Journal of Magnetism and Magnetic Materials 365 (2014) 14–22

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Effect of crystallographic texture on the bulk magnetic properties of non-oriented electrical steels

Pampa Ghosh [a,*], Richard R. Chromik [a,*], Babak Vaseghi [b], Andrew M. Knight [b]

[a] Department of Mining and Materials Engineering, McGill University, 3610 University Street, Montreal, Quebec, Canada H3A 0C5
[b] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2V4

ARTICLE INFO

Article history:
Received 20 August 2013
Received in revised form
29 January 2014
Available online 26 April 2014

Keywords:
Non-oriented electrical steel
Crystallographic texture
Magnetic property
Texture parameter
Texture factor
Magnetic texture factor

ABSTRACT

Quantitative physical models for non-oriented electrical steels require precise knowledge of chemical and microstructural parameters for the material, with crystallographic texture being one of the most important. Describing the structure–property relationships in these materials is made difficult in that all of the parameters have an effect on magnetic properties. In the present study, a set of non-oriented electrical steel specimens are examined, where chemistry and grain size are kept similar from sample to sample, but texture is varied. A new texture parameter called *Magnetic Texture Factor* is introduced which is defined as the ratio of the volume fractions of $\langle 100 \rangle$ direction to $\langle 111 \rangle$ direction along magnetization vector. It was found that this *Magnetic Texture Factor* was a better parameter for identifying trends of magnetic properties with crystallographic texture than the often used *Texture Factor*, which is described as the ratio of the volume fractions of {100} planes to {111} planes.

1. Introduction

Electric motors and drives have become increasingly popular in various modes of transport due to their high efficiency and environment-friendliness [1,2]. These machines require a magnetic core with uniform magnetic properties due to their continuously changing magnetization direction with time. Non-oriented electrical steels (NOES) are well suited and vastly used for this purpose. Unlike their oriented counterpart, they possess relatively uniform magnetic properties along all the directions of the sheets. The non-oriented electrical steels share 80% of the world's total electrical steels production [3].

Many models for the hysteresis behavior of NOES exist [4–9], but only some of them attempt to make connections; mostly qualitative, between materials related parameters and the magnetic properties and features of the hysteresis curves [5,9]. It is difficult to construct a material-based model for magnetic behavior because it is difficult to isolate the effect of individual parameters on the magnetic properties. Many of the materials parameters have a mutual and sometimes synergistic effect on the magnetic properties. From a materials standpoint, the isolation of the effect of each parameter is further exacerbated by the fact that the processing of NOES to obtain one parameter (e.g. a particular grain size) will inevitably affect another parameter (e.g. the crystallographic texture).

In order to build robust and reliable models, metallurgical parameters should be used as inputs, where the effect of each individual parameter on magnetic properties (e.g. core loss and permeability) must be known. The metallurgical factors which influence these properties are chemistry, grain size, crystallographic texture, cleanliness and residual stress [10–12]. The effect of grain size and chemistry on the magnetic properties of NOES is known in terms of general trends and expected optimum values. For instance, hysteresis loss decreases and eddy current loss increases with increasing grain size. An average grain size of $\sim 150\ \mu m$ is often considered optimum for NOES to obtain minimum core loss [13,14]. Addition of Si (and Al) decreases the magneto-crystalline constant, which is directly proportional to hysteresis loss. But Si and Al also increase electrical 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 [14]. Thus, depending on the requirements, Si percentage can be varied to optimize the magnetic properties in NOES.

Another important variable that affects the magnetic properties is the crystallographic texture. Unlike grain oriented electrical steels (GOES), NOES do not have a very strong preferred orientation and it is almost impossible to vary their texture without changing either grain size or chemistry. This leads to the difficulty

* Corresponding authors.
E-mail addresses: pampaghosh@gmail.com (P. Ghosh), richard.chromik@mcgill.ca (R.R. Chromik).

http://dx.doi.org/10.1016/j.jmmm.2014.04.051
0304-8853/

Table 1
Chemical composition of studied steels (mass %).

Steel	C	Al	Si	O	Other elements (Mn, P, N, S, Cr, Co, trace elements)	Balance
B1L /B1C	0.007	0.54	3.27	0.007	< 0.3	~Fe
B1SRAL/B1SRAC	0.006	0.53	3.26	0.006		
B3L/B3C	0.007	0.26	2.81	0.006		
B3SRAL/B3SRAC	0.007	0.25	2.78	0.018		

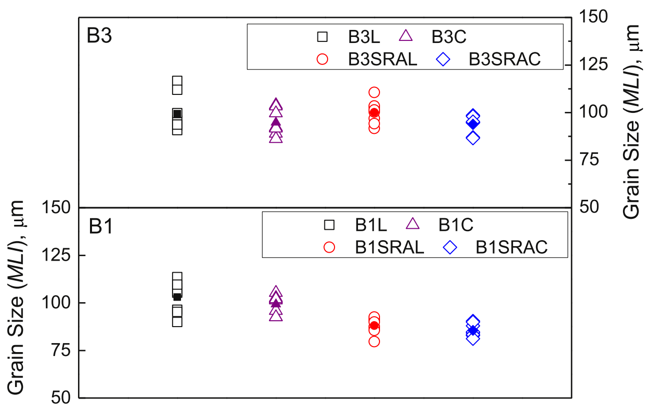

Fig. 1. Grain size distribution of studied steels. The open symbols represent the grain size in mean lineal intercept according to ASTM E112-10 using the *Heyn Lineal Intercept* procedure. For each type of samples (i.e. B1L) eight randomly chosen specimens were selected whose average is represented by the respective solid symbol. For B1 the average grain size varies between 85 and 103 µm whereas it is 94–100 µm for B3.

of extrapolating the knowledge obtained in GOES to NOES as far as the texture is concerned. For example, the well-known Goss component ({110}⟨001⟩) is responsible for the superior magnetic property of GOES. However, it is the Θ or cube fiber (i.e. {100}⟨*uvw*⟩) which is considered ideal for NOES [15]. For many years, researchers have been trying to define the precise effects of texture on the magnetic properties in order to predict the magnetization behavior of these steels [12,15]. Yet, as described above, these efforts are often made difficult as there are always effects from other metallurgical variables to consider as one compares one sample to another. It is also the case that most studies on texture effects were conducted at low frequency.

Recently, the present authors studied the effect of metallurgical parameters (i.e. texture, grain size and chemistry) on the magnetic properties of NOES at different inductions as well as with varying frequencies [16]. The study revealed that it was quite difficult to isolate the effect of one parameter. In the case of a texture effect, isolation was not possible for magnetic properties at higher frequencies even for the small differences in grain size (~50 µm) and composition.

In the current work, a set of NOES specimens were investigated primarily in terms of the effect of crystallographic texture on magnetic properties, where all other material parameters were kept similar amongst the samples and where differences exist, were smaller than in previous studies [12,15]. Core loss and permeability were determined and their dependence on texture was explored at different frequencies. Through this research a new texture parameter called the *Magnetic Texture Factor* (MTF) was defined and found to explain well the effect of varying crystallographic texture on the magnetic properties of NOES.

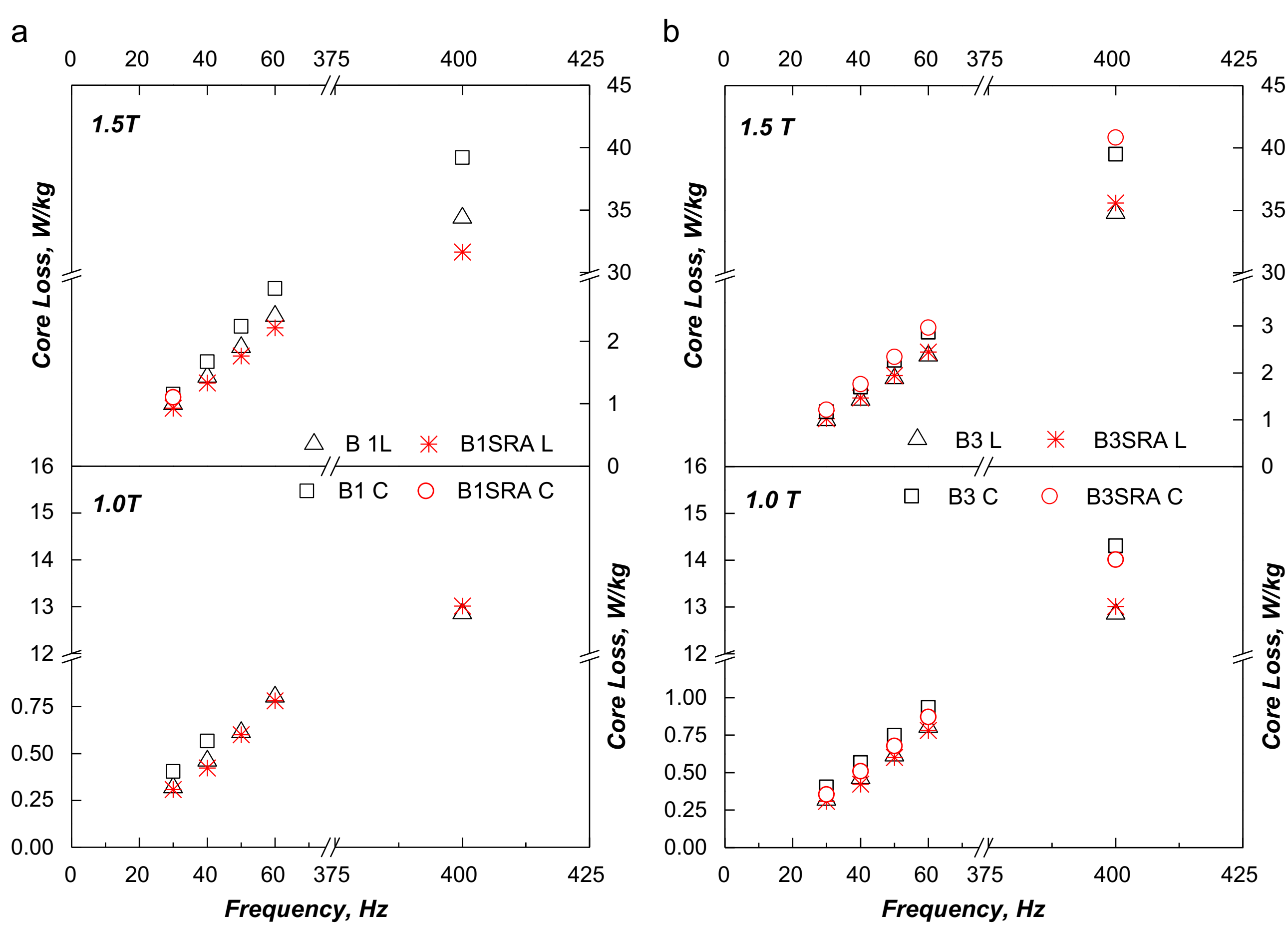

Fig. 2. AC core loss is plotted against varying frequencies measured at two different inductions for steels: (a) B1 and (b) B3. Core loss continuously increases with increasing frequency.