MAGNETIC PERMEABILITIES OF 50000

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Ten or fifteen years ago we used to read about great improvements being made in iron for magnetic purposes, due chiefly to the excellent work done by Sir Robert Hadfield. He succeeded in raising the maximum permeability of Swedish charcoal iron, at that time regarded as the best magnetic iron obtainable, from 2000 to 5000 by alloying it with small percentages of silicon or aluminum. Furthermore, the area of the hysteresis loop, or the hysteresis loss, was proportionately reduced, at the same time as the electrical resistance was enormously increased by the addition of either one of these alloying elements. As Hadfield's alloys could be readily produced in commercial quantities it was not surprising that his discoveries resulted in the almost immediate adoption of silicon steel for transformers, in which efficiency and high permeability are of the utmost importance.

Since that time only minor improvements have been made, and whatever has been done has been due largely to modifications of Hadfield's alloys. Even in the laboratory maximum permeabilities above 10000 have been obtained only in very rare cases, and have been regarded as exceptional. It has been the privilege of the Engineering Experiment Station of the University of Illinois recently to produce iron and iron alloys with permeabilities all the way from 20000 to 50000 and with hysteresis losses of one-half to nearly one-tenth that of the best commercial silicon steel. It is unsafe at the present time to state exactly what the values are, as the methods of testing that have hitherto been regarded as standard have proved to be inadequate for this high permeability iron. The Burrows compensated double bar and yoke method gives too high a maximum permeability, too high retentivity and coercive force, too low hysteresis loss for low densities and too high for high densities. The ring method, while more satisfactory in this respect, is open to the objection that the flux distribution is not uniform, and besides is awkward to work with. The subject is at present being investigated both here at the University of Illinois and at the United States Bureau of Standards, and a more perfect method will undoubtedly be developed.

The method employed for the production of this high permeability material consists in melting electrolytically refined iron in a vacuum furnace, the absolute pressure being 0.5 mm. of mercury. The iron is allowed to cool in the furnace, and when removed has an appearance like that of nickel. The ingots thus produced are forged into rods and machined into proper test pieces. In this state, however, the magnetic properties are very poor, chiefly on account of the molecular strain caused by the mechanical treatment, and it is necessary to anneal the rods before the unusual properties are obtainable. This is done by heating the rods to 900° or 1100°C in vacuo followed by cooling at the rate of 30°C per hour down to room temperature.

Thus far we have investigated pure iron, iron-boron alloys, iron-carbon alloys, and iron-silicon alloys, besides the iron-cobalt alloy Fe_2Co. The iron-aluminum series is being investigated at the present time. It gives the average for a large number of samples of Vacuum Iron, the best of which is below what we can produce with certainty today. The curve just below that for the "Vacuum Iron" proper represents Swedish charcoal iron remelted in vacuo, showing the improvement obtained by the treatment. The curves for the commercial grades of iron are far below.

Turning now to the more recent results obtained with the silicon alloys. Here it is seen that two maxima occur in the curve for maximum permeability corresponding to two minima in the curves for hysteresis loss and coercive force. The first of these occurs with a silicon content of 0.15 per cent and the second with a silicon content of 3.5 per cent. The electrical resistance increases uniformly with the silicon content so that an alloy containing 3.5 per cent silicon has a specific resistance nearly five times that of pure iron.

Fig. 4 gives a comparison between the 3.5 per cent silicon vacuum-alloy and 4 per cent commercial silicon steel, both tested by the Burrows method. It is seen that the maximum permeability is as 20 to 1, the hysteresis loss for $B_{max}=10000$ as 8 to 1, and the hysteresis loss for $B_{max}=15000$ as 4 to 1 in favor of the vacuum product.

Could this vacuum alloy be substituted for the present commercial steel in transformers and used in a form to give the same properties as shown in Fig. 4 it would be possible to increase the flux density from $B_{max}=10000$ gausses to nearly 15000 without increasing the required magnetizing force and at the same time to decrease the hysteresis loss to less than one-third. Consequently the cross section of the iron core for a certain flux could be decreased to two-thirds and the length of the copper wire for the windings could be correspondingly reduced. Thus besides a lowering of the hysteresis loss there would result also a lowering of copper loss, and, with the eddy current loss only slightly increased, the sum total should be a transformer of about two-thirds the weight with an energy loss of about one-half that of a similar transformer with an ordinary silicon steel core.

It is well known, however, that the core of a transformer must be made up of iron in the form of very thin sheets in order to keep the eddy currents down to a proper value, otherwise the loss caused by these eddy currents would be excessive. Now, the properties of the vacuum alloy were obtained with the alloy in the form of a rod 1 cm. in diameter. Whether it is possible to duplicate them with the alloy rolled into sheets of from 0.015 to 0.025 inches in thickness is as yet doubtful. We are at present investigating this phase of the problem.

The mechanical properties of the silicon series offers points of particular interest. Here it is seen that the strength increases as the silicon content increases, until the maximum strength is reached with about 4.5 per cent silicon. From this point on, the elastic limit coincides with the ultimate strength and both decrease very rapidly. The curves for reduction of area and elongation show that the alloys below 2.5 per cent are unusually tough, much more so than corresponding alloys made by the ordinary methods.

Of great interest is the critical point that occurs with about 2.6 per cent silicon. This point was first observed by the fact that two ingots, containing 2.55 and 2.57 per cent silicon respectively, were not forgeable but fell into a mass of crystals that apparently had no adhesive strength. As critical points are usually associated with the formation of definite compounds, it is of interest to note that a compound of the formula $Fe_{19}Si$, if it exists, would contain 2.56 per cent silicon, and similarly that a compound of the formula $Fe_{19}Si_2$ would contain 4.99 per cent. It was stated above that a critical point in the present case occurs with a silicon content of 2.55 to 2.57 per cent.

Furthermore, it is seen that there is another sudden change at about 5 per cent silicon. Whether this agreement is a mere coincidence, or whether these compounds or others, actually exist, has not been definitely determined, as cooling curves for these particular alloys are not available.

In conclusion it should be said that, while it has been possible by the vacuum method to produce iron of unheard of magnetic quality this iron is not yet ready to be put into practical use. It is even doubtful whether it ever will be possible to realize these properties in commercial apparatus. However, this investigation has given a new indication of the possibilities obtainable in the realm of magnetism, and who dare say that this is the end? If it is possible to increase the maximum permeability in one step from 10000 to 50000, we might look forward to permeabilities of 100000 or even more.