VARIATIONS IN THE STEEL PROPERTIES AND THE EXCITATION CHARACTERISTICS OF FERMILAB MAIN INJECTOR DIPOLES

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Abstract

The Fermilab Main Injector project is building 344 dipoles, for which over 7000 tons of steel are required. Budgetary and logistic constraints prevented purchasing all of the steel required prior to production. Run to run variations in the magnetic properties of the steel have produced variations in the excitation curves of the dipoles. The variations in the B(H) curves for the steel as a function of run number, and the excitation characterisitics of the dipoles, are discussed.

1 INTRODUCTION

The Main Injector accelerator [1] will be constructed using new conventional dipole magnets [2-3]. An extensive R&D program was carried out [4] to assure the quality of the magnets and to determine the desired end geometry to minimize the effective length variation with excitation and the sextupole content of the ends. Twelve full-length, pre-production dipoles (six six-meter and six four-meter dipoles) were then built and measured. The FMI project was then ready to begin fabrication of the production magnets, and a contract was awarded for approximately fourteen million pounds of steel. This contract consisted of a (i) base quantity of 3,339,000 pounds to be delivered at a rate of 556,500 pounds per month over six months during calendar year 1993; (ii) an option for 7,813,000 pounds for delivery over twelve months spanning most of 1994: and (iii) an option for 3,562,000 pounds for delivery over eight months in 1995. The delivery schedule in the procurement contract was necessitated both by a lack of funding and by a lack of storage space for the steel.

The steel specification included two aspects regarding the magnetic properties: the coercive force was specified to be less than 1.0 oersted and to fall within a range relative to the running average of all previous batches, and the permeability at 100 Oe was specified to be between 176 and 181. The steel specifications were written with the goal of producing magnets with strength variations over the production which would be a random distribution with a root mean square deviation of less than 0.1%.

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All of the steel that was received was within our specification. There were, however, some changes in the characteristics of the B(H) curves of the steel during the production runs which will be described below.

2 STEEL PRODUCTION

The steel, a standard low-silicon electrical steel, was produced by LTV Steel Company at their Cleveland Works. The steel was produced in a total of thirteen "runs" over the course of three years. Each run involves the consecutive processing of a number of coils through their Continuous Anneal Line (CAL). The number of coils processed at a time ranged from 8 to 86. These coils in turn came from a number of "heats", with a given heat having a particular chemistry and producing seven to ten coils. Coils from a given heat were generally, but not always, processed during a single run. LTV demonstrated very good control over the chemistry throughout the production. Between the melting and casting and the CAL runs, the steel is hot- and cold-rolled to the final thickness. Subsequent to the CAL, the master coils are coated, slit into five strips the proper width for stamping with minimum waste, and then shipped to the lamination stamper (under separate contract to Fermilab).

The CAL consists of seven stages: direct-fired furnace, radiant tube heater, radiant tube soak, gas jet cooling, over-aging furnace, final jet cooling, and final water cool. An eighth stage, the roll quench, was not used for processing our steel. Prior to processing any steel for the FMI project, the CAL processed transition coils until the desired temperatures were attained. The temperatures at the various points in the CAL were also controlled very well. As the coils were exiting the CAL, samples of steel were taken from the head and tail of each coil and longitudinal and transverse specimens were prepared according to ASTM A343. These were measured by LTV Steel at their Technical Center in Independence, OH, and then forwarded to Fermilab where the samples were remeasured. The Fermilab measurement results were forwarded to the accelerator physics group which was responsible for the assignment of the "recipes". The recipe assignment [6] used both the magnetic information and measurements which were made of the gap as the laminations were being stamped. The recipes were formulated for half-cores, with the intention to be able to mix any pair of half-cores together during the final assembly. Only in a few cases were two specific half-

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cores assigned for assembly within a given dipole, and this was driven by the desire to investigate some property of the steel rather than from some limitation in the ability to formulate recipes.

Given the production schedule outlined above, and the project schedule requirements which required us to commence production as early as possible, the first 13 magnets assembled at Fermilab used steel exclusively from Run 1. After that, steel from different runs was generally mixed together within half-cores, although again, there were instances where dipoles were intentionally fabricated containing steel from only one run.

3 DIPOLE STRENGTH COMPARISONS

The first twenty-five to thirty magnets demonstrated a very narrow spread in their integrated strengths at all excitations. The rms of the distribution was about 0.03%. These magnets were all composed of steel from runs 1-3, although very little from run 2. (Run 2 steel was primarily used for the quadrupoles for the FMI project.) As steel from run 4 began being used in magnets, the strength of the dipoles began increasing, and the difference in strength was approximately proportional to the fraction of run 4 steel in the magnet. The strength variation was current-dependent, indicating a difference in magnetic properties of the steel, as opposed to a geometric effect which should be current independent. The change in strength peaked at about 13.8 kG, with a maximum change of about 0.5% being observed; this is shown in Figure 1.

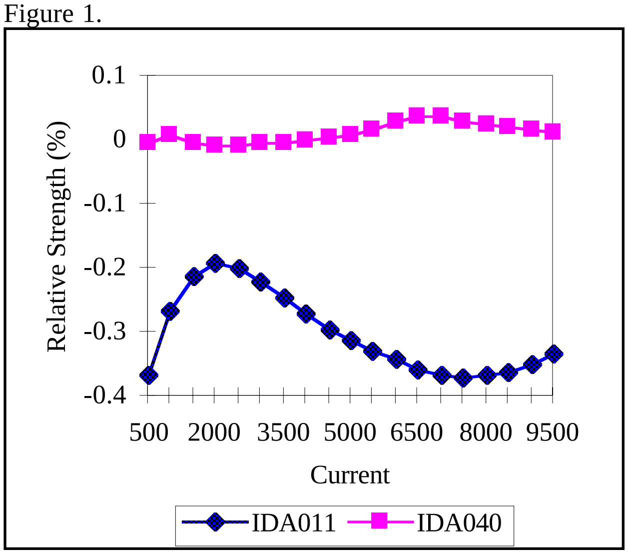

Figure 1. Strength variation vs. excitation for two dipoles, one early and one later in production.

In this figure, the relative strengths of two dipoles are plotted as a function of current, where the strength is relative to the later "production average". As production continued, it became evident that the later steel runs were the normal ones, and steel from the first three runs produced magnets which were anomalously weak. Figure 2 shows the strength at 13.8 kG of the early magnets produced using LTV Steel; data on all magnets produced to date can be found elsewhere [6]. Up through the first fifty or so magnets, the production of the magnet half-cores and the final assembly of the magnets (and their subsequent magnetic measurements) proceeded together as a well-matched chain of parallel processes. After the first fifty magnets, with the half-core stacking proceeding more rapidly, the correlation between production date and the run number of the steel used in the half-cores became less distinct as half-cores were used randomly rather than in order of their production (which would have required additional handling.) Records on what steel was used in each magnet are maintained.

These magnet-strength variations led to numerous, lengthy discussions between Fermilab and LTV Steel to better understand the production process and its influence on the magnetic properties of the steel. A consultant was hired to assist Fermilab and he was present at many of the discussions and witnessed several of the subsequent runs through the CAL; he provided reports [7] of his observations both to Fermilab and to LTV Steel. Much of the information on temperature control in the CAL discussed in section 2 above is derived from our consultant's reports. One result of these discussions was that all subsequent steel production had a minimum as well as a maximum speed specified during the CAL processing. Although an explanation for the difference in steel properties exists, namely differences in residual strain in the steel, there is no clear understanding of where in the

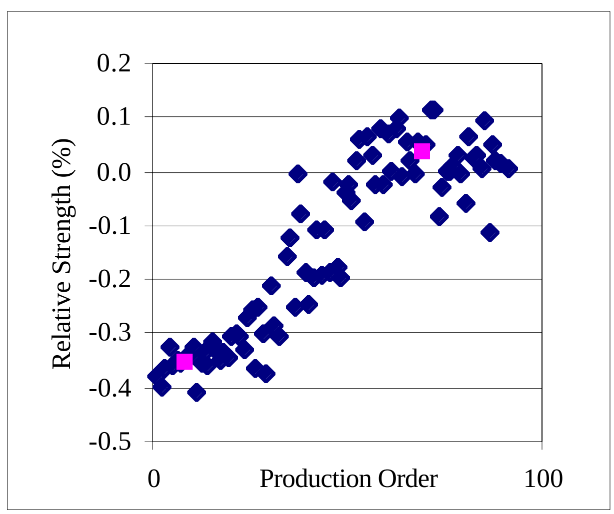

Figure 2. Relative strength at 13.8 kG for the dipoles for the early dipoles, in order of production. The two dipoles shown in Figure 1 are denoted with different symbols.

processing of the steel these differences arise. Much of the discussion between Fermilab and LTV Steel focussed on our desire to have the remaining steel as uniform as possible. To a very large extent, that desire was realized.

During the period these discussions were taking place, much effort at Fermilab was also being devoted to understanding the phenomenon through magnetic field calculations. The measurements of the steel samples from each coil are maintained in a database so the information is readily available for analysis. The variations between all the coils within a run exhibit a spread on the order of ±200 Gauss at H > 20 Oe, which is larger than the differences from run to run, for runs 4 through 13. Plots of the average B(H) curve for each of the thirteen runs are shown in Figure 3; an analytic function was fit to the data for run 6, and subtracted from each of the other runs to make the differences between runs more visible. The difference between the first three runs and the remaining runs is significant, particularly in the region H < 40 Oe.

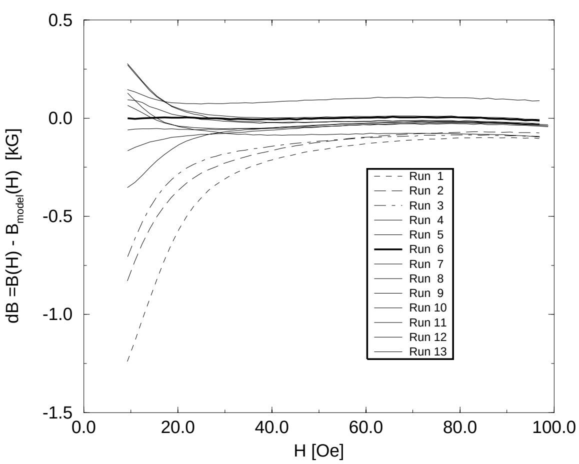

Figure 3. B(H) curves averages for each of the thirteen runs of steel, relative to a fit to run 6.

Using the averages (over each run) of the measured B(H) curves for run 1 and run 4 steel as input to the magnetic field calculation program OPERA2D predicts differences in dipole strength that are very similar to what we observe. It is perhaps of interest to note that the differences in the B(H) curves that contribute most to the strength differences are in the vicinity of 15 Oe, around the "knee" of the B(H) curve, and that in order to achieve uniform magnet strengths one would have to specify the B(H) curve in this range as well. Specifying only the high and low ends is insufficient.

A number of other aspects of the production process were also studied. A measurable correlation is observed between magnet strength and the fraction of steel which came from the edges of the master coil. Although the magnitude of the effect was small, all subsequent recipes were formulated with the goal of maintaining 20-60% edge-slit laminations. Packing factor, i.e. the density of the half-core relative to the maximum obtainable, was measured for about 10% of the magnets. The correlation between strength and packing factor is small: a 1% change in packing factor is expected to produce roughly a 0.1% change in magnetic strength. The packing factor of the half-cores did increase somewhat as the vendor fabricating them gained experience, but the change was less than 0.5%.

The Main Injector lattice has a phase-advance per cell of nearly ninety degrees, which allows using anomalously strong (or weak) dipoles in pairs, producing only a local closed orbit distortion. By assigning magnets, the strength differences described above are expected to have only minimal impact upon the Main Injector closed orbit, as discussed more fully in reference 6.

It should be stressed that all the steel which LTV Steel produced was within our specification, and exhibited excellent magnetic and mechanical properties. The Fermilab Main Injector project management would like to acknowledge the dedication of the LTV Steel Company, and of R. Blotzer in particular, to producing a high-quality steel for use in our magnets, and the cooperative spirit of the LTV Steel personnel in our extensive discussions with them. Our consultant, E. W. Collings of Ohio State University, provided much valuable guidance during our discussions. The authors would also like to acknowledge the many contributors who were essential to this effort, including G. Kobliska and W. Pritchard in the Fermilab Technical Division, J.-F. Ostiguy and B.C. Brown in the Beams Division, and many others too numerous to acknowledge individually.

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