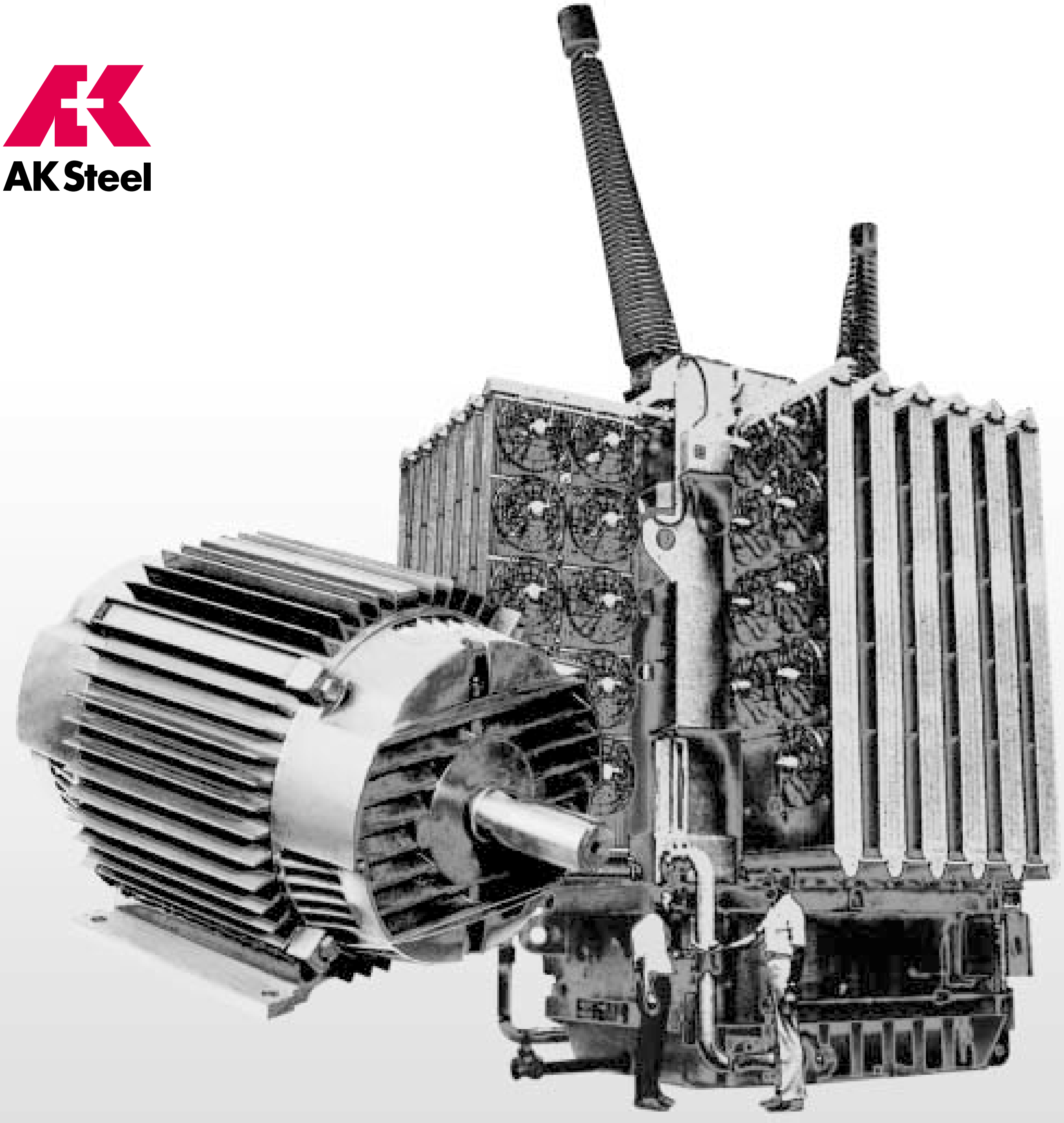
PRODUCT DATA BULLETIN

SELECTION OF ELECTRICAL STEELS FOR Magnetic Cores

AK Steel



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AK Steel Electrical Steels for Magnetic Cores

Magnetic cores for the wide range of modern electrical and electronic devices require magnetic materials with many combinations of properties and characteristics. Of all the soft magnetic core materials, the most widely used are known as "electrical steels." AK Steel, as a major producer, offers a wide variety of electrical steels. These give designers a choice of core materials so they can obtain the necessary properties for a given design and fabricating procedure, and can produce the desired end product at minimum cost.

In addition, AK Steel electrical steels offer full selectivity because they are produced in a full range of thicknesses, types of treatment, degrees of grain orientation, and surface finishes.

To discuss adequately even the fundamental factors that are involved in selection of all types of magnetic materials would require a voluminous textbook. The purpose of this manual is to present only practical information that can be helpful in the selection and use of electrical steels. Major attention is focused on those that are used in wound or stacked magnetic cores for transformers, motors and allied apparatus operating primarily at 50 or 60 hertz. Detailed data and information on the classes of AK Steel magnetic materials or grades within major classifications are not included. Such information is contained in the design manuals *AK STEEL Nonoriented Electrical Steels* and *AK Steel Oriented and TRAN-COR H Electrical Steels*, References 5 and 11.

Table 1 lists the complete range of electrical steels produced by AK Steel.

Classification of Electrical Steels

Because of their low carbon content, a more fitting metallurgical name for these materials would be "iron-silicon alloys." However, the term "electrical steels" has been universally accepted as the designation for flat-rolled magnetic materials in which silicon is the principal alloying element. Their electrical and magnetic characteristics make them well suited for laminated cores where the flux reverses direction or pulsates many times each second. There are several classes of electrical steels and grades within each class, suited for application in specific types of electrical apparatus.

Grading by Core Loss

For uniformity in specifying, producing, and purchasing, electrical steels are primarily graded by core loss. This is because maximum permissible core loss usually is one of the most important considerations for cores of power frequency apparatus and for some electronic devices. Each electrical steel producer has an identifying trade name for each grade. This resulted in confusion for many years until the American Iron and Steel Institute assigned a type number to each grade according to its core loss. Thus, each grade is readily identifiable whatever the source. AK Steel adheres to this nomenclature system wherever possible to facilitate use of the electrical steels and avoid confusion. ASTM and International Standardizing Groups have other systems of identification. While the AISI system (M-grades) is the most universally accepted, ASTM is the only group presently supporting a standardizing system in the United States.

Core loss is the electrical power expended in the form of heat within the core of electrical equipment when those cores are subjected to alternating magnetizing force. This, of course, is incidental to the production of the desired magnetic flux (See Figure 1).

According to classic magnetic theory, core loss is considered to be composed of several types of loss. These are hysteresis loss, eddy current loss within individual laminations, and interlaminar losses that may arise if laminations are not sufficiently insulated from one another. Core loss and each of its elements are discussed more completely in subsequent sections.

Figure 1

Diagrammatic illustration of the flow of magnetic flux in a laminated core.

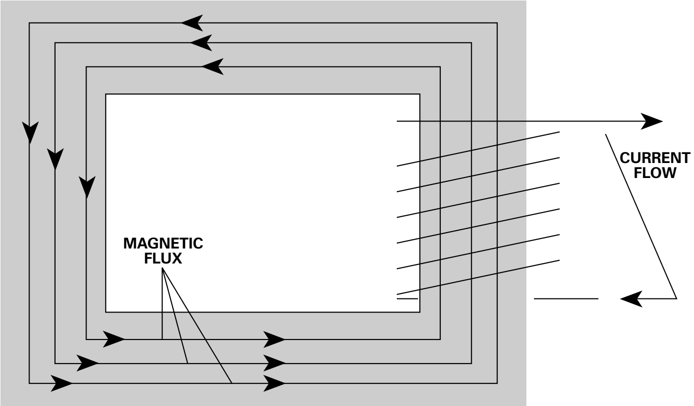


Table I

AISI Designations and AK Steel Trademark

Silicon Steels General Type	Grade AISI Designation	AK Steel Trademark
Nonoriented	M-15	DI-MAX M-15
	M-19	DI-MAX M-19
	M-22	DI-MAX M-22
	M-27	DI-MAX M-27
	M-36	DI-MAX M-36
	M-43	DI-MAX M-43
	M-45	DI-MAX M-45
	M-47	DI-MAX M-47
Oriented	M-2	Oriented M-2
	M-3	Oriented M-3
	M-4	Oriented M-4
	M-6	Oriented M-6
High Permeability Oriented	—	TRAN-COR H-0
	—	TRAN-COR H-1
	—	TRAN-COR H-0 DR
	—	TRAN-COR H-1 DR

Grade Designations

The American Iron and Steel Institute type numbers and AK Steel designations for electrical steel grades consist of the letter M followed by a number. The M stands for magnetic material; the number is representative of the core loss of that grade. At the time the AISI system was adopted, the type number assigned to each grade was approximately ten times the core loss expressed in watts per pound for a given thickness (29 gauge), tested under given conditions (15 kilogausses and 60 hertz). Today the type numbers do not have this specific association with core loss because electrical steels have been improved significantly and the core loss guarantees reduced substantially. However, the numbers do indicate not only a specific grade, but also the relative core losses of grades within a class.

General Classes

In practice, electrical steels are divided into several general classes. These have been established by common acceptance in the industry but are so universally used that an understanding of them is necessary. They are made on the basis of the primary magnetic property of the material, the form, the difference from the majority of grades, or the method by which the material is produced. Following are four of these general classes that are discussed in detail in other sections of this book. Only brief descriptions are given here for basic reference.

1. Nonoriented. These are electrical steels in which the magnetic properties are practically the same in any direction of magnetization in the plane of the material. The term "nonoriented" is used to differentiate these materials from those produced by processes that create a definite orientation or directionality of magnetic properties.

2. Grain-Oriented. This term is used to designate electrical steels that possess magnetic properties which are strongly oriented with respect to the direction of rolling. By a process of rolling and annealing, alloys of suitable composition can be produced with a metallic crystal structure in which the grains are aligned so that magnetic properties are vastly superior in the direction of rolling. This results in inferior properties in other directions, however.

3. Fully Processed. These are electrical steels in which the magnetic properties are completely developed by the steel producer. The name is derived from the fact that the materials are completely processed, ready for use without any additional processing required to achieve the desired magnetic quality. However, a low-temperature heat treatment may be employed by the user to eliminate stresses introduced by fabrication of the material into cores.

4. Semi-Processed. These electrical steels are finished to final thickness and physical form (sheets* or coils) by the producer but are not fully annealed to develop final magnetic quality. With these materials, the achievement of magnetic properties by the annealing treatment becomes the responsibility of the user. Due to the intricacies of developing adequate magnetic properties, grain-oriented steels are produced fully processed.

*Not produced routinely.

Manufacture

Production Methods

AK Steel electrical steels are refined, melted and rolled by processes similar to those used for carbon steels. However, much more careful control is exercised at every stage of production.

The term "electrical" refers to the application of the steels rather than to the method used in their melting. AK Steel does use electric furnaces for melting these steels, however, and modern production methods such as continuous casting and vacuum degassing help to assure consistent quality.

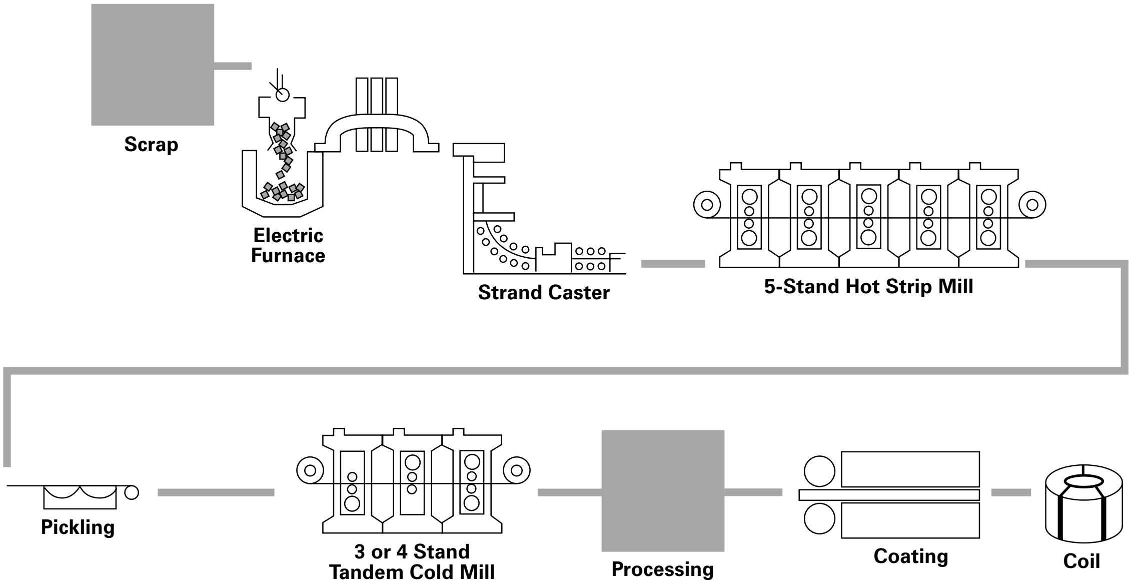
Slabs of electrical steel are rolled at high temperatures into heavy gauge coils. Coils are then acid pickled to remove scale.

The material is then cold rolled to final gauges in coil form and annealed. An AK Steel-developed process, DI-MAX, provides cold-reduced nonoriented grades that have superior magnetic properties.

AK Steel Oriented Electrical Steels are cold reduced and subjected to various processing steps that are essential for developing their preferred grain orientation.

Figure 2

FLOW OF STEELMAKING FOR ELECTRICAL STEELS AT AK STEEL



AK Steel DI-MAX

DI-MAX grades are specially strip annealed after being cold rolled to gage. This modification in processing is of special importance because it produces valuable advantages such as: 1) Excellent flatness; 2) Smooth surface providing high lamination factor and 3) Excellent stamping characteristics.

Composition of Electrical Steels

Flat-rolled electrical steels are produced to meet magnetic property specifications rather than specific chemical composition. Magnetic characteristics are of first importance and are dependent on processing as well as on chemical composition. However, to indicate the varieties of core materials and show how they are generally classed according to composition, the typical chemical analyses of a few of these materials are listed in Table II.

Silicon is the primary alloying element in electrical steels. It is added because it increases the volume resistivity of the steel and thereby reduces the eddy current component of core loss. Silicon is more effective in this respect than any other element which may be conveniently added. Silicon has an added benefit in that it affects the grain structure of the steel and thus gives somewhat improved core loss by its reduction of the hysteresis component in nonoriented electrical steels. Additionally, certain levels of silicon must be maintained to avoid a phase change and thus aid the crystal orientation process in oriented electrical steels.

Depending upon the type of product, the other main alloying elements added to electrical steel are aluminum and manganese. Each of these usually is added in amounts less than 1.0% and more often between 0.1 and 0.5%. These elements are added mainly for their metallurgical effect rather than for any physical effect such as volume resistivity. They also favorably affect grain structure of the steel, thereby contributing to the lowering of the hysteresis component of the core loss.

Other elements are present in electrical steels but are essentially impurities and are found only in residual amounts. Carbon is one element that changes in content from that present in the melt to that in the final product. Special heat treatments are given during mill processing to lower carbon content of the fully processed material to very low values. This removal of carbon occurs during annealing of the semi-processed grades by the customer. In the case of grain-oriented steels, impurities such as sulfur and nitrogen are required initially to help develop the final crystal orientation, but these elements are then removed in the final anneal. Since the magnetic quality of electrical steel is a function of chemical analysis and of mill processing, there may be some overlapping of the grades as shown in Table II. However, core loss will generally vary with silicon content, with increasing silicon producing an improved core loss grade but resulting in lowering of high induction permeability.

Table II

Approximate Composition of AK Steel Flat-Rolled Electrical Steels* (After Final Anneal)

		Composition, %				
AK Steel Designation	Description of Material	C	Mn	P	S	Si
M-45	Low Silicon Steel	0.003	0.15	0.03	0.001	1.6
M-27	Medium Silicon Steel	0.003	0.15	0.01	0.001	2.0
M-15	High Silicon Steel	0.003	0.15	0.01	0.001	2.7
M-4	Grain-Oriented Silicon Steel	0.003	0.07	0.01	0.001	3.1

*These compositions are merely illustrative but are useful in differentiating these grades from other ferro-alloys. Chemical specifications are not acceptable in ordering electrical steel. Elements other than those listed are usually present in relatively small amounts.

Gauge System

The Electrical Steel Standard Gauge (ESSG) is based upon the thickness of material, whereas other gauge systems are based upon the weight of metal per unit area. In electrical steels, weight per unit of surface area for material of the same thickness is not constant for different grades. Table III shows how density varies with silicon content.

The ASTM currently recommends use of the assumed values of density shown in Table III. This is done to eliminate the necessity of calculating the density for every individual melt of steel.

Although electrical steels are available in a variety of thicknesses, only a few grades are used extensively. These include ESSG No. 24 (0.025" [0.64 mm]), No. 26 (0.0185" [0.47 mm]), and No. 29 (0.014" [0.35 mm]) for nonoriented electrical steels; ESSG No. 29 (0.014" [0.35 mm]), 0.011", 0.009" and 0.007" (0.27, 0.23 and 0.18 mm) for oriented electrical steels. The decimal thickness for each gauge is a nominal value or aim point used in manufacture. Standard American Iron & Steel Institute and ASTM tolerances apply to each gauge.

Table III

Variations of Density of Electrical Steel with Silicon and Aluminum Content

% Si + 1.7 X % Al	Density Assumed By ASTM g/cm^3
0.00 - 0.65	7.85
0.66 - 1.40	7.80
1.41 - 2.15	7.75
2.16 - 2.95	7.70
2.96 - 3.70	7.65
3.71 - 4.50	7.60

Table IV

Thickness Corresponding to Electrical Steel Standard Gauge Numbers (ESSG No.)

ESSG No.	Inches	Millimeters
29	0.014	0.36
26	0.0185	0.47
24	0.025	0.64

Coils and Cut Lengths

Fabricating operations will determine whether coils or cut lengths are used, based on the kind of equipment available for the production of laminations and on the cost of material in the size and form required.

AK Steel Electrical Steels are normally supplied in coils. Cut lengths can be special ordered for nonoriented materials and can be sheared to width. Coils can be ordered slit to a width used most economically by the fabricator. Many fabricators have their own slitting or shearing equipment where volume warrants. This reduces the amount and variety of stock that must be carried in inventory.

Nonoriented and Oriented Electrical Steels

AK Steel Nonoriented Grades

The term "oriented", when used in conjunction with electrical steels, refers to a crystal structure having magnetic properties that are materially better in a given direction. Some silicon steels are not intentionally oriented and can be called nonoriented steels. Actually, since the great proportion of mechanical working of the steel is in one direction, these materials do assume some crystal directionality. However, differences in the magnetic properties measured in the direction of rolling as contrasted to a direction at right angles to rolling are relatively minor in nonoriented grades.

For all practical purposes, AK Steel Electrical Steels, from grades M-15 to M-47, are nonoriented materials. In other words, their magnetic properties with respect to the direction of rolling are primarily random. In applications such as motor laminations, where flux may flow in any direction with respect to the rolling direction, and in many other applications where cost of producing the part is of paramount importance, the nonoriented grades provide satisfactory performance.

To provide an effective range of these materials that will meet the varied needs of electrical equipment manufacturers, AK Steel produces nonoriented grades in both the fully processed and semi-processed conditions. See Table V for a complete listing.

Table V

AK Steel Nonoriented Electrical Steels

AK Steel Grade	Fully Processed (FP) or Semi-Processed (SP)
DI-MAX M-15	FP
DI-MAX M-19	FP
DI-MAX M-22	FP
DI-MAX M-27	FP
DI-MAX M-36	FP
DI-MAX M-43	FP, SP
DI-MAX M-45	FP
DI-MAX M-47	FP, SP

AK Steel Oriented Electrical Steels

Knowledge of the tremendous improvement in magnetic properties available from a high degree of crystal orientation was available for a number of years before the achievement of obtaining preferred crystal texture in 3% silicon iron. The major breakthrough came when cold rolling instead of hot rolling methods were employed by experimenters and a different grain orientation, called "cube-on-edge" resulted.

The outstanding magnetic characteristic of grain-oriented electrical steel is its strong magnetic directionality. Both core loss and permeability vary markedly, depending on direction of the magnetic flux relative to the direction in which the metal was rolled. For example, under certain conditions, the difference in the exciting currents for a favorable and unfavorable direction in grain-oriented steel may be more than 20 times greater than the difference in conventional steels.

Usually, oriented iron-silicon alloys contain approximately 3.0 to 3.5% silicon. If the silicon is much lower, the eddy-current loss (and, as a result, the core loss) in the desired thickness will be too high. If silicon content is much higher, the metal has poor ductility. High silicon content also reduces saturation density, therefore requiring higher exciting current at high flux density and limiting the operating induction.

Grain-oriented electrical steels are produced by carefully controlled processing of metal of specific compositions. Subsequent to initial hot rolling, the processing usually involves two stages of cold reduction with an intervening anneal. During rolling, the crystals or grains are elongated and their orientation altered. During final mill annealing they undergo a secondary recrystallization where some crystals grow in size at the expense of smaller crystals, creating cube-on-edge orientation. Metal crystals in the final product are large enough to be seen easily by the naked eye but have lost their elongated shape and no longer reveal the rolling direction.

The final crystal orientation can be represented by a cube with four of its edges parallel to the rolling direction and the remaining eight edges at 45 degrees to the sheet surface. This is illustrated by Figure 4. Since the crystals are magnetized most easily in a direction parallel to the cube edges, the magnetic properties of oriented steels are best in the direction parallel to the direction of rolling.

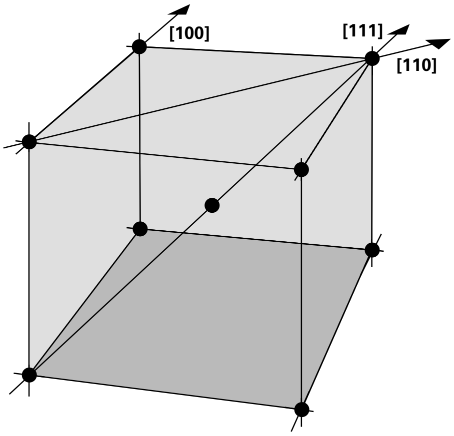
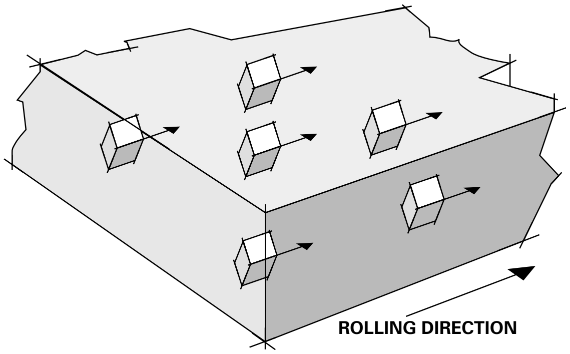


Figure 3

Magnetic permeability of iron alloys varies depending upon the direction of flux flow with respect to the basic atomic structure of iron, body-centered cubic. Best permeability is in the direction of the cube edges [100], as illustrated.

Figure 4

This sketch shows how the crystal or basic structure is aligned in grain-oriented electrical steels. The cube direction for best permeability (See Figure 3) is strongly oriented in the direction of rolling.



Development of Oriented Grades

The first patents on grain-oriented electrical steels were issued in 1933. Intensive laboratory studies of these steels, as well as the development of special production equipment, were underway at AK Steel (formerly Armco) before that date. Several years of such development work were required before grain-oriented grades AISI Types M-10 and M-9 were first commercially produced. Continued progress in improving the magnetic properties resulted in production of a better grade, M-8, within about 10 years of the first laboratory work. In 1947, the first catalog containing design curves and other essential information on grain-oriented steel was published.

By 1955, new oriented grades, M-7 and M-6, had been developed and became the most widely used grades of grain-oriented steel. Later, AK Steel 12-mil Oriented M-5 and 11-mil Oriented M-4 with still better magnetic properties were developed. In 1969, AK Steel introduced Oriented M-3 produced in 9-mil thickness, later to be produced in 11-mil thickness.

In 1972, stringent 17-kilogauss core loss limits were announced which permit closer control of losses in tight electrical designs of transformers operating at high flux densities. So called "Super Oriented" or "High Permeability" electrical steels with a higher degree of grain orientation followed shortly thereafter. This resulted in a lower core loss than possible with a conventional grain-oriented electrical steel at or near the 17-kilogauss range. AK Steel called these materials TRAN-COR H Electrical Steels.

In 1984, two new materials, AK Steel 9-mil TRAN-COR H-0 and 7-mil Oriented M-2, were developed that provided lower core losses with thinner materials than ever before possible in conventional electrical steels.

Significant developments that enhance commercial production of oriented grades include:

a. Economical methods of rolling coils of light gauge and wide widths on high-speed, cold-reduction mills.

b. Good thickness control across the strip width and throughout its length.

c. A smooth surface that results in high core solidity.

d. Production of a very thin coating having high insulative value (CARLITE 3) that could be applied to coils before shipment from the steel plant.

e. Further improvement of permeability and hysteresis losses.

f. Beneficial core loss reductions through laser scribing TRAN-COR H Electrical Steels for domain refinement. Since stress-relief annealing will nullify the beneficial effects of domain refinement of these materials, AK Steel TRAN-COR H-0 DR and H-1 DR are most appropriate for stacked-core applications where stress-relief annealing is not needed.

Advantages

Designers now specify grain-oriented electrical steels, such as M-2, M-3, M-4, M-6 and TRAN-COR H-0 and H-1, for a large proportion of all distribution and power transformers.

The reason for the intensive demand for grain-oriented steel was the remarkable opportunity these steels afforded to reduce the size of magnetic cores in electrical apparatus, thereby also reducing the amount of other materials required. Related factors that expanded the application of this class of electrical steel include the following:

a. Permeability at high flux densities is improved while core loss is reduced. This is in contrast to the improvement of nonoriented grades where core loss improvements usually are accompanied by lower permeability at high flux densities.

b. Power production and transmission economy warrant design of more efficient apparatus using better core materials, especially with the increasingly heavy demand for energy conservation through more energy-efficient equipment.

c. With grain-oriented steel, the cost of the core generally is not increased, even though the price per unit weight of core material is higher. In fact, the cost of a transformer of suitable design and a given rating is nearly always lower with grain-oriented steel.

d. Transformers with oriented steel cores are decidedly smaller than those of the same rating made of conventional silicon steel. This lowers handling cost and increases the kva rating of distribution transformers that can be mounted on a single utility pole. Oriented steels also greatly increase the power rating of the largest transformers that can be manufactured and shipped economically.

e. In large two-pole generators with suitably segmented cores, much of the yoke flux flows parallel to the best magnetic direction. This results in a considerable reduction in the ampere-turns required in this section of the magnetic path. Oriented steel is sometimes specified for laminations forming a section of the yoke from which the teeth extend. This is an advantage in many cases even though the magnetic flux flows in an unfavorable direction in the teeth. As the teeth are relatively short, the ampere-turns required for them can be kept reasonably small.

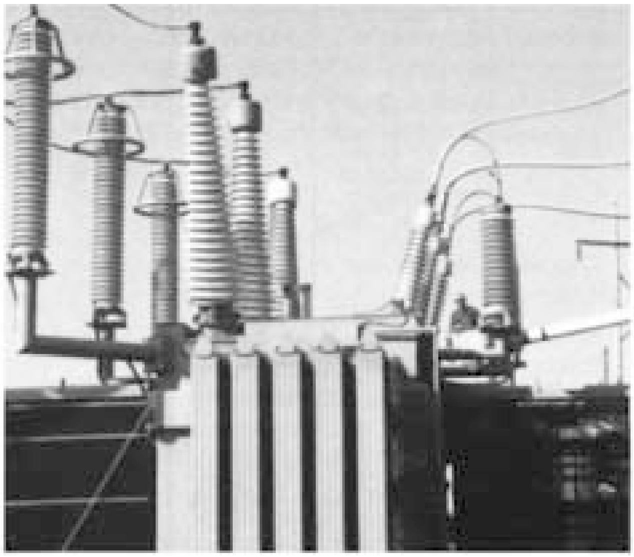
Core Loss

The core loss of a magnetic material depends not only on its relative magnetic quality, but also upon the induction and frequency at which the material is used. For purposes of testing and grading electrical steels, certain inductions, frequencies, and other test conditions have been standardized. Specific core loss limits are assigned to grades tested under these standard conditions (Reference 1).

Maximum core losses for AK Steel grades and gauges of electrical steel are listed in Table VI. In this table, the grades are designated by the AISI type number. All grades may be obtained in the fully processed condition, but a few are available semi-processed.

Grading tests are made under standard conditions that are quite similar throughout the world. All steel suppliers and fabricators of magnetic cores in the United States normally use the same core loss limits for grading electrical steel of a given AISI type designation.

Core loss limits for fully processed as-sheared material apply only to specimens of standard Epstein (3 cm) width. Because the effects of shearing strains tend to increase the core loss as the sheared width is reduced, the core loss in laminations may be slightly higher or lower than that of test specimens.



Oriented electrical steels, by combining low core loss with high permeability at high inductions, have permitted designers to achieve highly efficient transformers.

Core loss limits for the semi-processed quality annealed (QA) condition are made on standard specimens of semi-processed material given an evaluation anneal under carefully controlled standard conditions. The anneal consists of heating for 1 hour at 1550°F (843°C) in a decarburizing atmosphere. Annealing eliminates possible variations in core loss due to strain effects, but variations can occur due to differences in annealing practice. Even though limits apply to magnetic quality obtained on Epstein samples, they approximate commercially attainable core loss limits.

The purchaser can choose whether the grading tests, within grade limitations, are to be made at 15 or 17 kilogausses for Oriented M-3, M-4 and M-6 as well as TRAN-COR H-0 DR and H-1 DR. This provides the option of selecting test conditions closest to the purchaser's particular requirements.

Table VI

Core Loss Limits for AK Steel Electrical Steels

			Core Loss at 60 Hertz - Watts per Pound*		
			15 kilogausses		17 kilogausses
AK Steel Grade	Nominal Thickness in. (mm)	Electrical Steel Std. Gage	Fully Processed As-Sheared	Semi-Processed Quality Annealed†	Fully Processed As Sheared
TRAN-COR					
H-0	.009 (.23)	–	–	–	.60**
H-1	.011 (.27)	–	–	–	.66**
H-0 DR	.009 (.23)	–	.39***	–	.535***
H-1 DR	.011 (.27)	–	.425***	–	.57***
Oriented					
M-2	.007 (.18)	–	.405**	–	–
M-3	.009 (.23)	–	.445**	–	.70**
M-4	.011 (.27)	–	.51**	–	.74**
M-6	.014 (.35)	–	.66**	–	.94**
Nonoriented					
M-15	.014 (.35)	29	1.45	–	–
	.0185 (.47)	26	1.60	–	–
M-19	.014 (.35)	29	1.55	–	–
	.0185 (.47)	26	1.65	–	–
	.025 (.64)	24	2.00	–	–
M-22	.014 (.35)	29	1.60	–	–
	.0185 (.47)	26	1.80	–	–
	.025 (.64)	24	2.10	–	–
M-27	.014 (.35)	29	1.75	–	–
	.0185 (.47)	26	1.90	–	–
	.025 (.64)	24	2.25	–	–
M-36	.014 (.35)	29	1.85	–	–
	.0185 (.47)	26	2.00	–	–
	.025 (.64)	24	2.35	–	–
M-43	.014 (.35)	29	1.95	–	–
	.0185 (.47)	26	2.10	1.55	–
	.025 (.64)	24	2.50	2.00	–
M-45	.0185 (.47)	26	2.40	–	–
	.025 (.64)	24	2.75	–	–
M-47	.0185 (.47)	26	2.80	1.65	–
	.025 (.64)	24	3.20	2.10	–

*Core loss tests are conducted in accordance with ASTM A 343 and A 804. For the nonoriented grades, tests are made on 3-cm-wide Epstein strips sheared half parallel and half transverse to the rolling direction.

**The core loss limits for the grain-oriented grades M-2, M-3, M-4, M-6 and TRAN-COR H-0 and H-1 are for parallel grain Epstein specimens given a stress-relieving anneal after cutting from fully processed steel.

***Core loss limits for H-0 DR and H-1 DR are for parallel grain wide sheet specimens.

†With anti-stick coating.

Lamination Thickness

Thicknesses for 50 and 60 Hz Applications

The thickness of electrical steel influences the core loss under A-C and pulsating conditions due to its marked effect upon the eddy current component of core loss. Under most conditions, the eddy current loss will vary approximately as the square of the thickness of flat-rolled magnetic materials. This limits the maximum thickness that can be used to advantage for laminations carrying magnetic flux alternating at 50 to 60 hertz or higher to one which is not much heavier than Electrical Steel Standard Gauge (ESSG) No. 24 (0.025" or 0.64 mm).

Modern insulating materials capable of withstanding relatively high temperatures have permitted the use of ESSG No. 24 in almost all motor applications (under 200 hp) and in other devices where a large temperature rise is permissible.

ESSG No. 24, both in low silicon (below 2%) electrical grades and in motor lamination (low carbon) steels, is widely used because of lower material and labor costs. If a gauge much heavier than No. 24 were to be used, an increase in exciting current would result due to increased eddy currents and skin effects in such thick material. Reduction of eddy currents by increasing silicon content much above 2% would be undesirable since this would result in increased exciting current at high inductions. In view of these factors, No. 24 gauge is often a good compromise.

The soaring cost of electrical energy has led to renewed interest in the use of better grades of electrical steel and in the use of thinner gauges to achieve maximum efficiency in motor and other devices.

An intermediate gauge (ESSG No. 26, 0.0185" [0.47 mm]) is frequently specified for many 60 hertz applications. This gauge is used when core loss must be held to moderate values and the product does not warrant the use of thinner, more expensive No. 29 gauge.

AK Steel Nonoriented Electrical Steels are available in standard gauges other than Nos. 24, 26 and 29, but their use is justified only if large tonnages are needed regularly. For power frequency applications utilizing nonoriented steel, it is advisable to specify one of these three thicknesses. They are used more extensively and, as a result, can be obtained faster. Also, the fabricator has the added advantage of maintaining fewer thicknesses in inventory.

Effective Lamination Thickness

"Skin effect," caused by eddy currents within each lamination, results in crowding magnetic flux out of the mid-thickness section of the laminations. This occurs because eddy currents set up a counter magnetomotive force. If the lamination is too thick for the frequency of alternation of the magnetic flux, or if permeability of the material is quite high, only a portion of the lamination cross section will be effective in carrying the flux. Consequently, effective thickness of the lamination is less than actual thickness. Therefore, the A-C permeability considering the entire cross section will apparently be less than that normal for D-C flux or A-C flux of low frequency. Curves for A-C excitation will be found in References 5 and 11.

If the average flux density of the entire cross section of a lamination is high enough, the skin effect at comparatively high frequency may be sufficient to cause saturation of the surface layers. The exciting current then may be quite high. However, under such conditions, excessive core loss usually results from these high eddy currents before the saturation of the surface layers of the lamination becomes a limiting factor. This is especially true when both the flux density and frequency are high.

Many years ago, a first approximation of the effective thickness was usually calculated from theoretical considerations. These calculations usually showed the effect of frequency on the depth of penetration of the magnetic flux below the surface. Such formulas may be found in References 6, 7 and 8.

Influence of Thickness on Cost

The production and fabrication costs per unit weight of electrical steels increase rapidly as thickness is decreased. While the thinnest materials may be warranted for certain applications, use of thinner laminations than absolutely necessary is wasteful.

Effect of Stresses on Magnetic Properties

The magnetic properties of electrical steels are especially sensitive to stress. Substantial reductions in magnetic properties can be caused by a stress of only a few hundred pounds per square inch which would, of course, produce an elastic strain. Likewise, stresses that produce plastic deformation of electrical steel create even greater changes in the magnetic properties. These changes occur because the metal crystals in the strained metal are distorted. This distortion of the crystal or atomic structure affects the relationship between magnetizing force and induction, and consequently affects all the magnetization characteristics of the material. Normally, stresses create a harmful effect by causing a degradation of magnetic properties.

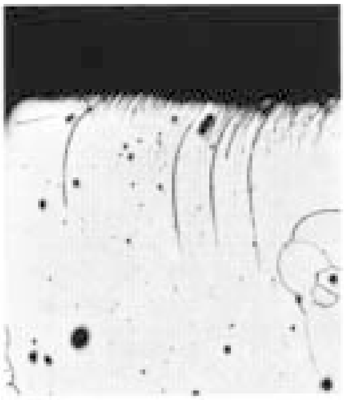
If the stress is so low that it creates only an elastic strain in the metal, removal of the load or restraining force will permit the metal to return to essentially a stress-free condition. But if material has been plastically deformed, it will retain a permanent set and likewise retain stresses even after the load is removed. During fabrication of electrical steels into cores, it is obvious then that preventing elastic strains prevents the stress. But, if material is plastically deformed, an anneal is required to return the material to a stress-free condition.

Stresses introduced into electrical steel as it is being wound into cores or as laminations are assembled can be eliminated only by annealing. Even though stresses have been produced by elastic strain, as by holding a core in a constrained position, there is no way of completely eliminating this stress in an assembled core except by annealing the core in its final form and maintaining that form.

When electrical steels are fully processed by the steel producer, they are annealed under carefully controlled conditions of temperatures, time and atmosphere to obtain the desired magnetic properties. This mill anneal, at comparatively high temperatures, develops final magnetic quality through several accomplishments. These include developing the proper metallurgical structure, insuring that desired chemical refinement will take place, and developing some degree of surface insulation for certain grades. After such an anneal, electrical steel is substantially free of stress. But stresses will be introduced by subsequent operations such as shearing and coiling that elastically strain or plastically work the steel.

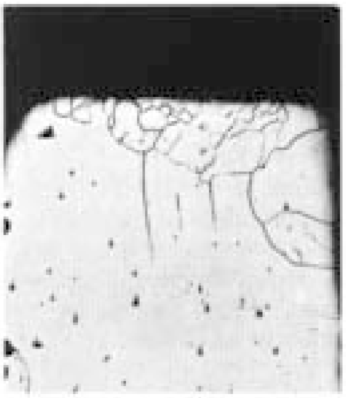
The magnitude of the effect of stresses on magnetic properties is governed by the extent of the unfavorable stresses introduced by any handling or fabrication step after the last annealing operation. Such stresses can materially influence the selection of material or the design for a given application unless the stress is

Figure 5A



Edge of a 24-gauge lamination. Deformation and strains, produced at the edge by punching, are clearly visible.

Figure 5B



The same lamination after a stress-free anneal at 1475°F (802°C) for one hour. Note the recrystallization that indicates elimination of the high stresses.

removed. For example, if a particular piece of electrical apparatus required the core loss of a stress-free core made of M-19, it would possibly be necessary to use M-15 to obtain the same magnetic performance if appreciable stress remained in the finished magnetic core. Fortunately, this procedure is not normally necessary because the sometimes unpredictable stresses produced in finished cores can be eliminated by a stress-relief anneal at only moderate temperatures. However, with grain-oriented material, the normal stress-relieving anneal may not always completely restore "material curve" values when most of the steel in the core has been plastically deformed.

Recommended procedures for stress-relief annealing AK Steel Electrical Steels are given in the AK Steel design manuals. (References 5 and 11.)

How Stresses Are Created

Undesirable stresses are created adjacent to the cut edge by stamping, shearing, or slitting operations. These result from distortion of the crystal structure that is caused by the cutting operation. Figure 5A shows a micrograph taken at the punched edge of a lamination 0.025" (0.64 mm) thick. These strain lines are visual evidence of stresses created by punching and seem to bend in the direction of movement of the punch. Some extend away from the punched edge for a distance equal to about half the thickness of the metal. Magnetic experiments indicate that such stresses affect the properties of the lamination at a distance away from the cut edge approximately equal to the lamination thickness. This highly stressed area usually has extremely low permeability and a hysteresis loss several hundred percent over that of unstressed metal.

Since the stressed area extends so far back from the cut edge, it has an increasingly important effect upon the core loss as lamination width decreases and material thickness increases. Figure 5B shows the same lamination as shown in 5A after it had been annealed for one hour at 1450°F (788°C). Note how new equiaxed crystals have grown at most of the places where strain lines were seen in Figure 5A. This recrystallization evidences a relief of stress.

One investigation (Reference 2) has indicated that the magnitude of the effect of cutting stress upon the core loss of nonoriented silicon steel can be approximated by the following simple relation:

$$P = \frac{k}{w}$$

P is the percent increase in hysteresis loss averaged over the entire lamination width; w is the width of the lamination in inches between the cut edges; and k is a constant that depends upon the thickness of the material, its physical properties, and the flux densities involved. A value of k equal to 14 was indicated by the investigation of various widths of 29-gauge transformer steel, similar to M-15, operating at 10 kilogausses and 60 hertz. The corresponding figure at 15 kilogausses is 10. From this equation, it will be noted that for 1-1/2" wide (38 mm) laminations, without reannealing, approximately one grade better should be specified than if the shear stresses were removed by a stress-relief anneal. Stress effects caused by shearing may have an even greater effect on oriented steels but are usually not so obviously dependent on width.

Bending of electrical steel will also produce stresses that affect its magnetic properties. This is especially marked in oriented steels. Such bending can occur in handling either coils or flat sheets, in the shop, or in winding strip into wound cores.

Figure 6 shows one way that harmful bending stresses can be produced in handling or storing loosely wound coils without being detectable in subsequent shop operations. Figure 7 shows another way that stresses can be accidentally produced in sheets or strip as they are pulled at an angle off a flat table or pulled around any radius that is too small. The minimum radius of curvature that can be used varies with the thickness of the strip, the strip tension during the pulling, and with the elastic limit of the material, which in turn, varies with its silicon content. Normally, for material 0.014" (0.35 mm) and thinner, any radius around which the material is bent should be 8" (127 mm) or greater to avoid plastic strain.

The prevention of stresses, due to either elastic or plastic deformation that might occur in handling electrical steel is primarily one of mechanics. If stresses are to be avoided, the material must be returned to the physical form in which it was at the time of its last anneal without incurring any intervening plastic deformation. For example, if coil diameters are sufficiently large for a given strip thickness, the strip can be uncoiled to the flat position without introducing any stresses. An inside diameter of at least 17" (432 mm) is adequate to prevent coil set in high-silicon steel of thicknesses no greater than No. 26 gauge, provided the coiling was done while the steel was cold.

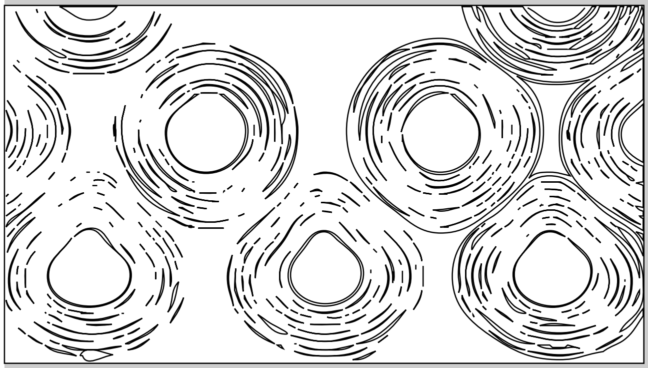
Fortunately, a very simple check is available to determine the severity of these stresses; namely, whether the material returns to its original shape when unwound. This is simply an observation of whether or not the material will lie flat when it is unwound from the coil. In laying a lamination or sheet on a flat surface for such an observation, its weight might offset the stress. When a sheet or lamination is set on edge, the tendency to distort is evidence of residual stress.

When electrical steel strip is wound to form cores, stresses are introduced. The severity of the stress depends upon whether or not the material has been annealed flat or annealed in coil form. Another factor is the relation of the radius of the core to the radius of the original coil. However, in practically every case, a significant degree of either elastic or plastic strain is produced in winding cores. Consequently, stresses are introduced. To eliminate these stresses and obtain magnetic properties in the core, a wound core must be given a stress-relief anneal.

When the core is made from stacked laminations sheared from fully annealed material, the usual practice has been to give the sheared laminations a stress-relief anneal before stacking. In such an anneal, extra care is required to obtain a high degree of flatness in the laminations so that stresses will not be reintroduced in stacking and clamping the assembled core.

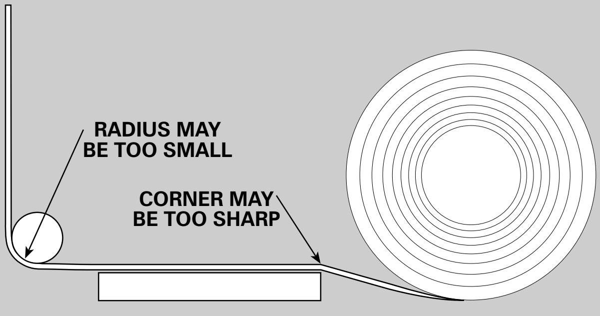
It is now possible to provide grain-oriented electrical steels for flat laminations with a degree of freedom from stresses that stress-relief annealing of the laminations, or the slit widths intended for laminations, is not necessary to obtain optimum core loss and other magnetic characteristics. In widths greater than about 3" (76 mm), AK Steel Oriented and TRAN-COR H CARLITE-coated materials provide properties so close to those of fully stress-relieved laminations that stress-relief annealing treatments usually cannot be justified. With Oriented and TRAN-COR H CARLITE-coated materials, the lamination width strip is very flat and requires only shearing to length with very sharp shears to provide essentially stress-free laminations that produce a nearly stress-free core when carefully stacked.

Figure 6



UNINTENTIONAL INTRODUCTION OF EXCESSIVE STRESS IN STEEL DURING STORAGE OF COILS

Figure 7



COIL SET INTRODUCED IN HANDLING STRIP OR LONG LAMINATIONS

Annealing of Laminations or Cores

Fully Processed Steels

Even for the most severe plastic strain encountered in wound or formed cores of fully processed steel, the annealing temperature for stress-relief should not exceed 1550°F (843°C). If only shearing stresses are involved, as with flat laminations of narrow widths, the temperature used in the fabricator’s anneal need not be higher than 1350°F (732°C). For wound or formed cores where there has been a substantial amount of both plastic and elastic strain, the annealing temperature may have to be increased to 1450°F (788°C) for optimum stress relief. Temperatures higher than required for complete stress relief produce no beneficial results to magnetic properties in fully processed steels and increase the hazard of magnetic damage through chemical contamination. In fact, it is necessary that recommended annealing procedures be followed closely to avoid degradation of magnetic properties even though the effects of plastic strain may have been removed.

Semi-Processed Steels

Semi-processed electrical steels (nonoriented) are those which have not been given the full annealing treatment by the steel producer. Users prefer, in some cases, to develop the final magnetic quality and simultaneously achieve relief of fabricating stresses in laminations or assembled cores for small apparatus. This involves increased responsibility on the part of the fabricator. He must carefully control annealing temperatures, time cycle, and atmosphere to produce the desired optimum magnetic quality.

Semi-processed steel must be annealed at substantially higher temperatures and may involve different “soaking” times and atmospheres than if stress relief were the only objective. Other responsibilities, such as providing proper conditions to produce grain growth, chemical refinement, prevention of adhesions, and the formation of an adequate insulation on the surface of the steel, must also be accepted by the user. Quite often these requirements impose severe limitations on final annealing. Optimum conditions for grain growth and necessary chemical refinement are dependent, in a considerable degree, upon the width and thickness of the material being annealed.

The use of semi-processed electrical steels may be attractive if there is a high level of continuous production in one size and type of part in relatively narrow widths.

Mechanical Properties

Typical Mechanical and Physical Properties

Since the silicon content of nonoriented low core loss grades is high, ultimate strength, yield point, and shear strength will generally be greater than higher core loss grades with lower silicon content. Typical physical and mechanical properties of representative types are given in Table VII. Variations from these values must be expected, however, because of different compositions, heat treatments, and processes used by steel manufacturers in making a given core loss grade.

Punchability

Punchability is the combination of properties of electrical steel that result in long tool life and a minimum of burr formation.

Good punchability is one of the most important physical characteristics of electrical steel. If it is not satisfactory, then a compromise between that characteristic and magnetic properties must be made. The change from the designer's selection of material may involve sacrificing some magnetic properties to achieve longer die life or the other advantages of good punchability. Considerations that affect punchability include:

a. The steel being punched should be flat within the feasible limits of good commercial practice. It should be free of stress that might result in distortion of punched laminations.

b. Hard particles on the surface, or carbides embedded in the relatively soft matrix of the steel, must be avoided to reduce die wear.

c. Other surface conditions are also important. For example, quite a number of users of electrical steel have noted that a baked enamel insulative coating or core plate (ASTM C-3) on the surface of steel improves its punchability up to 30% as measured by the number of laminations obtainable between die grinds.

d. Hardness, stiffness and ductility are important factors, but their exact effects on punchability are not known.

Tool life has always been an important consideration. However, improvements in the control of surface conditions during processing of the electrical steels and more extensive use of carbide dies in punching operations have led to a marked reduction in die life problems.

A few important general considerations that seem necessary to obtain long tool life and punched laminations of good quality are (Reference 3):

a. The punch press must have adequate capacity and rigidity.

b. Punches and dies must be correctly designed and properly adjusted. Die setting must provide a uniform clearance at all points between the punch and die. This clearance must be established in proper relation to the thickness of the lamination and hardness of the material being punched. It must be maintained very carefully for satisfactory die life when punching some materials.

c. Tools must be made from a suitable steel or alloy with the proper combination of hardness and ductility for good resistance to wear and chipping.

d. A lubricant applied to the steel surface usually improves punching operations. Various lubricants and methods are used.

Table VII

AK Steel Grade Designation	Density gm/cm^3	Electrical Resistivity Microhm-cm	Ultimate Tensile Strength psi (MPa)	Yield Strength psi (MPa)	Elongation % in 2" (50 mm)	Hardness Rockwell B	Modulus of Elasticity
TRAN-COR H-0 and H-1	7.65	50	52,000 (359)	50,000 (345)	11	83	The modulus of elesticity will depend largely upon the grain orientation. In the following, the modulus is expressed in millions of pounds per square inch: M-6 Parallel – 18 Transverse = 29
Oriented M-2 to M-6	7.65	51	51,000 (352)	48,000 (331)	9	81	
DI-MAX M-15 FP	7.65	50	71,000 (490)	52,000 (358)	23	72	
Di-MAX M-36 FP	7.70	43	63,000 (434)	42,000 (290)	30	64	
DI-MAX M-47 FP	7.75	37	62,000 (427)	39,000 (269)	34	61	
DI-MAX M-43 SP	7.70	43	70,000 (483)	50,000 (345)	32	64	
DI-MAX M-47 SP	7.75	37	67,000 (462)	48,000 (331)	33	62	

Factors in Selecting a Grade

Long-time design and production experience has established the grades of AK Steel Electrical Steels shown in Table VIII as suitable for the listed applications. However, specific requirements of each design determine the combination of characteristics that must be considered in selection of the most suitable grade of core material. Sometimes compromises are necessary. For example, it is obvious that the lowest-priced material cannot be specified if low core loss is required. If permeability at high inductions is of prime importance, it might be necessary to use a lower-priced grade with higher core loss.

Following are some examples that illustrate various considerations of combinations of requirements that affect the selection of the proper grade of core material. For most useful application to design problems, the examples cited are grouped into general classifications where one primary requirement was the most important factor but, of course, not the only consideration.

Type of Application

In general, AK Steel Oriented and TRAN-COR H Electrical Steels are used in power and distribution transformers. AK Steel Nonoriented Electrical Steels are used in applications where directionality is undesirable or is unnecessary, such as punched laminations for large and small rotating machines and for small transformers and motors.

a. The higher cost of a low-loss material such as AK Steel M-15 may be warranted where low core temperature or high efficiency is essential. Thousands of tons of this material have been used for applications with this requirement.

b. Where transformer cores must be kept relatively light or core dimension small, a very high operating flux density is quite desirable. If there is a rigorous limit on both the core loss and exciting current, one of the AK Steel Oriented and TRAN-COR H grades may be indicated. However, to use this grade to advantage, cores must be designed so that the magnetic path is primarily in the direction of best magnetic properties — the rolling direction. For distribution transformers, such a design will usually involve a spirally wound core or one of equivalent construction.

c. For large power transformers, AK Steel Oriented grades M-3 through M-6 and TRAN-COR H-0 and H-1 can be used advantageously in the form of rectangular laminations. However, the length of the laminations, particularly in the leg members, should be made as great as practicable compared to their width so that the corner areas are relatively small. Mitered laminations also help to reduce exciting current and corner losses with oriented material. If the length of the laminations in such cores is so small that directional properties of the oriented grades cannot be effectively utilized because of the predominance of joint effects, a nonoriented grade, such as DI-MAX M-15, may prove to be suitable.

Table VIII

Grades of AK Steel Electrical Steel
Suitable for Various Applications

		Grades of Electrical Steel													
		TRAN-COR		Oriented				Nonoriented							
		H-0 and H-0 DR	H-1 and H-1 DR	M-2	M-3	M-4	M-6	M-15	M-19	M-22	M-27	M-36	M-43	M-45	M-47
Transformers	Large Power	*	*	*	*	*	*								
	High Efficiency Distribution	*	*	*	*	*	*								
	Dry Type Distribution					*	*	*	*	*	*				
	Current (Instrument)					*	*								
	Voltage-Regulator					*	*	*	*	*	*	*	*		
	Lighting (Ballast)						*	*	*	*	*	*	*	*	*
	Welding and Battery Charger						*	*	*	*	*	*	*	*	*
	Adjustable Variable				*	*	*								
	Television and Electronic Power						*	*	*	*					
	Audio and Chokes						*	*	*	*	*	*			
Motors and Generators	Large Rotating (Over 200 HP)						*	*	*	*					
	Standard Efficiency Integral (1-200 HP)										*	*	*	*	*
	High Efficiency Integral (1-200 HP)								*	*	*	*	*		
	Fractional Industrial													*	*
	Domestic Appliance and Refrigerator													*	*
	Stand-By and Small Generators							*	*	*	*	*			
Other	Watthour Meters							*	*	*	*				
	Relay Cores and Pole Pieces												*	*	
	Magnetic Amplifiers Saturable Reactors				*	*									
	Electromagnetic Shielding				*	*	*	*	*	*	*				

d. For relays, signal units, and other magnetic devices that operate only a few minutes a day, the principal requirement may be minimum cost. In such cases DI-MAX M-45 may be adequate.

e. For domestic appliances and tools that operate only an hour or so at a time, M-43, M-45 and M-47 are widely used, especially where initial cost must be held to a minimum and operating time is both intermittent and of short duration.

f. If the electrical apparatus is to be operated for a total of many hours per year, such as a refrigerator motor, efficiency of operation has some importance. One of the lower core loss nonoriented grades, such as M-36 or better, probably would be justified by the power savings over the life of the equipment.

g. The grade of steel best suited for many transformers and motors will be influenced by the size of the core and the corollary problem, which can be costly, of keeping the core temperature within reasonable limits.

Magnetic Properties

a. The lowest core loss grade may not always be suitable for some high efficiency applications when there is an additional requirement, such as low exciting current at high induction. To meet this need, it may be necessary to sacrifice some efficiency by choosing a grade of higher core loss. This may result in a larger, more expensive core, but in some cases, the increase in size and cost may be negligible.

b. For small laminated cores in which both the core loss and permeability at high inductions are quite important, a U-shaped lamination with very long legs cut parallel to the rolling direction may make it feasible to use Oriented M-6. Such shapes reduce the effects of joints in the magnetic circuits. By making the cross-grain section very short and up to 35% wider than the legs, the relatively poor magnetic properties in this section of the core and in the corners can be minimized. But if core loss and permeability at inductions lower than 8 kilogausses are most important, scrapless EI laminations with the center leg of the E and the length of the I parallel to the rolling direction would probably be the best form for stamped laminations.

Table IX

Relative Order of Permeabilities* of Grades at Different Flux Densities

			Permeability Range							
			High		Intermediate			Low		
Kilogauss	Flux Density Tesla	Kilomaxwell per sq. in.	(Grades with highest permeability in each range are listed in left-hand vertical columns; columns to the right list grades with successively lower permeability.)							
18	1.8	116.0	M-4	M-43	M-36	M-27	M-19	M-15	–	–
15	1.5	96.7	M-4	M-36	–	M-19	M-15	–	–	–
13	1.3	83.8	M-4	M-15	–	M-19	M-36	M-43	–	–
10	1.0	64.5	M-4	–	–	M-15	M-19	M-22	M-36	M-43
5	0.5	32.2	M-4	–	–	M-15	M-19	M-22	M-36	M-43
0.1	0.01	0.645	M-4	–	–	M-15	M-19	M-22	M-36	M-43

*To make the permeability comparison on the same basis, all were based upon stress-free material tested in the rolling direction.

c. The exciting current, and hence the permeability, may be of great importance at various operating inductions, depending upon the type of equipment. Some grades possessing the best initial and maximum permeability have relatively poor permeability at high flux density.

Therefore it is important to know the magnetizing force or the operating flux density in order to select a grade of suitable permeability. Table IX lists several grades and relative order of their permeabilities at various flux densities. However, the actual material design curves should be consulted for the final selection.

Note how the relative order of the grades in Table IX changes between 13 and 15 kilogausses. This table also shows how the relative order of core loss corresponds to the relative order of permeabilities, since the core loss is approximately proportional to the M-number.

Mechanical Properties

The mechanical properties (Table VII) of electrical steels may result in selecting a grade to minimize difficulties in fabrication or meet mechanical design requirements where strength and ductility are critical factors. An example of the first case is the mass production of appliance motors and similar apparatus, where better punchability alone may be reason enough for selecting one grade over another. In the second case, motors or generators with high peripheral speeds might impose strength or ductility requirements that override differences in magnetic properties.

Cost

Sometimes more than one combination of grade and gauge has a suitable core loss. Then consideration of material and fabrication costs determine the choice of grades. For example, if the design calls for a core loss equivalent of 2.0 watts per pound at 15 kilogausses and 60 hertz, the core loss requirement might be met by any one of the three materials listed in Table X.

The price of M-36 in No. 29 gauge and desired width and finish may reveal that it is considerably cheaper than M-22 in No. 24 gauge. However, a further study may show that the finished laminations made of 24-gauge M-22 are cheaper since only about half as many will be needed because they are that much thicker. There is also the possibility that the ultimate choice might be a grade such as M-27 in appropriate gauge, particularly as this grade was already an inventory item and would prevent the need to stock an additional item.

Table X

Materials of Similar Core Loss

Grade	EGS Gauge No.	Normal Thickness Inches	Core Loss Watts per Pound Maximum
M-36	29	0.014	1.85
M-27	26	0.0185	1.90
M-19	23	0.025	2.0

It is obvious that price of electrical steel relative to the total cost of the core is an important factor in design. For certain intermittently operated motors of small size, the cost of the steel may be the most important factor in selection of grade. However, in many other applications, the use of one of the lower-priced materials might result in higher total cost because of other factors. For example, the cost of eliminating heat to keep the temperature of large machines within a safe operating limit may be more than the savings obtained by using high core loss, low-priced laminations.

Loss Evaluation of Transformers

There is a well-accepted mechanism in place by which electric utilities cause transformer manufacturers to provide energy-efficient, cost-effective transformers.

Via this mechanism, which is called loss evaluation, each utility takes transformer power losses into account when making transformer purchasing decisions. For each bid received for a transformer from the manufacturers, the utility calculates the present worth of its costs for the quoted transformer losses over the assumed transformer lifetime (usually 30 years) and combines that value with the quoted transformer purchase price to obtain the transformer total-owning-cost. The utility then accepts the bid having the lowest total-owning-cost.

The loss multipliers (expressed in dollars per watt of power loss and commonly called the A and B factors) developed and used by each utility in the present-worth calculation take into account all of the utility's projected costs to produce and supply electricity over the assumed transformer lifetime. These projected costs include expected energy (fuel) charges, system capacity (demand) charges, environmental charges, etc.

In preparing to respond to a request for a bid for a transformer, each manufacturer creates many, many designs. One of the design variables is the grade of core material. The design which is selected for the quote is the one which has the minimum total-owning-cost. Thus, the quoted core material is the most energy-efficient, cost-effective material.

Surface Insulation of Core Materials

Limitation of eddy current losses to appropriate values requires electrical steel with adequate resistivity, sufficiently thin laminations, and effective electrical insulation of laminations. Eddy currents will flow not only within core laminations, but also within the core as a unit, across the lamination surfaces. Figure 8 shows the two types of eddy currents set up by the induced voltage. Laminating a magnetic core is ineffective in keeping excessive currents from circulating within the entire core unless the surfaces of the laminations are adequately insulated and burrs are small.

The resistance of lamination surface insulation can be considered quite adequate when the interlaminar power loss is limited to a small fraction, usually about 1 or 2%, of the total core loss. What magnitude of insulation is adequate and which of the many available surface insulations should be used are somewhat complex questions. Their answers depend not only on the desired efficiency of the apparatus, but also upon a number of design and fabrication factors, each of which affects the magnitude of the interlaminar power loss.

Determination of Required Resistance

A theoretically required insulation resistance can be calculated based on design parameters. One method, described in Reference 9, yields a theoretical resistance by taking into consideration the induced voltage, specified interlaminar power loss, number of laminations in the core, and the area of a lamination. However, this theoretical value of required insulation resistance must be considered as identifying only the general range of required resistance. Core pressures and resistance paths usually cannot be determined or controlled well enough to make such theoretically determined resistances of value in close design work.

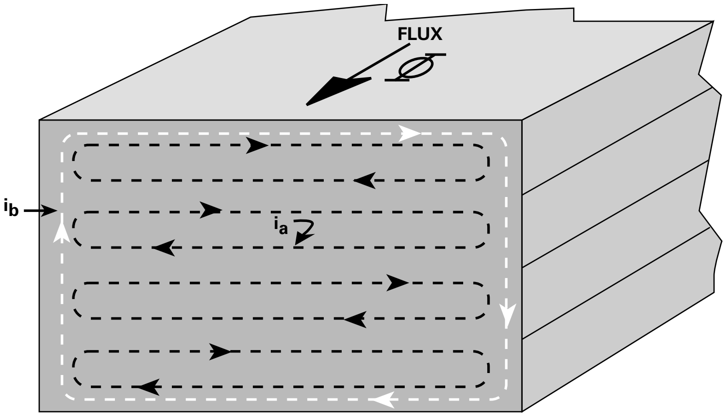


Figure 8

Eddy currents in a laminated core. Interlaminar eddy current, i_a, is governed by flux per lamination and resistance of the lamination. It is, therefore, dependent on lamination width, thickness, and volume resistivity.

Interlaminar eddy current, i_b, is governed by total flux and resistance of the core stack. It is primarily dependent upon stack weight and height, number of laminations, and surface insulation resistance per lamination.

Despite the difficulties in precisely determining required surface insulation resistance, the problem cannot be resolved by using more insulation to be sure resistance is adequate. More than enough insulation resistance achieves no significant reduction of total loss if the interlaminar component of loss is already essentially zero. In addition, thicker than necessary insulation results in a poor lamination factor. If this is not considered in the design, it will increase the actual operating flux density in the core steel and may cause an excessive increase in exciting current.

In practice, an empirical approach to the problem is used. Experienced designers arrive at an approximation of the necessary surface resistance based on what has proved satisfactory with certain fabrication practices, then adjust for the size and rating of the proposed apparatus. Because of the multiplicity of variables, the designer's most reliable guidepost in critical design is practical experience.

Selection of necessary insulation resistance by this method is not as difficult as it appears. Years of production experience have established that certain insulations give satisfactory resistance for specific designs and types of apparatus. Thus, the preliminary selection of a general type of insulation resistance values can usually be made rather rapidly. Further delineation of coatings or resistance specification depends upon the requirements of each design. Analysis of pertinent design requirements and evaluation of all the design and fabrication factors as they apply to the specific apparatus are necessary.

Small electrical apparatus, such as fractional horsepower motors, may not require surface insulation beyond that provided by the natural oxide film produced in processing core steel or in stress-relief annealing. But insulation may be needed for other reasons; e.g., in apparatus where the core may be subjected to corrosive environments, core plate coating may be desirable to prevent deterioration of the limited resistance provided by the oxide film.

Core plate coatings are also used in some cases primarily because they improve punchability of the steel. By increasing die life and reducing punching costs, their use can be justified even though the added resistance is not required.

An anti-stick coating available on semi-processed nonoriented electrical steels reduces lamination sticking. Coating improvements by AK Steel enable laminations to be annealed at higher temperatures than ordinary anti-stick coatings, resulting in increased productivity or in improved magnetic quality. This special coating makes the furnace atmosphere and heating rate less critical.

Table XI

Types of Surface Insulation Resistance and Typical Applications*

ASTM Insulation Designation	Description	Typical Applications
C-0	The natural oxide surface which occurs on flat-rolled silicon steel which gives a slight but effective insulating layer sufficient for most small cores and will withstand normal stress-relief anneal of finished cores by controlling the atmosphere to be more or less oxidizing to the surface. Available on all nonoriented grades.	Fractional horsepower motors, pole pieces and relays, small communication power transformers, and reactors.
C-2	An inorganic insulation which consists of a glass-like film which forms during high-temperature hydrogen anneal of grain-oriented silicon steel as the result of the reaction of an applied coating of MgO and silicates in the surface of the steel. This insulation is intended for air-cooled or oil-immersed cores. It will withstand stress-relief annealing temperatures and has sufficient interlamination resistance for wound cores of narrow width strip such as used in distribution transformer cores. It is not intended for stamped laminations because of the abrasive nature of the coating. Available on oriented grades only.	Wound- core, power frequency devices, distribution transformers, saturable reactors and large magnetic amplifiers.
C-3 (AK Steel Core Plate No. 3)	An enamel or varnish coating with excellent insulation resistance intended for air-cooled or oil-immersed cores. The C-3 coating will enhance punchability, is resistant to normal operating temperatures, but will not withstand stress-relief annealing. Available on fully processed nonoriented grades only.	Air-cooled, medium-sized power and distribution transformers; medium-sized continuous-duty, high efficiency rotating machinery. Can be oil cooled.
C-4 (AK Steel Core Plate No. 4)	A chemically treated or phosphated surface intended for air-cooled or oil-immersed cores requiring moderate levels of insulation resistance. It will withstand stress-relief annealing and serve to promote punchability. Available on fully processed nonoriented grades only.	Applications requiring insulation similar to C-3 and a stress-relief anneal. Used extensively for small stamped laminations requiring higher resistance than provided by annealing oxides.
C-5 (AK Steel CARLITE 3)	An inorganic insulation similar to C-4 but with ceramic fillers added to enhance the interlaminar resistance. It is typically applied over the C-2 coating on grain-oriented silicon steel. Like C-2, it will withstand stress-relief annealing in a neutral or slightly reducing atmosphere. Available on oriented and TRAN-COR H grades.	Principally intended for air-cooled or oil-immersed cores which utilize sheared laminations and operate at high volts per turn. Also finds application in apparatus requiring high levels of interlaminar resistance.
C-5 (For Fully Processed Nonoriented Electrical Steels)	An inorganic/organic insulation. It will withstand stress-relief annealing in a neutral or slightly reducing atmosphere. Available on fully processed cold rolled nonoriented grades.	Principally intended for air-cooled or oil-immersed cores which utilize sheared laminations and operate at high volts per turn. Also finds applications in apparatus requiring high levels of interlaminar resistance.
C-5-AS (AK Steel Anti-Stick)	An inorganic insulation similar to C-5. Available on semi-processed nonoriented grades.	A superior surface treatment providing improved magnetic quality and protection against sticking of laminations during the quality annealing of semi-processed material.

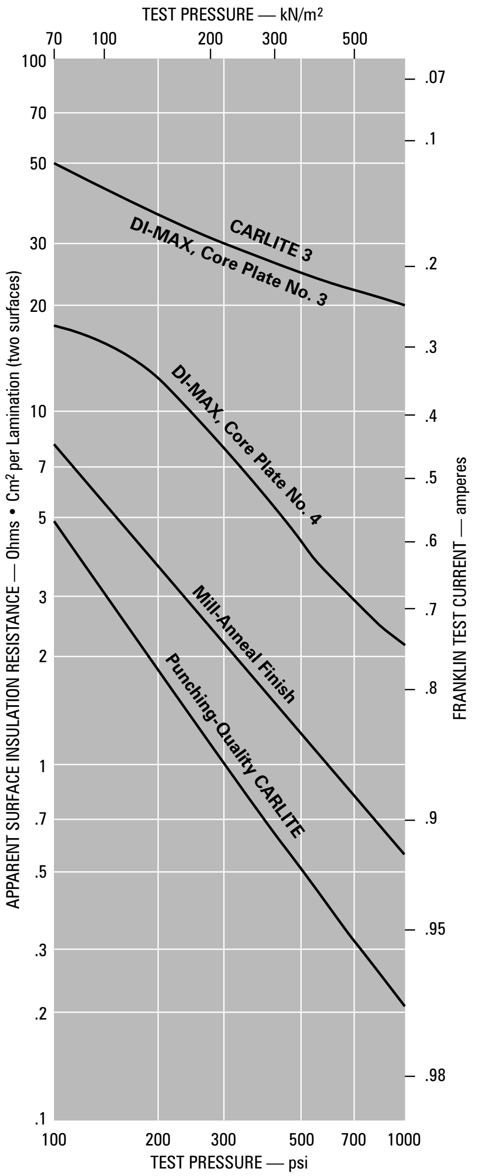
*Based on the classification of surface insulations by ASTM (A 976).

Note: AK Steel's Type C-0 and C-2 coatings are produced by normal processing used to develop magnetic quality. They are an integral part of the steel surface. The other AK Steel surface insulations are coatings that are applied alone to bare steel or may be added to either the C-0 or C-2 insulations to boost their insulative capabilities in severe applications.

Table XI indicates the types of insulations that generally prove to be adequate for a variety of typical applications. These insulations will normally provide adequate resistance assuming normal or average fabricating conditions. However, they are subject to some variation, depending upon how laminations and cores are fabricated. When laminations are not to be stress annealed, Core Plate No. 3 is usually recommended. If annealing is to be done, Core Plate No. 4 may be adequate. For grain-oriented materials that will be used in the form of sheared laminations for power transformers and other apparatus with high volts per turn, CARLITE 3 insulation is recommended. In addition to supplying all the benefits of AISI C-5 insulation, AK Steel CARLITE 3 provides several important advantages, including improved core loss quality, an improved stacking factor, easier assembly of laminations due to smoothness of coating, lower coefficient of friction, and the potential for reducing transformer destruction factor from added resistance to elastic strain damage.

Figure 9

Typical Surface Insulation Characteristics of
AK Steel Electrical Steels at Various Pressures*



*Values Determined by the Franklin Test

Factors Affecting Interlaminar Loss

Design of the apparatus determines the induced voltage tending to produce interlaminar loss, and subsequently the range of surface resistance, as well as the type of insulation that must be used. However, fabrication operations exert a major effect not only on the actual loss that occurs, but also on the effective functioning of the insulation. Consequently, control of individual manufacturing operations in producing a core can be as important as design in keeping interlaminar losses within prescribed limits.

Design

The basic transformer equation for the flux voltage induced in a single turn

$$\frac{E}{N} = 4.44fBA10^{-8*}$$

makes evident most of the fundamental design factors that determine interlaminar power loss. Because the induced rms volts per turn is the electrical potential effective in producing eddy currents, the eddy current power loss varies as the square of the volts per turn for any given set of core conditions. As a result, any factor that increases volts per turn greatly increases the power loss. From the equation it is obvious that as the frequency, size, or flux density is increased, the induced voltage in the core and the interlaminar loss are likewise increased. Therefore, large units, apparatus with high power ratings, or equipment that operates at frequencies above 60 hertz will require more effective surface insulation resistance. However, it should be kept in mind that it is only the percentage of the total loss that is interlaminar that must be kept low. An appreciable interlaminar loss is often encountered in the practical design of large apparatus.

*10^{-8} when B is in Gausses; A in cm^2;
f in Hertz

10^{-4} when B is in Teslas; A in cm^2;
f in Hertz

10^{0} when B is in Teslas; A in m^2;
f in Hertz

Additional design factors of importance are the method of holding the laminations in a core assembly and the mechanical pressure applied to the assembled core. Uninsulated bolts or rivets in the core, or assembling by welding on one side of the core, provide a low-resistance path for eddy currents. But if the interlaminar resistance is sufficiently high, the induced voltage will be impressed primarily across a high-resistance path and the interlaminar loss will be kept small. Yet, such assembly practices must be viewed as hazardous to control of interlaminar losses. High assembly pressures decrease the effective surface resistance. Therefore, pressure between laminations must be considered in designing the core and specifying the insulation. Figure 9 shows how the resistance of surface insulations varies with pressure.

The width of laminations and the number of laminations used to achieve a given core cross-sectional area are also factors that affect interlaminar loss. Basic design establishes the core area required, but width and number of laminations may be varied for a number of reasons.

For any given core area, if the lamination width is increased, the number of laminations must necessarily decrease. Both cause an increase in power loss because they lower resistance to eddy current flow. The increased width of the laminations creates a lower-resistance current path vertically through the lamination assembly. Fewer laminations also reduce the number of insulated lamination surfaces. So, the width of the laminations becomes an important consideration in determining insulation requirements when the volts per turn become quite high.

Fabrication

Burrs on punched laminations drastically reduce the insulative effect of any insulation. Under assembly pressures, burrs establish metal-to-metal electrical contact at lamination edges where the induced voltage between laminations is greatest. Control of stamping or shearing operations is necessary to insure that burrs on laminations are kept as small as possible, or edges must be deburred when effective control is difficult or impossible. Annealing laminations after punching usually creates an oxide film on the burrs, thereby reducing the conductivity of burr contact and minimizing losses.

Annealing laminations to restore their magnetic properties can also have a detrimental effect on the resistivity of surface insulation. Enamels and organic insulators deteriorate under heat. Consequently, they will not withstand annealing temperatures. If laminations with inorganic or oxide coatings are annealed, time and temperature of the annealing cycle, as well as furnace atmospheres must be adequately controlled to insure that the insulation value does not deteriorate during annealing.

Measurement of Surface Insulation Resistance

Limitation of interlaminar losses to effective limits may require production controls. One of these is an adequate control of surface insulation quality. Sometimes manufacturers of very large electrical apparatus exercise this control by maintaining a quality check on the resistance of surface insulations. Practically all such controls use the standard ASTM procedures for the determination of surface insulation resistance.

One of these methods (ASTM Designation A 718-75 (Reference 1), discontinued in June 1966), measures the resistance of a stack of laminations under a recommended standard pressure of 300 psi (2 MPa).

Because of problems involved in using a stack of laminations for testing, ASTM Designation A 717-95 (Reference 1), believed to be better for quality control purposes, was developed to measure the resistance of insulation on only one side of a single lamination. It is more commonly known as the Franklin Test. Recommended standard test pressure is 300 psi (2 MPa), but other pressures can be used.

Current readings by the Franklin Test can be used directly to indicate satisfactory levels of surface insulation resistance. In any event, the indicated resistance values obtained by this test are not directly convertible to resistance values that would be obtained by the stack method. Because the Franklin Test eliminates the effect of burrs and other variables on insulation values, requires little time, and provides more reproducible measurement, it has become the most widely used method for the control of the application of insulative coatings. The stack method probably gives resistance values more closely related to electrical design factors involved in interlaminar core loss but is less useful for control of coating application.

Definition of Terms*

AISI — American Iron and Steel Institute

ASTM — American Society for Testing and Materials

Coercive Force, Hc — The magnetizing force required to bring the induction to zero in a magnetic material which is in a symmetrically, cyclically magnetized condition. It is equal to half the width of a normal hysteresis loop at zero induction.

C-0, C-2, etc. — ASTM designations of various types of surface insulations on electrical steels.

Coil Set — The curvature assumed by a strip of steel in or from a coil when subjected to no external force.

Core Loss — The electrical power expended in the form of heat within the cores of electrical equipment when those cores are subjected to alternating magnetizing force.

Crystal — An essentially homogeneous particle in which the atoms are arranged in a three-dimensional pattern. Commonly used to denote the smallest visible units, macroscopic or microscopic, of a metal structure. Synonymous with “grain”.

DI-MAX — The registered trademark for electrical steel with a special strip-annealed process that maximized punchability.

Eddy Current Loss — The energy expended by circulating current induced in the metal by the variation of magnetic fields in the metal.

Electrical Steels — The generic term for flat-rolled magnetic alloys of iron and silicon.

Equiaxed — A descriptive term indicating that the axes are of equal length. In metallurgy it applies to grains that are not elongated.

ESSG — Electrical Steel Standard Gage

Flux Density — Same as Induction, Magnetic. The magnetic flux per unit area. The area considered is that at right angles to the direction of the flux.

Grain — Used synonymously with “crystal”. See definition of crystal.

Grain-Oriented Steel — A steel in which a large proportion of similar axes of the grains are aligned in the same direction. The arrangement of the grains is such that the best magnetic properties are in the direction in which the steel was rolled in making the final reduction to gauge.

Grade — In this text, grade refers to the AISI “M” System.

Hysteresis, Magnetic — The property of a ferromagnetic material exhibited by the lack of correspondence between the changes in induction resulting from the increase or decrease of magnetizing force.

Hysteresis Loss — The power expended in a magnetic material as a result of magnetic hysteresis when the flux density is cyclic. It is one of the components of core loss.

Induction, Magnetic — The magnetic flux per unit area considered is that at right angles to the direction of the flux. The term usually means the maximum value of the flux density in symmetrically cyclic magnetization.

Limit, Core Loss — The maximum value of core loss used in classifying a material as a grade.

Mil — 0.001 inch or 0.0254 millimeter.

Nonoriented Steel — A term applied to electrical steel when the crystal orientation is more nearly random with respect to the direction of rolling that it is in the grain-oriented steels.

Oriented Steel — A term used synonymously with "grain-oriented steel".

Resistivity, Electrical — The electrical resistance of metal of uniform cross-sectional area, multiplied by the area and divided by the length measured.

Resistance, Interlaminar — The electrical resistance measured in ohms, in a direction perpendicular to the plane of the laminations.

Saturation Induction — The maximum excess of induction possible in a given material above that produced in a vacuum by a given magnetizing force. It is numerically equal to the maximum induction expressed in Gausses minus the magnetizing force expressed in Oersteds (B minus H).

Semi-processed Steel — An electrical steel in which the magnetic properties have not been fully developed at the steel mill. The user must anneal at a comparatively high temperature to fully develop the magnetic properties of the grade.

Stress-relief Anneal — A heat treatment given by the fabricator to laminations or cores for the purpose of eliminating stresses induced in fabrication and which impair the magnetic properties of stacked or wound cores.

Surface Insulation Resistance — The resistance of a unit area of surface coating measured perpendicular to the surface. It is usually expressed in ohm-cm^2 per lamination, two surfaces in series.

*ASTM 340-96[1]

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