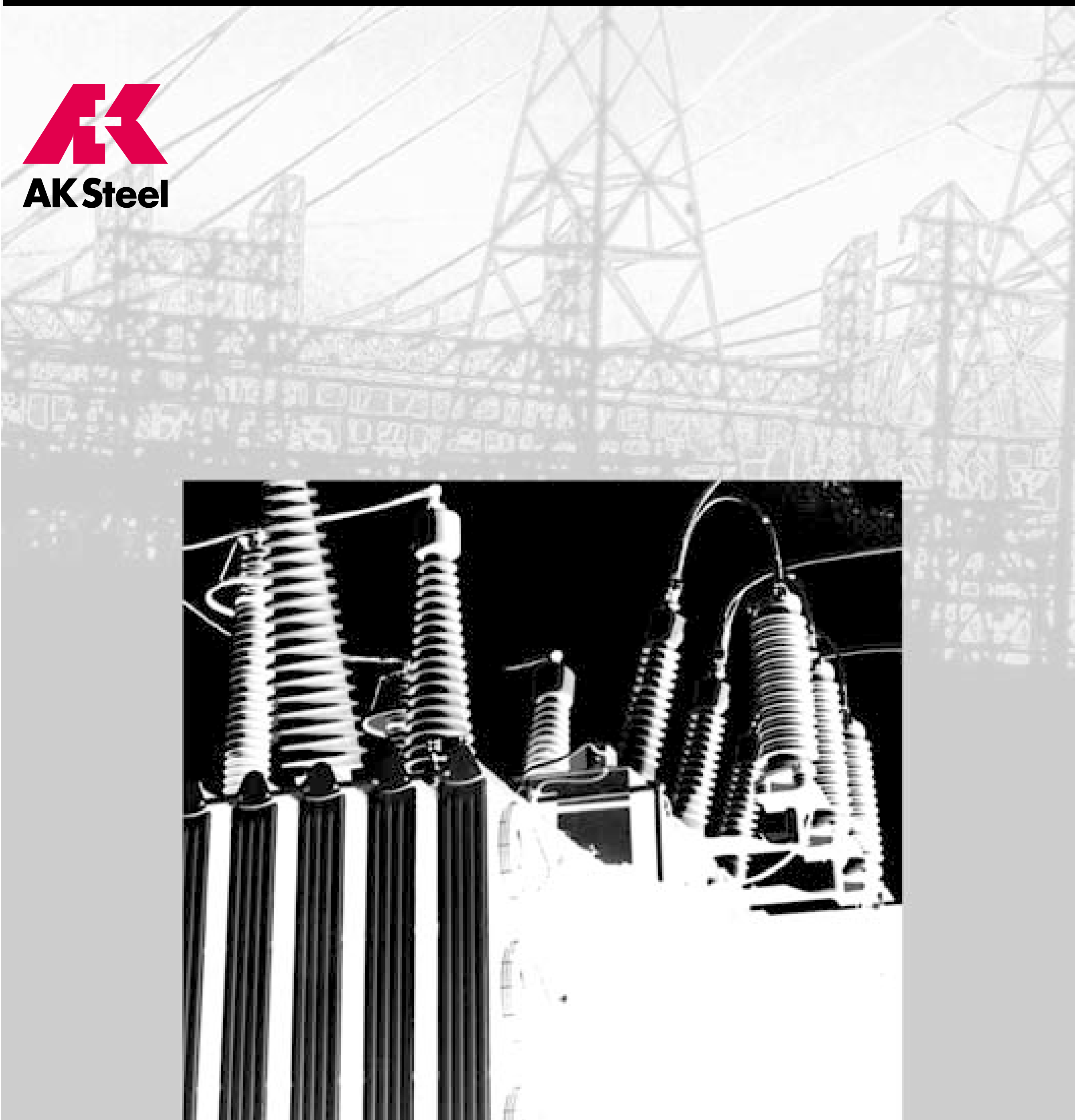
PRODUCT DATA BULLETIN

Oriented & TRAN-COR® H ELECTRICAL STEELS

AK Steel



AK Steel Oriented and TRAN-COR H Electrical Steels

AK Steel Oriented Electrical Steels M-2, M-3, M-4 and M-6

Oriented electrical steels are iron-silicon alloys that were developed to provide the low core loss and high permeability required for more efficient and economical electrical transformers. First produced commercially by AK Steel, these magnetic materials exhibit their superior magnetic properties in the rolling direction. This directionality occurs because the steels are specially processed to create a very high proportion of grains within the steel which have similarly oriented atomic crystalline structures relative to the rolling direction.

In iron-silicon alloys, this atomic structure is cubic and the crystals are most easily magnetized in a direction parallel to the cube edges. By a combination of precise steel composition and rigidly controlled cold rolling and annealing procedures, the crystals of these oriented electrical steels are aligned with their cube edges nearly parallel to the direction in which the steel is rolled. Consequently, they provide superior permeability and lower core loss when magnetized in this direction. This phenomenon is clearly illustrated by Figure 3 which shows the polydirectional permeability of AK Steel Oriented Electrical Steels.

AK Steel Oriented Electrical Steels are used most effectively in transformer cores having wound or sheared and stamped laminations with the magnetic flux path entirely, or predominately, in the rolling direction. They also are used in large generators and other apparatus when the design permits the directional magnetic characteristics to be used efficiently. Since the inception of the oriented grades in 1933, AK Steel Research has continued to develop new and improved grades to provide the electrical industry with core materials for the manufacture of more efficient electrical apparatus.

AK Steel TRAN-COR H Electrical Steels H-0 and H-1

AK Steel TRAN-COR H High-Permeability Electrical Steels offer an outstanding degree of grain orientation. The result is far lower core loss than possible with conventional grain-oriented electrical steels.

In addition, these “super-oriented” materials provide better permeability, particularly at higher operating inductions, and the potential for producing less noisy core structures due to lower magnetostriction.

Advantages of AK Steel Oriented Electrical Steels

The inherent characteristics of grain-oriented electrical steels plus AK Steel’s long-time experience in producing these materials yield a valuable and unique combination of advantages over nonoriented electrical steels.

Lower Core Loss and Higher Permeability in the Rolling Direction

AK Steel Oriented Electrical Steels give the transformer designer a choice of grades that have much lower core loss in the rolling direction than nonoriented grades.

This low core loss is also combined with high permeability even at high inductions. All the advantages of lower core loss can be used without the penalty of lower permeability at high flux densities.

Laser Scribing Refines Domains

Laser scribing AK Steel TRAN-COR H Electrical Steels provides additional beneficial core loss reductions through domain refinement. In this process, a highly focused Nd:YAG laser beam rapidly scans the material surface perpendicular to the rolling direction. The resulting thermal shock produces compressive microstrains in the material which generate new domain walls. By forcing the existing domains to subdivide, the refined domain wall spacing requires less movement during AC magnetization, thereby reducing core loss in the steel.

In addition to Domain Refined TRAN-COR H-0 and H-1 Electrical Steels, AK Steel Oriented M-3 Electrical Steel (CARLITE 3 coated material only) is available in the domain refined condition.

Stress-relief annealing will nullify the beneficial effects of laser scribing domain refinement. These materials are most appropriate for stacked-core applications where stress-relief annealing is not needed.

Superior Lamination Factor

The lamination or stacking factors of AK Steel Oriented Electrical Steels are remarkably good. As a result, efficient use of core volume for carrying magnetic flux is obtained.

Shipped Insulated

AK Steel Oriented Electrical Steels are supplied with glass-type insulation formed during the final stages of manufacture and/or additionally applied inorganic insulation. The former is usually adequate for wound cores of the type used in distribution transformers.

Oriented and TRAN-COR H Electrical Steels also are supplied with CARLITE 3 Insulation. This coating supplies a beneficial tensile stress which contributes to the significantly better magnetic properties and decreased stress sensitivity of these materials. CARLITE 3 Insulation, applied to any of the oriented and TRAN-COR H grades, provides high interlaminar resistivity with minimal effect on lamination factor.

Stress-Relief Anneal May Be Required

The type of material, design considerations and fabrication practices dictate the potential need for annealing to achieve satisfactory magnetic performance in various applications. When needed, only a low-temperature, 1400-1550°F (760-843°C) stress-relieving anneal with proper furnace atmosphere conditions is required to optimize magnetic properties and remove the harmful effects of punching, shearing or winding.

When appropriate annealing procedures are followed, high insulation resistance is retained after stress relief annealing.

Due to the nature of the CARLITE 3 Insulation application process, the resulting low-stress product normally eliminates the need to stress-relief anneal laminations for stacked core structures.

Assured Quality

AK Steel Oriented Electrical Steels are supplied with magnetic properties fully developed at the mill by a special high-temperature heat treatment. Transformer manufacturers may design to known electrical characteristics established by grading tests at the mill.

Available Forms

Grade and Thickness

AK Steel Oriented and TRAN-COR H Electrical Steels are produced in the following grades and nominal thicknesses:

AK Steel Oriented M-2: 7 mils (0.007")
AK Steel Oriented M-3: 9 mils (0.009")
AK Steel Oriented M-4: 11 mils (0.011")
AK Steel Oriented M-6: 14 mils (0.014")
AK Steel TRAN-COR H-0: 9 mils (0.009")
AK Steel TRAN-COR H-1: 11 mils (0.011")

Grades and thicknesses listed are available in the form of coils subject to the following limits:

Widths from 3/4" to 34". (Above 34" up to 36", please inquire.)

Average coils weigh approximately 260–350 pounds per inch of width.

Surface Insulations

Three types of surface insulations on AK Steel Oriented Electrical Steels meet specific design and fabrication requirements. First is the insulation provided by the magnesium-silicate coating formed during annealing, called Mill-Anneal Insulation. Then, there are two types of special AK Steel CARLITE Insulation – CARLITE 3 and Punching Quality CARLITE Insulations. TRAN-COR H Electrical Steels are supplied only with CARLITE 3 Insulation.

Mill-Anneal Insulation

This insulative coating forms in the final mill-annealing operation at very high temperatures. It is a tightly adherent, magnesium-silicate type of coating corresponding to ASTM C-2 Insulation. Mill-Anneal Insulation provides insulative properties suitable for transformers operated at flux densities where the induced voltage is about 10 volts per turn or less (as in distribution transformers normally used by public utilities). This glass-like surface supplies good resistance to abrasion in winding into core form, and will withstand the recommended stress-relieving anneal without loss of insulative value. No danger of transformer oil contamination exists with this coating. Prolonged exposure to oils or air at transformer operating temperatures does not endanger insulating qualities.

AK Steel Oriented grades usually are used with a mill-anneal finish for wound or formed transformer cores, except in larger ratings where the insulation or flatness of a CARLITE 3 product may be required. However, where the induced volts per turn may be unusually high or where the strip width exceeds 10 inches, the increased resistance of CARLITE 3 Insulation may be worthwhile.

CARLITE Insulation

CARLITE Insulations are inorganic coatings produced by combined thermal and chemical surface treatments. They provide thin, uniform coverage of the surface with a high-resistance film that protects against energy loss from induced currents. To permit these insulations to be used in a broader range of applications, two types of CARLITE Insulation are available: CARLITE 3 for sheared laminations and Punching Quality CARLITE.

AK Steel-developed CARLITE 3 Insulation consists of a special insulative coating applied over the Mill-Anneal finish produced in annealing. It has higher insulative properties than Punching Quality CARLITE Insulation, and corresponds to ASTM C-5 Insulation. CARLITE 3 Insulation is applied to both TRAN-COR H and regular grain oriented materials and is intended for materials that will be used in the form of sheared laminations for power transformers and other apparatus with high volts per turn.

For AK Steel Oriented M-2 (.007"), a much lighter CARLITE 3 insulative coating is applied when thermal flattening is specified. This product is called M-2 Light CARLITE, or M-2 LC, and is intended for wound-core applications only.

Punching Quality CARLITE Insulation is a product variant designed to give good die life by removing the Mill-Anneal finish before applying CARLITE Insulation. Although the punching quality product has an insulative quality of the ASTM C-5 type, it provides lower insulation resistance than CARLITE 3 Insulation (C-5 over C-2), but affords adequate resistance for applications where volts per turn are moderate. It is not recommended where very high surface insulation is required.

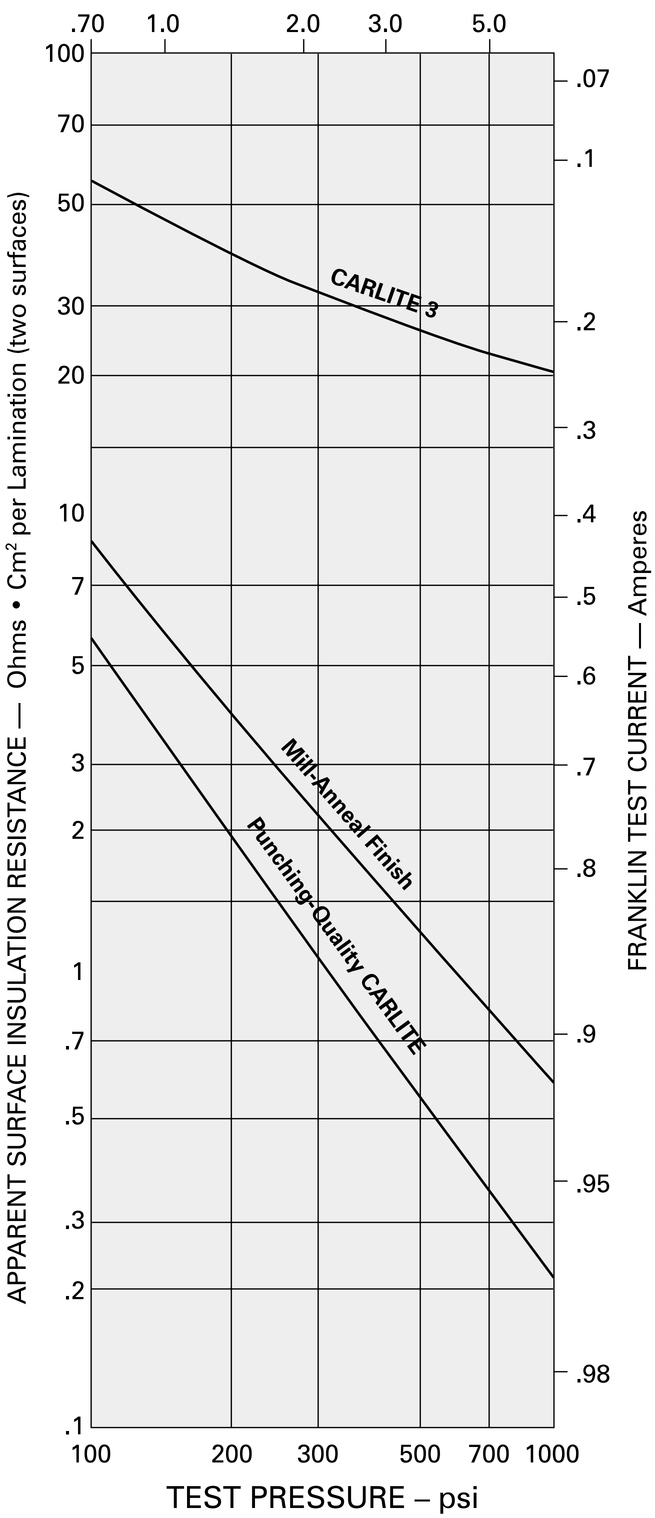
The effect of CARLITE coatings on lamination factor is quite small. CARLITE coatings retain their insulative capability after stress-relief annealing if suitable annealing procedures are followed. CARLITE coatings will not contaminate transformer oils, nor is there any deterioration of the insulative coating in either oils or air at operating temperatures.

Surface Insulation Curves

Figure 1 shows the variation of surface insulation resistance versus pressure and provides a guide to users interested in knowing the relative insulative capabilities of the available surface finishes. Resistance values are typical of those which should be equalled or surpassed in most tests made on such surfaces by the Franklin Test (ASTM A717). However, the user should recognize that the normally small variations in mill oxide and coating thickness within a lot necessitate allowing for some test values lower as well as higher than those shown in the curves.

Figure 1

Typical surface insulation characteristics of AK Steel Oriented Electrical Steels at various pressures as determined by the Franklin Test.



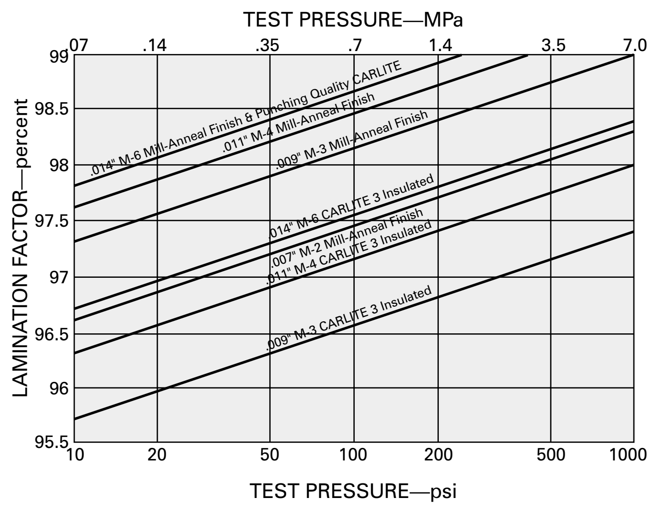
Lamination Factor

Lamination factor is the measure of compactness of an electrical steel core. This is also referred to as "stacking factor" and "space factor." Lamination factor is the ratio of the equivalent "solid" volume, calculated from weight and density of the steel, to the actual volume of the compressed pack, determined from its dimensions.

Special processing gives AK Steel Oriented Electrical Steels (either with Mill-Anneal finish or CARLITE types of insulation) exceptionally and consistently high lamination factors.

Test Method. The lamination factor of electrical steels is determined from measurements of a stack of Epstein strips under known pressure in accordance with ASTM A 719. Figure 2 illustrates how the ASTM lamination factor varies as a function of pressure for the most widely used forms of AK Steel Oriented Electrical Steels. The values shown are representative of the lamination factor determined by this test.

Figure 2



Mechanical and Physical Properties

Representative Mechanical Properties	Oriented	TRAN-COR H
Ultimate Tensile Strength, psi (MPa) in rolling direction	51,000 (352)	52,000 (359)
Yield Strength, psi (MPa) in rolling direction	48,000 (331)	50,000 (345)
Percent Elongation in 2 inches (50.8 mm) in rolling direction	9	11
Microhardness (Knoop Hardness Number, HK)	167	173
Equivalent Rockwell B Scale Hardness	81	83
Modulus of Elasticity, psi (MPa)*		
in rolling direction	17,700,000 (122,000)	16,500,000 (113,800)
at 20 degrees to rolling direction	20,800,000 (143,000)	20,000,000 (138,000)
at 45 degrees to rolling direction	34,300,000 (236,000)	35,000,000 (241,000)
at 55 degrees to rolling direction	37,500,000 (258,000)	40,000,000 (276,000)
at right angles to rolling direction	29,000,000 (219,500)	29,500,000 (203,000)

*Values may vary as much as plus or minus 5%

Physical Properties	Oriented	TRAN-COR H
Density, grams per cubic centimeter	7.65	7.65
Electrical Resistivity, microhm-centimeters	51	50
Saturation Value of Ferric Induction* (B-H) in kilogausses	20.0	19.9
Curie Temperature, °F (°C)	1375 (746)	1380 (749)

*Effective value for coated specimen.

Maximum Core Loss Limits

For grading purposes, core loss tests on AK Steel Oriented and TRAN-COR H Electrical Steels are made at inductions of 15 and 17 kilogausses. This testing procedure approximates the operating conditions in transformers designed for these types of materials. Test results agree closely with those made on single-phase transformers with stress-free cores having no joints.

AK Steel Grade	Test Specimen	Thickness inches	Maximum Core Loss* 60 Hertz Watts per lb 15 kG	60 Hertz Watts per lb 17 kG	60 Hertz Watts per kg 15 kG	60 Hertz Watts per kg 17 kG	50 Hertz Watts per lb 15 kG	50 Hertz Watts per lb 17 kG	50 Hertz Watts per kg 15 kG	50 Hertz Watts per kg 17 kG
Oriented M-2	(1)	.007	.405	—	.89	—	.31	—	.68	—
Oriented M-3	(1)	.009	.445	.70	.98	1.54	.34	.53	.75	1.17
Oriented M-4	(1)	.011	.51	.74	1.12	1.63	.39	.56	.85	1.24
Oriented M-6/PQ	(1)	.014	.66	.94	1.46	2.07	.50	.71	1.11	1.57
TRAN-COR H-0	(1)	.009	—	.60	—	1.32	—	.46	—	1.01
TRAN-COR H-1	(1)	.011	—	.66	—	1.46	—	.50	—	1.11
TRAN-COR H-0 DR†	(2)	.009	.39	.535	.86	1.18	.30	.41	.65	.90
TRAN-COR H-1 DR†	(2)	.011	.425	.57	.94	1.26	.32	.43	.71	.96

(1) Annealed Condition, Epstein type test specimen

(2) As-sheared single sheet test specimen.

*Customer has option of specifying either 15 or 17 kG inductions for 9-mil M-3, 11-mil M-4, 14-mil M-6, 9-mil H-0 DR, and 11-mil H-1 DR.

†DR designates domain refinement by laser scribing.

Typical core losses of AK Steel Oriented and TRAN-COR H Electrical Steels are significantly lower than the maximum limits. Contact AK Steel for computer spread sheet for typical core loss and exciting power.

The core loss and exciting power of the AK Steel Oriented and TRAN-COR H grades are determined by magnetic tests performed in accordance with general procedures approved by the American Society forTesting and Materials.

The following conditions apply:

1. Epstein Specimens
   a. Sheared parallel to the rolling direction of the steel from fully processed coils.
   b. Annealed again after shearing to relieve stresses per ASTM A 876.
   c. Tested after stress-relief anneal per ASTM A 343.
2. Single Sheet Specimens
   a. Sheared parallel to the rolling direction of the steel from fully processed coils.
   b. Tested as-sheared per ASTM A 804.
3. Density of all grades — 7.65 grams/cm^3 per ASTM A 34.

ASTM A 664 is a grade identification system for electrical steels. While this system has not been widely adopted by the manufacturers and consumers of electrical steels, it is used in ASTM A 876 to designate various grades of grain oriented electrical steel. The following is a listing of the corresponding AK Steel and ASTM grades of grain oriented electrical steels.

AK Steel grade 7-mil M-2 is approximately equivalent to ASTM Core Loss Type 18G041.
AK Steel grade 9-mil M-3 is approximately equivalent to ASTM Core Loss Types 23G045 and 23H070.
AK Steel grade 11-mil M-4 is approximately equivalent to ASTM Core Loss Types 27G051 and 27H074.
AK Steel grade 14-mil M-6 is approximately equivalent to ASTM Core Loss Types 35G066 and 35H094.
AK Steel grade 9-mil H-0 is approximately equivalent to ASTM Core Loss Type 23P060.
AK Steel grade 11-mil H-1 is approximately equivalent to ASTM Core Loss Type 27P066.
AK Steel grade 9-mil H-0 DR is approximately equivalent to ASTM Core Loss Type 23Q054.
AK Steel grade 11-mil H-1 DR is approximately equivalent to ASTM Core Loss Type 27Q057.

Stress-Relief Annealing

General Requirements

A mill anneal develops the full magnetic potential and reduces harmful elements in AK Steel Oriented Electrical Steel. Stress relief annealing relieves stresses thermally after the steel has been fabricated into its final size and shape. In stress-relief annealing, the user should first recognize that the parameters of time, temperature and atmosphere are not interchangeable with those for annealing of semiprocessed grades of nonoriented silicon steels or carbon steels.

Basically, stress relief is accomplished by heating the laminations or fabricated parts to the 1400-1550°F (760-845°C) range, followed by cooling to room temperature. The stress relief must be done under time, temperature and ambient atmosphere conditions that will avoid even minute adverse changes in the steel chemistry and prevent excessive thermal gradients that might reintroduce stresses into the steel or perhaps distort its shape. Cores or laminations usually can be removed from the protective annealing atmosphere at about 600-700°F (315-370°C) without ill effects.

Insulation

AK Steel Oriented Electrical Steels are supplied with either a Mill-Anneal finish or CARLITE types of insulation. TRAN-COR H Electrical Steels are supplied with CARLITE 3 Insulation. Surface finish has a very important bearing on the selection of the proper annealing atmosphere.

The Mill-Anneal finish (sometimes referred to as glass film) is developed at very high temperatures in a hydrogen atmosphere. Consequently, it is completely compatible with hydrogen-nitrogen mixtures ranging from 0 to 100 percent nitrogen without adversely affecting the interlaminar resistance quality of the electrical steel. However, for economy and safety, the hydrogen content usually is maintained below 10 percent. Vacuum annealing gives very satisfactory results with a Mill-Anneal surface, but may be too costly.

The insulative quality of CARLITE types of insulation is best maintained or enhanced by an atmosphere that is neutral or slightly oxidizing to iron. Pure, dry nitrogen is recommended for batch annealing CARLITE types of insulated material when the cycle time requires hours.

Continuous stress relief of slit widths or single laminations may be carried out in an air atmosphere if exposure time is only a matter of minutes. Vacuum annealing of CARLITE types of insulated material is not recommended.

Atmosphere Conditions to Avoid

AK Steel Oriented Electrical Steels are produced under very exacting limits and careful control of composition, rolling and annealing. Consequently, these steels are extremely low in impurities such as carbon and oxygen. Destructive magnetic effects will ensue if either of these impurities are reintroduced into the steel by the user. Any annealing atmosphere which contains carbon or oxygen compounds may contaminate the steel with these elements. If they are present in the annealing atmosphere or evolved from lubricants or other foreign matter within the annealing chamber, the best magnetic quality will not be obtained. For instance, contamination with carbon can occur if the annealing atmosphere has an equilibrium value with the steel of greater than .0025 percent carbon and if the steel is so exposed for any appreciable length of time when it is at temperatures over 1200°F (650°C).

Oxygen compounds, such as water vapor, oxidize silicon in oriented steels even under conditions highly reducing to iron. Long exposure to conditions oxidizing to silicon can undermine glass film by continued oxidation of silicon, especially at or near the exposed edges. Oxidation is not only somewhat harmful to magnetic properties, but it also causes growth in the steel thickness which can cause excessive tightening of uncut wound cores. This results in dimensional difficulties and deleterious stress effects in reassembly of wound cores after cutting.

Do not use unmodified exothermic atmospheres obtained from the partial combustion of natural gas or similar hydrocarbons. They are oxidizing to silicon during the entire annealing cycle. In addition, they usually are carburizing in part of the heating and cooling cycles even when noncarburizing at the soak temperature.

Satisfactory annealing atmospheres can be produced from natural gas or similar hydrocarbons only by (1) complete combustion and removal of carbon dioxide and water vapor or (2) partial combustion followed by conversion of the CO to CO_2 with steam and final removal of CO_2 and water vapor by scrubbing and drying. Process (1) results in essentially pure nitrogen and process (2) results in nitrogen containing 3 to 10 percent hydrogen.

Mill-Anneal

Oriented steel with a Mill-Anneal finish is used primarily for wound and formed transformer cores. The material normally has some residual coil set which can be tolerated in the manufacture of wound cores, but this curvature is undesirable for punched or sheared laminations that are subsequently stacked.

Annealing Furnaces

Two general types of furnaces, batch type and continuous batch type, are widely used for stress-relief annealing of wound or formed cores made from oriented electrical steel with a Mill-Anneal finish.

Batch-Type Furnaces

Required Features – Batch furnaces have advantages, particularly where the volume of steel being annealed at any one time is small, production is intermittent, or core sizes being annealed vary considerably. Such furnaces can provide considerable flexibility and the opportunity to vary the cycle from charge to charge. With tight-fitting inner covers that isolate the annealing space, it is possible to maintain accurate control of the atmosphere surrounding the charge at all times and yet maintain atmosphere flow rates at economical levels. Heat input to the furnace charge must be adjustable so that temperature variations can be controlled properly. This is necessary to ensure that the lagging temperature at the bottom center of the charge is sufficient without the top temperature exceeding the maximum desirable for the anneal conditions. Furnaces with recirculating fans are particularly advantageous for annealing wound cores since they permit more uniform heating of the charge and shorter annealing cycles.

Inner Covers – Always use inner covers with box furnaces to protect against contamination from furnace brickwork or combustion products. Covers should be made from material of very low carbon content such as Types 304L or 316L stainless steel. The cover preferably should fit tightly with a base plate of comparable material. The metal base which covers the brick furnace base, plus the removable cover, should form a metallic enclosure for the charge within which there is no brickwork. Atmosphere inlet and outlet pipes are usually placed in the base and located to ensure positive flow around the charge. The joint between the inner cover and base may be sealed with sand. When the furnace is a "bell" type, it is advantageous to flange the inner cover. This provides a seal outside the furnace where it may be kept cool enough to maintain a positive seal with water.

Piling the Charge – Exercise care in piling the charge in batch furnaces to ensure that the charge receives the maximum exposure to direct radiation from the heat source. Conduction of heat within cores takes place principally along the plane of the strip. Heat is radiated to or from the exposed cut edges of the strip rather than through strip surfaces. As a result, cores in the heat shadow of others may take substantially longer to be heated. This can cause severe temperature variations to exist within the furnace. However, such variations can be minimized by the shape and design of the annealing chamber considering the usual makeup of the charge, or by using forced recirculation of the heated atmosphere.

Atmosphere Flow Rate – To avoid exposing cores made from glass film material to danger of growth and tightening from oxidation of either the silicon or iron constituents of the material, eliminate oxygen from the atmosphere as early as possible in the cycle. Thereafter, provide maximum protection against oxidation during the entire annealing cycle. This may require that the annealing chamber be thoroughly purged of oxygen quite rapidly at the start of the heating cycle. The amount depends upon the gas volume involved (volume inside the inner cover minus the charge volume). It is a good practice to provide at least 10 volume changes by the time the charge has heated to 1000°F (540°C). Then, the atmosphere flow rate can be reduced to about five volume changes per hour until the charge cools to at least 700°F (370°C).

Temperature Cycle – Annealing time should be as short as possible without producing excessive thermal gradients. Proper time must take into account the size and weight of cores being annealed and their relative degree of exposure to heating and cooling. For instance, 100-pound cores with good exposure to the heating and cooling sources might require a minimum of six to eight hours to go from room temperature to the annealing temperature and back to 700°F (370°C) without experiencing thermal strains. With a lesser degree of exposure, it might require 10 hours for equivalent results. A temperature of about 1450-1500°F (790-820°C) is usually adequate for stress relief of most wound cores. It is usually desirable to hold or soak at 1500°F (820°C) until the desired minimum temperature is reached at the most protected location within the charge. If cores are not well exposed, this soaking period may be up to two hours in length. With maximum exposure, it might be as short as one-half hour. Furnace heat input should be adjusted so that the heating rate is not too great when approaching the soaking temperature. Rapidly forcing cores up to temperatures with extra high heat input is never advisable. It may be desirable to begin the cooling cycle at a controlled rate if the natural cooling rate of the furnace is so rapid it might cause thermal strain.

If cores are fabricated by cold-working procedures that produce plastic deformation of a relatively large percentage of the core volume, it may be desirable to employ a slightly higher soaking temperature for the anneal. A temperature of about 1550°F (845°C) will assure all the stress relief possible for drastically strained steel. However, this higher temperature should not be used unless experimentation with the cores being annealed shows that it is definitely beneficial.

Continuous Batch-Type Furnaces

Continuous furnaces usually yield best results in high production volume, primarily because relative exposure of cores or laminations to the heat source is much greater than in box furnaces, resulting in minimum annealing time and maximum exposure to the protective atmosphere. These furnaces usually fit well into automated production lines, but are less flexible and less economical than box furnaces or batch-type furnaces for varied or low-volume production.

Continuous furnaces must have several controlled heating and cooling zones with individual control. These permit the heating rate to be adjusted so that heating and cooling gradients, particularly going into and out of the maximum temperature region of the cycle, will not be large enough to produce stress effects or distortion in the core. Unlike batch furnaces, continuous furnaces cannot be kept sealed for the entire cycle. So, atmosphere flow rates usually are substantially larger than for batch furnaces of equivalent volume. Separate entrance and exit chambers may be needed to minimize admission of air into the furnace when the charge is introduced or removed.

Special Precaution for Annealing Wound Cores

Exercise care to maintain the shape of rectangular or formed cores during annealing. Unless the cores come out of the anneal stress-free and in a shape that minimizes the reintroduction of stresses in assembly or as a result of framing, then even the most careful attention to other features of the stress-relieving treatment may be wasted.

CARLITE Types of Insulation Finish

A thermal flattening treatment is an integral part of the process for the application of CARLITE 3 Insulation. Because of the special insulation and flatness, material with CARLITE types of insulation is used primarily for flat sheared laminations and punchings. If CARLITE 3 types of finish offer special advantages, they can be used for wound cores. However, when used for wound cores, instead of Mill-Anneal Finish, the stress-relief anneal should be in an oxygen-free nitrogen atmosphere and the maximum charge temperature should never exceed 1500°F (820°C). If the atmosphere contains hydrogen, it should be kept below five percent to avoid deterioration of insulative capabilities.

Batch-Type Furnaces

When annealing flat, sheared laminations for stacked transformer cores in batch-type furnaces, care of annealing bases and stacking plates, as well as the heating and cooling rates, become especially critical. Unless such laminations are extremely flat after annealing, strains will be built into the transformer when the laminations are stacked and clamped together.

Flat lamination production requires that the furnace base must be maintained flat, and piling plates must be flat and of adequate thickness to give firm support. Shearing burrs must be kept very small or removed. This prevents the accumulation of burr buildup that causes the sheared edges of the laminations to stack higher than the body of the laminations. Avoid furnaces that require laminations to be stacked rather high for effective use of furnace space. Bowed laminations may result from the accumulative burr buildup in high stacks of laminations.

Practical experience shows that heating and cooling rates, together with the width of the laminations, have an important influence in maintaining lamination flatness in batch annealing. This is particularly true where only one edge of the lamination is exposed to direct radiation from the heat source. Rapid temperature changes create thermal gradients in the charge and nonuniform thermal expansion or contraction. This may result in the production of wavy laminations if the thermally induced forces exceed the yield point of the steel which is relatively low at elevated temperatures. Once developed, such waviness cannot be removed readily in a reanneal and will cause increased core loss in the assembled transformer.

To prevent thermal distortions, keep temperature gradients small when laminations are quite wide and the charge is near the maximum temperature during both heating and cooling. For 10-inch-wide (254 mm) laminations heated almost entirely from one edge (as might be the situation where the charge is piled several stacks wide), this might require that the edge heating rate not exceed 40°F (22°C) per hour at 1400°F (760°C). Yet, with the temperature at 1200°F (650°C) and the same piling arrangement, the heating and cooling might be at 80°F (44°C) per hour with safety.

On the other hand, with 5-inch-wide (127 mm) laminations and heating from one edge, the heating and cooling rate at the exposed edge might safely be about 150°F (85°C) per hour at 1400°F (760°C) and 300°F (165°C) per hour at 1200°F (650°C) without causing thermal distortion. With single-width stacks exposed to equal heating from opposite edges, these heating rates could be up to four times as fast.

In any event, the recommended maximum charge temperature for flat laminations with CARLITE types of insulation should not exceed 1450°F (790°C), except that CARLITE 3 Insulation can withstand temperatures up to 1500°F (820°C). If all parts of the charge reach 1400°F (760°C), this is usually adequate for stress relief of material. The requirements for inner covers, purging of the annealing chamber and flow rate of the protective (nitrogen) atmosphere are generally the same as those recommended for Mill-Anneal finish.

Continuous Batch-Type Furnaces

Small punched laminations are usually continuously batch annealed in trays, frequently with the plane of the laminations vertical. Consequently, they do not pose the same temperature gradient problems encountered with large sheared laminations. A soaking temperature in the range of 1400-1450°F (760-790°C) is usually sufficient to remove the shearing strains present in oriented grades with CARLITE types of surface insulation.

When continuous furnaces are employed for stress relief of oriented materials, it is most important that the temperature of the furnace zones and the speed of the charge through the furnace are suited to producing a desirable time-temperature cycle for the charge. Laminations are often introduced into the furnace with the first zone at maximum temperature. However, for best flatness, it might be found that the first zone in the furnace should not exceed a temperature of 1200-1300°F (650-704°C). Likewise, when laminations are at a temperature over 1300°F (704°C), the gradient between adjacent zones should not be more than about 150°F (85°C) during heating or 100°F (55°C) during cooling. This prevents excessive temperature gradients with the attended possibilities of distortion of shape or thermal strain. At temperatures substantially under 1200°F (650°C), cooling in continuous furnaces may usually be as rapid as desired. Temperature cycles should be checked by placing thermocouples in the most shaded part of the charge before deciding on final temperature and speed for different charges.

A continuous flow of annealing gas should be maintained through the furnace. The charge may exit from the protective atmosphere at 600-700°F (315-370°C).

Continuous Furnaces - Single Thickness Annealing

Excellent results can be obtained by continuous annealing of slit widths which are later cut to lamination length or by the continuous annealing of single laminations on a suitable conveyor. Heating and cooling must be uniform from the plane of the strip, and conditions conducive to good flatness must be maintained. An air atmosphere can be used because the entire cycle requires only a few minutes. Temperatures in the range of 1450-1550°F (790-845°C) are usually employed.

Summary of Recommended Annealing Procedures

The principal requirements for stress-relieving of AK Steel Oriented and TRAN-COR H Electrical Steels according to the type of material are shown in the following procedures chart:

Annealing Procedures

	Mill-Anneal Insulation (for wound cores)	CARLITE Type Insulation (for flat laminations) Punching Quality only	CARLITE 3
Maximum Charge Temperature	1550°F (845°C)	1450°F (790°C)	1500°F (820°C)
Minimum Charge Temperature	1450°F (790°C)	1400°F (760°C)	
Atmosphere	Dry nitrogen with 0 to 10% H_2	Dry nitrogen with 0 to 2% H_2	Dry nitrogen with 0 to 5% H_2
Time	Minimum necessary to reach temperature in coldest part of charge without imposing thermal strain from excessive heating and cooling gradients.		
Special Precautions	Meticulously avoid oxidation as well as carburization. Always use inner covers in furnaces.	Keep piling plates flat and give strict attention to avoiding excessive temperature gradients in 1300-1450°F (704-790°C) range. Avoid exposure to hydrogen over 2% (5% for CARLITE 3)	

For advice on annealing specific sizes of laminations or cores with specified piling arrangements, ask our AK Steel specialists for technical assistance.

Core Design

AK Steel Oriented and TRAN-COR H Electrical Steels offer outstanding magnetic properties when the flux path is parallel to the direction in which the steel was rolled. This is due primarily to their highly perfected "grain orientation."

However, this same orientation that improves magnetic characteristics in the rolling direction impairs magnetic properties when the flux path is not parallel to the rolling direction. This is illustrated in Fig. 3.

Figure 3

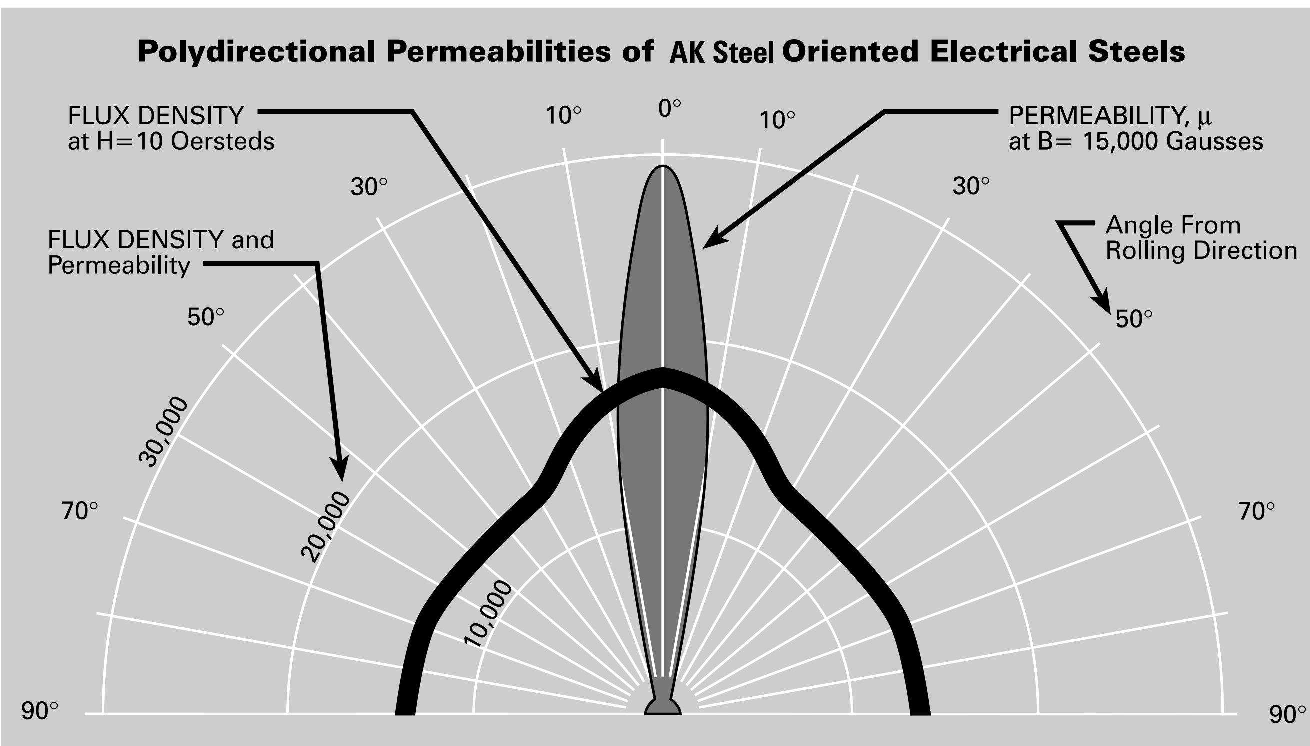


Figure 3. Tests made on Epstein samples cut at various angles to rolling direction, stress annealed after shearing. Negligible joint effects. Assumed density 7.65 grams per cubic centimeters.

Note how rapidly the permeability at 15 kilogausses is reduced when the direction of magnetic flux departs substantially from the rolling direction. For example, the magnetizing force must be about 100 times as large to produce an induction of 15 kilogausses in the 45-degree direction as in the rolling direction.

Tape wound or spirally wound cores are the ideal core form for the oriented electrical steel grades because the flux path is in the rolling direction. Design allowances will have to be made for the effects of any joints in the magnetic circuit and other basic differences between cores and Epstein test values. Stresses introduced by fabricating or assembly operations after stress-relief annealing also must be taken into consideration in design. Fabrication methods which cause a very large percentage of the core volume to be deformed beyond the elastic limit should be avoided. These methods may cause some slight permanent deterioration of magnetic properties not recoverable in subsequent stress-relief annealing.

In stacked core, the presence of joints and flux paths in unfavorable directions make precise core design less simple. The successful use of oriented grades demands careful core design to minimize, or eliminate if possible, all magnetic paths in unfavorable directions and high reluctance in joints.

For approximating the excitation requirements and losses of a particular core shape, break up the magnetic path into parallel-grain, cross-grain and corner sections, and calculate each section separately. Then combine values for all sections to obtain the total for the core.

In small stacked cores, any flux paths not in the rolling direction should be limited to relatively short sections such as corners of conventional cores with fairly long windows. In E and I assemblies, the legs of the E and all of the I laminations should be blanked in the rolling direction. Where E and I cores operate at rather high inductions, it is often helpful to widen the back of the E by as much as 35 percent to reduce flux density, because here the flux path is transverse to the rolling direction.

When stacking small E and I cores of oriented material, interleaving of laminations one at a time is desirable for best results at low and moderate inductions. Cores operated at high inductions can be stacked two or three laminations at a time.

Effects of Fabrication

The detrimental effects of stress introduced into laminations by shearing, forming, riveting or other fabricating operations is almost always extremely important with oriented materials. These effects usually can be eliminated by a suitable stress-relieving anneal after fabrication to final shape (see section on Stress-Relieving Anneal). Great care must then be exercised to assemble the stress-free laminations to avoid any appreciable stress due to bending in assembly. When stress-relief annealing is impractical, or when some stresses in assembly are unavoidable, these shortcomings must be compensated for by design allowance.

Effect of Joints

Joints in a magnetic core can greatly increase the total excitation requirements especially when operating at inductions where the permeability of the material itself would normally be very high. In cases where flux is forced to pass perpendicularly to the laminations as in areas adjacent to gaps formed by abutting laminations, core loss may be increased appreciably. To reduce such losses, care should be taken to minimize the number of joints and the reluctance associated with them. Where lowest exciting current is of prime importance and where the path length in "iron" is relatively short as in small cores, designers can profit by giving major consideration to improving the joints in their design.

Effects of Wave Forms

If the flux wave form is not closely sinusoidal, harmonic components of flux will cause an increase in core loss and exciting current because of increased eddy currents and skin effect. These increases become comparatively large if the exciting current is forced to approach sinusoidal wave shape at moderate and high inductions, because then the flux wave form will be approaching relatively square wave shape. Since harmonic components of flux cause increases in both the "in-phase" and quadrature components of exciting current, the operating a-c flux-current loop will be somewhat widened and altered in shape from that for sinusoidal flux.

Effects of Non-Uniform Flux Distribution

A factor usually overlooked, but not always negligible in core design, is the ratio of maximum to minimum length of magnetic path. If this ratio is too much greater than unity, the elements of shortest magnetic path length may be operating at exciting forces (NI/1) excessively higher than those for the longest elements of magnetic path. This will cause greatly increased flux density at the inside periphery of the core compared with that computed for the mean path length.

This non-uniformity of flux density in the core in turn causes the wave form of the flux at the extremes of the magnetic path to be distorted — even when the total flux is sinusoidal. As a result, effects of nonsinusoidal wave form will be present, to a degree, depending upon the departure of the path length ratio from unity and the moderating effects of the joint reluctance along the maximum and minimum paths.

Conversion of Magnetic Units

The following conversion factors may be useful in the application of data on AK Steel Oriented and TRAN-COR H Electrical Steels:

Core loss at 50 Hertz ≈ Core loss at 60 Hertz x 0.76

$$\text{Kilogausses} = \frac{\text{Flux Lines per square inch}}{6450}$$

$$\text{Oersteds} = \frac{\text{Ampere-turns per inch}}{2.02}$$

$$\text{Webers} = \frac{\text{Flux Lines}}{10^8}$$

$$\text{Teslas} = \frac{\text{Kilogausses}}{10}$$

$$\text{Teslas} = \frac{\text{Flux Lines per square inch}}{64{,}500}$$

$$\text{Ampere/meter} = \frac{\text{Oersteds}}{0.01257}$$

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