

Energy-Efficient Steels for Motor Laminations

F.E. Werner and R.I. Jaffee

Motors use over 60% of all electricity generated, and their losses exceed 200 × 10^9 kW·hr/year. A significant part of this loss results from eddy currents and hysteretic processes in the motor laminations. These so-called core losses cost motor users about \$3 × 10^9/year. The metallurgy and economics of using various steels are considered, with emphasis on 5- to 125- hp polyphase induction motors. A lower core loss steel, even though it is more expensive, is economically justified most of the time when the operating costs of motors are considered. Impurities must be minimized, and steels can now be made with the principal impurities being less than 30 ppm. Further reduction of core losses depends on using the best steel processing equipment available, production of a consistently low carbon content so that decarburizing during the final anneal can be eliminated, developing a better understanding of the relation between material properties and performance in motors, and an increased willingness by the motor users to pay more for better motors that are cheaper to own in the long run.

1 Introduction

THE ac magnetic flux carried in laminations causes significant loss in electrical equipment due to induced eddy currents and hysteretic magnetization processes in the steel. Most of this so-called core loss is found in transformers, motors, and lamp ballasts and was estimated to account for 4.5% of the total electricity generated in 1977 in the United States, with a cost to the users of over \$3 × 10^9/year[1] Considering that electricity usage and price have increased since 1977, it is estimated that the current annual cost of these core losses exceeds \$7.5 × 10^9, a significant economic penalty.

This paper is concerned primarily with motors, which utilize over 60% of the electricity in the United States. Losses in motors result from the I^2R (I=current, R=resistance) heating in both stator and rotor windings, eddy current and hysteresis losses in the laminations, friction and windage, and stray load. Except in a few instances, only the core loss component is considered herein.

Motors come in a bewildering array of sizes and designs for many different applications. To reduce the subject to manageable proportions without losing any essential features, this paper concentrates on 5- to 125- integral hp polyphase induction motors. Many such motors are relatively standardized, they consume a large fraction of the total motor electricity, they utilize a range of steels, they are made with several levels of efficiency, and they represent opportunities for significant energy savings.

The term "electrical motor steel" is used generically herein to denote any steel used for laminations in motors. In the United States, two subclasses are usually termed "nonoriented steel" and "motor lamination steel," to denote, respectively, steels containing significant amounts of silicon made by specialty producers, and steels with low amounts of silicon made by the large integrated steel producers. There is now significant overlap in alloy content between these subclasses, with resulting confusion in terminology.

F.E. Werner, Consultant, Pittsburgh, Pennsylvania, and **R.I. Jaffee**, Electric Power Research Institute, Palo Alto, California. Work sponsored by the Electric Power Research Institute, Contract No. RP3070-24.

Electrical motor steels have been significantly improved in the past 10 to 20 years, leading to steels with better and more uniform properties. Continuous casting, vacuum degassing, and ladle refining are now being widely used. This paper discusses the economics and metallurgy of using such materials in motors. Prospects for further reduction in core loss are also considered. Much of the material in this paper is taken from Ref 2.

2 Losses in Motors

The numbers of motors 1/6-hp and larger and their energy consumption in 1985 are summarized for various size ranges in Table 1.[3-5] The data in the original sources for 1- to 20-hp were aggregated differently from Table 1; the conversion to 1- to 4- and 5- to 20-hp ranges is described in Appendix A of Ref 2. The efficiencies are the weighted averages of installed motors in 1977 (Table 3-11, Ref 3). Motors smaller than 5 hp constitute about 97% of the numbers of motors, but use only 22% of the electricity. Their efficiencies are modest, many are operated relatively few hours annually, and they contribute 44% of the loss. Most customers for these small motors purchase them on the basis of initial cost only. Motors larger than 125 hp constitute only 0.1% of the numbers, but use 32% of the electricity. Even through they operate under high duty cycles, their high efficiency leads to their contributing only 14% of the loss. These motors tend to be purchased by customers who consider the total cost of owning the motors; hence efficiency is an important consideration. The 5- to 125-hp range constitutes about 3% of the motors, uses 46% of the electricity, and produces 42% of the loss. Many motors in this range are purchased by OEM's and distributors, not by the ultimate users of the motors. Consequently, initial cost tends to outweigh operating cost as a purchasing criterion. However, an increasing number of customers for these medium-horsepower motors are buying higher efficiency models to reduce the total cost of owning the motors. This medium-horsepower range was previously identified as having the highest potential for energy conservation.[3]

The total electricity used in all motors represented in Table 1 is over 60% of the total generated in the United States. Core losses are generally 10 to 30% of the total motor loss of 218 × 10^9 kW·hr/year in Table 1. Taking 20% as a typical value, core

Table 1 Motor Numbers, Electricity Use, and Losses in the United States in 1985[3-5]

Motor size, hp	Number of motors Millions	%	Electricity used 10^9kW·hr	%	Efficiency average, %	Losses 10^9kW·hr
<1	878	90.0	133	8.4	65.0	47
1 to 4	67	6.8	217	13.7	77.0	50
5 to 20	24	2.5	236	14.9	82.5	41
21 to 50	3.8	0.4	163	10.3	87.5	20
51-125	2.0	0.2	330	20.8	91.0	30
>125	1.3	0.1	506	31.9	94.0	30
Total	976	...	1585	...	86.2	218
Total electricity generated			2568			

Table 2 Payback Period for High-Efficiency Motors

Input data	Standard motors			High-efficiency motors		
Horsepower	5	25	125	5	25	125
List price, $	340	1230	7425	480	1610	9275
Efficiency, full load, %	83.4	87.9	90.7	89.0	93.0	95.9
Calculation of cost of losses,						
Power output, kW	3.73	18.65	93.25	3.73	18.65	93.25
Power input, kW	4.47	21.22	102.81	4.19	20.05	97.24
Total losses, kW	0.74	2.57	9.56	0.46	1.40	3.99
Cost of losses, $/hr	0.037	0.128	0.478	0.023	0.070	0.200
Payback period calculated						
Price differential, $				140	380	1850
Cost of losses differential, $/hr				0.014	0.058	0.278
Payback period, hr				10,000	6550	6650

Note: NEMA design B, 1800 rpm, TEFC, polyphase. Electricity cost: $0.05/kW·hr.

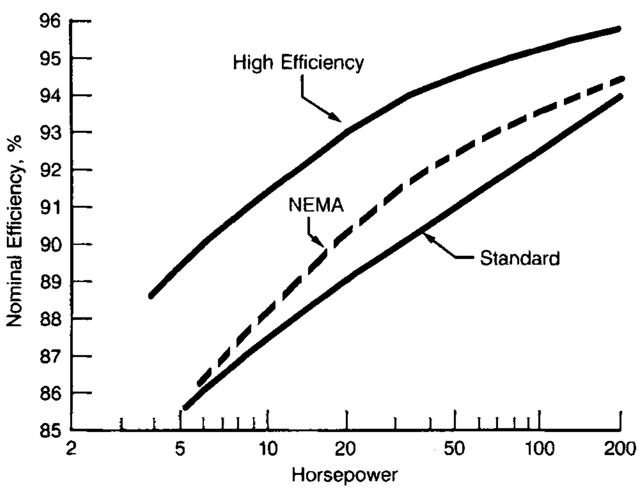

Fig. 1 Efficiencies of motors. Average nominal full-load efficiencies of standard, NEMA energy-efficient and high-efficiency motors. Standard and high-efficiency curves are averages of major manufacturers in the late 1980s. Polyphase, 1800 rpm, NEMA design B, TEFC.

losses thus amount to about 45×10^9 kW·hr/year, or 1.8% of the total electricity generated in the United States. At an average electricity cost of $0.065/kW·hr in 1985 [Table 53, Ref 5], these core losses cost the users of motors about $3 billion/year.

Efficiencies of medium-horsepower motors on the market are shown in Fig.1, which shows the three efficiency levels available.[6,7] High-efficiency motors are 2 to 4 percentage points more efficient than standard motors. Motors meeting the NEMA energy-efficient criteria have intermediate efficiencies. Higher efficiency is achieved by such means as greater quantities of conductor and steel, a better grade of steel, better bearings and fans, and improved slot designs. It appears that perhaps a third or more of the sales of integral horsepower motors built to NEMA standards are high-efficiency models.[8] Both standard and high-efficiency motors have efficiencies today that are 1 to 2 percentage points higher than a decade earlier. Consequently, the efficiencies shown in Table 1 are somewhat low for today's installed motors, and the losses shown are thus somewhat high for the average motors in use today. However, because motor life is on the order of 20 years, the efficiency of the installed motor population changes very slowly, so that the values in Table 1 can be taken to be a reasonable approximation.

A high-efficiency motor has a higher initial cost, but the increased efficiency leads to a lower operating cost. Although a variety of economic analyses are used to determine whether to buy a high-efficiency motor, for the purposes of this paper, the simple payback period is used. The payback period is simply the length of time the high-efficiency motor must be operated before the savings in electricity cost equal the higher initial cost. Although economic criteria differ, a payback period less

Table 3 Annual Hours of Use for Industrial 5- to 125-hp Motors

Annual usage, thousands of hours	Percentage of motors for each period of annual use 5 to 20 hp	21 to 50 hp	51 to 125 hp
<1	21.8	3.6	2.0
1 to 2	59.6	26.6	10.4
2 to 3	7.7	29.7	28.2
3 to 4	5.0	14.3	23.7
4 to 5	2.0	11.2	15.5
5 to 6	1.6	7.4	11.2
6 to 7	0.9	3.8	6.0
7 to 8	0.8	1.6	2.8
>8	0.7	0.8	0.3

Source: Table 1-6, Ref 3.

than 5 years may be considered a good investment. In Table 2, the payback periods for three sizes of a common design of medium-horsepower high-efficiency motors are calculated from the list prices and efficiencies of current motors produced by one manufacturer, using $0.05/kW·hr electricity cost, typical for industrial users. For motors operating at least 2000 hr/year, common for these sizes (Table 3), the payback period is generally less than 4 years, making high-efficiency motors a good investment. Discounting from list prices is common and would lead to a shortening of the payback period shown.

In applications with variable loads such as pumps, the use of solid-state driven adjustable speed drives (ASD) also reduces the overall electricity supplied to motors. It has been estimated that, in 1985, 12% of the motor drives above 7.5 hp were adjustable speed drives.[9] Although the system operates at a higher efficiency under partial load, the motor itself may have on the order of 20% higher loss due to the high harmonic content of the inverter output.[10,11]

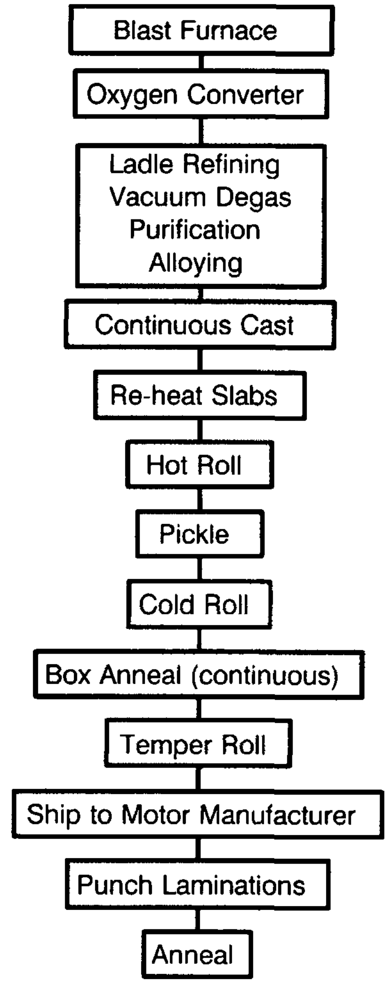

Fig. 2 Motor lamination steel processing. Item in parentheses is used infrequently.

3 Electrical Motor Steels

The United States produces about 1,000,000 tons/year of motor lamination grade and 250,000 tons/year of nonoriented steel. The total value of these steels is about $\$1 \times 10^9$/year. Such steels are used not only in motors, but also in transformers, ballasts, and other electrical apparatus. Although there are no published statistics, it is estimated that 70,000 to 100,000 tons/year are used in 5- to 125-hp motors. A related magnetic material, oriented electrical steel, is produced in quantities of about 250,000 tons/year in the United States.

A flow chart for the processing of motor lamination grade steel is shown in Fig. 2. This product is made by large integrated steel makers, for whom this grade represents a small part of their total production. All steel in this grade is produced in the semiprocessed condition, *i.e.*, the motor manufacturer must anneal it to develop the desired magnetic properties. The anneal decarburizes the steel, produces the desired large grain size, oxidizes the surface to provide electrical insulation, and relieves the punching stresses. The temper rolling produce the critical strain necessary to yield the exaggerated grain growth during the anneal. No coating is applied to this grade by the steel maker. Changes in this product have been described in some detail.[12]

The flow chart for nonoriented steels is shown in Fig. 3. This product is made in the United States by specialty steel makers in both semiprocessed and fully processed grades. The semiprocessed product must be annealed by the motor producer to develop the magnetic properties as described for the motor lamination grade. The antistick coating minimizes welding during the anneal, but is essentially destroyed by the anneal and thus provides no consequential insulation. The magnetic properties of the fully processed product are fully developed by the steel maker, who also applies an insulative coating. This insulation is required for large-diameter motors (greater than about 20 to 25 in., corresponding to 100 to 150 hp) to prevent large current flows between laminations, which result in large I^2R losses.

Magnetic properties are commonly specified under alternating flux conditions at 1.5 T and 60 Hz, conditions used throughout this paper. The standard test is the Epstein, with half the strips cut parallel and half perpendicular to the rolling direction.[13] Ring specimens are superior, because they provide a closer approximation to the flux in motor laminations, but Epstein tests are simpler to carry out. The various grades are de-

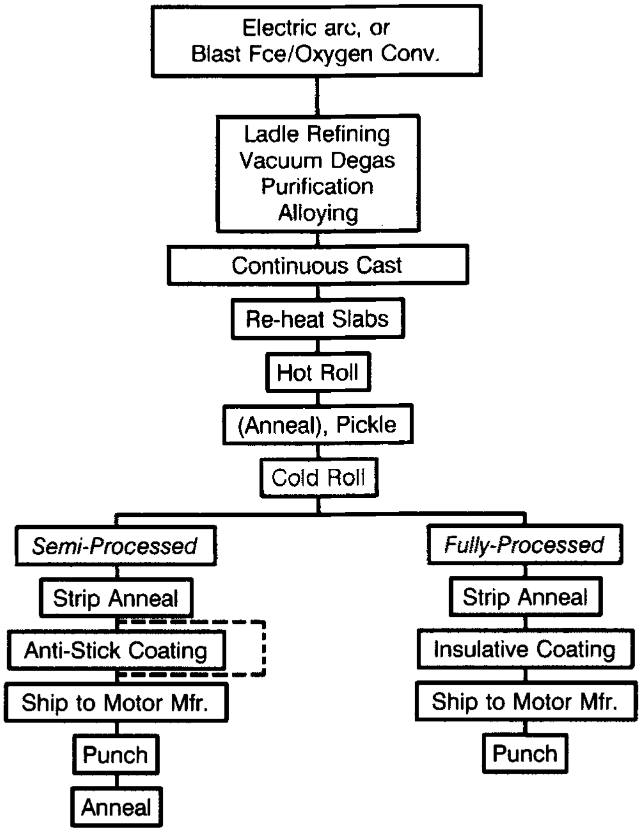

Fig. 3 Nonoriented steel processing. Item in parentheses is not universally used.

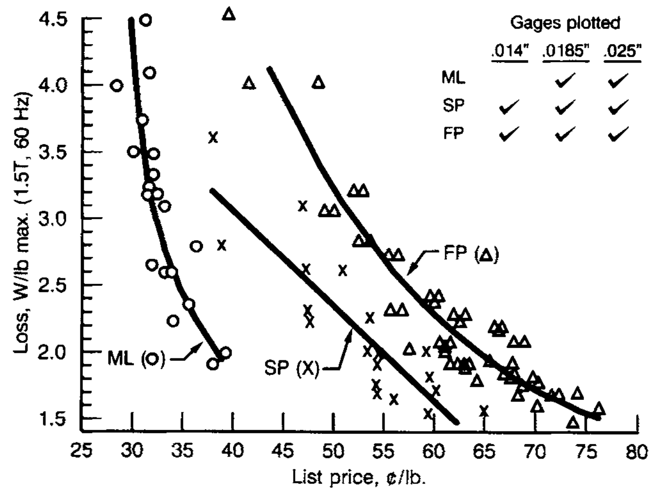

Fig. 4 Loss and price of steels. ML ≡ motor lamination; SP ≡ semiprocessed nonoriented; FP ≡ fully processed nonoriented. Prices are for early 1990. Grade, gage, and coating (fully processed only) extras included.

fined by their maximum core loss by ASTM,[14] AISI,[15] or by the manufacturers. Although the AISI "M" grades have been formally supplanted by ASTM grades, the "M" terminology is still in common use. Losses and permeability are the important magnetic properties. A high permeability is desirable, because it reduces the magnetizing current, which is a source of loss. Permeability is typically desired to be 2000 or above.

The relation between guaranteed maximum losses and the published list prices of electrical motor steels is shown in Fig. 4 for three common gages for the products on the market in early 1990. The prices in mid-1991 were about 5% above those shown. Typical losses are significantly less than the maximum shown in Fig. 4. Discounting from the prices shown may occur. In addition, although a steel may be sold under a particular grade labeling with its associated price, its properties may correspond to a better grade; *i.e,* the customer obtains a better steel than that for which he paid.

Losses are usefully considered in terms of their hysteresis and eddy current components, the latter further divided into classical and excess terms. Hysteresis loss results from fundamental irreversible magnetization processes, which occur even under "dc" conditions. Eddy current loss results from the currents induced in the laminations by the ac field. Classical eddy current loss is that calculated, assuming uniform magnetization (no domains), and excess eddy current loss results because magnetization actually occurs by domain wall motion. These components are typically distributed as follow:[16-19]

Type of steel	Hysteresis loss, %	Classical eddy current loss, %	Excess eddy current loss, %
< 0.5 % Si........	30-50	40-60	0-20
> 0.5% Si.........	55-75	10-30	10-20

Hysteresis loss is the largest component in the high-silicon (high-resistivity) steels. Excess eddy current loss can be consequential in all steels.

The components of loss have the following functional dependencies on induction, B, and frequency, f:[16,20-24]

Factor	Hysteresis loss	Classical eddy current loss	Excess eddy current loss
B................................	$B^{1.6\text{-}2}$	B^2	$B^{1.5\text{-}2}$
f.................................	f^1	f^2	$f^{1.5}$

These dependencies show that lowering the induction lowers the loss, a strategy employed in high-efficiency motors. Note also that high-frequency harmonics increase the loss.

The principal materials factors affecting the magnetic properties are alloy content, gage, grain size, impurities, and texture. Alloy additions, because they increase the electrical resistivity, lower the eddy current loss; the principal elements used are Si and Al, with Mn and P also being added for some steels. Silicon also lowers the hysteresis loss because it lowers the magnetocrystalline anisotropy.[25] On the other hand, these alloying elements lower the magnetic saturation, thus decreasing the high-induction permeability.

Motor lamination steels, once containing only Mn and P as alloying elements, now are being made with significant amounts of Si and Al. Newer motor lamination grades are being developed with Si + Al contents up to 1.5 to 2.0%. Nonoriented

Table 4 Desired Values of Material Factors for Optimum Magnetic Properties

Factor	Permeability	Hysteresis loss	Classical eddy current loss	Excess eddy current loss
Alloy content	Low	High Si	High	High
Gage	No effect	No effect	Thin	Thin
Grain size	Large	Large	No effect	Small
Impurities	Low	Low	No effect	Unknown
Texture	"Cube"	"Cube"	No effect	Unknown

steels rely principally on Si and Al for high resistivity, with a limit of 3.5 to 4.0% Si + Al due to producibility considerations.

A decrease in thickness lowers the eddy current loss, with no effect on permeability and hysteresis loss at normal gages. A thinner gage is more expensive to manufacture, for both the steel maker and the motor manufacturer, and 0.36 mm (0.014 in.) is the thinnest commercial product commonly used for motors.

Grain boundaries are pinning sites for domain walls. Minimizing the grain boundary area, *i.e.*, a larger grain size, thus increases the permeability and lowers the hysteresis loss. However, the excess eddy current loss increases when the grain size increases because there are fewer domains in the large grains to participate in the magnetization. It has been found that a grain size around 150 μm minimizes the sum of the hysteresis and excess eddy current loss components.[26]

Impurities that lead to particles in the steel are important for several reasons. Particles with a size around 0.1 μm are especially deleterious to losses, because they interact most strongly with domain walls, which have about the same thickness.[27] Particles also inhibit grain growth and affect the texture. The most important impurities are C, N, S, and O. It is possible today with good practice to make steel with a limit to each of these impurities of 30 ppm and in many cases considerably lower. The reduction of these impurities has been a major factor in improving electrical motor steels.

Carbon and nitrogen must be low not only to produce low loss initially, but also to prevent aging (the deterioration of magnetic properties due to nitride and carbide precipitation in service). Current electrical motor steels all contain sufficient Al to tie up the nitrogen as AlN and prevent aging. Carbon must be less than 30 ppm to produce a low loss and to prevent aging, and the final anneal has been used to reduce it to this level. However, the decarburizing atmosphere during the final anneal may also internally oxidize the steel, increasing the loss. The carbon can be removed sufficiently by degassing the molten steel so that the final decarburization step could be eliminated, thus lowering the loss, as has been shown for both motor lamination and nonoriented grades.[28-30] There are several implications to such an elimination of the decarburization requirement:

- The steel suppliers would have to guarantee their carbon level in semiprocessed steel.
- The motor manufacturers would have to have the capability of annealing in dry atmospheres.
- The productivity of steel processing would be increased.
- The current oxide insulation would be affected, perhaps requiring a further change in annealing atmosphere or the application of an insulative coating by the supplier.

In a motor lamination, the magnetic flux travels uniformly in all directions in the plane of the sheet, and thus the in-plane magnetic properties are desired to be isotropic. However, iron is very anisotropic magnetically, with the easiest principal direction to magnetize being the <001>, with <111> being most difficult, and <110> being intermediate. For crystal planes, the losses follow the same directionality, increasing in the order:—{100}, {110}, {111}.[31] Some texture is normally developed during processing of electrical motor steels, and the term "nonoriented" is only an approximation. The deliberate increase of the {100} planes parallel to the sheet surface at the expense of the unwanted {111} planes significantly improves the magnetic properties,[18] especially at high inductions.[32]

The ideal texture is the {100}<0vw>, or "random cube," which maximizes the number of easy magnetization directions in the plane of the sheet. Although in many current steels an attempt is made to minimize deleterious components of texture, no current steels approach at all closely this random cube texture. A 3% silicon steel having very nearly this texture was produced[33] about 20 years ago and used in aircraft generators.[1] This steel had a loss less than 2.2W/kg (1.0 W/lb) at a gage of 0.30 mm (0.012 in). This material developed its final texture through surface energy controlled grain growth under conditions where sulfur adsorbed on the surface, making the {100} the lowest energy plane. A tendency toward the random cube texture can also be induced in plain-carbon steels through atmosphere control during the austenite-to-ferrite transformation.[34] In more conventional processing, an increase in purity[31] or the addition of Sb[35] reduces the incidence of {111} grains through minimizing preferential nucleation sites. Even if a {100}<0vw> component is developed, it may be eliminated during further annealing while the grains are growing to the desired size.[26] Thus, there are several known methods to improve the texture of electrical motor steels, but the realization of these in practice is not necessarily straightforward.

The desired values of the material parameters discussed above are summarized in Table 4. The factors are not necessarily independent; for example, development of the desired grain size may depend on the impurity content. Lowest losses are obtained in a steel having high alloy content, thin gage, an optimum grain size, low impurities, and an appropriate texture. For highest permeability, the steel should have low alloy content, large grain size, low impurities, and an appropriate texture. The requirements of lowest loss and highest permeability thus conflict to some extent.

Although the thrust of this paper is motors, most of the above considerations apply also to ballasts and other apparatus. The major difference is the desired texture. In a ballast, an in-

Table 5 Payback Periods for Substituting Existing Better Steels

Base steel, W/lb	Replacement steel, W/lb	Calculated simple payback period, hr 5 hp	25 hp	125 hp
Standard motors using motor lamination grade of steel				
4.50	4.00	310	230	280
	3.00	480	360	420
	2.00	1030	780	920
3.50	3.00	530	400	470
	2.00	1150	860	1020
2.50	2.00	1350	1010	1200
High-efficiency motors using semiprocessed nonoriented grade of steel				
2.30	2.00	5630	5040	6680
	1.50	5660	5080	6720
2.00	1.50	4940	4430	5870
1.75	1.50	4330	3880	5130

plane directional texture may be desired because the flux travels primarily parallel and perpendicular to the rolling direction, rather than in all directions. Thus, it is desired that the density of the <001> directions be maximized in the rolling and cross directions.

Losses are usually measured only under standard alternating in-plane flux conditions at the fundamental frequency. In motors, however, there are regions where the flux rotates, harmonics are present, and there may be out-of-plane fluxes. In addition, there may be strains present from handling and assembling the laminations. All these conditions serve to increase the core losses in motors compared to those measured in the laminations under standard test conditions. These "extrinsic" losses must be considered in selecting the steel to use and in predicting the performance of materials in motors.

Behind the teeth in motors, rotating flux exists. In a 2-hp motor, it was found to cause 21 to 25% of the total core loss.[36,37] The ratio of the rotational loss to the alternating flux loss decreases in nonoriented steel as the induction increases,[38] with an upper limit of the ratio being the sum of the orthogonal alternating-flux loss components.[39,40] Although the desired values of the material factors in Table 4 are expected to hold in general for rotating fluxes, the behavior must be considered in detail. For example, a steel with lower alternating flux loss was shown to have a higher rotational flux loss than another steel at inductions above 1.5 T, which occurred behind the teeth in the particular motor examined.[37]

Harmonic fluxes exist primarily at the tooth tips in motors; as noted previously, these higher frequencies lead to higher losses. These fluxes were found to have frequencies above 500 Hz in a model motor, for which it was suggested that a smaller grain size, producing smaller domains, would lower the high-frequency losses.[37] For inverter-fed adjustable speed drives, the waveform imposed on the motor contains many harmonics. A method for calculating the core loss for any arbitrary waveform has been developed; this method predicted quite well the losses for the fundamental plus third harmonic flux in nonoriented steel.[41,42] This method takes into account the excess eddy current loss, as well as the hysteresis and classical eddy current loss. The use of higher alloy contents and thinner gages minimizes the high-frequency losses.

The I^2R losses in the conductors of the rotor of medium-horsepower are on the order of 15 to 30% of the total motor loss. This loss is eliminated when permanent magnets are used to provide the field. Such "brushless dc" motors have a potential especially in variable speed drives that utilize solid-state inverter power supplies. For this application, the use of higher alloy contents and thinner gages minimizes the losses produced by the high-frequency components of the power supply output.

4 Economics of Using Improved Steels

Use of a lower loss, more expensive steel is economically justified only if the resulting reduced operating cost offsets the higher initial cost of the motor sufficiently so that the total cost of owning the motor over its lifetime is reduced. Such "life-cycle" cost calculations are done by an increasing number of purchasers of motors, but there are many who do not do so. If rational economic judgments were always made, significantly more motors purchased today would be high-efficiency designs.

To estimate the savings that could result from the use of better steels, several assumptions were made: (1) the performance of a steel in a motor is directly related to its measured properties, (2) the curves in Fig. 4 describe the loss-price relation, (3) the increased cost of the steel is passed through to the motor purchaser, (4) a lamination is blanked from a square of steel whose sides equal the diameter of the stator, with the production of the squares from the coils being scrapless, and (5) core losses are 20% of the total loss of a motor. In practice, each of these assumptions may be violated to some extent. Both standard and high-efficiency motors were considered. Because many of these are used in industrial applications, a typical industrial electricity cost of $0.05/kW·hr was used. List prices and efficiencies of 5-, 25-, and 125-hp motors in effect in 1990 were used as a base. Standard motors were assumed to use motor lamination grade and high-efficiency motors to use semiprocessed nonoriented grade.

Using the assumptions stated in the preceding paragraph, payback periods were calculated for replacing a given steel with a better grade, with the results shown in Table 5. Optimization of motor design using the better material will result in shorter payback periods than those shown. The payback period when a base steel is replaced by a better motor lamination steel in a standard motor is generally less than 1000 hr of use, which most motors in this size range exceed in 1 year, as shown in Table 3. The payback period for using a better grade of semiprocessed nonoriented steel in a high-efficiency motor is on the order of 5000 hr, which a large majority of motors in this size range exceed in 3 years of operation. These numbers are, of course, approximate because of the assumptions made. They show, however, that it is nearly always cost-effective to use the best material possible for laminations in medium-horsepower motors, a conclusion also reached when designs are optimized.[43]

A calculation was also performed, using the same assumptions, to determine the average payback period if all 5- to 125-hp motors used a steel having 10% lower loss than at present, assuming that equal amounts of motor lamination and semiprocessed nonoriented grades are used. The calculated operating cost of the motors would be reduced about $100,000,000/year, and the payback period would be about 1 year. This calculation shows, as did the calculations in the previous paragraph, that better lamination steels make economic sense.

The results may be extended somewhat to smaller and larger sizes of motors, as well as to other equipment such as ballasts. However, to the extent that a lower loss is accompanied by a lower permeability, the conclusion that lower loss steels *per se* are "always" economically justified may not be warranted. For example, in a single-phase fractional horsepower motor, increasing the Si + Al content lowered the loss in Epstein tests, but increased the total loss in the motor. Although the iron loss was lowered in the motor, the copper loss was increased due to the lower permeability of the higher alloyed steels.[44] For larger motors, the gains would be less because the efficiency improvements possible are also less. Other considerations such as the need to minimize heat generation to prevent excessive temperature rise may also justify the use of lower loss materials.

5 Further Lowering of Core Loss

As discussed above, better steels are usually economically justified. However, unless the motor user is willing to pay more for a better motor that has a lower life-cycle cost, the motor manufacturer has no incentive to use the better material. No technological change is required to reduce the total losses, including core losses, in motors. The only action required is for motor purchasers to order higher efficiency motors. Various strategies are employed to encourage users to purchase high-efficiency motors, *e.g.*, education and rebates by the electric utilities. Although the federal government has not set standards on motor efficiency at this time, appliances and fluorescent lamp ballasts now must meet legislated efficiency standards, with better core materials being used to help meet these standards.

A further reduction of the average loss levels of the steels now used would occur if all steel producers and motor manufacturers simply improved their processes in ways that are known and are technologically feasible. For example, increased utilization of processes to produce the lowest impurity levels would reduce the average loss of all steels. Also, elimination of the final decarburization step would lower the loss; the requirement is that the carbon be reduced below 30 ppm in the steelmaking process. Equipment is not universally in place to accomplish these goals at this time.

The development of even better steels and determination of the best steel for a given application would be greatly assisted if there were increased knowledge of the quantitative relation between material tests and motor performance. The studies on this subject are very limited in scope. A complete metallurgical and magnetic characterization of a range of steels and their performance in integral-horsepower motors is required, with sufficient replication of tests to ensure confidence in the results. The fluxes in various parts of the motor must be known, including rotating and harmonic fluxes; the materials need to be evaluated for these same flux conditions.

What are the prospects for a very significant reduction in loss in electrical motor steels? For example, could a steel with a loss at 60 Hz of 2.2 W/kg (1.0 W/lb) and a permeability of 2000 be made at a gage approaching 0.47 mm (0.0185 in.)? Such a loss level is on the order of one third less than the current best material. Texture would certainly be a major consideration in the development of such a steel. Purity and variations in Si, Al, and Mn would be important factors. Scribing of the surface to reduce excess eddy current losses as is practiced for some grain-oriented steels might remove the current constraint that the grain size be no larger than about 150 μm. Thin-strip casting technology is a new process that could affect the results, *e.g.*, by the development of an as-cast texture that would affect the final texture. It is impossible to say at this time whether such a steel can be made and produced economically, but if it could the economic consequences could be great.

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