reducing to less than 0.008% in the finished product. The specified density of 7.85 grams per cubic centimeter is within 0.3% of the density of pure iron and thus implies a certain degree of control over the lighter impurities (O,N).

The magnetic properties specified are the coercivity, permeability at two magnetizing forces and intrinsic saturation induction. The specified values are: coercive force of 1.1 ± 0.4 Oersted after excitation to 10 Oersted; permeability between 1500 and 3400 at 1 Oersted and between 1400 and 1530 at 10 Oersted. These specifications have been accepted by Armco, Inc. The intrinsic saturation induction is required to be a minimum of 2.120 Tesla and be reproducible to $\pm 0.05\%$. This requirement was not accepted by Armco, and was waived for Armco special CR magnet steel.

General Properties of B-H Curves

We now look at the detailed shape of the B-H curve and how it is constrained by the specification. Data on Armco special CR magnet steel are used for illustration because they are available both from the vendor and from our own measurements. Data from Armco³ on low field permeability are shown in Fig. 1, with μ plotted as a function of B. Three samples of material were used: ranging in coercive force from 0.95 to 1.29 Oe. The correlation of high permeability with low coercive force (both given by large grain size)² is clearly evident.

Figure 1

* Work performed under the auspices of the U.S. Department of Energy.

In the region of magnetizing forces above the value corresponding to the maximum permeability, the Frolich-Kennelly relation¹ is an empirical equation for describing the magnetization curve:

$$\frac{1}{\mu-1} = a + \frac{H}{M_s} \quad (1)$$

This is a simple formula involving only two parameters: a dimensionless parameter a , which defines the rate of approach to saturation, and M_s , the intrinsic saturation induction. The quantity $1/(\mu-1)$, denoted by u is also a convenient variable in analytical expressions for the central field in CBA dipoles.

Magnetization Measurements of Armco Special CR Steel

Recent measurements of B-H curves for samples of Armco special CR magnet steel from yokes now in production are tabulated in Table I for both room temperature and at 4.2°K.

The apparatus used is essentially the one described by McInturff and Claus.⁴ Measurements at 300°K were done to H fields ~ 300 Oe but at low temperatures (4.2K) the B-H curves were determined to H ~ 3000 Oe. The apparatus consists of two concentric rectangular pick up coils the cross-section of which is shown in Fig. 2. Two samples of the laminations 0.75" wide and ~ 9" long are stacked on either side of the inner pick-up coil (H-coil) and enclosed by the outer coil (B-coil). The magnetizing force was provided by a copper wire solenoid for fields up to 300 Oe and by a superconducting solenoid for fields up to ~ 3000 Oe at 4.2°K.

So far no attempt has been made to measure the B-H curve in the very low field $0 < H < 5$ Oe region. Data have been taken with the sample in the "cyclic magnetic state" where H is continuously cycled between $+H_{max}$ and $-H_{max}$. It is fairly easy to get accurate values for the induction, but the determination of the corresponding value of H is more difficult. It is estimated that the value of H has an error of ± 0.5 Oe. Table I lists the data at 300 K and at 4.2 K.

The coercive force, H_c , is readily determined in the cyclic case to an accuracy of ± 0.05 Oe. Table II lists the H_c of a few samples that have been tested.

As mentioned earlier, the determination of the H field for a given induction has an uncertainty of ± 0.5 Oe. This can lead to an error in $\mu \sim \pm 100$ at high μ . However at a μ of 180, this error in μ is only ± 1 . The measuring apparatus has a B-field sensitivity of ± 15 G at 21 kG, but the major error in

determining B comes from the measurement of the area of cross section of the sample. This can amount to an absolute accuracy of $\pm 0.3\%$ and is the major source of error in comparing B,H curves for different samples.

Table I
Armco Special CR Magnet Steel

H (Oe)	B(kG) 300K	B(kG) 4.2K
10	14.81	
20	15.81	16.30
30	16.34	16.82
40	16.71	17.22
50	16.99	17.51
60	17.21	17.74
70	17.41	17.94
80	17.61	18.12
90	17.83	18.29
100	18.05	18.42
200	19.40	19.88
300	20.30	20.79
400	20.90	21.51
500	21.32	21.86
600	21.62	22.16
700	21.82	22.35
800	21.98	22.48
900	22.11	22.61
1000	22.22	22.72
2000	23.27	23.80
3000	24.29	24.81

Sample #	H_c (Oe) 300K	H_c (Oe) 4.2K
11C-H&V	0.90	0.93
13C-1V&2V	1.18	—
15C-2H&3H	1.05	—
16C-1H&4H	1.32	—
16C-2H&3H	1.24	—

Analysis of the Magnetization Curve

If Eq. (1) were exact, the intrinsic saturation induction could be derived from the difference of any two measurements in Table I.

$$M_s = \frac{H_1 - H_2}{\frac{1}{\mu_1} - \frac{1}{\mu_2}} \quad (2)$$

The best sensitivity is at the highest magnetizing forces. The estimated saturation inductions for the sample of Table I 2.133 Tesla at 300°K and 2.185 Tesla at 4.2°K. Better precision on the saturation induction could have been obtained by plotting $1/(B-H)$ versus $1/H$ and taking the intercept:

$$\frac{1}{B-H} = \frac{1}{M} = \frac{a}{H} + \frac{1}{M_s} \quad (3)$$

Also, the non-ferromagnetic susceptibility of iron has been ignored in this analysis but must be taken into account for high precision evaluations.⁵ It should be noted that the 2.4% increase in saturation induction from 300°K to 4.2°K is about twice that expected from the Langevin-Brillouin equation.¹ Further investigation shows that at low temperature the empirically corrected Bloch $T^{3/2}$ law applies,¹ and the expected increase in saturation induction is actually ~ 1.9%. This is considered to be in excellent agreement with the measurements.

The quantity H/M_s has been calculated for each data point in Table I, using the values of M_s given above, and the quantity $a(H)$ computed. If the Frolich-Kennelly relation were exact, then $a(H)$ would be

a constant independent of H . In fact, $a(H)$ is not a constant but varies in a characteristic way (Fig. 3). Nevertheless, this is evidently a convenient representation of the magnetization curve since $a(H)$ varies by a factor of only 5 for a 3 order of magnitude range in H , over which the permeability varies by a factor of 500. Also, it is clear from this representation that the change in the magnetization curve from room temperature to 4.2°K is due almost entirely to the change of M_s , with the change in a being typically less than 0.00004.

Figure 3

The Frolich-Kennelly relation can be used to help understand random variations in the magnetization curve for different lots of materials. Differentiation of Eq. (1), at fixed H , yields

$$\Delta \left(\frac{1}{\mu-1} \right) \bigg|_H = \Delta a(H) - \frac{H}{M_s} \frac{\Delta M_s}{M_s}. \quad (4)$$

Thus the effect of variation in the saturation induction can be separated from the variation in $a(H)$. At low fields $H < 100$ Oe, the variation in $1/(\mu-1)$ is dominated by variation in $a(H)$. The good data base³ of 100 samples at 100 Oe which showed a permeability range of 179 to 181 corresponds to a $1/(\mu-1)$ variation of 0.00006. This variation is the same as Armco's agreed μ specification of between 1400 and 1530 at 10 Oe, which corresponds to a Δa variation of 6×10^{-5} . At high fields $H > 1000$ Oe, the variation in saturation induction is a maximum of

$$\frac{\Delta M_s}{M_s} = 0.45\%, \quad \frac{\Delta M_s}{M_s} \bigg|_{\text{rms}} = 0.13\%.$$

Relationship Between Permeability Variation and Central Field Variation

In the low field region, $B < 1.8$ Tesla $H < 100$ Oe in the iron, ($B_0 \lesssim 3$ Tesla central field in the gap), the variation in the magnetization is controlled entirely by Δa . The central field variation is approximately

$$\frac{\Delta B_0}{B_0} \approx 5 \times \Delta a,$$

so that

$$\begin{aligned} \frac{\Delta B_0}{B_0} &= 3 \times 10^{-4}, \text{ full variation} \\ &= 1 \times 10^{-4} \text{ rms, for } B_0 < 3 \text{ Tesla.} \end{aligned}$$

This is well within the tolerance. At higher magnetic fields, $B_0 > 4$ Tesla, the M_s variation is dominant, and a computer calculation was performed varying M_s

from 2.033 to 2.233 Tesla. The exact computer result is

$$\frac{\Delta B_0}{B_0} = \frac{1}{4} \frac{\Delta M_s}{M_s},$$

for $4.42 < B_0 < 6.0$ T.

Summary & Conclusions

A simple parameterization based on the Frolich-Kennelly relation is shown to be an excellent representation of the B-H curve for the nearly pure iron desirable for high field accelerator magnets.

Specification No. 94 for lamination steel in CBA magnet magnets has been described. The full variation that this specification allows in the magnetization curve can be expressed conveniently as

$$\Delta a = 0.00006$$

$$\frac{\Delta M_s}{M_s} = 0.45\%.$$

The saturation induction is not routinely measured by vendors and above number represents an educated guess for Armco Special CR Magnet Steel. These allowed magnetization curve variations are converted into expected variations of the central field transfer function with the result:

$$\frac{\Delta B_0}{B_0} = 3.3 \times 10^{-4} \text{ rms for } 4.4 < B_0 < 6 \text{ Tesla,}$$

controlled by the saturation induction variation; and

$$\frac{\Delta B_0}{B_0} = 1.0 \times 10^{-4} \text{ rms for } B < 3 \text{ Tesla,}$$

controlled by the permeability variation specified at 10 Oersted (Δa term). At the injection field of 0.4 Tesla the central field variation is controlled by the coercive force specification of 1.1 ± 0.4 Oersted. $\Delta B_0 = 3 \times \Delta H_c$. It is expected to be no worse than

$$\frac{\Delta B_0}{B_0} = 1.7 \times 10^{-4} \text{ rms,}$$

and possibly even half this value.

Apart from the high field variation, which is a factor of two too large, all the other expected variations are within the CBA central field iron design tolerance of $\Delta B_0/B_0 = 1.7 \times 10^{-4}$ rms without the need of shuffling. It is of course imperative that the weight of the lamination stack be controlled to better than the saturation induction variation, say 0.1% total variation, 0.03% rms, so that no significant additional variation is added to the above estimates.

References

1. R.M. Bozorth, Ferromagnetism, D. Van Nostrand Co. Inc. NY (1951).
2. A. Marcantonio, Specifying Magnet Steels, Proc. of 1965 Int. Symposium on Magnet Technology, SLAC, U.S. Dept. of Commerce, Springfield, VA.
3. We would like to thank Armco, Inc. for permission to publish their data.
4. A.D. McInturff and J. Claus, Proceedings of the 3rd Int. Conf. on Magnet Technology, Hamburg, 1970.
5. For a more complete treatment see H. Danan, J. Phys. Radium 20, 203 (1959), and H. Danan, et. al., J. Appl. Phys. 39, 669 (1968).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.