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SOME INITIAL RESULTS FROM THE NEW SLAC PERMEAMETER*

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ABSTRACT

A new permeameter has been built and is now available for testing samples of steel and other ferromagnetic materials for their magnetic characteristics such as permeability, remanent induction, coercive force and saturation induction. The present range of operation for the permeameter is from 0.5 Oe to 1250 Oe. Results are presented for two samples of low-carbon steel as well as some preliminary results for Vanadium Permendur.

INTRODUCTION

Our initial motivation for building this new permeameter was to generate new, more accurate permeability tables for the magnet design program POISSON, which has been in use here at SLAC for many years. More recently, the magnet design programs TOSCA and PE2D have become available here and they also require that permeability tables be supplied. It also was felt that it would be useful to be able to measure the magnetic properties of materials being used at SLAC on a routine basis. It is well known that these properties can vary in important ways for the same nominal material. One of the tables in use at SLAC (POISSON material 2) was known to be too optimistic. This is the old original default table from LBL and corresponds to annealed pure iron on the G.E. chart.

We became interested in Vanadium Permendur, when in 1988 several of the South LTR bend magnets were modified to have steel yokes and Permendur poles. This

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allowed us to widen the pole for a required larger good field width and maintain the same induction at a given excitation current as before modification.[1] Questions were raised about the permeability tables for the Permendur, with many questions about how to heat-treat the Permendur to achieve maximum induction. The available information on this subject from vendors and the literature has been unclear and contradictory. We decided to solve this problem, for the future at least, by building a permeameter that would utilize easy-to-manufacture samples upon which we could perform heat treatment tests, measure the magnetic characteristics, and then use the data obtained to make the tables of magnetic induction versus magnetizing force suitable for POISSON and other magnet codes. As previously mentioned, the present range of operation for the permeameter is from 0.5 Oe to 1250 Oe, and while this is enough to drive most materials into saturation, higher values would improve the precision of saturation induction measurements. Therefore we plan to extend the top value of magnetizing force to 2500 Oe by installing a modified set of coils.

THE PERMEAMETER

The configuration for the permeameter is shown in Fig. 1. A somewhat similar device was built at LBL several years ago.[2] It is a C-type electromagnet with a single excitation coil of 324 turns (6 layers of 54 turns) of No. 14 square copper wire insulated with polyamide GP-200. The coil form itself is made of low-carbon steel to minimize the reluctance of the apparatus. Bolted to the excitation coil are the two yokes of 2-in. by 4-in. low-carbon steel bars 12 in. long. The pole pieces are threaded into the yoke bars so that the sample under test can be clamped into position by screwing the pole pieces down tightly against the ends of the sample. The samples to be tested are cylindrical with a 0.191 in. hole (No. 11 drill) drilled on the axis. The hole allows the introduction of a Hall probe which measures the magnetization force H in the center of the sample. This method utilizes the fact that the tangential component of H is constant across the metal/air boundary. The outside diameter of the sample is 0.749 in. and the length is 2.000 in., although other lengths also can be used because of the adjustment range of the threaded poles. The magnetization force is inversely proportional to the sample length, but POISSON runs show that short

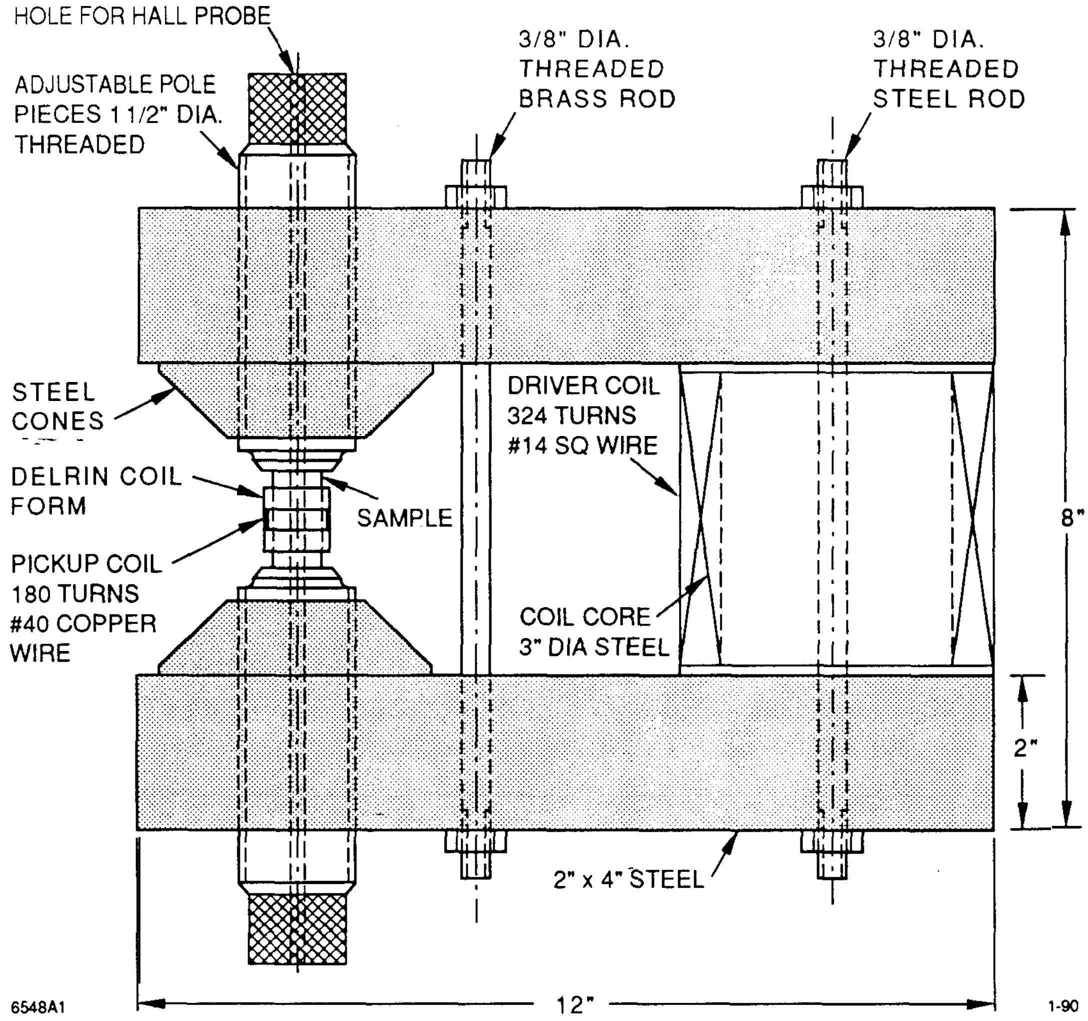

Fig. 1. Configuration of the SLAC Permeameter.

samples have nonuniform fields. These runs also show that the pickup coil should be wound as close to the sample as possible and also close to the sample center.

The induction pickup coil, which measures B is made of Delrin and has 180 turns of No. 40 copper wire with Isonel insulation. The wire diameter is 0.005 in., including insulation. The coil length is 0.250 in. and the average diameter of the windings is 0.780 in.

A diagram of the permeameter measurement system is shown in Fig. 2. Details of the measurement system and associated computer programs have been given previously.[3]

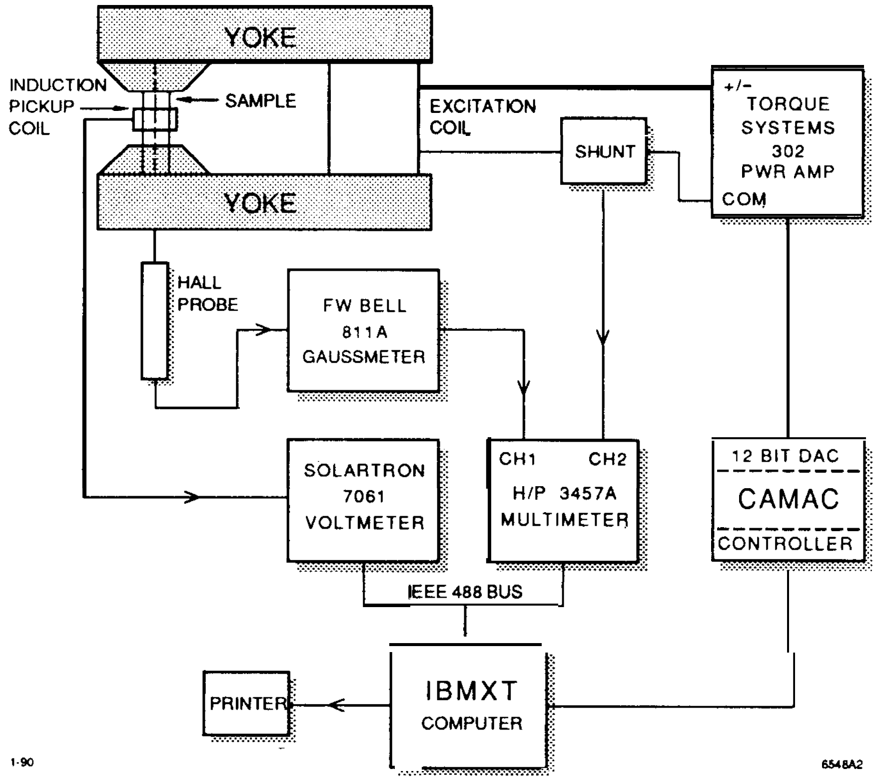

Fig. 2. The Permeameter measurement system.

FITTING THE DATA

Splines and polynomials of various orders were considered for fitting the data. The best method for our purposes was to use a seventh degree polynomial of the induction as a function of the logarithm of the magnetizing force. The resulting functional relationship can then be used to calculate the induction for many values of the magnetizing force, and this results in a table which can be entered directly into POISSON. Care was taken to assure that both first and second differences of B with increasing H were always smooth and did not change sign. The problem of proper fitting for magnetization tables has been studied by Pissanetzky.[(4)]

The latest version of POISSON at SLAC has been modified to accept tables of up to 199 points. There is also an option to change the internal interpolation method from one varying with B^2 (the old method) to one linear in B. This removes a serious problem with the variation of magnetization with H. The B^2 interpolation causes cusps in the relationship between magnetization and H. This in turn can cause convergence failure, especially at high fields where the BH curve flattens out. Whatever external or internal table is selected, POISSON does its own interpolation in order to reduce B, or B^2 to an index by dividing by a step size. Corresponding values of reluctivity (H/B) are then stored in an array with corresponding indices. So in operation, the program does not do a table search, but merely divides B or B^2 by a proper step size. This becomes the index for the reluctivity array. A further refinement is done on the slope. Linear interpolation increases the running time about 20% since a square root must now be taken for every mesh point at every cycle. However, the number of cycles to convergence is less because of the improved stability, so this has been left as an option for users with convergence problems. We have found that a 50 point table is generally satisfactory. Test cases have converged at high fields with the program default conditions set, and with reasonably short running times. -When materials are driven well into saturation, special constant settings may be necessary. This is generally- the case with Vanadium Permendur.

RESULTS

For the steel samples, the final heat treatment in each case was to hold for two hours at 750° C in a hydrogen atmosphere, with a slow cooldown of 60° C/hr. Any previous heat treatment for the steel samples is unknown. Hardness tests and grain size indicate that the 1010 sample had been previously annealed. The second anneal produced only a small change in magnetic characteristics. This was also true for the 1004 steel sample. Both samples were chemically analyzed to confirm carbon content.

Figure 3 is a graph of intrinsic induction $(B-H)$ versus magnetizing force H for the 1010 steel sample compared to low-carbon steel from the G.E. chart. Figure 4 shows the old POISSON table compared to the results for 1010 steel.

The results for Vanadium Permendur should be considered to be preliminary. The cooling rate for the oven used could not be controlled. Cooling rates were very slow (60° C/hr) and the samples were cycled through several annealing temperatures. We

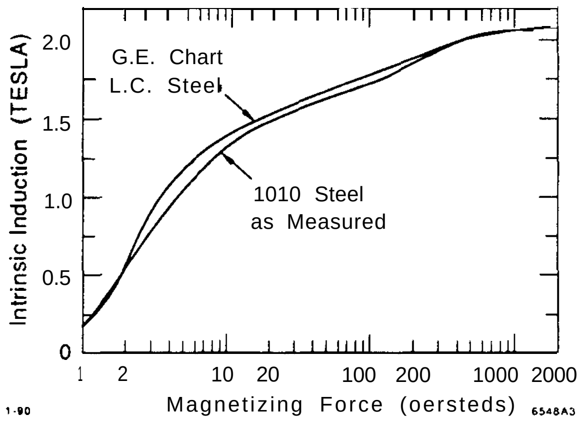

Fig. 3. Intrinsic induction (B-H) versus magnetizing force H for annealed 1010 steel and low-carbon steel from the G.E. chart.

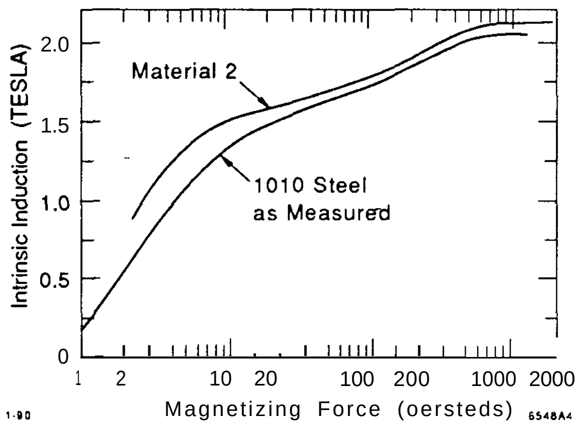

Fig. 4. Old POISSON table, and the new 1010 steel table.

have no way of quenching the samples between the various heat treatments at this time.

The first Vanadium Permendur sample was machined from a larger piece which had been heat-treated for four hours at 1120° C in a hydrogen atmosphere, with a slow cooldown of 60°/hr. This sample was later annealed after machining at 750” C for two hours and oven cooled. This produced our best results so far for Permendur.

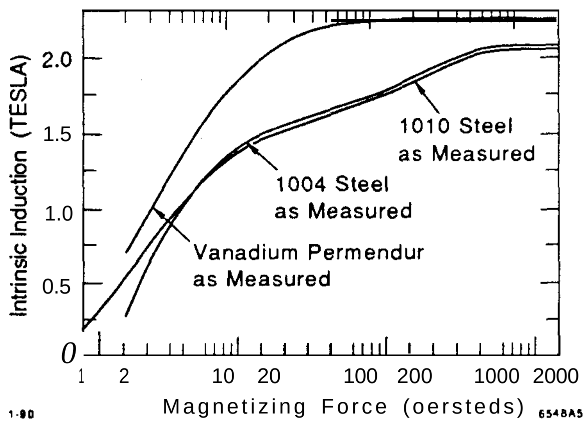

Fig. 5. Intrinsic induction (B-H) versus magnetizing force H for measured samples.

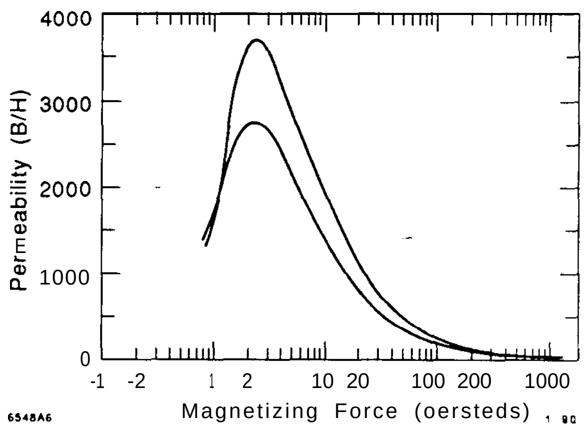

Fig. 6. Permeability versus magnetizing force H for annealed 1010 steel and Permendur.

Figure 5 is a graph of intrinsic induction versus magnetizing force for the steel and first Permendur samples which were measured. This is shown in terms of permeabilities in Fig. 6. Figure 7 shows the demagnetization curves for 1010 steel and Permendur.

Two more samples were machined from a larger piece which had been forged. They were later heat treated at several different temperatures, but in different sequence; the results were virtually identical. One of the problems which we encountered in Ref. [1] was that while the LBL work had recommended an anneal at 1120° C, manufactur-

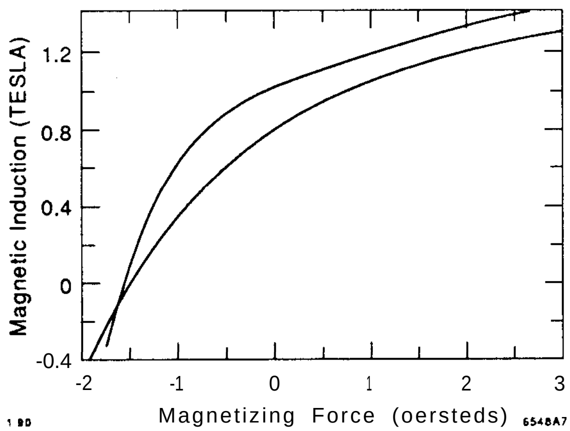

Fig. 7. Demagnetization curves for annealed 1010 steel and Permendur.

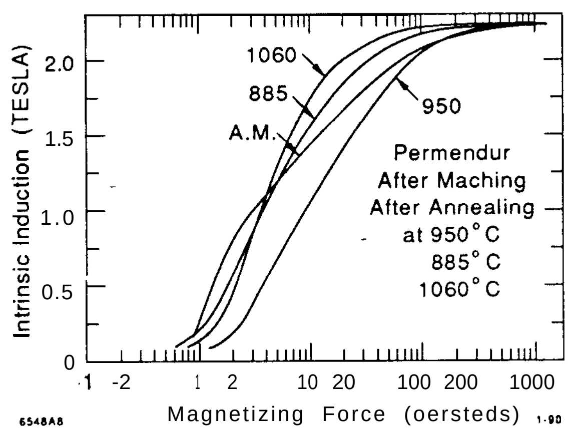

Fig. 8. Intrinsic Induction versus H for Permendur after machining and after annealing at three different temperatures.

ers warn against temperatures above 900° C. The Curie temperature for Vanadium Permendur is 932° C, and we found that an anneal at 950° C did indeed produce poor magnetic properties. However, subsequent heat treatment at temperatures of 885° C and 1060° C restored the samples to the characteristics previously obtained by heat treatment at those temperatures before the 950° C anneal; these results are summarized in Fig. 8.

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