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Viewpoint Paper

Energy efficient electrical steels: Magnetic performance prediction and optimization

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Abstract—Magnetic losses in electrical steel cores account for 5–10% of all electrical power generated, despite continuous improvements to their magnetic properties. This paper emphasizes the needs for greater appreciation of the limitations and oversights in present magnetic characterization and also in methods of loss prediction which do not take account of magnetization processes. Possible approaches which might lead to reduced losses in electrical steels exploiting our increasing understanding of relationships between magnetic properties and microstructure are discussed.
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Keywords: Soft magnetic materials; Iron alloys; Microstructure; Magnetic domains

1. Introduction

Almost 97% of soft magnetic materials produced today are electrical steels [1]. Over 12 million tons are produced annually, around 80% of which are non-oriented (NO) grades, the remainder being grain-oriented (GO) 3% silicon steels. The increasing global demands for efficient electrical power generation and distribution equipment are strong drivers for the development of steels with lower magnetic losses and higher permeability. Magnetic losses in electrical steel cores account for 5–10% of all electrical power generated in developed countries [1], despite continuous improvements over many decades, as shown in Figure 1. It is interesting to note that the occasional more rapid improvements shown in the figure are due to the introduction of new processes in the steel production and processing route, in contrast to the major step improvements found in permanent magnets, which have resulted from the discovery of completely new families of materials [1].

NO grades usually contain around 0.2–3.3% silicon (balance iron) and are produced as wide strip, 0.30–0.65 mm thick. Their magnetic properties are similar when magnetized along any direction in the plane of a sheet. The main application is for magnetic cores of rotating electrical machines.

GO grades contain around 3.2% silicon and are mostly produced as a 0.28–0.35 mm thick strip. The special feature of GO steel is the presence of large grains, up to more than 10 mm diameter, most with a [1 0 0] direction close to the direction in which the strip has been rolled (RD), with their (1 1 0) planes close to the plane of the sheet. This leads to far better magnetic properties when magnetized along the RD rather than when magnetized alone the transverse direction (TD) or intermediate directions. An electrically insulating coating is applied to the surface of GO steel partly to induce a tensile stress which enhances its magnetic properties. GO steels are divided into conventional grain oriented (CGO) and highly grain oriented (HGO) grades. HGO material is produced via a more complex production route which results in more controlled grain growth during high-temperature annealing. This leads to larger grains that are on average much closer to the ideal [0 0 1](1 1 0) orientation, giving the steel much higher permeability than CGO [2]. The main application of GO steel is for energy-efficient power transformer cores.

For many applications, steels must have low losses, high permeability and high saturation magnetization, together with acceptable physical properties. Today, emphasis is placed on improving consistency and productivity, but there is also a growing customer call for reduced losses and increased permeability. There are incentives for developing competing energy-efficient materials, possibly by scaling up production of iron-based amorphous alloys,

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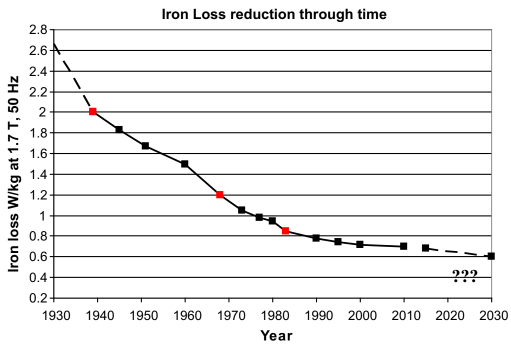

Figure 1. Losses (at 1.7 T, 50 Hz) in highest available grades of commercial electrical steels produced since 1930, showing occasion rapid improvement due to the introduction of new technology.

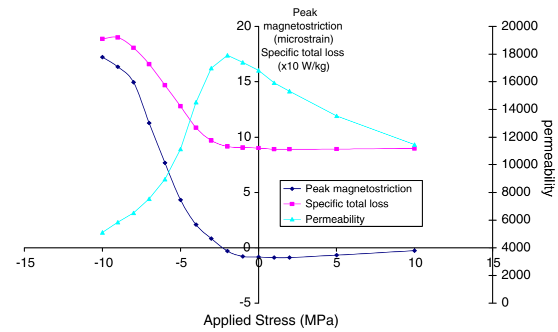

Figure 2. Variation of loss, permeability and magnetostriction of an Epstein strip of typical GO steel magnetized (1.5 T, 50 Hz) along its longitudinal direction (RD) while external stress is applied simultaneously along the same direction. The harmful effect of compression is clearly demonstrated.

microcrystalline materials, high silicon alloys, etc. [3]. The magnetic properties of some of these materials are potentially far superior to those of electrical steels, but the higher basic material cost and the necessary large investment in innovative production plant mean these are unlikely to be produced in the foreseeable future. Hence advances in soft magnetic materials for general use in energy-efficient power applications are likely to come from incremental improvements in traditional electrical steel technology, which should result from steel makers capitalizing on their increasing ability to manipulate and control microstructure and composition, underpinned by the increasing understanding of how they control magnetization and loss processes.

2. Characterization of losses in electrical steels

In order to develop models to accurately predict losses, or to quantify the controlling effect of metallurgical and other physical features, it is necessary to take account of possible inaccuracies in loss measurements which are usually ignored in commercial grading of electrical steels. The steels are mainly used under AC magnetization conditions, so their magnetic properties are assessed by testing under sinusoidally time varying flux density, with peak values of 1.5 or 1.7 T at 50 or 60 Hz in the IEC standard Epstein square or a single sheet tester (SST) [4], which are well established methods for commercial grading of electrical steel. However, the use of the Epstein square as a research tool for investigating loss mechanisms is limited, and in some cases misleading, since it does not give an accurate reference or absolute value of loss under specified ideal magnetizing conditions.

The most significant error is caused by the specification in the standard that a fixed value of the magnetic path length of the Epstein square should be used, even though it has long been known that it varies with material composition and with magnetizing conditions [5]. Recent reports demonstrate that treating this as a constant leads to significant errors when comparing the losses of even similar grades of steel [6]. In the worst scenario, although highly reproducible, the loss indicated by the Epstein square may be 5–10% different from the absolute value.

In electrical machine cores, factors such as mechanical stress, flux harmonics and rotational magnetization increase lamination losses to differing extents in different grades of steel, so it is important to be sure that they will not outweigh the improvements in basic material characteristics indicated by the Epstein test. The effects of these harmful factors can be minimized by careful magnetic core design and construction, but they still increase core losses by typically 10–30%.

In particular, losses and other structure sensitive magnetic properties can be extremely sensitive to mechanical stress [7]. Since it is very difficult to eliminate many of the sources of stress in electrical machine cores, it is necessary to take account of stress sensitivity curves such as those shown in Figure 2, and to ensure that the stress characteristics of proposed new steels are at least as good as those of existing materials. It is difficult to directly apply such characteristics to core loss prediction since the stress in a large core is randomly distributed in magnitude and direction to the extreme where localized compressive stress can even be beneficial [7].

The deficiencies in the Epstein square and SST as absolute methods of characterizing electrical steels are widely recognized and generally accepted by users. The simplest solution would be to develop a standard approach based on direct measurement of the magnetic field and flux density in the region of interest based on the Rogoski – Chattock potentiometer concept [8].

3. Traditional approach to analysing losses in electrical steels

It has proved useful for many years to divide losses into hysteresis and eddy current components to help understand the influence of controlling factors and also as a tool for predicting losses in electrical machine cores. The loss per cycle W, at magnetizing frequency f and peak flux density B_m, is commonly expressed as the sum of the static (DC) hysteresis loss W_h, the classical eddy current loss W_{cl} and the excess loss W_{exc}, and is written in forms such as:

$$W = W_h + \frac{d^2 \cdot \pi^2 \cdot B_m^2}{k \cdot \rho} \cdot f + C_3 \cdot B_m^{1.5} \cdot f^{0.5} \quad (1)$$

where d is the sheet thickness, ρ is the electrical resistivity, k is a magnetization waveform-dependent constant and C_3 is a material-dependent fitting parameter.

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