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A Review of Some Interdisciplinary Work on Grain-Oriented Silicon-Iron and Its Use in Large Power Transformers

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Over the last few years, the interdisciplinary approach of the materials scientist has lead to a number of advances in both the quality and efficient utilisation of grain-oriented silicon-iron, particularly for large power transformers. The advances have been directed along three lines: (i) to a better utilisation of the material, arising from a better appreciation of its properties; (ii) improvements in the material itself, i.e. improved orientation; and (iii) the investigation of similar, but new, materials.

Of course, these aims are interconnected and interrelated, since the work is directed towards the increased efficiency and lower cost of electrical apparatus.

Although most of the work has been reported elsewhere, it is opportune to review and integrate these papers, and to suggest and to discuss future possible lines of investigation.

1. Introduction

Grain-oriented silicon-iron is used in large quantities in the electrical engineering industry. Over the years, since the introduction of silicon into iron, in the early 1900's, there has been continuous improvement in the properties of the material. Early improvements were obtained by better metallurgical manufacturing techniques, but later ones depended on the production of a grain orientation in the material, which enabled the anisotropic properties to be utilised in a beneficial way. However, during recent years, it has become apparent that some metallurgical and physical properties are related and that the desirable properties can be modified (more often than not in a detrimental manner) by the way in which the material is used in electrical machinery. This does not mean that the material is deliberately misused, but rather that the interconnexions between the various factors, and their relative importance are not understood. Consequently, most of the recent improvements that have occurred have evolved from the results of interdisciplinary investigations by physicists, metallurgists, and electrical engineers.

In addition to this better utilisation of the material, improvements in the material itself have been sought, such as an improved degree of orientation. Furthermore, investigations of the properties and possible means of manufacture for similar, but new, materials have been started.

2. Magnetostriction and Transformer Noise

A good example of the way in which a material can be improved by the combined efforts of physicists, metallurgists, and engineers is to be found in the field of magnetostriction and transformer noise.

Magnetostriction is the general name given to the change in shape and size of a ferromagnetic body on magnetisation or during changes in magnetisation; although it is usually applied to changes in length in the direction of flux.

Some electrical devices depend for their operation on magnetostriction, but in power transformers magnetostriction is undesirable; since it is responsible largely for transformer noise. Although the noise can be controlled by surrounding the transformer in a noise-reducing enclosure, it is desirable to eliminate the noise at its source.

2.1. Stress, Sheet Flatness, and Noise

Measurements on the movements and vibrations of large transformer cores showed that the changes in dimensions were greater than expected, from measurements on laboratory samples of silicon-iron, by at least a factor of four. A number of possible causes of this difference were investigated [1]. It was soon shown that the most influential parameter was compressive stress, introduced in the plane of the sheet along the direction of flux and orientation. Fig. 1 shows this relationship. It should be noted that the magnetostriction/stress curve is not unique; considerable differences are found from sample to sample, although the curves generally fall within the band shown on the figure. Invariably, the manner of variation is similar: a tensile stress causes a reduction in the magnetostriction. Considerable variations can be found not only from sheet to sheet, but also within a sheet [2, 3].

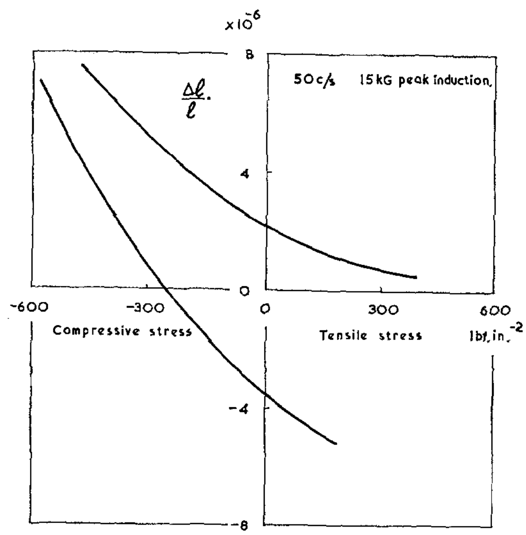

Figure 1 The magnetostriction of grain-oriented silicon-iron increases with compressive stress and decreases with tensile stress. The general shape of the curve remains the same from sample to sample and usually falls between the two limiting curves. (*Note* 1 lbf/in.^{2} = 69 $\times$ 10^3 dyn/cm^2)

In transformer construction, it was thought originally that two factors might have the most important effect on noise. Large sheets are moved around the factory in stacks by a crane, supported only at the edges. The sheets bow, but it was shown that the degree of bending involved was not significant, since the material was not taken beyond the elastic limit [1]. During the construction of a core, the sheets are clamped by means of bolts which apply a pressure perpendicular to the plane of the sheet. While this pressure itself is not detrimental, all sheets contain deviations from perfect flatness and, when the sheets are flattened, stresses in the plane of the sheet are generated. By general metallurgical standards, the sheets may be very flat; but they must be considerably flatter to avoid the generating stresses of the level that affect the magnetic properties. The deviations from perfect flatness are of two kinds, dimples or waves. For example, waves of an amplitude $\frac{1}{8}$ in. in a wavelength of 40 in. (1 in. = 2.5 cm) were common, which give rise to a compressive stress on one side of the plate, and a tensile stress on the other, of about 300 lb/in.^{2} (1 lb/in.^{2} = 7 $\times$ 10^{-2} kg/cm^2) when the sheet is flattened – assuming too that the ends are free to move. If the ends are not free to move, and motion in the plane of the sheet is restricted, then the stress will be entirely compressive.

In order to test the conclusions obtained from the laboratory, transformers were built from good-quality material; in two cores, the material was used as supplied, in two others, material with greater flatness was selected [4]. The difference in noise level between transformers built of non-selected and selected sheets was 8 dB – a worthwhile reduction. In general, the deviation of the noise level from the mean of the group of 15 MVA transformers is about 3 dB, so that this difference is probably significant. Although sheet flatness was obviously important, the improvement was not so marked as had been anticipated; but the reason for this will be examined later.

2.2. Measurement of Sheet Flatness

Having established the importance of the flatness of the sheets, it is necessary to have some simple and accurate method of measuring sheet flatness. To measure the wave size physically would be difficult and tedious and, anyway, it is the average stress that is produced on flattening the lamination that is important. One method [4] that is gaining general acceptance is shown in fig. 2. A stack of laminations is placed on a bed plate and, over the laminations, an aluminium plate attached to a flexible rubber gasket is lowered. The aluminium plate and its rubber-edge seals form an air-tight chamber, and the gasket allows the upper plate to move

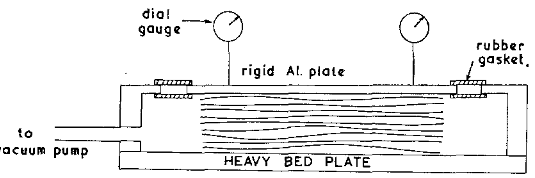

Figure 2 A simple means of comparing the sheet flatness of batches of laminations.

freely. As air is exhausted from the chamber, the differential air pressure gradually flattens the laminations, and the flattening is measured by dial gauges. A curve of load and deflection is plotted (see fig. 3) and the "area under the curve" represents the work done in compressing the plates, which is equal to the mechanical store of energy in the laminations, from which the stress can be determined. The average of the curves, with both increasing and decreasing load, is taken to eliminate frictional effects; a pressure of 5 lb/in.^{2} is sufficient to produce almost complete flattening.

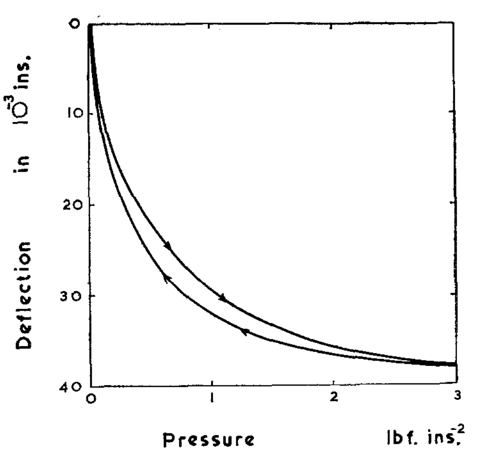

Figure 3 A typical graph of the depression of the stack from a datum line related to the applied pressure, taken with the pressure increasing and decreasing. From the graph, the mean stress in the laminations can be evaluated.

2.3. Methods of Producing Flatter Sheets

Flat sheets can be produced [4, 5] conveniently during the manufacturing process, by allowing the sheets to creep at high temperatures and utilising the differential stretching forces in the sheet to eliminate any non-uniformity in flatness. Curves of the creep rate and stress for grain-oriented silicon-iron at various temperatures are shown in fig. 4. The required value of the fractional change in length to remove all undulations is about 10^{-3}, which can be achieved by treatment at 850° C for $\frac{1}{2}$ min. Such a treat-

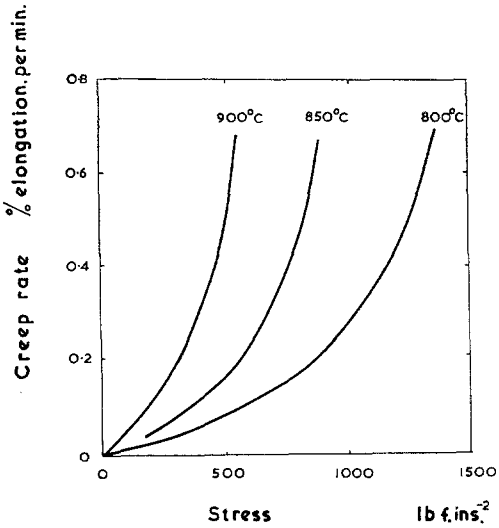

Figure 4 Curves of the mean creep rate and applied stress for grain-oriented silicon-iron at various temperatures.

ment would have to be followed by a suitable cooling treatment, and one possible scheme for producing flat sheets by this means is shown in fig. 5. Provided that the fractional change in length does not exceed 10^{-3}, the final magnetic properties are not altered; but, if this value is exceeded, an unexplained, and unrecoverable, detrimental change takes place.

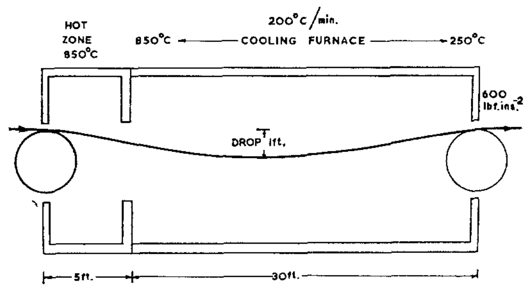

Figure 5 A scheme for producing flatter sheets by heat-treatment under tension.

2.4. Harmonics and Transformer Noise

As mentioned earlier, the selection of flatter sheets did not produce as much improvement in the noise emission of a transformer as had been hoped. One reason for this involved the presence of harmonics. In most investigations, the magnetostriction is taken to be the peak magnetostriction under ac conditions; but, whilst this is reasonable for many cases, it is important also to consider the shape of the magnetostriction loop (often called a "butterfly" loop) and the magnitude of the harmonics of the 100 c/sec fundamental. These may be small in magnitude, but very significant in the production of noise. It is worth noting that, if the magnetostriction $\Delta l/l$ is proportional to the square of the flux density (B^2), and there are no hysteresis effects, then no harmonics would be present. Although magnetostriction results in core vibration or movement, the noise level (in decibels) is calculated from the sound pressure level, which is proportional to vibration velocity. Table I compares the amplitude of the harmonics of core surface vibrations (edge-on), then after conversion to velocity, and finally, as decibels, relative to an arbitrary base velocity. The significance of the various harmonics depends also on the sensitivity of the human ear to pure tones of various frequencies. This is allowed for by using the "A" weighting scale on a noise-level meter. Table II gives the results of the noise from a power transformer derived from core vibrations and as measured by a noise-level meter. It will be noted that, in this particular case, it is the second harmonic that contributes primarily to the total noise. Not all frequencies are radiated equally well by the core, which accounts for the changed magnitude of the noise level at various frequencies.

3. Stress and Magnetic Properties

Having established the important connexion between stress, magnetostriction, and transformer noise, it was clearly indicated that a similar investigation of the effect of stress on other magnetic properties, power loss [6] in particular, was desirable. The mean variation of power loss with stress at various temperatures from a number of samples is shown in fig. 6. The curves are similar in shape to the corresponding ones for the magnetostriction, but the order of magnitude of the change is quite different. Nevertheless, the change in loss due to a compressive stress of 300 lb/in.^{2}, say 20%, is sufficient incentive to make transformer manufacturers anxious to avoid such stresses. These

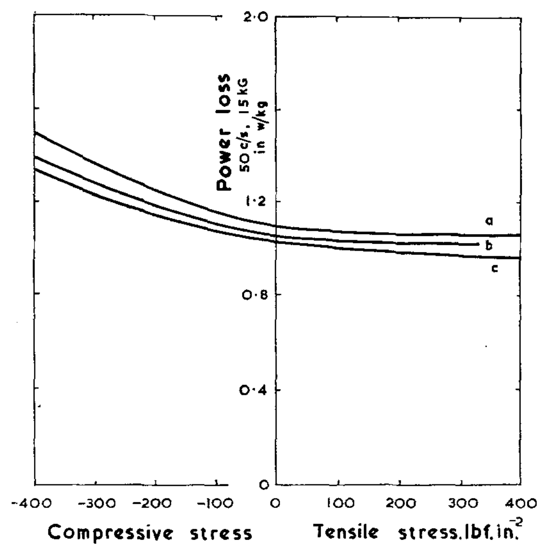

Figure 6 Typical variation of total power loss with stress at 15 kG peak induction in 46 grade material at various material temperatures: curve a, 20° C; curve b, 200° C; curve c, 300° C.

TABLE I Derivation of noise spectrum.

Frequency (c/sec)	100	200	300	400	500
Core vibration rms amplitude (10^{-3} in.)	0.076	0.025	0.006	0.002	0.0007
Core vibration rms velocity (in./sec)	0.047	0.031	0.021	0.0049	0.0023
Velocity expressed as decibels above arbitrary base velocity of 3.16×10^{-6} in./sec	83.7	79.9	71.2	63.7	57.0

TABLE II A transformer noise spectrum.

	"A" weighted				
Frequency (c/sec)	100	200	300	400	500
Derived from core vibration (dB)	64.4	68.7	63.8	58.6	53.3
Measured core noise (dB)	52.8	68.7	64.9	66.4	65.3

Scaled so that equal magnitudes at 200 c/sec for the purpose of comparison.

stresses would arise using sheets of normal flatness [6] and can arise also from thermal gradients in a core. One interesting feature that emerged was that the static hysteresis loss passed through a minimum at a tension of a few hundred pounds per square inch; the remanence passed through a maximum at a similar value (see fig. 7); the exact value varied from sample to sample and depended on the grade. It would be expected that any minimum or maximum would occur at zero stress, so that it is likely that the material is stressed already in some manner. One suggestion is that the phosphate coating, after heat-treatment, produces a net compressive stress in the strip, which arises from a difference in the coefficients of thermal expansion between the strip and the coating. Indeed, one way in which the detrimental effects of non-flatness might be reduced could be by using a coating that would place the strip under tension, so that, on flattening, no net compressive stress would be generated. Such a coating must be thin, of comparable thickness to the phosphate coating, in order that the packing factor is not changed in transformer construction. But, since the stress levels are relatively small, this idea is practicable.

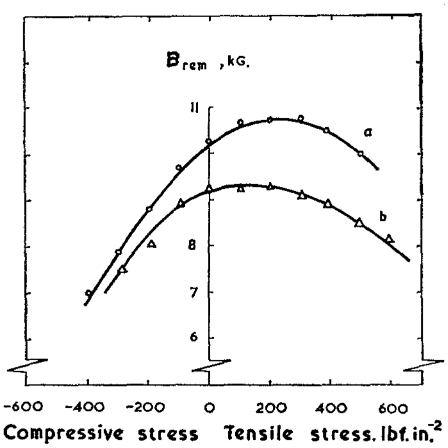

Figure 7 Variation of B_r (static) in both 46 grade (△) and 56 grade (O) material with tension and compression at 15 kG peak induction.

4. Rotational Hysteresis Loss

In the design of power transformers, a number of design factors are not known precisely. One of these is the loss occurring under rotating flux conditions. Loss occurs in magnetic materials under two different conditions. The first arises when the flux changes cyclically in magnitude and sign, but not in angular direction, and produces the normal, alternating power loss. The second arises when the magnitude of the flux remains constant, but the direction varies cyclically, giving rise to a rotational power loss. Although rotational power loss is of some interest to the electrical engineer, it has received little attention since the work of Brailsford in 1938 [7].

To measure rotational and alternating power loss, a method developed recently has been used [8]. This method determines the power loss by measuring the rate of rise of temperature of a small volume of a sample, in a short period of time after switching on the field. As applied to silicon-iron laminations, the method enables the loss in individual grains to be measured, from which the appropriate mean or macroscopic value can be obtained by averaging the results of a number of readings. The method has the great advantage of enabling loss to be studied under both alternating and rotating flux conditions. In fig. 8, typical curves for the variation of these power losses (50 c/sec) with flux density are shown for hot-rolled 0.013 in. thick laminations of silicon-iron. It will be noticed that the rotational power loss is greater than the usual, alternating power loss over most of the flux range.

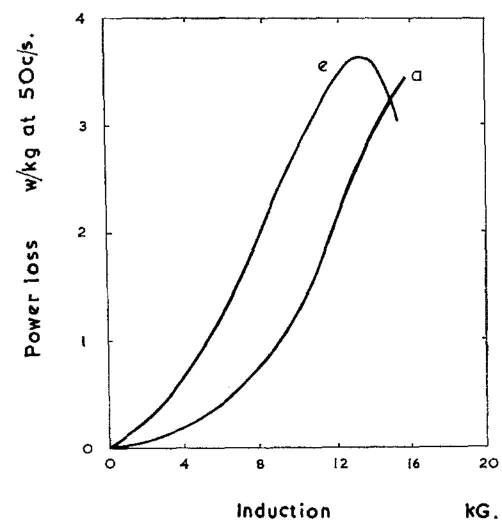

Figure 8 Rotational and alternating losses in 0.013 in., hot-rolled, 3 wt % silicon-iron sheets at 50 c/sec: curve a, pure alternating flux; curve e, pure rotational flux.

Rotational loss is an important parameter that must be considered in any comparison of new materials, or new forms of old materials, with the existing products.

5. Oriented Silicon-Iron – Its Production and Properties

The original, commercial, Goss type [9] of material, as produced about 1937, had some preferred orientation in the texture arising from primary recrystallisation. The power loss at 50 c/sec and 15 kG was about 1.0 W/lb for 0.012 in. thick laminations. Modern Goss-oriented silicon-iron originated somewhat later, 1940, when it was found possible to produce a higher degree of orientation by secondary recrystallisation, which reduced the loss to about 0.55 W/lb. The same basic process is still used extensively, although general metallurgical improvements have reduced this figure to 0.4 to 0.5 W/lb (1 UK ton = 2240 lb; 1 lb = 454 g).

However, in 1957, Assmus [10] described how another orientation could be developed, with a [001] direction parallel to the rolling direction and the (100) plane parallel to the rolling plane – often referred to as a "cubex" or "four-square" texture. The preferred orientations present in both Goss-type and "four-square" materials are shown in fig. 9.

"Four-square" silicon-iron presents a challenge to scientists of various disciplines. Whether or not the material will gain general commercial acceptance depends upon the net saving to the user of electrical plant – the difference between the saving from improved performance and the increased cost of the material. The basic advantage of the material is that it has almost equal magnetic properties in two directions at right-angles in the plane of the sheet, although, in addition, the rotational hysteresis loss is lower. Consequently, the engineer has to design his transformer to take maximum advantage of these properties. The metallurgist has to evolve a processing schedule that will produce the material at minimum cost. In this latter connexion, it is worth noting that the basis of the process being developed to give "four-square" silicon-iron is fundamentally different from that used in producing "Goss" texture. The development of a "Goss" texture is thought [11, 12] to occur during secondary recrystallisation by the selective release of certain grain boundaries. In the case of "four-square" silicon-iron, both Kohler [13] and Dunn [14] have suggested that the driving force for recrystallisation arises from surface energy differences between low-order crystal planes, and that impurities in the annealing atmosphere can cause changes in these surface energy relationships.

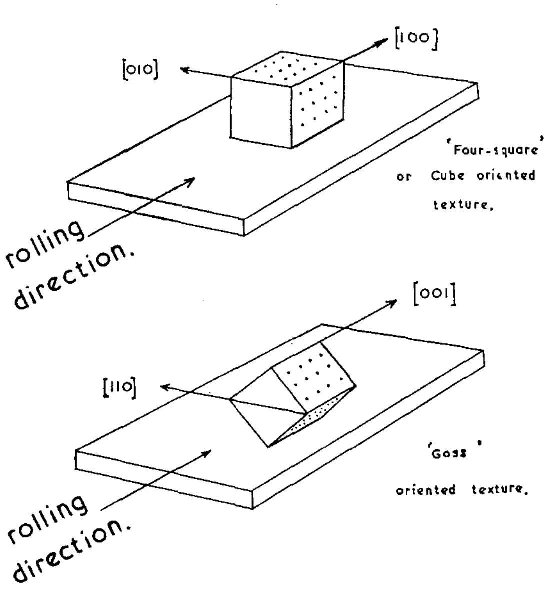

Figure 9 Schematic diagram of the ideal position of a unit cube with respect to the strip for "cube" and "Goss" textured material.

The saving to be expected from the engineering considerations is about £20 per ton for a large transformer [15]. Consequently, the new process must make the material for less than the price of Goss-oriented silicon-iron plus £20 per ton. Originally, it was considered that this was unlikely to be possible, since control of the annealing atmosphere, to the purity required, would be expensive. In addition, all development work had been carried out on high-purity material, and the degree to which impurity levels could be relaxed to normal commercial levels was unknown. Fortunately, recent work indicated that the orientation can be developed in material whose impurity level is similar to commercial material.

6. $6\frac{1}{2}$ wt % Silicon-Iron as a Transformer Material

Adding silicon to iron increases the resistivity of the alloy, thus reducing the power loss of the laminations. The practical limit to the amount of silicon that can be added is about $3\frac{1}{2}$ wt %, above which the material becomes brittle and the cold-reduction stage of the normal process to produce an orientation is no longer possible. A $3\frac{1}{2}$ wt % silicon-iron in oriented form has superior magnetic properties to a non-oriented form of any higher silicon content. An attempt has been made to predict the properties of 6½ wt % silicon-iron in oriented form, from a comparison of the properties of single crystals of 6½ and 3 wt % silicon-iron [16]. A silicon content of 6½ wt % was selected, since it has been reported on a number of occasions that zero magnetostriction and minimum loss occur at this composition. A comparison of the properties of 3 and 6½ wt % silicon-iron single crystals is shown in Table III.

The power loss of single-crystal 6½ wt % silicon-iron is 0.2 W/kg lower than that of the 3 wt% silicon-iron, so a similar reduction is to be expected if commercial, 6½ wt % silicon-iron can be developed to the same extent as a magnetic material. It will be necessary to develop an orientation in the material, since the anisotropy constants are of comparable magnitude. The magnetostriction constant λ_{100} is lower by a factor of 10, so that a worthwhile reduction in noise should be obtainable in oriented material.

Incidentally, it can be seen that the power loss of single-crystal 3 wt % silicon-iron is about 0.3 W/kg lower than that of commercial (46 grade) material at 15 kG; so that improvements should still be possible in the quality of the commercial product.

From the point of view of transformer construction, although it is expected that a reduction in power loss of about 20% can be achieved by increasing the silicon content from 3 to 6½ wt %, this is accompanied by a reduction in the magnetic saturation induction, and, taking all factors into account, it is unlikely that an extra cost of more than £30 per ton can be paid for commercial, grain-oriented, 6½ wt % silicon-iron. Thus there is some incentive to produce grain-oriented, 6½ wt % silicon-iron, particularly in the "four-square" form. Indeed, to develop a "four-square" orientation is quite attractive metallurgically and commercially, since this orientation could be developed without the necessity of a large cold-reduction.

TABLE III A comparison of the properties of 3 and 6½ wt % silicon-iron.

Flux density (kG)	Silicon content (wt %)	Commercial (α 46) Power loss (W/kg)	Single crystal Power loss (W/kg)	Single crystal Static loss (W/kg)
12	3	0.6	0.47	0.094
12	6.5	?	0.35	0.19
15	3	1.0	0.70	0.14
15	6.5	?	0.48	0.25

7. Other Possible Alloys

Iron-aluminium has attracted attention over the years and it has been reported to have good magnetic properties. But, using the Goss process, it would appear that special precautions are needed in the rolling and annealing stages. Aluminium oxidises quite readily and, during rolling, small particles of the oxide usually are forced into the bulk material, with subsequent deterioration in properties. The problems associated with the production of oriented iron-aluminium are being restudied by Cahn [17], particularly the possibility of developing the orientation by the surface energy process. As with silicon-iron, the surface energies of the various crystal planes are modified by surface contaminants.

In the development of new alloys, cooperation between the physicist, metallurgist, and engineer is important. Any improvement in properties in new alloys can be expressed in economic terms for any specific usage by the engineer. In the particular case of a power transformer, an initial assessment of this potential of new binary alloys can be determined by evaluating the effect of the resistivity and saturation induction on transformer costs – expressed as a saving in £'s per ton of core material (see fig. 10). There have been suggestions that, in ternary alloys, the additions might have greater beneficial effects, owing to interactions, than either of the two additions on their own. This is quite possible, since such interactions are known in other spheres. The development of oriented forms of

Silicon content (% wt)	Saturation magnetic flux density (kG)	Anisotropy constants k_1 (erg/cm³ × 10^5)	Anisotropy constants k_2 (erg/cm³ × 10^5)	Magnetostriction constants λ_{100} ($\times 10^{-6}$)	Magnetostriction constants λ_{111} ($\times 10^{-6}$)
3	20.3	3.65	—	25.4 ± 0.3	−5.06 ± 0.03
6.5	18.3	2.13	0.91	2.8 ± 0.1	2.5 ± 0.1

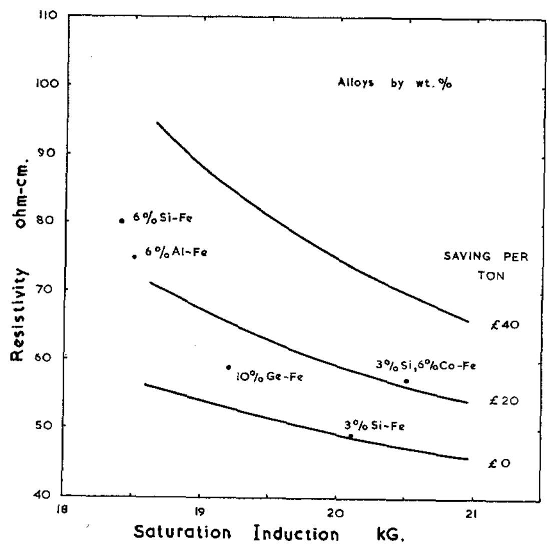

Figure 10 Curves showing the effect of resistivity and saturation induction on typical transformer costs – expressed as a saving per ton of core material.

any new alloys, that are competitive in price, lies in the province of the metallurgist.

8. Some Lines for Future Work

8.1. Improved Basic Properties

Improvements will continue to be made in commercial, grain-oriented silicon-iron. These will arise undoubtedly from improvements in the degree of preferred orientation, from greater purity, and from uniformity within the sheets.

The discovery that a "four-square" orientation could be developed in 3 wt % silicon-iron was one of the most interesting developments of recent times; although the practical implementation of the process from the laboratory, through the pilot plant, to commercial production will bring many problems. Perhaps the most profitable line of development would be to apply the process to 6 wt % silicon-iron.

8.2. Improved Understanding and Utilisation

Many of the improvements in the utilisation of silicon-iron laminations have arisen from a greater understanding of their behaviour and the interplay of various properties. A typical example of this was the work on the importance of sheet flatness.

The effect of stress, applied parallel to the direction of orientation, on the magnetostriction and power loss has been discussed already. But now it is being realised that cross-stresses (applied in the plane of the sheet perpendicular to the direction of orientation) might be of importance.

Although stress itself is important, the stress sensitivity of a material should be studied. A material may have a higher magnetostriction in the unstressed state, but its change (or increase) in magnetostriction with stress could be much lower.

In the construction of power transformers, other factors and parameters are involved and their relative importance and value need elucidation. For example, the variation of thickness within a roll of silicon-iron may be less than ± 0.0001 in. in 0.013 in., but the variation in mean thickness from one roll to another may be considerably in excess of this figure. The relative importance of variations in thickness within a lamination, and from lamination to lamination, needs to be studied.

8.3. Detailed Investigation of Domain Behaviour

Much of our understanding of the behaviour of magnetic materials has evolved from the studies of domain patterns, in which the domains are made visible by the simple, but elegant, Bitter-pattern technique. In this technique, the small magnetic particles which are suspended in a colloid are attracted to the domain walls, where there exist free poles (or magnetic flux emerges from the surface), enabling the wall configuration to be studied. Unfortunately, the technique can only be used to study essentially static wall-configurations. For most engineering applications, the magnetic material is used under rapidly alternating flux conditions. However, during the last few years, the Kerr magneto-optic technique of studying domains has been developed. With this technique, a beam of plane polarised light is reflected at an angle from the surface of a magnetised specimen. The plane of polarisation is rotated a small amount, depending on the direction of magnetisation of the area from which the beam is reflected. When viewed through an analyser, the presence of a domain wall is indicated by the difference in optical contrast between the two adjacent regions or domains. The technique can be used to study domain behaviour at frequency and opens up a new field of investigation for the engineer and applied physicist. For example, most magnetic properties measured at frequency are quite different from those measured under "static" or slowly varying conditions. In particular, the loss at 50 c/sec is considerably greater in silicon-iron laminations (by a factor of about 3) than the loss associated with slowly traversing the hysteresis loop. This additional loss is attributed to eddy currents of one form or another, but the loss predicted by "classical" theory is too small by a factor of about 2. Various modifications have been evolved based on domain concepts, but these have failed to clear up the discrepancy satisfactorily. One possible reason for this failure is the uncertainty over the correct domain spacing – it is doubtful if all walls move or move equally well at frequency, and so to take a "static" value for the domain spacing would lead to errors. The Kerr magneto-optic technique should enable an "effective" domain spacing to be evaluated. In addition, the "effective" spacing may depend on grain size and vary from region to region; so that it may be necessary to measure the loss in the associated regions, rather than take an average for the material. Many other problems of a similar type await investigation.

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