SILICON STEEL SHEETS — AN OUTLINE OF PROPERTIES, APPLICATIONS AND RECENT DEVELOPMENTS

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Introduction

SILICON steel should be regarded as something more than just another alloy steel. It is a basic necessity of modern civilization. Industrial development, as we know it today, has been made possible very largely by the harnessing of electrical energy to provide power and light, heat and cold, wherever they are required.

Everyone of the alternators which generate the electric power, the transformers which distribute it, and the motors which utilize it to drive the wheels of industry, is composed largely of stampings or laminations manufactured from thin sheets of silicon steel.

The reasons for the choice of this material are not difficult to find. Electric machines and transformers depend for their operation on interactions between electric currents and magnetic fields. These fields can be concentrated in the required places by cores of ferro-magnetic material. The phenomenon of ferro-magnetism is found in only three elements — iron, nickel and cobalt. These elements and their alloys provide magnetic materials with a wide range of properties.

Most people are familiar with the general characteristics of ferro-magnetic materials. Fig. 1 shows the relationship between magnetic induction (or flux density) B measured in lines per sq. cm., and the magnetizing force H, measured in ampere turns per cm. length of magnetic path. B may be regarded as a measure of the power output which we can obtain from a given core of magnetic material, while H is a measure of the magnetizing current or input which we have to provide. As in most walks of life we are concerned in obtaining the maximum return for the minimum effort, so a material which provides a high B for a low H can be regarded as a good one. The ratio B/H is called the permeability of the material.

But no matter how large an H value we provide, B is limited by an intrinsic property of the material called the saturation induction. It will be apparent that a high saturation induction is a desirable property, for by increasing the saturation induction we can obtain a greater output from a machine or a transformer of a given size. One other property is of the utmost importance. When a magnetic material is subjected to alternating magnetization, the B/H curve widens into the familiar hysteresis loop of Fig. 1.

The area of this loop represents a loss of energy which is converted into heat in the material by internal molecular friction as the magnetic domains change their directions. This loss of energy reduces the efficiency of the machine or transformer and creates cooling problems. Further energy loss is caused by the flow of eddy currents which are induced in the magnetic material when the flux alternates from one value to another.

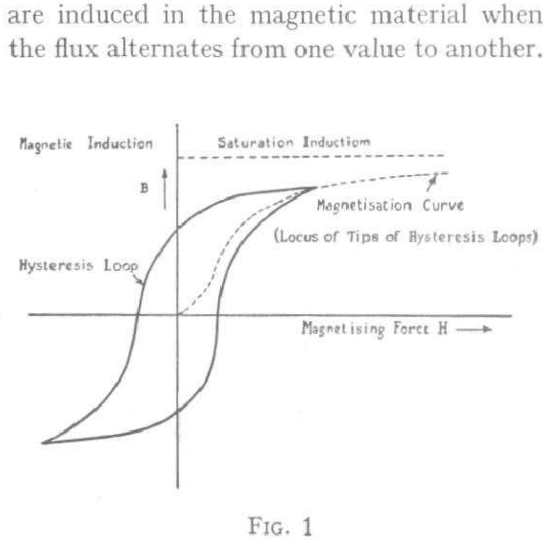

FIG. 1

To reduce the eddy current loss we may increase the resistivity of the material or reduce its thickness.

Of the ferro-magnetic elements iron is the most plentiful and the cheapest. When alloyed with considerable quantities of nickel, very high permeability and low losses are achieved, but the saturation induction is reduced and the cost is high.

When alloyed with silicon, the magnetic properties of iron are improved in certain respects and it is this material which provides the most economic solution to most power engineering problems.

Properties of Hot-rolled Silicon Iron Alloys

The earliest electrical machines and transformers employed Swedish iron as the core material. The work of Hadfield[1] and others, at the beginning of the present century, showed that the addition of silicon to iron had a fourfold advantage:

(1) It increased the permeability, thereby causing a reduction in magnetizing current.

(2) It reduced hysteresis loss, thereby causing a reduction in waste heat and increasing electrical efficiency.

(3) It increased the resistivity of the material, resulting in a reduction in eddy current losses.

(4) It eliminated 'ageing', i.e. deterioration of magnetic properties when subjected to temperatures of about 100°C. over long periods.

Subsequent work in the United States by Yensen, Cioffi and others[2] showed that very pure iron has a much higher permeability and lower hysteresis loss than any of the silicon iron alloys. With total impurities less than 0·05 per cent, initial and maximum permeability of 10,000 and 200,000 respectively were recorded. It was shown, however, that very small amounts of impurities, particularly oxygen, carbon and sulphur, have a very severe effect on the magnetic properties, and the permeabilities quoted above are reduced perhaps 40 times in commercial iron, while the hysteresis loss is increased about 20 times.

The addition of silicon does not improve the inherent magnetic properties of pure iron. But by acting as a deoxidizer, and by precipitating other elements, it allows the inherent properties of pure iron to be approached and to be retained throughout manufacture, fabrication and use. Moreover, as already mentioned, it does increase the resistivity and hence reduces eddy current losses, which are inversely proportional to resistivity. Fig. 2 shows this effect.

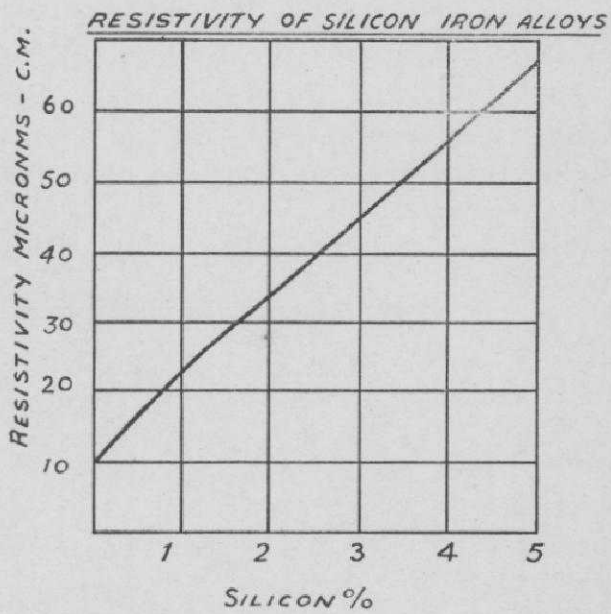

FIG. 2

The effect of silicon on losses of 0·014 in. sheet is shown in Fig. 3. The losses decrease as the silicon content is increased up to 4 per cent. The '4 per cent Best Quality' material is further improved by virtue of less total impurity and better annealing treatment. Four per cent or 4½ per cent silicon content is not exceeded because the sheet becomes so brittle that it cannot be punched or sheared.

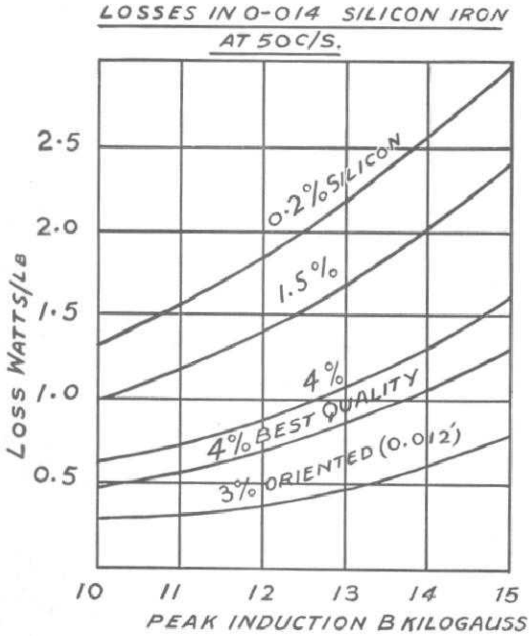

FIG. 3

Fig. 4 demonstrates the effect of silicon on the B/H curve. At inductions below the knee of the curve, the permeability is increased by the addition of silicon.

At high inductions silicon has the detrimental effect of reducing the saturation induction. It acts as a diluent, and causes the saturation induction to drop in proportion to the atomic percentage of silicon.

The relative outputs in the United Kingdom of various grades of sheet material are plotted in Fig 5, which shows peaks at each end of the silicon range. The lowest silicon grade is most widely used, partly because it is cheapest and partly because it has the highest saturation induction. The highest silicon grade is widely used in those applications in which improved magnetic quality justifies the higher cost.

The eddy current loss is proportional to

$$\frac{B^2f^2t^2}{\rho}$$

where B is the induction, f is the frequency, t is the thickness and ρ is the resistivity.

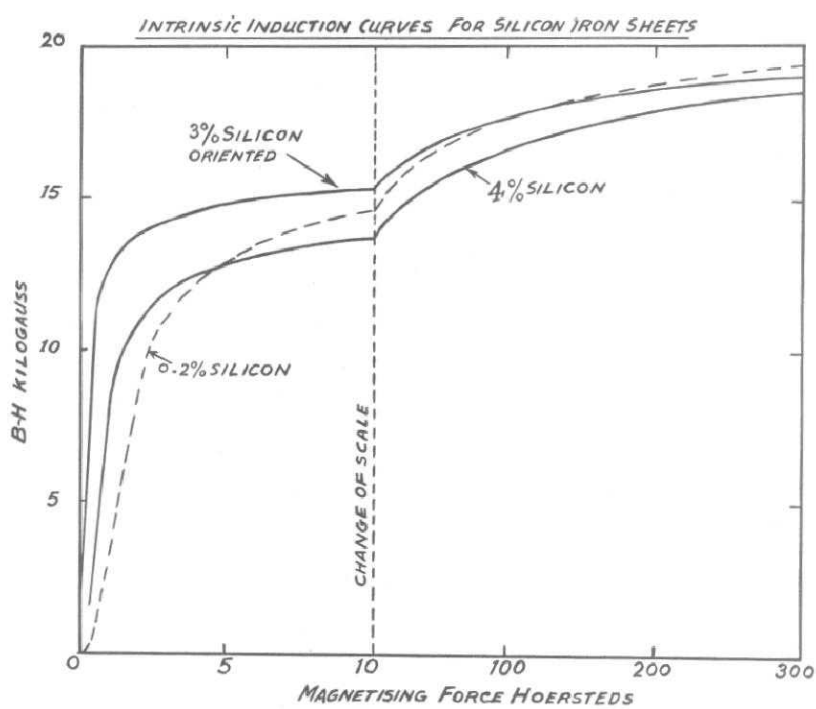

FIG. 4

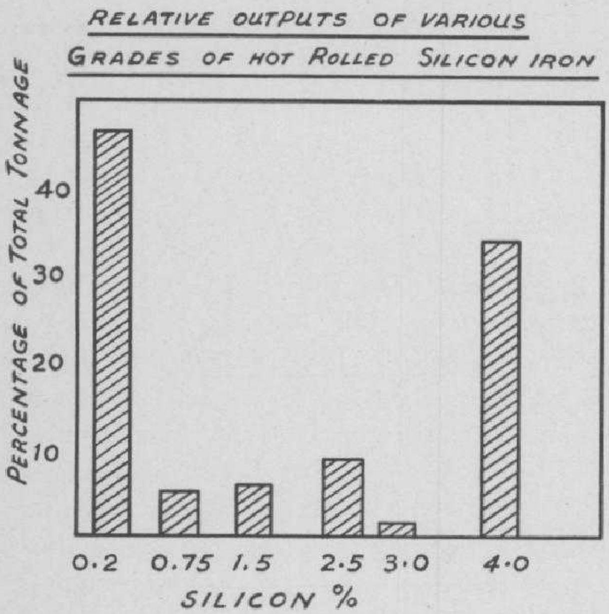

FIG. 5

Although reduction in thickness reduces the eddy losses, it increases both the sheet-manufacturing costs and the assembly costs. The low-silicon grades are usually rolled to a thickness of 0·020 in. or more, while the 4 per cent silicon material is almost entirely 0·014 in. thick. This results, at a frequency of 50 cycles per second, in eddy current losses of the order of 20 per cent of the total loss. If the material should be required for use at higher frequencies, it may be necessary to roll it down to 0·007 in. gauge. Thinner material cannot readily be manufactured by the hot-rolling technique.

Applications of Hot-rolled Silicon Iron Sheets

Small Machines — Since the output of a machine is limited by the useful flux which can be passed through the teeth, high saturation induction is most important and low-silicon grades are mainly used. As the size of the machine increases, it becomes necessary to use lower loss material.

In the case of an induction motor, the stator is excited at mains frequency, while the rotor is excited at the very low slip frequency. In many cases the best performance would be achieved by using a medium grade for the stator and a low-silicon grade for the rotor; but this introduces practical difficulties since the disc blanked from the stator is most conveniently used for the rotor.

A further factor to be considered in the choice of material for machines is the question of brittleness, which is inherent in the high-silicon grades. Stampings with very narrow teeth may be difficult to manufacture and even more difficult to assemble, if made from brittle material, because the teeth will break off very readily.

Large Machines — This group consists mainly of turbo-alternators, water-wheel alternators and synchronous condensers. Machines of this size have not yet been manufactured in India. The problem of heat dissipation and efficiency outweighs the need for the highest possible saturation induction, and it is customary to use $3\frac{1}{2}$ or 4 per cent silicon sheet. Inductions of 18-20 kilogauss are experienced at the narrowest sections of the teeth.

Direct-current Field Systems — In d.c. and synchronous a.c. machines, the field carries a unidirectional flux. Laminations are unnecessary, and the field system may be solid.

The field system of a d.c. machine is usually formed by the stator, which is of salient pole construction. The yokes were formerly made of cast iron, but drawn steel tubing is now commonly used. It is often more convenient to build the poles from laminations than to cast and machine them. Here either mild steel or 0·2 per cent silicon iron are used. Both have high saturation inductions.

In synchronous a.c. machines the rotor carries the field system. If salient poles are used, they may be solid or laminated, as in the d.c. machine. Non-salient pole machines, such as large turbo-alternators, employ a rotor which is machined from a solid steel forging.

Power Transformers — To prevent excessive magnetizing current and waveform distortion, the working induction is limited in power transformers to a point near the knee of the magnetization curve — 13 to 14 kilogauss being the usual range for hot-rolled materials. Even though the iron loss is only 0·2 per cent of the transformer rating, the cost of iron losses, in the lifetime of the transformer, may easily exceed its first cost. Four per cent silicon iron is used exclusively, and the present trend is towards increasing the use of the lowest loss material.

Hot-rolled transformer cores, except for sizes below about 1 kVA., are built from straight strips with interleaved joints. It is usual to cut these strips with the axis parallel to the rolling direction, because of a slight amount of preferred orientation. (The losses in the rolling direction are usually about 15 per cent less than the losses across the rolling direction.)

Small transformers of the type used in the radio industry are built from E and I or T and U laminations. Low-silicon grades are frequently used, because the losses are relatively unimportant.

Grain-oriented Material

The crystal structure of iron forms a body-centred cubic lattice which is most easily magnetized along the cube edge. A technique has been developed by Goss[3], involving cold-rolling and high temperature annealing, which causes the crystals to have the preferred orientation shown in Fig. 6. This material has greatly reduced losses (FIG. 3) and increased permeability (FIG. 4), when magnetized in the rolling direction. It will be seen from Fig. 6 that an angle of 90° to the rolling direction corresponds to a face diagonal of the cubic lattice. This is an unfavourable direction of magnetization, in which losses are high and permeability is low.

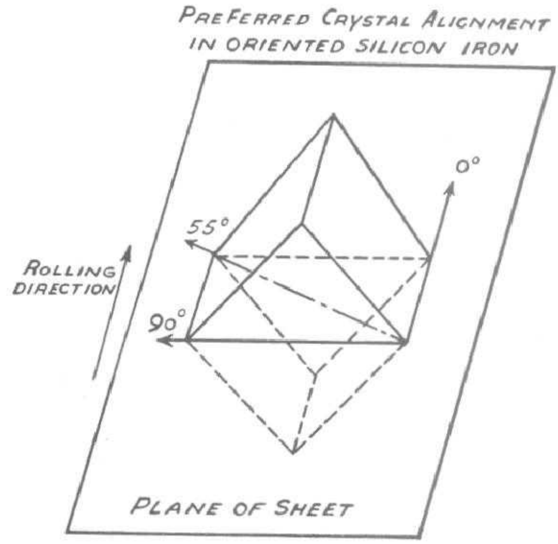

FIG. 6

Magnetization at an angle of 55° to the rolling direction, corresponding to a cube diagonal, is even more unfavourable (FIG. 7).

The silicon content of grain-oriented material is limited to a little more than 3 per cent. Above this figure the material becomes too brittle for cold reduction. A recent report[8] from Germany indicates that higher silicon contents may be used if the temperature is first raised to about 300°C.

Applications to Transformers — Because of its highly directional properties, it is not possible to utilize the familiar T and U, E and I, or L stampings. For large transformers the conventional interleaved core, consisting of rectangular strips cut parallel to the rolling direction, is often utilized; but a considerable proportion of the material in the corner regions carries flux in unfavourable directions, so that losses and magnetizing current are increased.

Much effort has been applied in finding other methods of utilization of oriented material. The use of mitred corner joints is advantageous in reducing the amount of cross-fluxing, but is mechanically less robust and sometimes more wasteful of material.

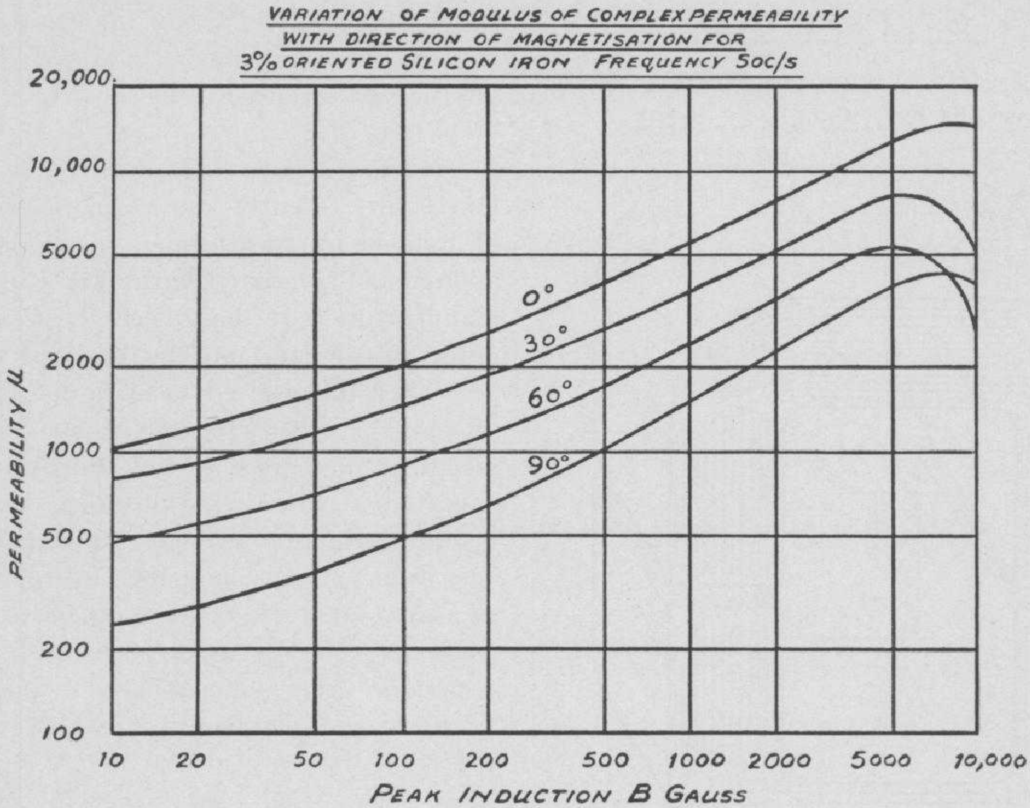

FIG. 7

From the magnetic circuit point of view, spiral cores provide an excellent solution to the problem, but the difficulty of applying toroidal windings rules them out except in a few special cases, such as current transformers. The now familiar C-type core[5] is a development in which the core is wound on a suitable mandrel, strain-annealed, and impregnated with a suitable bonding material. The core is then cut in two, and may be re-assembled with butt joints round preformed windings (FIG. 8).

For sizes above a few kVA. the butt joint of the C-type core is objectionable, and other methods have been developed. In one method[6], which has been used for cores up to 3300 kVA., the core is formed from strips in such a manner that there is one joint in each convolution. The joints are staggered over a region of the upper yoke, so that, after annealing, the yoke may be hinged back to allow the windings to be placed in position.

These methods are intended for single-phase transformers. In the case of 3-phase transformers the problem is further complicated by the need for three interlinked magnetic paths of approximately equal reluctance, and a number of methods have been patented. Some of these[7] incorporate multiple C-type cores.

Applications to Rotating Machines — There is no advantage in applying grain-oriented material to the circular stampings of most electrical machines. In the case of large machines, however, the stator stampings are usually manufactured, not in complete circles, but in 30° segments. This reduces waste.

A recent development[4] has been the utilization of oriented material for these segments, with the preferred direction either along the yoke in the case of the two-pole machines which have deep yokes, or along the teeth in the case of multi-pole machines,

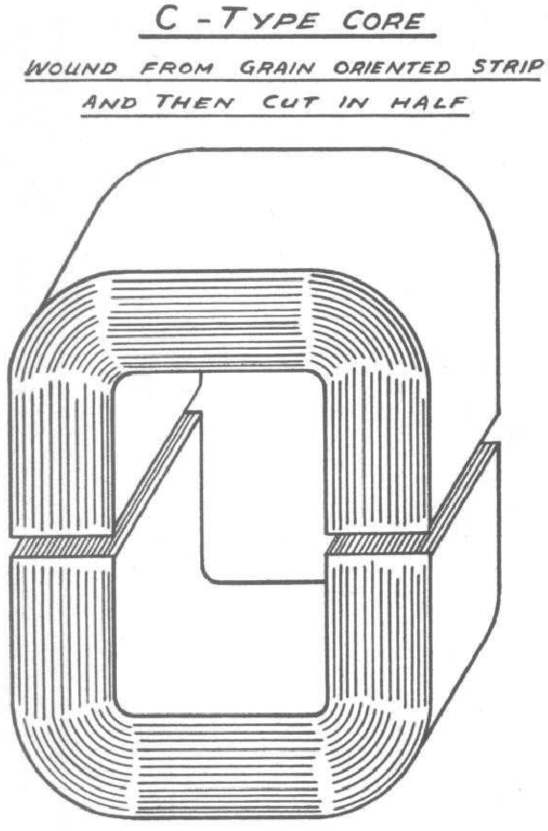

FIG. 8

A saving has been reported of 20-30 per cent in core loss, and of 50 per cent in the m.m.f. for the yoke and teeth (though this is only about 5 per cent of the total m.m.f. requirement).

Indigenous Supplies of Silicon Steel

Having reviewed properties and applications of silicon steel, it is appropriate to consider the extent to which indigenous supplies are capable of meeting the demand of the consumers.

Hot-rolled Sheets: Low-silicon Grades — At present the supply of these sheets, both in quantity and in quality, is quite adequate to meet the demands of the industry. It may be assumed that larger quantities will be required as industrial expansion continues, and that there will be an increased demand for the medium-silicon grades when the production of heavy electric machinery is undertaken.

Hot-rolled Sheets: High-silicon Grades — Until quite recently, the magnetic behaviour of indigenous transformer sheets has been anomalous, compared with sheets of foreign manufacture. It has been customary to grade silicon steel on the basis of the iron loss when magnetized to an induction of 10 kilogauss at a frequency of 50 cycles per second. Since most power transformers are operated at about 13 kilogauss, the losses at this induction are of great importance. The table below compares average losses, measured at 13 kilogauss, of corresponding grades of sheet (a) imported from the United Kingdom; (b) indigenously manufactured in 1954; (c) indigenously manufactured in 1955. It will be seen that the 1954 material shows very high losses at 13 kilogauss, whereas the 1955 material is comparable with the imported material. Anomalous behaviour of the type shown in column (b) is characteristic of overoxidized material. It is satisfactory to note that improvements have been made.

TABLE 1

LIMITS OF LOSS IN WATTS PER LB. AT B=10 KILOGAUSS	LOSS IN WATTS PER LB. AT B=13 KILOGAUSS		
	(a) Imported from U.K.	(b) Indigenous sheet, 1954	(c) Indigenous sheet, 1955
0·59-0·63	1·030	1·110	1·070
0·54-0·59	0·977	1·050	0·998
0·49-0·54	0·910	0·978	0·928

Regarding the general quality of transformer sheet, it may be pointed out that the bulk of the present indigenous production falls into the 0·59 and 0·63 watt/lb. grades. A considerable demand exists for lower loss grades. It is met at present by importing.

This demand is certain to increase when larger transformers are built. It follows that, if the industry is to become self-supporting, there is a need for a general improvement in the loss figures for transformer sheet and an increase in output.

Some comments may also be made on the question of sheet thickness. When laminations are built up into cores, it is important that they should stack closely together and that loss of space due to surface roughness or non-uniformity of thickness should be minimized. When interleaved joints are used, as in transformer cores and large machines, thickness uniformity is required not only within each sheet, but between one sheet and another. Maintenance of uniformity of thin hot-rolled sheets is admittedly a difficult problem, but the consumer is entitled to expect that indigenous sheet will reach the same standard as imported sheet.

Grain-oriented Sheet — In recent years considerable use has been made of this material in the U.S.A. and more recently in Europe. It is too early to say whether it will be widely used in India in the future. The cost of plant for cold-rolling and high temperature annealing is very high, and it seems likely that Indian requirements may have to be met by importation for a good many years to come.

References

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8. LIHL, F. & ZEMSCH, P., *Arch. Eisenhüttenwesen*, (Oct. 1955), 599-602.

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