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Effect of metallurgical factors on the bulk magnetic properties of non-oriented electrical steels

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ABSTRACT

Non-oriented electrical steel (NOES) is one of the most common material used in electrical motors. Core loss and permeability are the most important properties that the motor manufacturers look for. Both these properties are structure sensitive and depend on several metallurgical factors; such as chemistry, grain size, crystallographic texture, cleanliness and stress states in non-oriented electrical steels. It has been observed in this course of the study that the grain size and Si content of NOES are the primary controlling factors to core loss, especially at higher frequencies. On the contrary, crystallographic texture plays an important role at lower frequencies. At higher frequency, core loss increases with increasing grain size and decreasing Si content of the steels. Small difference in grain size ($\sim 50\ \mu m$) at lower frequency range has little influence on the magnetic properties but has significant adverse effect as frequency reaches high enough.

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1. Introduction

Electrical steels play an important role in the generation, transmission and distribution of electrical power and are among the most important magnetic materials produced today. These steels are essentially Fe–Si alloys with varying Si percentage (normally 1–3.5%) and possess certain magnetic properties which allow them to be employed as the flux carrying core of the electrical machines; such as transformers, electrical motors, etc. Depending on the requirement of magnetic properties, electrical steels can be classified into two broad categories; Grain oriented electrical steel (GOES) and non-grain oriented electrical steel (NOES) [1]. Grain oriented electrical steels are mainly used in the core materials of transformers and are designed in such a way that they have highly improved magnetic properties (e.g. high permeability, low core loss) along one direction (normally along rolling direction (RD)). On the contrary, non-oriented electrical steels are used in electric motors where the magnetization vector changes its direction continuously with time. This application thus demands uniform magnetic properties along the strip surface, not in a specific direction like GO electrical steels. This enables the magnetic NOES rotor core (as in the case of motors) to achieve a low average core loss value [2,3]. The non-oriented electrical steels share 80% of the world's total electrical steels production [4].

Electric motors and drives become increasingly popular in various modes of transport, whether it is road, aircraft, marine or rail. The hybrid electric car gives fuel economy advantage over the conventional ones whereas the replacement of hydraulic and mechanical systems with electrical alternatives in aircrafts increases the efficiency of the pumping system and reduce the overall mass of the aircrafts. The most rail systems worldwide are now electrically driven with induction motors drives whereas in marine transports, ships engine now drives a generator which in turn feeds the propeller. According to US Department of Energy, electric motors consume over half of all electricity generated. The relatively high efficiency of electrical motors along with their environment friendliness makes them one of the most desirable choices for these applications [5,6].

A new proposed efficiency class in Europe (IE4) [IEC 60034-30] requires significant improvements in efficiency over existing equipment, e.g. for a 75 kW motor, losses must be reduced by more than 50%. As a result, it is important for motor manufacturers to have an improved understanding of the relationship between microstructure, manufacturing processes and macro-magnetic properties of electrical steels.

Typical magnetic properties of interests for a motor manufacturer are the core loss and the permeability [7,8]. Both these properties are structure sensitive and depend on several metallurgical factors; such as chemistry, grain size, crystallographic texture, cleanliness and stress states in non-oriented electrical

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steels [7–9]. Traditionally, core loss (or iron loss/watt loss) is divided into two components; hysteresis loss and eddy current loss. However, effect of metallurgical factors on these two components does not always follow similar trends and very often an optimum value of these metallurgical variables (e.g. grain size) is required to achieve best magnetic properties in NOES.

Chemistry is a primary factor that affects magnetic properties. While low carbon content ($C\% < 0.01$ wt%) is essential for NOES, it is the Si percentage that primarily dictates the core loss. Si decreases magneto-crystalline constant which is directly proportional to hysteresis loss and increases resistivity which is inversely proportional to the eddy current loss. The net result is a decrease in core loss with increasing Si content. However, Si reduces the saturation magnetization which in turn decreases permeability [2,10]. Thus depending on the requirements, Si percentage can be optimized in NOES. Aluminum has similar effect to Si [10,11], but to a lesser degree. Al is believed to influence the core loss by grain coarsening, texture [12] and/or by changing the amount and distribution of the impurities [12–14]. Phosphorus and Mn are reported to decrease the core loss by reducing the eddy current component of the loss [7]. Interstitial elements in steel like C, S, O and N, are considered to cause lattice distortion and this way decrease permeability. Apart from that, they can form small particles along with other elements (such as Fe, Mn, Al, etc.) and affect the magnetization process by pinning domain movement [15]. However, few researchers [13,16] have observed that higher content of O, N and even S results in a better core loss (i.e. low) which is attributed to formation of coarse precipitates/inclusions and their sparse distribution in the matrix.

Grain size has opposite effects on hysteresis and eddy current components of the core loss; while hysteresis loss decreases with increasing grain size, eddy current loss increases. As a result of these, the core loss reaches a minimum at some optimum grain size. However, the optimal grain size varies with chemistry and texture in these steels [1,2].

Crystallographic texture is another important variable to control magnetic properties in NOES. The (200) planes show the lowest core loss while (211) and (111) planes show the highest loss [2]. This is a well-known fact that ⟨100⟩ directions are the easy axis of magnetization while ⟨111⟩ is the hardest [17]. Crystal planes with (100) and (110) orientations posses two and one ⟨100⟩ direction, respectively while (111) and (211) planes contain none. Moreover, (211) planes contain ⟨111⟩ direction, the hard direction of magnetization. This is why (100) planes have the lowest core loss followed by (110) and (111) planes for a constant field intensity value. The loss is the highest in case of (211) oriented planes as these planes not only contain any ⟨100⟩ easy magnetization direction but also contain ⟨111⟩ direction, the hard direction of magnetization. In rotating applications the flux lines are more or less distributed in the laminated sheets. Thus in rotating applications such as motors, the useful texture to be developed is the cube fiber texture, in which the {001} planes are parallel to the rolling plane. This configuration gives rise to low average core loss in NOES.

The cleanliness is determined by the presence of second phase particles in the iron matrix; lower their fraction, the cleaner are the steels. These particles are essentially formed by the chemical reactions taking place between the elements present in steels. The elements are sometimes intentionally added as alloying elements (such as Si in this case) or may be present simply as impurities (such as N in steels). These second phase particles act as pinning sites to the movement of domain walls in electrical steels and results in higher core loss and lower permeability. They can also affect grain size and texture of these steels. The effect of these second phase particles on the magnetic properties is dictated by their size, shape, type and distribution. It is observed that the particles with size distribution from 0.1 μm to 1 μm in diameter are the most harmful [7].

Residual stress influences the magnetization process by interacting with magnetic domain walls and in this way affect the core loss and the permeability of the NOES. Depending on the nature of the stress present, the magnetic properties can be either improved or become worse. For example, presence of tensile stress generally decreases core loss while compressive stress increases it [2].

Research is being carried out to predict magnetization behavior of NOES materials by quantitatively modeling the hysteresis loops. Very often this involves metallurgical variables as inputs. In order to build a sound and consistent model, effect of each individual parameters on magnetic properties (such as core loss and permeability in this case) has to be known. Unfortunately, the sole effect of single variable on magnetic properties is often missing in the published literature. This is because of the mutual effect of variables on each other and their synergistic influence on magnetic properties. For example, Shiozaki and Kurosaki [18] pointed out the difficulty to derive grain size effect on magnetic properties. In their case, employing different processing conditions to obtain variable grain size not only altered grain size but at the same time modified texture. This is also responsible for change of optimum grain diameter with Si percentage to obtain minimum core loss. There was hardly any report on the consequence of these variables on the magnetic behavior at higher frequency for NOES. The other gray area is the representation of texture to realize its true effect on NOES properties. Thus the aim of the present study is to compare steels with variation in single parameter while the differences in rest of the variables are negligibly small. To facilitate this, an in-depth characterization of a series of as-received steels, both metallurgical and magnetic, are conducted followed by an attempt to explain the magnetic behaviors with respect to their metallurgical variables using magnetic domain concepts.

2. Experimental methodology

Four grades of as-received steels are considered for the current work. The steels are selected such a way that the effect of composition, grain size and texture on magnetic properties can be understood in a best possible way. However, the effect of residual stress cannot be evaluated in this study due to absence of any significant residual stress in the as received steels; both non-stress relieve annealed (Non-SRA) and stress relieve annealed (SRA). The following section will summarize the experimental results obtained in the present study.

2.1. Chemistry and grain size

The as-received steels were first subjected to ICP-AES and the combustion technique to determine their chemical compositions. Prior to testing, the surface coatings from both sides of the samples were completely removed by grinding followed by cleaning with acetone. The ASTM standards (E1479 and E1019) [19,20] were followed to determine the chemical compositions. Grain size measurements were carried out on the top surface of the as-received samples and mounting them in epoxy. Like chemical composition, here also the surface coating was completely removed by coarse grinding followed by fine grinding in 400, 600, 800 and 1200 grit SiC papers and polishing in 3 μm and 1 μm diamond paste to obtain a mirror-like finish. Subsequently, the samples were etched in a 2% Nital solution to reveal the grain structure. Images were captured at 50 × magnification using a Nikon Epiphot 200 optical microscope equipped with Clemex Image Analysis software. The grain size measurements were performed according to ASTM E112-12 using the Heyn Lineal

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