Report on the

INFLUENCE OF PROCESS PARAMETERS ON THE MAGNETIC PROPERTIES OF LTV-PROCESSED STEEL

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FERMI NATIONAL ACCELERATOR LABORATORY

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SUMMARY

The report commences with an elementary discussion of the approach to saturation of a ferromagnet and goes on to demonstrate how the form of the B-H curve responds to changes of applied stress, and by the same token, internal stress and strain. It is also pointed out that the coercive field also varies monotonically with stress and strain. Based on this model, attention is focussed on variable residual stress in the sheet-rolled laminations as the most likely cause of variability in magnet properties. In this context it is pointed out that Epstein-measured B-H traces show variability characteristic of variation of internal strain from sample to sample. In this regard, a sensitive criterion of this magnetic-property variation would be the variation of dB/dH at some field at the knee of the B-H curve. Evidence is produced to show that Epstein-test specimen preparation does not introduce stress sufficient to mask the above-mentioned variations. It can therefore be safely concluded that the Epstein variations carry through to the final magnet.

In seeking a source of internal-stress variation we look to the dominant stress-relieving step in the processing line, viz. LTV's Continuous Annealing Line (the CAL line). That the level of this annealing varies measurably from run to run is demonstrated by variation of grain size and an accompanying variation of H_c. It is suggested that Vickers microhardness, which is not presently being monitored by LTV, would provide another good measure of the level of residual cold deformation.

The report concludes by pointing out that process control can be exerted through the monitoring of one or more of the following parameters:

(1) μ_{incr} = dB/dH at some specified H near the B-H knee.
(2) grain size
(3) coercive field, H_c
(4) Vickers microhardness

Of these parameters, H_c is the most important. Any or all of the others could also be measured in support of the H_c findings.

It is pointed out that it is not possible to say at this stage just how much variation in parameters (1), (2), (3), and (4) can be tolerated. Some calibration is required to connect levels of parameter variation to permissible variations in magnet property.

It is recommended that an experimental program be initiated to perform this calibration.

INTRODUCTION

Approach to Saturation in Ferromagnets

As the applied field is continuously increased the magnetization (moment per unit volume, M) of a ferromagnetic material asymptotically approaches its saturation value, M_s, according to

$$M = M_s - \frac{b}{H^2} - \frac{c}{H^3} - \cdots + \chi_p \mu_0 H \tag{1}$$

where χ_p is the paramagnetic susceptibility. In terms of the measured induction, B, which is identically $M + \mu_0 H$, and neglecting χ_p, which is small compared to 1, the approach to saturation is given by

$$B = M_s - \frac{b}{H^2} - \frac{c}{H^3} - \cdots + \mu_0 H \tag{2}$$

where the free-space permeability, μ_0, is $4\pi x 10^{-7}$ H/m.

And in terms of the incremental permeability, $\mu_{incr} = (1/\mu_0)(dB/dH)$ it is given by

$$\mu_{incr} = 1 + \left(\frac{2b}{H^3} + \frac{3c}{H^4} + \cdots\right)/\mu_0 \tag{3}$$

As discussed in [1], for an isotropic polycrystalline material the coefficients *b* and *c* are given by

$$b = K^2/13.12\, M_s \tag{4a}$$

$$c = b/1.98\, M_s \tag{4b}$$

where K is the anisotropy constant.

Influence of Stress on the Approach to Saturation

If a stress σ, is applied to the above isotropic polycrystalline material the approach to saturation is modified according to

$$b = [K + 1.5(\lambda_{100} - \lambda_{111})\sigma]^2 / 13.12 M_s \tag{5a}$$

$$c = b[K - 4.67(\lambda_{100} - \lambda_{111})\sigma - 11.9\lambda_{111}\sigma] / 1.98 M_s \tag{5b}$$

wherein λ_{100} and λ_{111} are the magnetostriction constants.

To a first approximation, Eqn. (3) may be written

$$\mu_{inc} = 1 + (2b/\mu_0)/H^3 \tag{6}$$

according to which a plot of the measured incremental permeability versus $1/H^3$ is a straight line of slope $(2b/\mu_0)$ and intercept $(1 + \chi_p)$ -- the so-called "$1/H^3$ law". An example of this is given in Fig. 1.

Next, since we have chosen to neglect the coefficient *c*, the only coefficient needing to be evaluated is *b*, which from Eqn. (5a) is given by

$$\sqrt{(2b/\mu_0)} = A + B\sigma \tag{7a}$$

with

$$A = 348K/\sqrt{M_s} \tag{7b}$$

and

$$B = 522(\lambda_{100} - \lambda_{111})/\sqrt{M_s} \tag{7c}$$

This result indicates that the square-root of the Fig. 1 slope, i.e. $\sqrt{(2b/\mu_0)}$, plotted versus applied stress should be linear. An example is given in Fig. 2. The slope and intercept of such a plot (provided that M_s is known from a separate measurement) will yield values for K and $(\lambda_{100} - \lambda_{111})$.

Fig. 2 shows quite clearly that a positive correlation exists between *b* and σ. It is therefore possible to show qualitatively how a B-H curve based on Eqn. (2) might respond to changing $b(\sigma)$, Fig. 3. Using a comparable range of *b*-values, Fig. 4 shows how a $b(\sigma)$-induced variation of B about its average value might vary as function of H.

The model calculation has stemmed from an analysis of the influence of applied uniaxial stress on the sample's magnetization. However, with equal validity, σ could be regarded as a process-induced residual internal stress.

MAGNETIC PROPERTIES OF LTV STEEL

Model Results Compared to Those for LTV-Processed Steel

The B-H behavior of strips of LTV-processed steel were measured using the standard Epstein-square method. A pair of typical results are shown in Fig. 5 (B versus H) and Fig. 6 (deviation of B about the mean versus H). The similarity of Figs. 3 and 5 and Figs. 4 and 6 suggests that the inter-sample magnetization differences exhibited by the LTV-processed steel strips are caused by residual internal stress that varies from sample to sample.

Influence of Stress and Strain on Coercive Field

Stress: According to Becker and Doering [3] the coercive field, H_c, increases with strain according to

$$H_c = C(\lambda/M_s)\sigma_i \tag{8}$$

where C is a constant, λ is some "isotropic" magnetostriction coefficient, and σ_i is some "average" internal stress.

Strain: As for strain, Dietrich and Kneller [4] have given the relation

$$H_c = 1.5(\lambda/M_s)bG\rho^{1/2} \tag{9}$$

where *b* is the Burger's vector, G is the elastic modulus, and ρ is the dislocation density. The influence of strain on H_c has also been considered in detail by Trauble [5].

Thus on both accounts we would expect to H_c increase in response to cold deformation, and vary from sample to sample in response to changes in the level of strain and/or internal stress. We understand that this is being observed in samples of the LTV steel.

Measurements on Dipole Magnets

At Fermilab the field strengths of an extensive series of dipoles have been measured as function of exciting current, Fig. 7. The spread magnet constant has been taken to correlate with the spread in B(H) observed about the "knee" in the Epstein tests, Fig. 5. The latter, according to the introductory argument, is due to internal stress.

There is a ready consensus that the spread in Epstein results stems directly from variations of internal stress in the Epstein ribbons. To connect this to magnet behavior it is necessary to show that the Epstein strips have not been significantly strained during preparation by shearing. Or alternatively, that the shearing introduces a fixed background bias against which processing-induced variations can still be observed.

The influence of shearing can be determined by comparing the magnetic properties of as-sheared strip with strip that has been sheared+annealed and another that has been annealed+sheared. Fortunately such studies have been carried out and their results reported by G. Kobliska

Influence of Shearing on Epstein Test Data

Figure 8 shows a set of B-H curves for punched samples steel. The question being asked is "does the punching itself introduce significant deformation over and above that already present". The answer is "no" for the following reason:

Curve-1 is a typical B-H for a heavily deformed material -- high loss, depressed M_{max} (see Eqns. (2) and (7a)) and enhanced H_c (see Eqns. (8) and (9)). After annealing the loop is much "squarer" whether punching occurs before or after annealing. Of course the final-annealed sample has the best properties; but as far as deformation is concerned the effect of rolling-induced deformation dominates over that due to shearing.

It can therefore be concluded that the observed variation of Epstein characteristics can be interpreted in terms of stress variations in the sheet stock from which the Epstein samples were cut. It follows that the observed variations in magnet properties are due to variations in the internal stresses carried by the laminations.

Influence of Steel Chemistry on Magnet Properties

LTV-supplied heat analyses show very close control over composition. It is not believed that chemistry is causing any significant variation of magnetic properties.

INFLUENCE OF AS-ROLLED MICROSTRUCTURE ON MAGNET PROPERTIES

We have concluded that variation in residual strain in the rolled sheet is responsible for the observed variation in magnet properties, and that this variation is reflected reliably in the results of the Epstein test.

It has been stated that the metallurgical condition of the finished sheet is controlled primarily by "soak" (time/temperature) conditions that exist in the continuous annealing stage (i.e. in the CAL line).

Obviously it will be beneficial to ensure that time and temperature in the CAL line is controlled more precisely than at present.

Furthermore, in order to more tightly control the quality of the finished sheet further metallurgical and magnetic specification is desirable. On the other hand, it is not contractually possible at this stage to introduce any new product specifications. Accordingly we must focus attention on tightening process control in order to confine the range of variation of the existing specifications. In addressing this issue we are free to make what might be termed *process-control recommendations.* Both metallurgical and magnetic recommendations can be made. In order to "calibrate" them, experimental process simulation is needed.

Magnetic Recommendation

A magnetic recommendation can be formulated on the basis of Epstein data. Acceptable variation of B for given H (e.g. 20 Oe) could be specified; this is just a permeability specification. Perhaps a more sensitive permeability is $\mu_{incr} = dB/dH$. Taken in the vicinity of the knee, μ_{incr} would be a sensitive indicator of variation in magnetic property. An acceptable value of $\Delta\mu_{incr}$ will have to be determined.

Metallurgical Recommendation

Since chemistry is already being tightly controlled an excellent measure of the level of internal strain is microhardness. The microhardnesses of test samples emerging from the CAL line should be measured.

Grain size is another measure of the metallurgical condition of the sheet. It is clear that nothing approaching recrystallization takes place in the CAL line. Nevertheless LTV-supplied data indicates that variation of grain size does exist among the various heats of a run.

Figure 9, from LTV-supplied data emphasizes a remarkable positive correlation between ASTM grain size number and critical field. The ASTM grain size number varies inversely as the actual grain size. Thus Fig. 9 that from run to run, increases and decreases of grain size are accompanied by decreases and increases, respectively, of H_c. It is generally recognized that a positive correlation exists between grain size and time/temperature of annealing. It follows that the aggressiveness of the anneal that the sheet experiences in the CAL line varies measurably from run to run. Any increase in annealing level should also be accompanied by a lowering of internal stress and hence, according to Eqn. (8), a lowering of H_c. Thus if variation of grain size occurs a corresponding inverse variation of H_c is expected. Thus the variation of H_c provides additional confirmation of the above statement regarding the variability of CAL line conditions.

Since H_c is included in the specifications, it seems reasonable to use a close monitoring of H_c as a mechanism for exerting a tighter control over the CAL-line process parameters. In this way, residual strain can be more tightly controlled and with it the variation of knee magnetization.

It remains for model testing to convert the above qualitative observations into a quantitative recommendation.

CONCLUSION

It is concluded on the basis of LTV-supplied data that the composition of the steel is sufficiently constant from run to run and not a factor in magnet property variation.

Epstein-measured B-H traces show variability characteristic of variation of internal strain from sample to sample. A sensitive criterion of this magnetic-property variation would be the variation of dB/dH at some field at the knee of the B-H curve.

Epstein test specimen preparation does not introduce stress sufficient to mask the above-mentioned variations.

It is therefore concluded that the variation in magnet property is due to variation in internal strain in the laminations.

The rolled sheet receives strain-relieving annealing in LTV's Continuous Annealing Line (the CAL line). That the level of this annealing varies measurably from run to run is demonstrated by variation of grain size and an accompanying variation of H_c.

Vickers microhardness was not monitored by LTV, yet H_v would provide another good measure of the level of residual cold deformation.

Thus we have at our disposal several parameters that could be monitored in an attempt to reduce the variability of finished-magnet properties. As mentioned above, these are:

(1) μ_{incr} = dB/dH at some specified H near the B-H knee.
(2) grain size
(3) coercive field, H_c
(4) Vickers microhardness

Of the above parameters, H_c is the most important. Any or all of the others could also be measured in support of the H_c findings.

We cannot say at this stage just how much variation in parameters (1), (2), (3), and (4) can be tolerated. Some calibration is required.

An experimental program should be initiated to perform this calibration.

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LIST OF FIGURES

Figure 1: Plot of incremental susceptibility, μ_{incr} versus $1/H^3$ illustrating the validity of Eqn. (6) and providing a value of $\sqrt{(2b/\mu_0)}$ -- after reference [1].

Figure 2: Plot of $\sqrt{(2b/\mu_0)}$, from the slope of Figure 1, versus applied stress σ, illustrating the validity of Eqn. (7) -- after reference [1].

Figure 3: Plot of the function $B = M_s - b/H^2 + kH$ based on Eqn. (2) in order to illustrate how B(H) responds to changes of *b* which, according to Eqn. (7), increases as with increasing stress. For the purpose of illustration it has been assumed that $M_s = 20$, $k = 10^{-2}$, and that *b* varies from 30 (upper curve) to 48 (lower curve).

Figure 4: Plot of $\Delta B = B - <B>_{av}$ based on $B = M_s - b/H^2 + kH$ and under the assumption that *b* varies from 30 to 50.

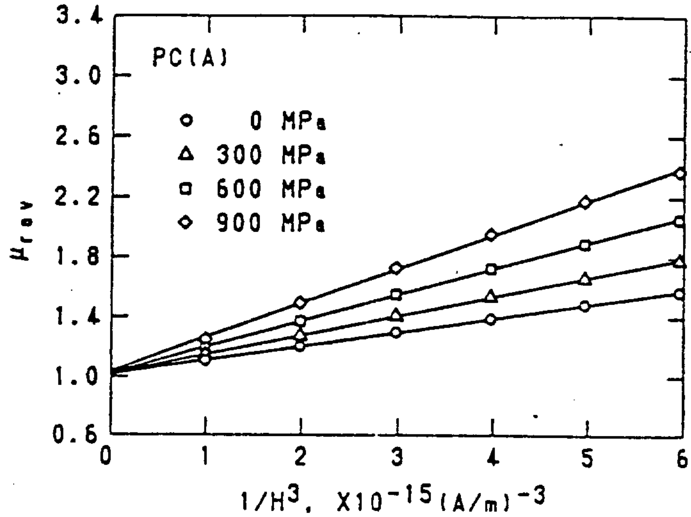
Figure 5: Epstein-test B-H data for LTV steel strips from Run 5 -- data of A. D. Russell (cf. Figure 3).

Figure 6: Data of Figure 5 plotted in the format ΔB ($= B - <B>_{av}$) versus H (cf. Figure 4).

Figure 7: Relative magnet field strength as function of exciting current -- Fermilab data.

Figure 8: B-H loops for LTV steel in the conditions: (1) as punched; (2) annealed plus punched; (3) punched plus annealed -- data of G. Kobliska.

Figure 9: Curves illustrating the run-to-run variability of ASTM grain size number (squares) and a corresponding variation in coercive field, H_c (triangles) -- after LTV-supplied data.



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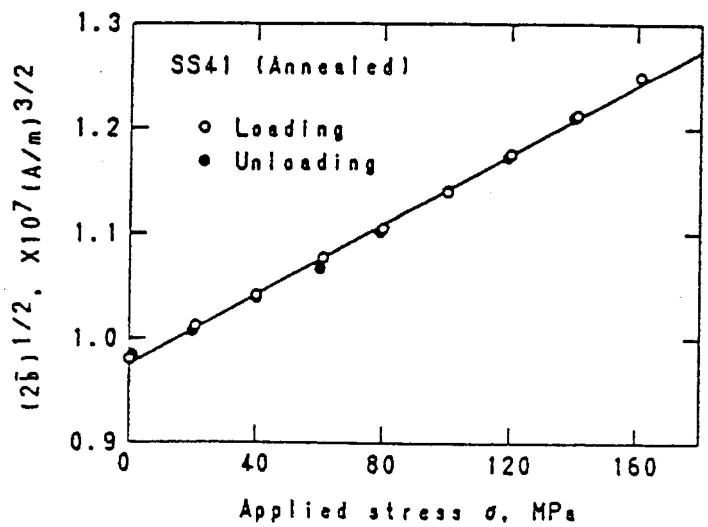

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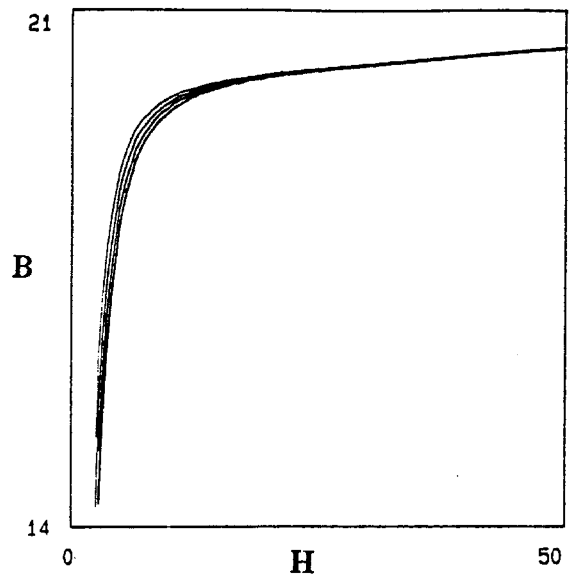

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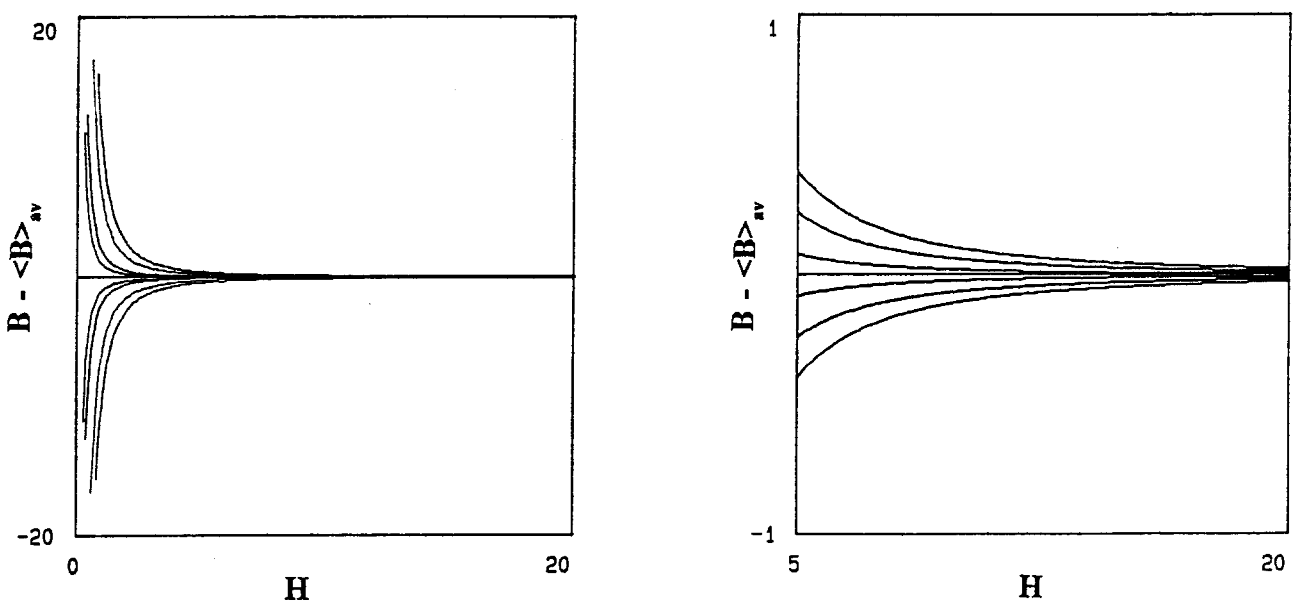

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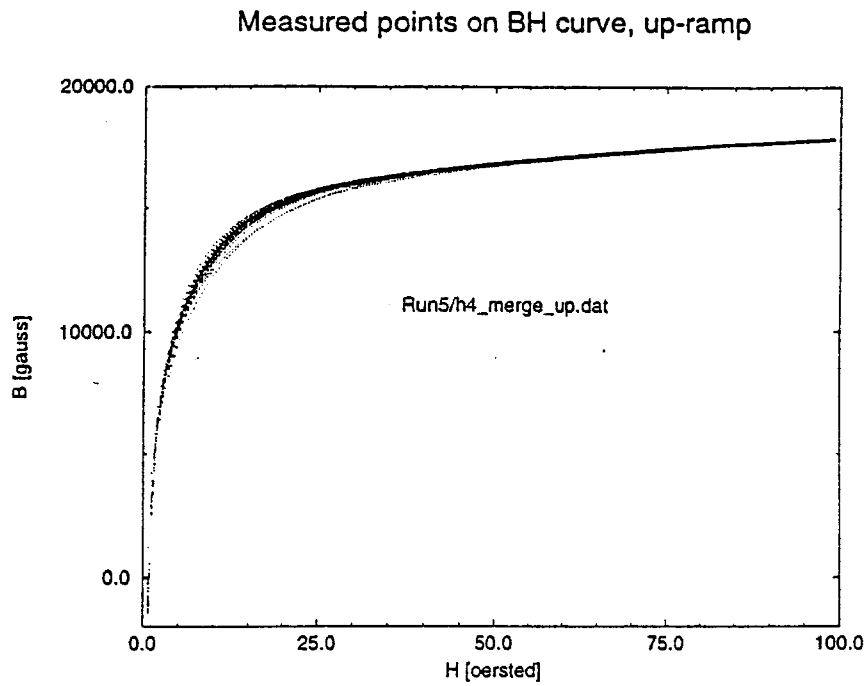

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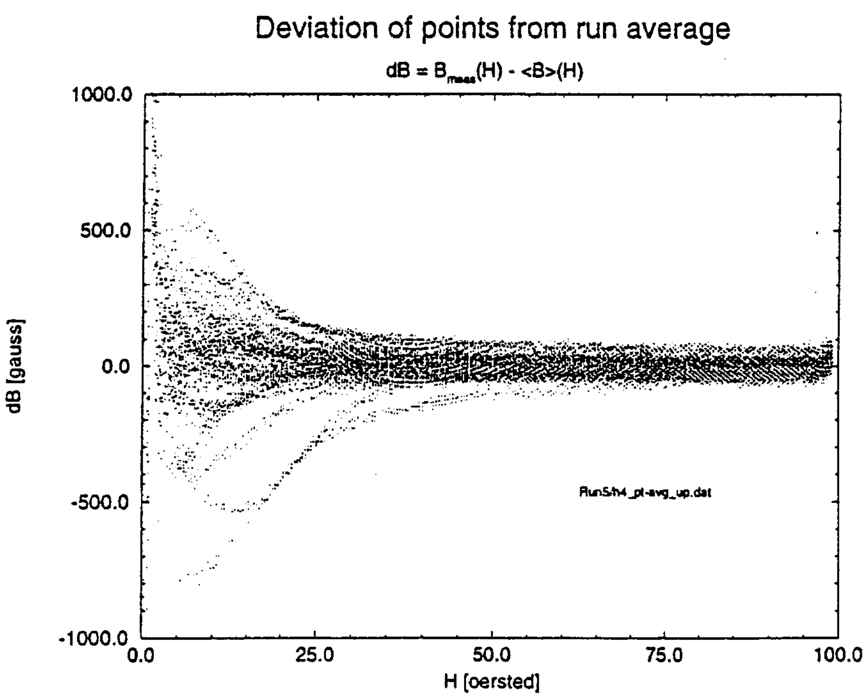

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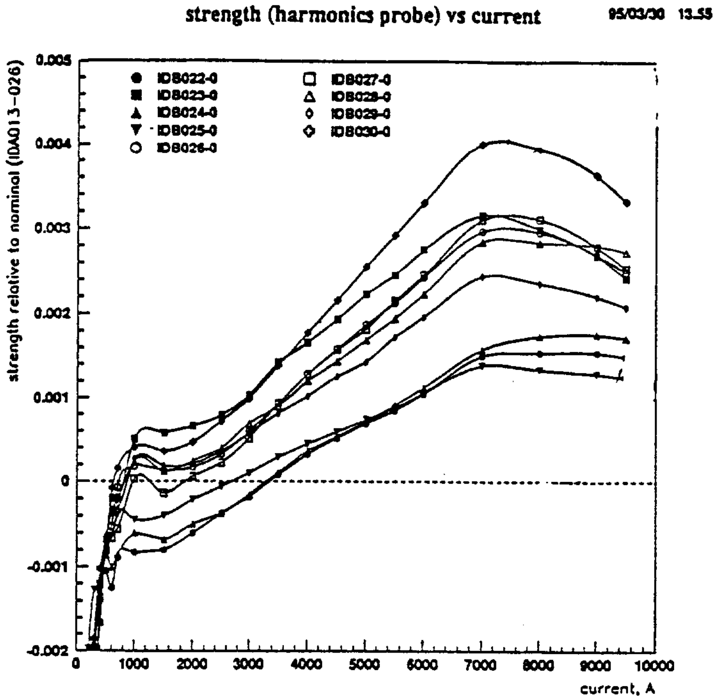

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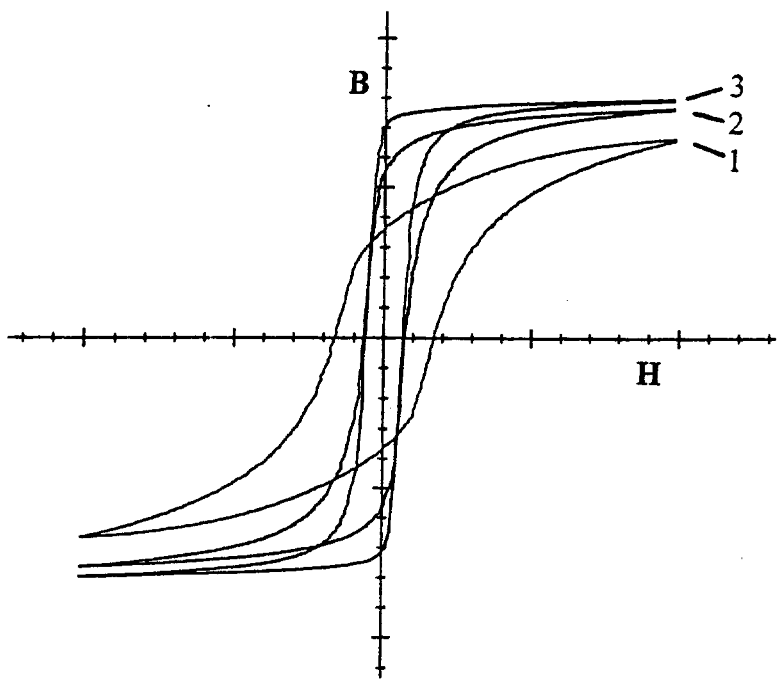

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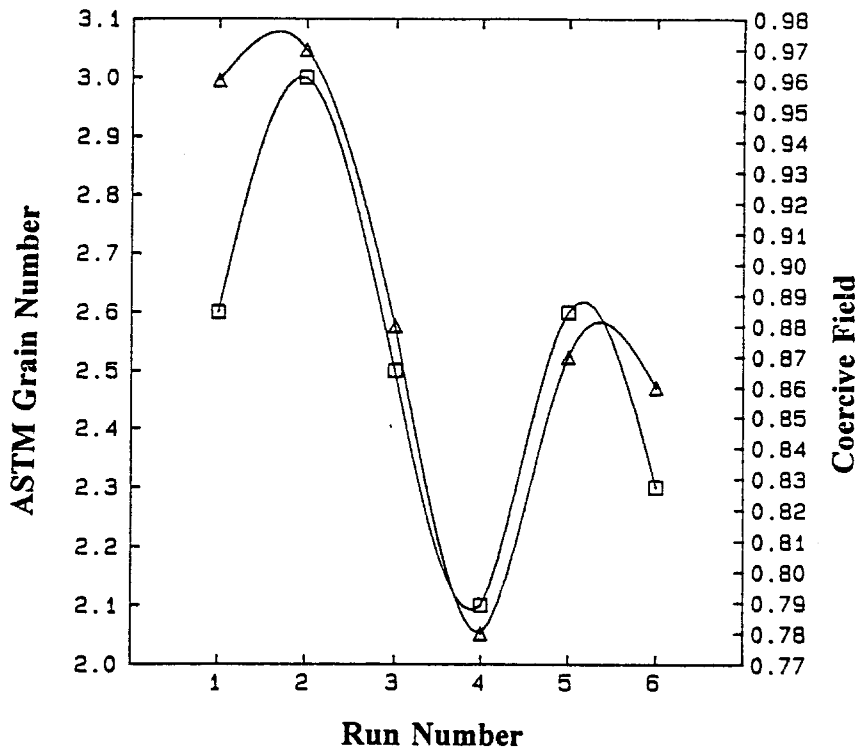

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