Steels, Silicon Iron-Based: Magnetic Properties ☆

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Introduction

Electrical steels are used in the cores of electromagnetic devices such as motors, generators, and transformers because of the ability of ferromagnetic materials to magnify the magnetic effects of current-carrying coils. Of the available ferromagnetic materials, iron and its alloys offer the best cost beneficial performance (Cardoso *et al.*, 2013; Zu *et al.*, 2015; Liu *et al.*, 2015). The torque of a motor is proportional to B^2, where B is the intensity of magnetization operating between its stationary and moving parts. Because of this square law relationship even small gains in B lead to useful increases in torque and thus output power.

In the case of transformers, the large magnetizations available from iron enable voltage transformations to be carried out by windings of an acceptable size. The voltage appearing at a transformer winding is related to the rate of flux change $d\Phi/dt$ for the core and is normally of sine form so that operation at high peak flux levels is important.

It is clear that for steels to be of the most use for electrical machines a high working induction is desired, as close as practicable to the approximately 2 T at which iron becomes saturated.

At the same time a high permeability (ratio of B to H) or flux magnifying property is desired (Liu *et al.*, 2015). The effective permeability of iron reduces as saturation is approached leading to heavier demands on magnetizing current.

Additionally the duties of core steel must be executed without serious wastage of energy within the metal (called power loss or core loss) due to the periodic magnetic reversals involved in use (Cardoso *et al.*, 2013; Tada *et al.*, 2013; Lee *et al.*, 2014). The range of electrical steels available has arisen out of the appropriate compromises struck between these factors. Different types of steel suit different applications (see **Table 1**).

1 Reduction of Power Loss

One of the primary sources of power loss within an electrical steel is eddy current loss (Cardoso *et al.*, 2013). If a solid iron core is placed within a magnetizing coil the iron core itself provides short-circuited current paths in which so-called induced 'eddy currents' can flow. These waste energy as heat and also produce magnetic fields which oppose the magnetization (Lenz's law effects) so that penetration of flux to the center of the core is inhibited. Eddy currents can be radically reduced by splitting up the core into laminae which restricts the flow of eddy currents (**Figure 1**). There are limits to the degree of lamination which can be applied set by the cost of rolling steel to reduced thickness and the complexity of handling this material for core building. Inevitably as thinner steel is used the effective space occupancy of the metal reduces since a pile of plates can never have the same mass as solid metal of the same superfacial dimensions.

Further the need to insulate laminae from each other by applying coatings reduces the effective space occupancy. Overall the effect is to reduce the apparent saturation induction of the core. Lamination creates much more metal surface, and surfaces produce power loss due to domain wall pinning.

A second means of restraining eddy currents is the use of alloying elements added to iron (Cardoso *et al.*, 2013). Adding some 3% of silicon to iron raises its resistivity fourfold. Many other elements have been tried as resistivity raisers (e.g., aluminum) but

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Table 1 Typical electrical steels

Type of steel	*Thickness (mm)*	*Power loss*	*Conventional density (g cm^{-3})*	*Relative permeability*	*Usage*
Non-oriented motor grade requiring customer anneal	0.65	7.0 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.85	3000 at 1.5 T	Small
Non-oriented superior motor grade, requiring customer anneal	0.5	3.8 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.85	3000 at 1.5 T	Small/medium motors
Non-oriented fully annealed	0.5	5.3 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.75	1620 at 1.5 T	Larger rotating machines small transformers
Non-oriented fully annealed	0.35	2.25 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.60	660 at 1.5 T	Large rotating machines
Grain oriented steel (CGO)	0.27	0.78 W kg$^{-1}\hat{B}$ 1.5 T, 50 Hz	7.65	1.83 T at 800 Am^{-1} Rel μ1830 at 1.83 T	Transformers
High permeability grain oriented steel	0.27	0.98 W kg$^{-1}\hat{B}$ 1.7 T, 50 Hz	7.65	1.93 T at 800 Am^{-1} Rel μ1930 at 1.93 T	Transformers
Relay soft steel	1.0	–	7.85	Coercive field strength	56–80 A m^{-1}

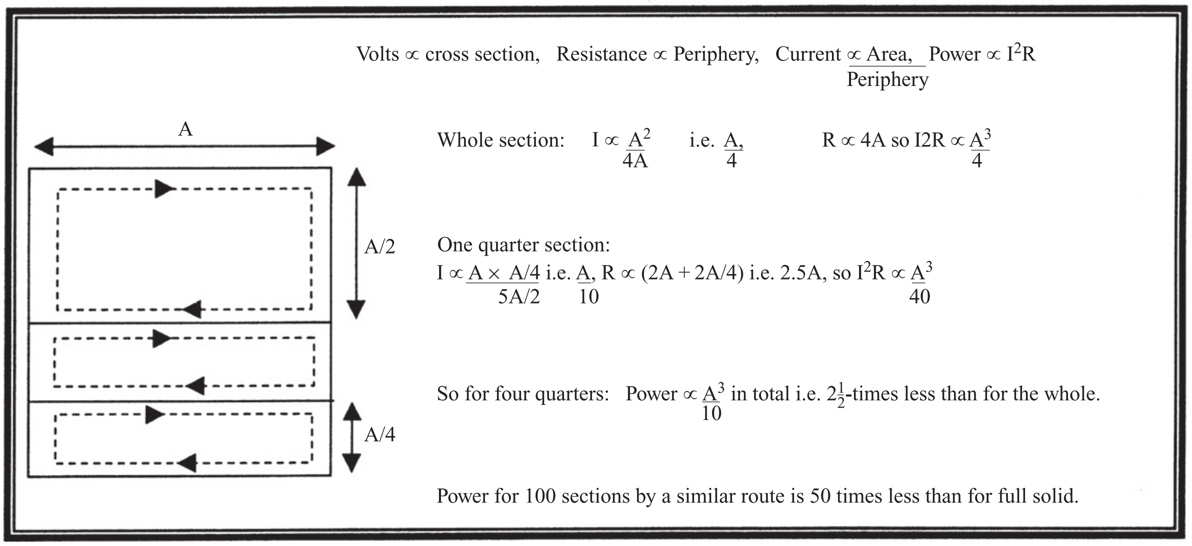


Figure 1 Lamination restrains eddy currents and reduces power wastage–a simplified model.

silicon has proved to be the most useful. Adding silicon certainly reduces eddy currents (and so power loss) but the resulting alloys are more difficult to roll and harder to punch into laminations. Further, added silicon dilutes the iron present and reduces saturation magnetization and high field permeability.

A second major component of power loss is hysteresis loss (Landgraf *et al.*, 2008; Tada *et al.*, 2013; Gallaugher *et al.*, 2015). If a plot is made of *B* vs. *H* over a cycle of magnetization then the area of the resulting *B-H* loop represents lost energy. The mechanism of this so-called 'hysteresis loss' relates to the fact that the magnetization in iron functions via ferromagnetic domain wall motion (Landgraf *et al.*, 2008). Easy domain wall motion is impeded by non-magnetic inclusions in the steel, stressed regions, and unfavorable surface states. Clearly it is advantageous for the steel to be inclusion-free (high purity) and free from stress. Domain wall pinning occurs at surfaces so that no more surface than is appropriate should be created (i.e., steel not too thin). The bonding of coatings to steel can produce effective roughness at the coating/steel interface which pins domain walls and adds to hysteresis loss. **Figure 2** shows the domain structure in an electrical steel in which a domain wall is clearly shown with part of its length pinned.

A further contribution to loss reduction comes from increasing grain size of the steel (Liu *et al.*, 2015; Lee *et al.*, 2014). With larger grains (crystallites) there is less grain boundary per unit volume. Grain boundaries are prime domain wall pinning sites. Special rolling and heat treatment regimes are used to promote grain growth. Appropriate heat treatments also relieve stress.

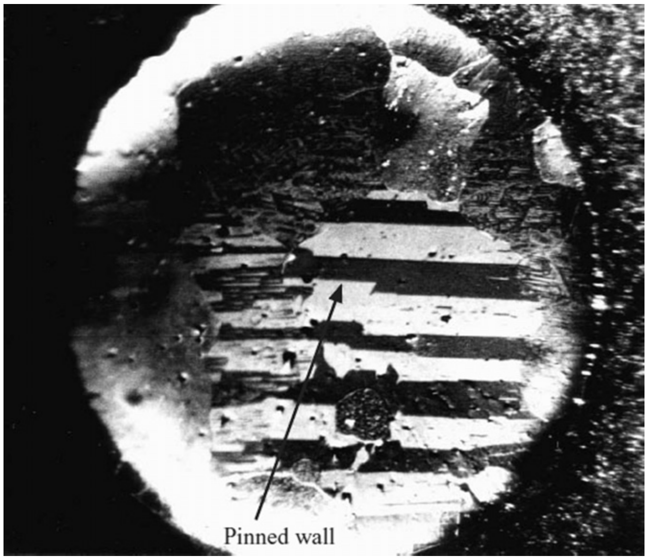


Figure 2 Magneto-optic image of ferromagnetic domains.

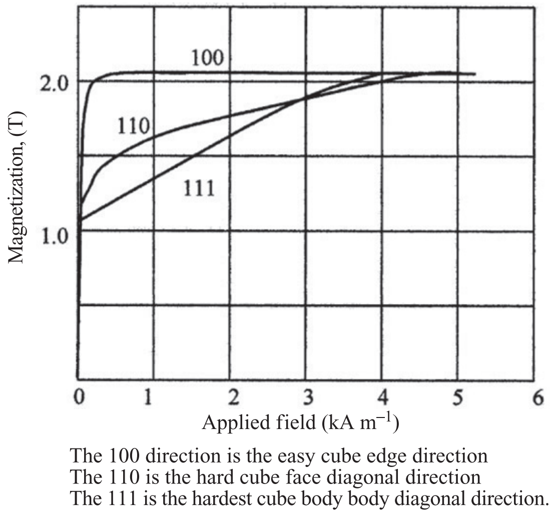


Figure 3 Responses to magnetizing fields of different crystal directions.

Permeability (in certain directions) can be enhanced by growing grains in which the easy direction of magnetization of the iron lattice (**Figure 3**) is caused to lie along the direction in which magnetization is desired (Liu *et al.*, 2015). This process of 'grain orientation' is commonly based on the creation of directionally organized impurity particles, which act to inhibit grain growth in directions other than that desired. To perform this operation, impurities are purposely added to steel at the melting stage (e.g., manganese sulfide, aluminum nitride) so that during subsequent metallurgical operations grains with easy directions of magnetic response in the rolling direction of production are grown preferentially. **Figure 4** shows the orientation for the most used Goss grains system.

The statistics of grain growth require that if only certain nuclei are allowed to grow, then from a reduced population the resulting grains will be large. In so-called conventional grain oriented (CGO) steel grains are some 3–4 mm across in metal 0.27 mm thick. The easy direction of magnetization of the grains lies within a spread of a few degrees about the rolling direction.

The desire to get the very highest in-rolling-direction permeability from steel has led to the devising of better and better grain growth inhibitors so that the so-called 'improved oriented steel' can have a directionality spread of only 1–2°. This precision has arisen from the requirement that only super-accurately oriented nuclei grow. The growth statistics now lead to grains, which may be 2–3 cm across. This sounds good as orientation is excellent and grain boundaries are few.

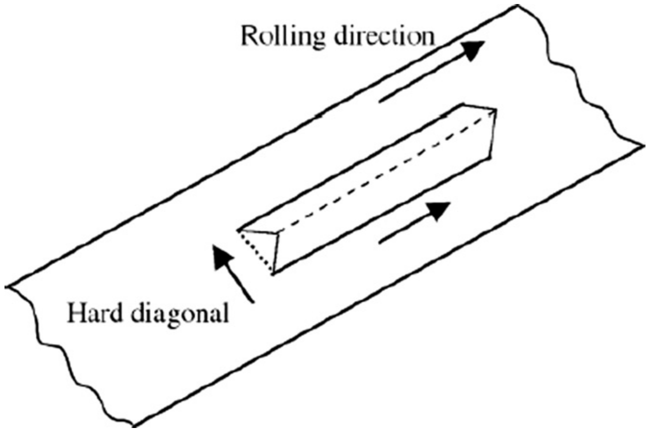


Figure 4 A 'Goss-oriented' crystal's relationship to the sheetrolling direction.

However, the magnetic energy considerations within a grain dictate that large grains support wide domain wall spacing. With a wide domain wall spacing walls must move more rapidly to execute the required flux reversal. A rapidly moving domain wall is a dissipative item due to the micro eddy currents induced by its movement.

This effect can be countered to some degree by creating artificial grain boundaries and reducing the domain wall spacing. Such artificial grain boundaries can be created by lines of mechanical damage or stress, or even gross displacement of metal at the steel surface. Such domain refinement can use laser treatments, spark ablation, ball scribing, etc., to give the desired effect. **Figure 5** shows the effect of domain refinement.

The addition of silicon not only restrains eddy currents but improves medium-field permeability and reduces the tendency for losses to rise over time due to the occurrence of fine precipitates within grains.

It is often suggested that eddy current losses increase with the square of frequency of excitation and hysteresis losses linearly. However, complex domain interactions produce losses in excess of this simple model. From the point of view of machine-design engineers, losses are fairly well described by the equation:

$$\mathrm{Loss} = Af + Bf^2 (f = \mathrm{frequency})$$

Here A is a coefficient linked to hysteresis, though not exclusively, and it is increased by the effects of stress and impurities. B is a coefficient influenced by material thickness and resistivity, but also by domain wall spacing.

In general power loss increases with the amplitude of magnetization and the hysteresis component rises with approximately the 1.6 power of B_{max}. This is a useful indicator within the normal range of magnetizations.

2 Steel for Transformers

The production of grain orientation is very valuable for materials destined for use in transformers since unidirectional flux is employed (except at joints and corners). In cores where the percentage of corner region is relatively high conventional grain oriented steel may be preferred as the less exact orientation eases flux rotation at corners. **Figure 6** shows cores of differing aspect ratio. Where the long limbs and smaller percentage of corner is used the super-oriented steel can be best exploited. It is usual to employ super-oriented steel at higher working inductions (B_{max} 1.7 T and above) than is usual for CGO ($B_{max} \approx 1.5$ T). However, in any system over voltage can more rapidly take steel operating at B_{max} 1.7 T into technical saturation when severe unwanted magnetizing currents will flow.

3 Steel for Rotating Machines

Grain orientation of the Goss type is unsuitable for the cores of most motors and generators where properties need to be equal at all angles in the plane of the sheet (Zu *et al.*, 2015). Here the benefits of lamination and added silicon still apply and enhanced purity with large grains is desirable. Large grains can be produced by two main methods.

3.1 Long Hot Anneal

Steel strip can be annealed at about 1000 °C in a strand anneal line so that grains may grow to some tens of microns in diameter. Combined with a moderate amount of added silicon, for example, 1–3%, a good core material is produced which is nearly

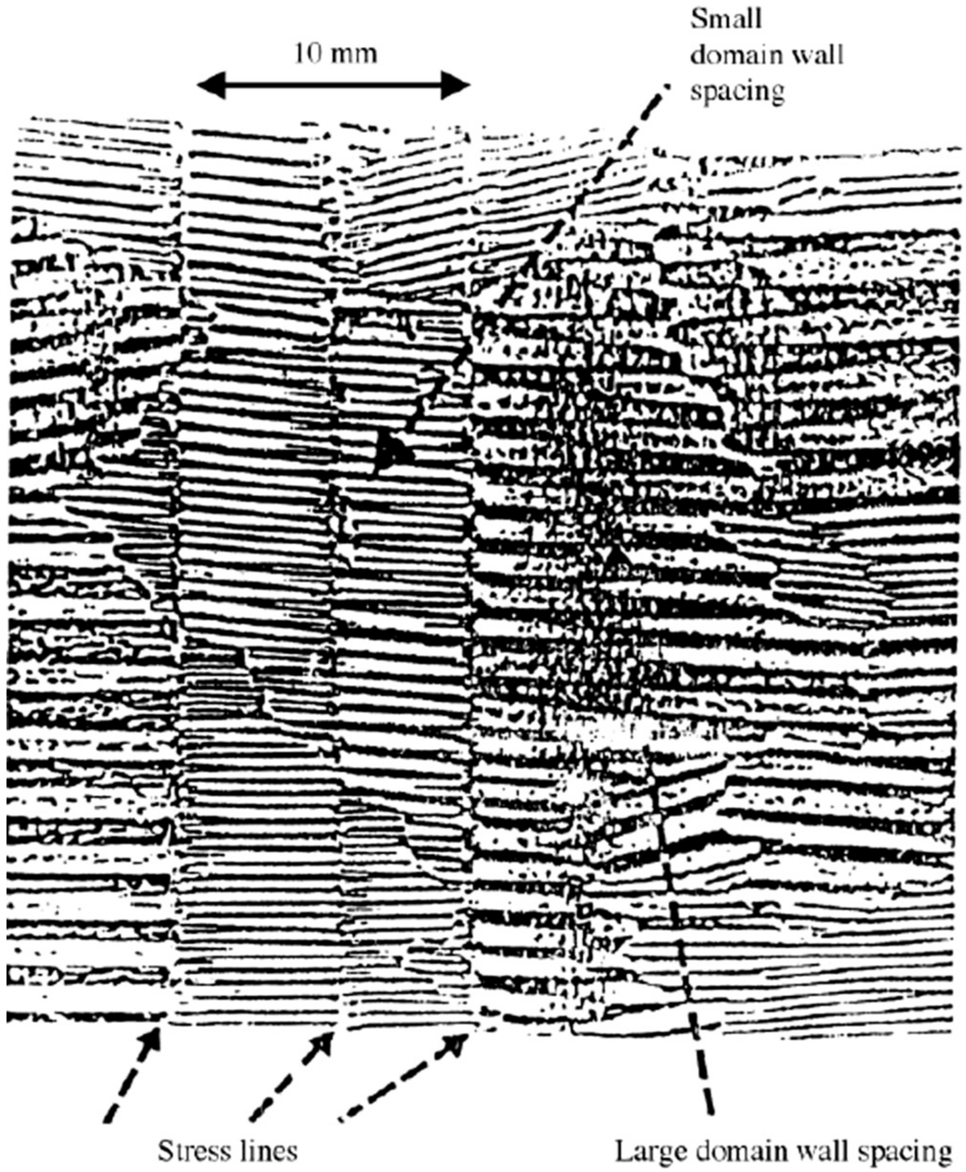


Figure 5 Example of domain refinement.

isotropic. After such an anneal the steel is soft but the added silicon raises hardness to a degree where stamping into motor laminations is fairly convenient.

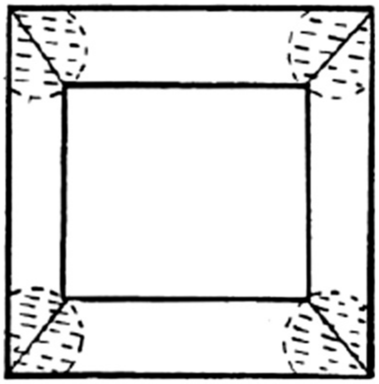
3.2 Critical Grain Growth

Here strip steel is annealed in a strand anneal line then given a small amount of cold rolling, reducing thickness by about 8%. This is just enough cold work to build in sufficient strain energy to provide 'explosive' grain growth when the metal is re-heat treated at about 800 °C. This can usefully be applied after stamping of the steel which was done while still hard from cold rolling. The removal of stamping stress is combined with the beneficial effects of critical grain growth.

3.3 Decarburization

A strand anneal conducted in wet hydrogen, for example, 800 °C and a dew point of 65 °C enables dissolved carbon to be removed down to some 0.003%. This practice helps reduce hysteresis loss. Further, end users can make the final post-stamping anneal a decarburizing anneal. In recent years it has become possible to reduce carbon to very low levels at the steel making stage of production so that anneals can be conducted in a neutral gas, for example, nitrogen. The application of a wet hydrogen anneal when carbon is already low can damage the metal by the production of sub-surface oxidation which harms permeability.

(a)



(b)

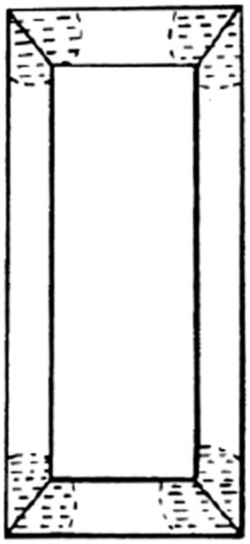


Figure 6 (a) A core with low aspect ratio, (b) a core with highaspect ratio.

A wide range of highly developed methods exists for the management of lamination annealing for stress removal and decarburization.

4 Coatings

A variety of coatings are used on electrical steels (Chivavibul *et al.*, 2010). On grain oriented steel a magnesium oxide coating is applied to the steel before final anneal so that the sulfur which was introduced to control grain growth for orientation can be finally removed. This coating reacts with the silicon in the steel to yield a magnesium silicate glass, which is both insulative and able to apply tension to the steel substrate due to the low thermal expansivity of the glass A supplementary tensile coating may be applied on top of the glass. Tension in the steel refines the ferromagnetic domain structure and reduces power loss. Non-oriented steel may be given a fully organic coating which aids stamping (no further anneal used), or it may require a mixed organic/inorganic coating, part of which survives anneal (Lindenmo *et al.*, 2000).

For small machines, for example, below kilowatt size, interlaminar insulation is not very dependent on applied coatings and provided that stamping burrs do not create unwanted current paths losses do not rise unduly.

A suitable coating can prevent sticking of laminations when these are annealed in stacks. More recently coatings have been developed which are able to survive cold rolling aimed at eventual critical grain growth so that the overall process is simplified.

5 Relay Steels

Electrical steels are normally classified by power loss, and further by permeability. Unalloyed iron intended for use in electromechanical relays is classified by coercive force. (H needed to bring B to zero after full magnetization in ampere-meters). **Table 1** shows some typical properties of electrical steels.

6 Conclusions

Iron–silicon alloys represent the most widely used and most cost effective core materials for devices used in electric power handling. Magnetic or power losses of electrical steels have to be optimized to improve the performance of electric power devices. Si improves the electric properties of the electrical steels by increasing the electrical resistance, decreasing the magnetic anisotropy and the magnetostriction. It also lowers the saturation magnetization and iron losses at high frequencies. Coarse grain size can effectively decrease the eddy current and hysteresis losses. Crystallographic texture is another important factor that needs to be controlled in electrical steels. Core losses of high silicon steel are affected by texture and grain size jointly in high frequency applications. Laminations and coatings are proved to be very useful in the reduction of power losses in electrical steels.

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