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Design and analysis of a toroidal tester for the measurement of core losses under axial compressive stress

Natheer Alatawneh [a,*], Tanvir Rahman [b], David A. Lowther [b], Richard Chromik [a]

[a] Department of Mining and Materials Engineering, McGill University, QC H3A 0G4, Canada
[b] Department of Electrical and Computer Engineering, McGill University, QC H3A 0E9, Canada

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ABSTRACT

Electric machine cores are subjected to mechanical stresses due to manufacturing processes. These stresses include radial, circumferential and axial components that may have significant influences on the magnetic properties of the electrical steel and hence, on the output and efficiencies of electrical machines. Previously, most studies of iron losses due to mechanical stress have considered only radial and circumferential components. In this work, an improved toroidal tester has been designed and developed to measure the core losses and the magnetic properties of electrical steel under a compressive axial stress. The shape of the toroidal ring has been verified using 3D stress analysis. Also, 3D electromagnetic simulations show a uniform flux density distribution in the specimen with a variation of 0.03 T and a maximum average induction level of 1.5 T. The developed design has been prototyped, and measurements were carried out using a steel sample of grade 35WW300. Measurements show that applying small mechanical stresses normal to the sample thickness rises the delivered core losses, then the losses decrease continuously as the stress increases. However, the drop in core losses at high stresses does not go lower than the free-stress condition. Physical explanations for the observed trend of core losses as a function of stress are provided based on core loss separation to the hysteresis and eddy current loss components. The experimental results show that the effect of axial compressive stress on magnetic properties of electrical steel at high level of inductions becomes less pronounced.

1. Introduction

IRON loss calculations in electrical machines are important for determining the efficiency of electromagnetic devices. Often, there are significant discrepancies between the predicted and measured values of the efficiency. One reason for the discrepancy between simulation results and measurements could be due to the omission of effects from manufacturing processes such as shrink fitting, cutting, pressing and clamping of steel laminations [1–5]. Shrink fitting, in particular, can have a significant impact [6]. Shrink fitting is a manufacturing technique by which metal components are combined together. Application of shrink fitting for an electric machine includes the shaft-rotor and the stator-house assembly processes, among others. This method of assembly is widely used in the industry and leaves residual mechanical stresses on the machine components which can affect the magnetic properties of the electrical steel and thus the electromechanical behavior of the machine [7–9].

Structural analysis of an electrical machine assembled by shrink fitting shows that the machine components experience three types of stresses including radial, hoop (circumferential) and axial stresses. Due to the lack of experimental data machine designers and finite element (FE) software packages consider only the effect of radial and hoop stresses during core loss calculations [10–12], *i.e.*, the effects of axial stress are generally ignored. Previously, a few articles have reported magnetic measurements including the B-H properties, hysteresis loops, core losses etc. of electrical steel under axial compressive stress [13–16]. However, the homogeneity of the stress distribution within the sample of the experimental fixture (an important requirement for such measurements) was not investigated and previous studies have used a superficial measure of the stress using the lamination sample surface area and the load (assuming uniform stress distribution), which is dependent on the apparatus and is not necessarily applicable. In this paper, an improved design test fixture has been developed for the measurement of the magnetic properties of electrical steel laminations under mechanical stress in the axial direction. The design process involved a study of stress distribution to choose the proper material of the frame and calculate the applied stress on the sample

* Corresponding author.
E-mail address: natheer80@yahoo.com (N. Alatawneh).

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accurately. The originality of this work can be seen from different angles; **First**: The improved design offers a better stress distribution compared with prior designs. **Second**: A FE study on the structural mechanics of the test fixture has been performed for the first time. This analysis helps in exploration the stress distribution within the sample, in addition, it provides a solid guideline to choose the proper material of the fixture to tolerate the desired applied stress. **Third**: A compensation coil has been developed which is basically a replication of the fixture without the sample. In literature, the toroid for compressive stress measurements was used without compensation coil [15], or an approximated mathematical factor was implemented to compensate for the flux leakage [14]. **Fourth**: Extensive measurements have been executed for a stress range up to 32.3 MPa (where in literature the maximum possible stress was 28 MPa [15]), with various frequencies from 50 Hz to 1 kHz. Also, physical interpretation for the loss trend as a function of stress is provided.

The remainder of this paper is organized as follows. Section II describes the proposed ring tester design. 3D FE analyses of structural mechanics and electromagnetics are carried out in sections III and IV respectively. A detailed description of the experimental setup is presented in section V, which is followed in Section VI by results and discussion. Finally, section VII provides some final conclusions and directions for future work.

2. Ring tester design

The determination of the magnetic properties of lamination materials as a function of stress requires setting up an experimental apparatus with a closed magnetic circuit in which the test samples are exposed to uniform in-situ stress distributions. To satisfy this condition a toroidal tester has been developed. The tester is composed of a single ring steel sample with inner and outer diameters of 60 and 80 mm, respectively (the reasons for choosing these dimensions are due to the dimension of the mechanical hydraulic press and magnetics related considerations discussed below). The sample is set in between two insulator rings of the same diameters as the sample. Each insulator ring has a thickness of 10 mm with 12 semi-circular grooves drilled from the side around the insulator perimeter. Each groove has a diameter of 8 mm, as shown in Fig. 1. The excitation and measuring coils are wrapped in the grooves which allows the axial force to be applied directly to the insulators and transferred to the specimen. The insulator rings are made from cast acrylic [Poly (methyl methacrylate)], which is a dielectric material (μ_r slightly less than 1) that allows the generated flux inside the winding to flow within the specimen. Other properties which encourage the use of acrylic are: its ability to withstand high temperature (recommended continuous service temperature 85 °C), cost effectiveness, high coefficient of expansivity, durability and ease of assembly [17,18].

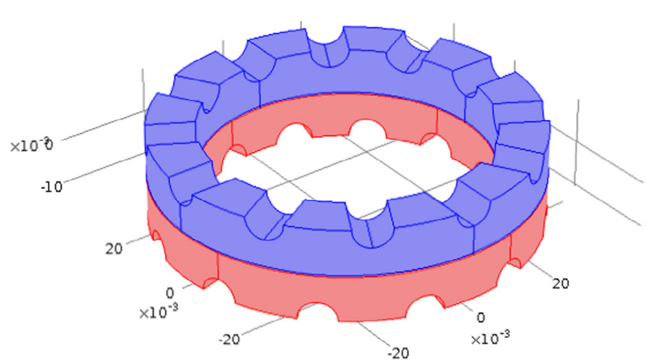

Fig. 1. The insulator rings with semi-circular side grooves.

Because of the fact that the magnetic field in the sample is non-uniform (larger near the inner perimeter and lower at the external edge), the sample dimensions have been chosen to fulfil the condition of $D_o/D_i < 1.6$, where D_o and D_i are the inner and the outer diameters, respectively [19]. When the ration D_o/D_i is less than 1.1 the length of magnetic path is $2\pi r_o$, where r_o is the average of inner and outer radii. However, if the ratio is greater than 1.1, the length of magnetic path has to be recalculated to compensate for the non–homogeneity of the flux. For the range of $1.1 < D_o/D_i < 1.6$ (as in our case $D_o/D_i = 1.33$) the mean length of magnetic path is given by,

$$l_m = \pi \frac{D_o - D_i}{\ln(D_o/D_i)} \quad (1)$$

In general, the higher the D_o/D_i ratio, the lower the uniformity of flux within the sample, thus the reliability of measurements is lower. However, the measurements can be improved since a larger D_o/D_i means a larger volumetric size of the sample and hence, the influence of the leakage flux in the air gap (between the coil and the sample) is less pronounced. Also, a larger ratio offers a larger sample surface that can be subjected to stresses, and consequently the influence of stress is more visible. To compromise between the prototyping effort, flux uniformity distribution and visibility of stress effect, a ratio of 1.33 was chosen.

3. Structural mechanical analysis

One of the goals of designing an appropriate tester is to ensure that the stress distribution in the sample is uniform. This can be investigated by performing a mechanical structural analysis of the apparatus. We carried out a number of simulations to determine the optimal shape of the insulator frame including the effect of different groove shapes (semi-circular and square), and the relative groove alignments (staggered and non-staggered) between the upper and lower insulators. These two aspects of the design affect the uniformity of the resulting stress distribution the most. Fig. 2 shows the initial design of the insulator rings with aligned square and semi-circular grooves. The material properties of the rings have been provided in Table 1. When a force of 35 kN is applied perpendicularly over the frame, the results of finite element analysis of the problem are shown in Figs. 3–6. A parameter which has been frequently used to assess the safety of the material against deformation is the Von Mises stress distribution in the material samples. In Figs. 3 and 4 the maximum value of the Von Mises stress induced in the material of the insulator frame (112.9 MPa for square and 108 MPa for semi-circular) is less than the strength of the material (124 MPa for cast acrylic). This means that the material would not deform at this applied pressure. Also, the semi-circular groove design achieves a lower maximum Von Mises stress compared with the square design for the same applied force. One more advantage of using the semi-circular groove design can be observed from the results of z-axis stress distribution on the test sample as shown in Figs. 5 and 6. The mechanical stress is distributed more uniformly over the sample in the semi-circular design with a variance of 4.43×10^{13} compared to 5.59×10^{13} for the square design. The variance decreases by ~20%. Another design improvement can be achieved by rotating the upper insulator in order to obtain staggered groove alignment between the upper and lower insulator rings, as shown in Fig. 1. A stress analysis comparison between the staggered and the aligned semi-circular groove design has been performed and the simulation results are presented in Figs. 7 and 8. The maximum Von Mises stress in the insulator ring drops to 98.6 MPa compared to 108 MPa for the aligned design. This means that higher forces can be applied to the staggered apparatus. Moreover, the variance