Simulation and Statistical Approaches on Electrical Steel's Magnetic Behaviour under Unidirectional Single Sheet Tester

(Pendekatan Simulasi dan Statistik ke atas Kelakuan Magnet Keluli Elektrik di bawah Satu Arah Penguji Kepingan Besi Tunggal)

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ABSTRACT

Evaluation of magnetic properties of electrical steel is vital in improving the quality of electrical machinery since it is used as magnetic cores for transformers, motors and generators. A double yoke single sheet tester (SST) was modeled using two identical C-cores wound with copper wires at limb side in horizontal arrangement. The magnetic properties for electrical steels, grade M4 and M19 were tested under a frequency of 50 Hz with the current ranging from 0.2 to 2.4A. The effects of the sample dimension and anisotropy on magnetic measurements were investigated. Evaluation on specimen dimensions indicate that the non-uniformity of sample magnetization in overhang sample can attribute to the flux leakage between the yoke legs. The stray flux is also increased with the overhang sample. However, the so-called fit-in sample which is fitted nicely between the yoke end poles can minimize the effect of stray flux. One way ANOVA and T-test were used as statistical methods and executed at the 5% significance level. It is statistically proven that the magnetic properties of both magnetic materials are influenced by their anisotropy.

Keywords: Anisotropy; magnetization; single sheet testerelectrical steel; stray flux

ABSTRAK

Penilaian sifat magnet keluli elektrik penting dalam meningkatkan kualiti jentera elektrik kerana ia digunakan sebagai teras magnet untuk transformer, motor dan penjana. Penguji kepingan besi tunggal (SST) yang diperbuat daripada dua teras-C yang sama saiznya, dililit dengan wayar tembaga di bahagian teras anggota secara mendatar. Sifat magnet keluli elektrik, gred M4 dan M19 diuji pada frekuensi 50 Hz dengan arus pada kadar 0.2 kepada 2.4A. Kesan dimensi sampel dan anisotropi ke atas pengukuran magnet dikaji. ANOVA satu hala dan ujian T digunakan sebagai kaedah statistik pada tahap kesignifikanan 0.05. Hasil statistik membuktikan sifat magnet untuk bahan magnet dipengaruhi oleh anisotropi bahan. Penilaian ke atas dimensi sampel menunjukkan ketidakseragaman pemagnetan sampel dalam sampel terjuntai yang mengakibatkan kebocoran fluks di kaki dening. Fluks yang terkeluar bertambah dengan penggunaan sampel terjuntai. Walau bagaimanapun, penggunaan sampel yang padan di antara hujung kaki dening berupaya mengurangkan kesan fluks yang terkeluar.

Kata kunci: Anisotropi; kebocoran fluks; keluli elektrik; pemagnetan; penguji kepingan besi tunggal

INTRODUCTION

Electrical steel sheets are widely used in many alternating current (AC) applications as a result of their ability to enhance the flux produced by an electrical current. They are indispensable in satisfying the basic requirement in society such as in electrical power generation and transmission, the storage and retrieval information and telecommunications (Fiorillo 2010; Pluta 2010).

Grain oriented (GO) silicon irons are used in large quantities in the electrical engineering industry. They are produced in so-called conventional form, a high permeability material with improved texture and coating or after special surface treatment, a high performance domain refined grade. The silicon level ranges from 2.9 to 3.2% in the GO steels. 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. This yields anisotropic properties and it is useful for stationary applications where the magnetic flux has a static and non-changing direction.

Non-oriented (NO) electrical steel contains around 0.2 to 3.3% silicon (balanced iron) and are mostly produced as a 0.30 to 0.65 mm thick strips. Their magnetic properties are similar when magnetized along any direction in the plane of a sheet, which makes it isotropic. They are implemented where efficiency is less important and towards high magnetic efficiency for use in applications where increased material cost was offset by higher efficiency. They are commonly used in large rotating machines, including electric motors, AC alternators and power generators where the direction of magnetic flux is random (Moses 2012).

As demand increased for the efficient electrical power generation and distribution equipment, it is necessary to characterize the magnetic properties of electrical steels. This study examined and analyzed their magnetic characterization under unidirectional SST which include factors of sample dimension and anisotropy of the magnetic material using simulation and statistical approach.

MATERIALS AND METHODS

A two dimensional cross-section of SST geometry was constructed inside finite element method magnetics (FEMM) interface, which included the double yoke of C-core, coil windings and sample under test. The laminated C-cores with thickness of 68 mm were positioned horizontally with the sample placed between them. Each limb side of yokes wound with 180 turns of enamelled 18 SWG copper wires. The double yokes formed a magnetic circuit that is driven by magnetizing coils at a frequency of 50Hz, with currents in the range of 0.2 to 2.4A. The air gap was inserted between the end pole faces and sample to achieve homogenous magnetization conditions.

FEMM software is used to analyze the magnetic properties of silicon iron steel sheet under one dimensional magnetizing system. It implies a finite element method, which uses Maxwell's equation as the basis of the electromagnetic field analysis. The magnetic characteristics of electrical steels are determined by considering the magnetic flux density, B and the magnetic field strength, H of the material in the direction of an applied magnetic field.

The effect of variation of sample's dimension was investigated on 0.28 mm thick of GO steel, grade M4. The samples were designed with an additional length about 30 and 60 mm at both ends of the former sample with a dimension of $(97.2 \times 93.4 \times 68)$ mm. The fit-in and overhang samples were assigned as LO = 0 mm, LO = 30 mm and LO = 60 mm, respectively. Anisotropy of electrical steels was investigated on 0.5 mm NO silicon iron steels, grade M19 and 0.28 mm of 3% GO silicon iron steel, grade M4.

Statistical analysis was performed to observe the statistical significance of samples dimension and anisotropy to the magnetic properties of electrical steels. The data were analyzed by using SPSS, Version 12.0. One way ANOVA and pooled T-Test were executed at the 5% significance level. Normality of data was examined by performing a correlation test for normality. A hypothesis test for normality is based on the linear correlation coefficient. If the variable under consideration is normally distributed, the correlation between the sample data and their normal scores should be near 1 because the normal probability plot should be roughly linear (Weiss 2005). The null and alternative hypotheses are executed at the 5% significance level.

Null hypothesis, H_0: The variable is normally distributed

Alternative hypothesis, H_a: The variable is not normally distributed

The critical value is denoted as Rp* , N is the number of data and the value of the test statistic is denoted as Rp. Tables 1 and 2 show the summary of the correlation test for normality for each analysis of data. Tables 1 and 2 indicate that the test results are on the normal distribution due to the fact that the test statistic, Rp is more than the critical value, Rp*. Therefore, it can be stated that at the 5% significance level, the data provide sufficient evidence to conclude that the variable data are normally distributed.

RESULTS AND DISCUSSION

Figures 1 and 2 show the magnetic field and flux densities in the center of the sample for different geometry of the sample with respect to the rolling direction. It can be

TABLE 1. Correlation test for normality for sample dimension analysis

Variable	Sample dimension (mm)	N	Rp*	Rp	Decision	Remarks
B (T)	97.2×68.0	5	0.880	0.971	Accept H_0	Normal distribution
	127.2×68.0	5	0.880	0.970	Accept H_0	Normal distribution
	157.2×68.0	5	0.880	0.954	Accept H_0	Normal distribution
H (A/m)	97.2×68.0	5	0.880	0.990	Accept H_0	Normal distribution
	127.2×68.0	5	0.880	0.990	Accept H_0	Normal distribution
	157.2×68.0	5	0.880	0.989	Accept H_0	Normal distribution

TABLE 2. Correlation test for normality for anisotropy analysis

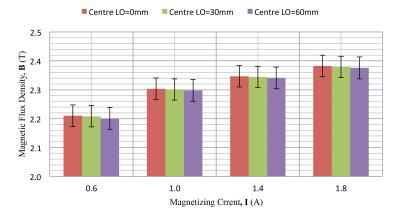| Variable	Types of samples	N	Rp*	Rp	Decision	Remarks
B (T)	GO steel, M4	6	0.889	0.891	Accept H_0	Normal distribution
	NO steel, M19	6	0.889	0.929	Accept H_0	Normal distribution
H (A/m)	GO steel, M4	6	0.889	0.991	Accept H_0	Normal distribution
	NO steel, M19	6	0.889	0.987	Accept H_0	Normal distribution

FIGURE 1. Flux density distribution for different sample's dimension, grade M4
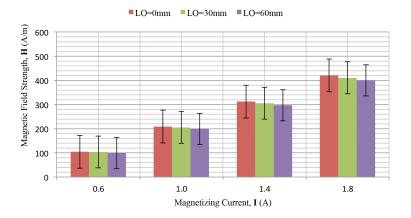

FIGURE 2. Field strength distribution for different sample's dimension, grade M4

observed that magnetic flux densities of overhang sample slightly decrease in the range of 0.1 to 0.2% with sample without overhang. The percentage differences between these overhang samples with so-called fit-in sample is in the range of 1.7 to 4.6%. The findings indicated that the magnetic properties are slightly deteriorated by overhang samples. It can be noted that as sample sizes is increased, the magnetic characteristic is worsen. This is because of the flux distribution near the H-coil of the tester with long overhang approaches uniformity more rapidly than that with a short overhang.

Figure 3 presents the normal flux density detected at the center of the overhang and fit- in sample of the GO steel, grade M4. The graph shows that the normal stray
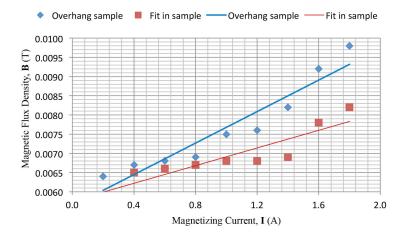

FIGURE 3. Flux distributions of normal stray flux at the center of sample, grade M4

flux is vary linearly with the current, I. It can be perceived that the stray flux is much higher for overhang sample compare to fit-in sample. This is due to inhomogeneous of sample magnetization as in overhang sample, the flux tends to magnetize the sample under yoke followed by the neighboring overhang part (Stupakov et al. 2009). For instance, the stray flux measured at I=1.2 A for overhang and fit in sample are 8.10 and 7.15 mT, respectively. The calculated percentage difference of stray flux between overhang sample and so-called fit in sample at I=1.2 A is about 13.3%. Even though the value of stray flux is small which is around 6 to 10 mT, it can affect the field and flux measurement as a whole. The result obtained suggests that the stray flux can be minimized using the fit-in sample.

Figures 4 and 5 show the analysis results on the distribution of amplitude of magnetic flux density, B and magnetic field strength, H for GO and NO steels. The magnetic flux density for GO steel, M4 and NO steel, grade M19 is gradually increased with the current, I until it reached saturation level. In case of magnetic field strength, the field distribution is increased linearly with the current. The intersection between the two graphs at about 1.8 A in

Figure 5 indicates that the NO steel, M19 already reached the saturation at about 1.8 A whereas for GO steel, M4, it is still has not been saturated. The experimental results showed that at a frequency of 50Hz, the flux density range of 0.27 mm thick GO, grade M4 is between 1.2 and 2.4 T. In contrast, for 0.5 mm NO silicon iron steel grade M19, the flux density is around 0.5 to 1.6 T.

It has been reported that NO steels can be tested up to 1.6 T whereas for GO steels, the normal range extends to 1.8 T (ASTM 2000; Nippon 2011). For the GO steel sheet, grade M4, a less current about 1 A is needed to achieve the maximum flux density of 2.3 T at the center of the sample while the NO steel, at 1 A, it only can magnetize the sample up to 1.6 T. The differences of their magnetic properties were due to grain size and thickness of the samples, with grade M4 and M19 with the thickness of 0.28 and 0.50 mm, respectively. Moses (2012) has stated that the optimum grain size is not only defined for giving magnetization but also depended on the texture and silicon content. In addition, this is also due to the fact that the GO silicon steel is specially designed to have a large anisotropic crystallographic orientation along the (110)
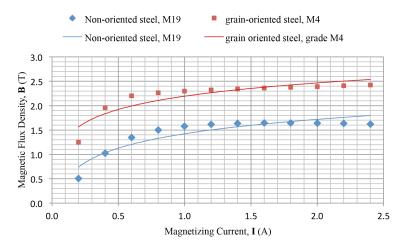

FIGURE 4. Magnetic flux density for electrical steels, grade M4 and M19
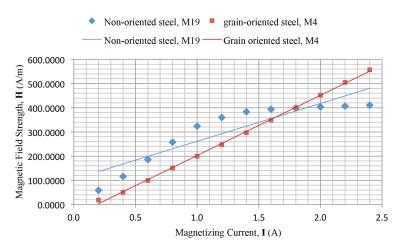

FIGURE 5. Magnetic field strength for electrical steels, grade M4 and M19

{001} or (100) {001} direction which has a dominant and excellent excitation characteristics in the rolling direction (Tamaki et al. 2010). Meanwhile, the crystal domain in the NO steel sheet is normally much smaller and the observed domain structure very much more complicated because of surface closure domains that form to reduce the local surface demagnetizing fields (Graham 1982).

Permeability, μ is the most important parameter for soft magnetic material since it indicates how much magnetic induction is generated by the material in a given magnetic field. In general, the better materials have higher permeability. Figure 6 shows the magnetization curves for different types of electrical steels for grade M4 and M19. The magnetizing curve was found to vary non linearly with the applied field. A good grade of electrical steel must have high permeability and require fewer magnetic fields to obtain higher flux. Based on permeability which is due to material grade and magnetizing curve as in Figure 6, it can be summarized that GO electrical steel is having excellent magnetic characteristics compared with NO electrical steel.

One way ANOVA test was carried out to analyze the significance different of the field and flux data distribution between the dimension of the samples which is 97.2 × 68 mm, 127.2 × 68 mm and 157.2 × 68 mm. The null hypothesis and alternative hypothesis are as follows:

Null hypothesis, H_0: $\mu_1 = \mu_2 = \mu_3$ (field or flux distributions have the same means)

Alternative hypothesis, H_a: Not all the means are equal

The responding variable in this testing was magnetic properties of the samples and the factor was the sample's dimension. Table 3 shows the output obtained by applying one-way ANOVA at the 0.05 significance level.

P-value which higher than 0.05 indicated that there is no significant difference between the dimension of the samples. At the 5% significance level, the data do not provide enough evidence to conclude that a difference exists in the field and flux distributions among the sample's dimensions. Although the field and flux distribution on sample's dimension is not significantly different, the precautionary step should be taken into consideration. This is due to the amount of stray flux increases with longer overhang sample and lead to inhomogeneous of sample magnetization (Stupakov 2012). Thus, it can affect the measurement of field and flux in the middle of the sample.

T-Test was executed to analyze the mean of magnetic properties, flux density and field strength for different type of samples which are NO silicon steels and GO silicon steels. The null hypothesis and alternative hypothesis test are executed as below:

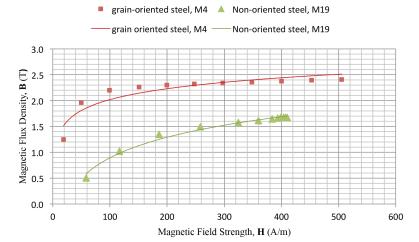Null hypothesis, H_0: $\mu_1 = \mu_2$ (mean field or flux distributions are the same)

FIGURE 6. Magnetization curves of electrical steels, grade M4 and M19

TABLE 3. One-way ANOVA summary test for the different sample dimension

Response variables		F	P-value	Decision	Remarks
B (T)	LO = 0 mm LO = 30 mm LO = 60 mm	.288	.755	Accept H_0	No significant difference between sample dimension
H (A/m)	LO = 0 mm LO = 30 mm LO = 60 mm	.013	.987	Accept H_0	No significant difference between sample dimension

TABLE 4. T-Test summary test for the different type of samples

Magnetic properties	Electrical steel	Means	2-tailed	Decision	Remarks
B (T)	M4	2.0819	.000	Reject H_0	M4≠M19
	M19	1.2949	.001	Reject H_0	M19≠M4
H (A/m)	M4	127.5849	.016	Reject H_0	M4≠M19
	M19	217.2220	.006	Reject H_0	M19≠M4

Alternative hypothesis, H_a: $\mu_1 \neq \mu_2$ (mean field or flux distributions are different)

The symbols μ_1 and μ_2 denoted as the mean field or flux distributions of the GO and NO silicon steel, respectively. The test is done at the 5% level of significance. Table 4 shows the summary of the T-test for the varying type of sample analysis.

Table 4 shows that there is a significant difference between the anisotropy of samples since the P-value was less than the specified significance level of 0.05. At the 5% significance level, the data provide adequate proof to conclude that differences exist between the mean field and flux distribution of the two types of samples which are NO steel, grade M19 and GO steel, grade M4.

CONCLUSION

The effect of design factors of SST such as sample dimension and anisotropy on GO steel, grade M4 and NO steel, grade M19 was successfully investigated with the aid of FEMM simulation. The findings showed that the stray flux was increased with the longer overhang sample due to non-uniformity of sample magnetization as in overhang sample, the flux tends to magnetize the sample under yoke followed by the neighboring overhang part. This attributed to the flux leakage between the yoke legs which affected the magnetic measurement of samples. The GO steel, grade M4 have better anisotropy and magnetic properties than NO steel, grade M19. The B-H curve for GO steel were higher compared with NO steel. The electrical steel which has high anisotropic structures and high permeability will require fewer magnetic fields to obtain high magnetic flux density. However, the magnetizing curve for each grade of electrical steels is different due to grain size and thickness of the sample. One way ANOVA and T-test were performed to evaluate the statistical significance of effect factor of SST to the magnetic properties of electrical steels. The statistical results are in good accordance with the simulation analysis. The data provided sufficient evidence for the effects of anisotropy that there is a significant difference between the mean field and flux distribution of GO, grade M4 and NO, grade M19. However for sample dimension, the data do not provide enough evidence to conclude that a difference exist in the field and flux distribution among the sample dimension. This is due to the percentage difference between the overhang and fit in the sample is in the range of 1.7 to 4.6%. However, the precautionary step must be taken into consideration as longer overhang sample will increase stray flux and flux leakage at the core end and sample might lead to inhomogeneous of sample magnetization.

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