Performances of SOMALOY 700 (5P) and SOMALOY 500 Materials under 1-D Alternating Magnetic Flux Density

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***Abstract*— In high magnetization frequency of the high speed electrical machine, core loss dissipation is a main contributor of the power loss that gives high percentage of loss compared to the other losses. Likewise, the researchers and engineers are aiming for the lower loss magnetic material that can offer higher efficiency during the operation of the electrical machines. In this paper, core loss of SOMALOY 700 (5P) is calculated and analyzed to identify the magnetic properties of that material. The magnetic properties of SOMALOY 700 material are properly measured under alternating magnetic fluxes at 50 Hz, 100 Hz, 500 Hz and 1000 Hz by using 3-D tester. LabVIEW and Mathcad software are used for the data acquisition and analysis, respectively. The performances of SOMALOY 700 (5P) are compared to SOMALOY 500 by plotting the core loss curves and hysteresis loops. The finding shows the core loss of both samples are proportional to the squared of magnetic flux density. This study also revealed that the core loss of SOMALOY 700 (5P) and SOMALOY 500 are 6 kg/Watt and 12 kg/Watt when the magnetic field is at 1.5 T, respectively. It concludes that the SOMALOY 700 (5P) offers lower core loss compared to the SOMALOY 500 and more suitable to be used in producing high performance of electrical machines. The details of core losses for both SOMALOY materials are important in order to provide the significance information to the real engineers in designing the electrical or electromagnetic machines in the future.**

Keywords—core loss, magnetic material, SOMALOY 500, SOMALOY 700 (5P)

I. INTRODUCTION

Magnetism is a phenomenon which has been exploited for many centuries. This non-contact force phenomenon is extremely used in real life including in the technological development currently. There are some magnetic materials which are employed in the distribution of electricity since these materials are able to generate energy by the movement of electrons. These materials are mostly applied in all electrical machines and they can act as a medium in shaping and directing magnetic flux densities for transferring and converting energy.

The changing of magnetic flux density during the operation will contribute to the core loss of magnetic materials. Alternating core loss is produced by alternating magnetic flux densities which reverse twice per cycle with the current. The currents are alternated back and forth through a wire and lead to change the direction and magnitude of magnetic flux density. This situation is known as the production of alternating magnetic flux densities which cause the core loss to the magnetic materials.

Based on Sakaki and Imagi [1], the anomalous loss also can be the one of the elements for core loss contribution. Because of that, Chen and Pillay [2] were introduced the core loss calculation as shown in (1)

$$P = P_h + P_e + P_a = C_h f B^n + C_e (fB)^2 + C_a (fB)^{1.5} \quad (1)$$

where P is referred to the anomalous loss and C_α is the coefficient of anomalous loss. This coefficient is related to the material thickness, cross-sectional area, conductivity, and the parameters that describe the material microstructure. The values of loss coefficients C_h, n, C_e and C_α can be deduced by fitting the model to the experimental results.

A. Hysteresis loop

The hysteresis loop is a magnetic characteristic which is able to describe the behavior of magnetic material core by knowing the magnetic flux density and magnetic field strength during magnetization and demagnetization process. This completed cycle produces a hysteresis loop that represents the total core loss of the magnetic material by calculating the area of the hysteresis loop [3].

B. Core Loss Curve

The total core loss of the magnetic material can be explained by the core loss curve which describes the specific core loss in different peak magnetic flux density. For instance, Fig. 1 is the plotted graphs that explain the total core loss of SOMALOY 500 material in the x-, y- and z-axes.

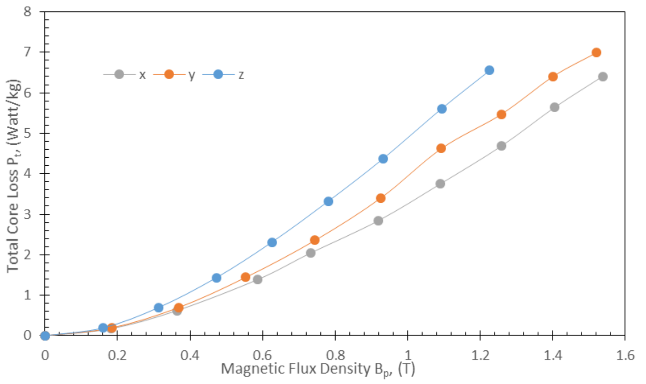

Fig. 1. The core loss curve of SOMALOY 500 at 50 Hz along the x-, y- and z-axes [4].

From Fig. 1, it explains that the core losses in x and y directions are quite similar due to the range of core loss value. However, the recorded core loss which is generated by penetration of magnetic flux in z direction is slightly different and high compared to x- and y-axes. This is caused by the effect of the manufacturing process that makes the distribution of particle in z direction is not uniform [4].

II. Experimental Set Up

A. *Calibration of Sensing Coil*

To ensure the accuracy of magnetic properties measurement of SOMALOY 700 material, the sensing coils are used in detecting the magnetic flux density during the measurement, B and H sensing coils have gone through calibration process in the middle of a long solenoid. The calibration process is important in order to eliminate the system errors before being employed to measure the magnetic field components in the 3-D testing system [5].

The electromotive forces of the sensing coils are induced inside the solenoid after magnetic flux changed as stated in Faraday's Law. In this experiment, the maximum magnetic field created by the solenoid is measured. The magnetic flux density for a long solenoid of many turns is given as

$$B = \mu_0 \frac{N_s}{l} \mathrm{I} \quad (2)$$

where *B* is the magnetic flux density within the solenoid, which is nearly uniform, N_S is the number of turns, *l* is the total length of the solenoid and I is the current passing through the solenoid. The magnetic flux over certain area *A* is

$$\emptyset = B.A \quad (3)$$

Faraday's Law relates the time rate of change of the flux, dØ/dt, to the electromotive force (EMF) voltage ε, as below

$$\varepsilon = N_s A_s \frac{dB}{dt} \quad (4)$$

As expressed in (4), the sensing coil is stationary and perpendicular to the penetration of *B*. If the AC current in the solenoid has a frequency *f*, $I = I_0 \sin(-\omega t)$ then, the magnetic flux density at the center of the solenoid is $B = B_0 \sin(-\omega t)$. Thus, the sensing coil induces an EMF voltage whose amplitude ε_o, is proportional to the angular frequency ω, and the amplitude B_o of the magnetic flux density.

$$\varepsilon_0 = \omega N_p A_p B_0 \quad (5)$$

where N_p is the number of turns of the sensing coil and A_p is the area of sensing coil.

If the sensing coil is located inside a solenoid, the induced emf of the coil is given by

$$\varepsilon_0 = 2\pi f\, N_p A_p\, \mu_0\, n_s\, I_0 \quad (6)$$

where $2\pi f = \omega$, n_s is the number of turns per unit length of the solenoid. The EMF of the sensing coil is proportional to both the frequency *f*, and the alternating current (AC) current I_o, in the solenoid.

A circuit diagram of the experiment is shown in Fig. 2. The AC voltage supply produces a sine-wave voltage which drives an AC current through the solenoid. The solenoid with 0.8 m of length, 0.11 m of diameter, 939 turns and 13.3 mH of inductance can produce the magnetic flux density *B*. The change of magnetic fluxes induces in the B and H sensing coils. The operational amplifiers are needed to amplify the sensing voltages; V_B and V_H before being measured by the LabVIEW.

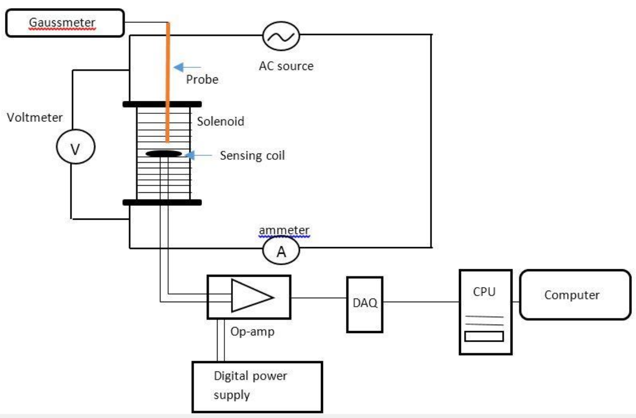

Fig. 2. Circuit diagram of calibration process.

The magnetic flux density *B*, which is generated by solenoid, and induced EMF of the sensing coil ε_0, are used in obtaining the sensing box coefficients, K_H and K_B.

Magnetic flux density produced inside the long solenoid is recorded before being compared to the excitation of B during the sensing coil calibration as shown in Fig. 3. From the figure, magnetic flux density is higher when the sample is located in the center of the solenoid. This is due to the existence of core material that will increase the inductance of the solenoid. However, it did not affect the process of obtaining the box coefficients.

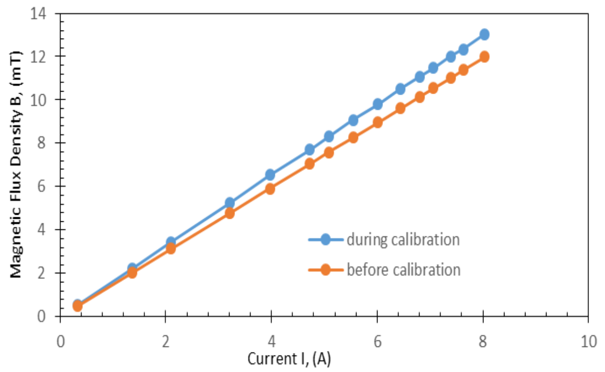

Fig. 3. Excitation of magnetic flux density before and during the calibration.

The plotted sensing voltages; V_B and V_H, along the x-, y- and z-axes versus alternating currents I, that passed through the solenoid are described in Fig. 4. It can be seen that the EMF of the B and H sensing coils is directly proportional to amplitude of the AC current in the solenoid as stated in (6).

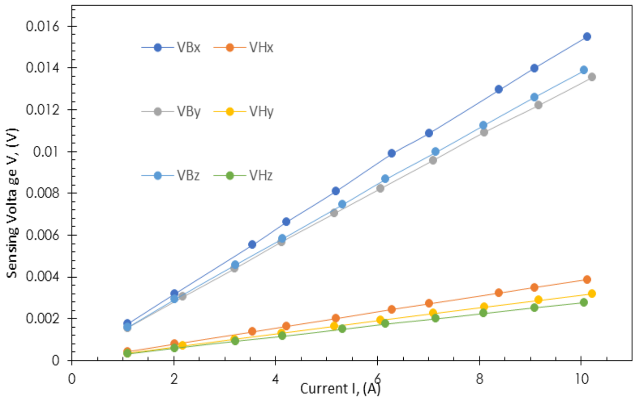

Fig. 4. The induced voltages of B and H coils during the calibration process.

Box coefficients $K_{H(x,y,z)}$ and $K_{B(x,y,z)}$ are obtained from (7) – (10) with V is the RMS value of the induced EMF, $\mu_0 H_m$ is the maximum flux density in the center of the solenoid, f is the excitation frequency, and A_{sp} is the cross-sectional area of the sample.

$$B_i = \frac{1}{K_{B_i}} \int V_{B_i} dt \qquad (7)$$

$$K_{B_i} = N_{B_i} A_{sp} \qquad (8)$$

$$H_i = \frac{1}{\mu_0 K_{H_i}} \int V_{H_i} dt \qquad (9)$$

$$K_{Hi} = \frac{V_H}{\sqrt{2}\pi f \mu_0 H_m} \qquad (10)$$

(i=x, y, z)

where the averaged box coefficients are K_{Hx} = 0.0012, K_{Hy} = 0.0010, K_{Hz} = 0.0009, K_{Bx} = 0.0048, K_{By} = 0.0042, and K_{Bz} = 0.0043.

B. 3-D Magnetic Properties Testing System

Each magnetic material that is excited under an alternating or rotating magnetic flux density has been experienced on the rotation of magnetic domain which makes the 3-D vector flux excitation also needed to take into account [6].

The 3-D magnetic property testing system was successfully created by Zhu *et al.* in 2001 in order to magnetize cubic samples of soft magnetic materials [7], [8]. This system consists of a 3-D yoke to guide the magnetic fluxes in three axes, which is wounded by three groups of excitation coils, a data acquisition system, three groups of coils to produce magnetic flux density *B*, along the orthogonal x-, y- and z-axes and they are able to produce different magnetic flux patterns such as alternating, rotating in a plane and rotating in a 3-D pattern with the loci of the flux density, thus various flux density loci like circularly and elliptically rotating flux density are able to be obtained by controlling the three components of the magnitude flux density *B*, vectors [9], [10], [11]. The 3-D tester also has been attached to a feedback control system which contains a control unit and three high power amplifiers [8], [12].

As shown in Fig. 5, the voltage waveforms of magnetic flux density for the x, y and z components are generated and controlled to be sinusoidal by LabVIEW. Then, the waveforms are exported to a three-channel linear power amplifier, which feeds the excitation windings of the tester, through three isolated channels of the analog to digital (A/D) and digital to analog (D/A) board. The cubic sample of SOMALOY 700 (5P) inside the 3-D tester is magnetized whereas the sensing coils that detect the magnetization will induce both sensing voltages; V_B and V_H before being amplified by operational amplifier. The x, y and z components of B and H sensing are collected by six independent input channels of the A/D and D/A board. The signals are used to determine the relationship of peak value of magnetic flux density *B*, and the corresponding of magnetic field strength *H*. The recorded data is imported to Mathcad in order to obtain the hysteresis loop to calculate the core loss of the sample during the operation.

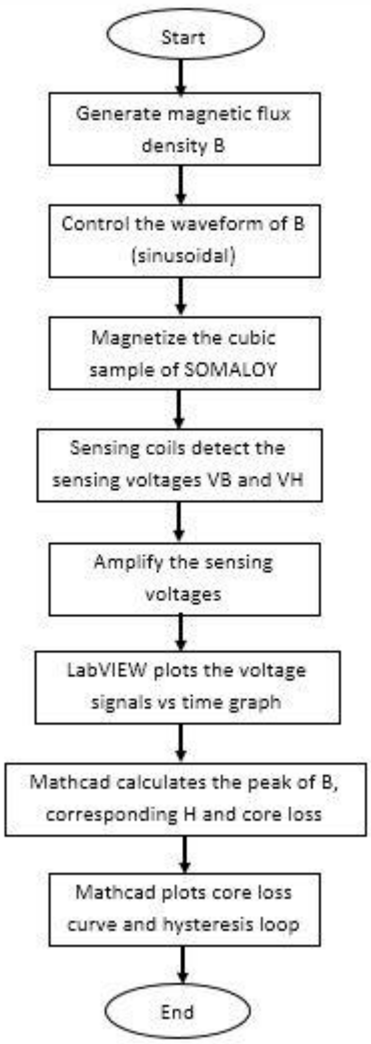

Fig. 5. Flowchart of core loss SOMALOY measurement by using 3-D magnetic property testing system.

III. Core Loss Measurement

The magnetic properties of SOMALOY 700 (5P) can be evaluated by conducting some measurements of alternating core loss. The magnitude of magnetic flux density is generated and controlled along the x-, y- and z-axes. The measurements are conducted under wide range of frequency, 50 Hz, 100 Hz, 500 Hz and 1000 Hz to magnetize the cubic sample of SOMALOY 700 (5P) which is located inside the 3-D tester as illustrated in Fig. 6.

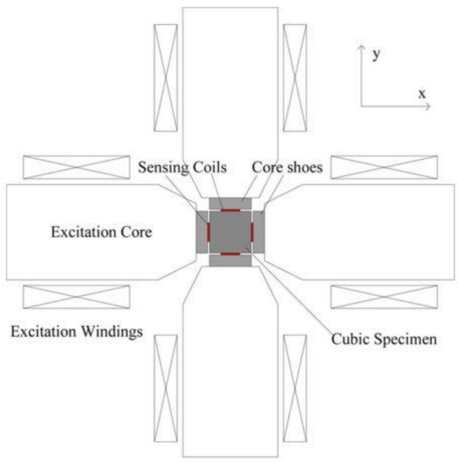

Fig. 6. Cross sectional diagram of 3-D tester [13].

These frequencies [14], [15], [16] are selected by considering the operation of high speed of rotational motion that leads to higher frequency such as electric vehicle. The cubic sample is magnetized by alternating magnetic flux density in transverse and sinusoidal direction in different axis by the aids of AC current from the winding coils of the 3-D tester. Due to the changes of magnetic flux with time, the heat will be dissipated. The dissipated heat during magnetization can be represented as a core loss of the sample.

The measured magnetic properties of SOMALOY 700 (5P) are then being compared to another material, SOMALOY 500.

IV. Results and Discussions

The magnetic properties of the SOMALOY 700 (5P) are investigated in this section by considering the core loss and the relationship between magnetic flux density *B*, and magnetic field strength *H*, i.e. the hysteresis loop.

The measurements of sample core losses are conducted under alternating magnetic flux density along three different axes; x, y and z, respectively. The hysteresis loop and the core loss curve are analyzed by comparing the performance of measured SOMALOY 700 (5P) and SOMALOY 500. The behavior of SOMALOY 500 is obtained from previous researchers [17]. The data verification is applied by considering the curve fitting technique in obtaining the core loss coefficients C_h, C_e and C_a which can be considered during the calculation of three elements of core losses such as hysteresis loss P_h, eddy current loss P_e, and anomalous loss P_a.

A. Hysteresis Loops of Alternating Core Loss

The characteristics of the SOMALOY 700 (5P) material at 50 Hz is depicted in Fig. 7. The loops for both materials are resulted from the alternating magnetic flux densities up to 2.3 T. From the figure, it can be seen that SOMALOY 700 (5P) gives smaller loop compared to the SOMALOY 500. Theoretically, the area of the hysteresis loop represents the core loss which can be experienced by dissipating the heat when the field is reversed [18].

This describes that the SOMALOY 700 (5P) has offered the lower loss compared to SOMALOY 500 due to the improved physical characteristic of the SOMALOY 700 (5P) particle during the manufacturing process. The larger grain of iron particles with ultra-thin insulation are produced by Hoganas to provide low loss during the magnetization process. These characteristics of SOMALOY 700 (5P) will also significantly reduce the eddy current loss as explained in (11)

$$P_e = \frac{\pi^2 B_p{}^2 d^2 f^2}{6k\rho D} \quad (11)$$

where P_e is the eddy current loss, B_p is the peak magnetic field, d is the thickness of the sheet or diameter of wire, f is the frequency, k is the constant which is 1 for thin sheet and 2 for this wire, ρ is the resistivity of material and D is the density of the material. Ideally, the eddy current loss is produced if there are changes of magnetic flux density within the conducting magnetic material which will cause the currents being circulated by induced voltage of the material.

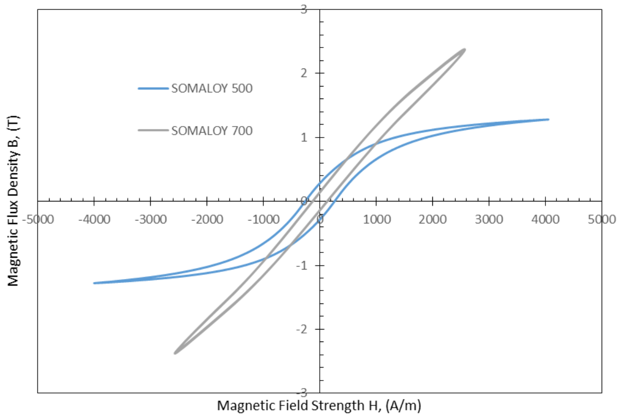

Fig. 7. The hysteresis loops of SOMALOY 700 (5P) and SOMALOY 500 at 50 Hz.

The remanence or residual magnetism of SOMALOY 700 (5P) is low which defines the remaining magnetization when magnetic field strength has been dropped to zero. The low remanence represents the low ability in memory and it explains that this material is not suitable for producing permanent magnets which demand a high remanence. From the figure, it is seen that the coercivity of SOMALOY 700 (5P) is low compared to SOMALOY 500 material.

This defines the behavior of this material which is magnetically soft due to the low coercivity. Low coercivity describes the needed applied field in reversing the magnetization of the magnetic material is low. Other than that, the figure above also describes that the SOMALOY 700 (5P) is saturated at higher magnetic flux density which provides in more wide applications.

Fig. 8 exhibits the hysteresis loops of lower loss material, SOMALOY 700 (5P) at certain range of operating frequency. Hysteresis loops is able to provide the information related to the core loss since the total core loss of magnetic material is proportional to the area of hysteresis loops. The hysteresis loops of SOMALOY 700 (5P) material at 50 Hz, 100 Hz, 500 Hz and 1000 Hz have been described in Figs.8 (a), (b), (c) and (d), respectively.

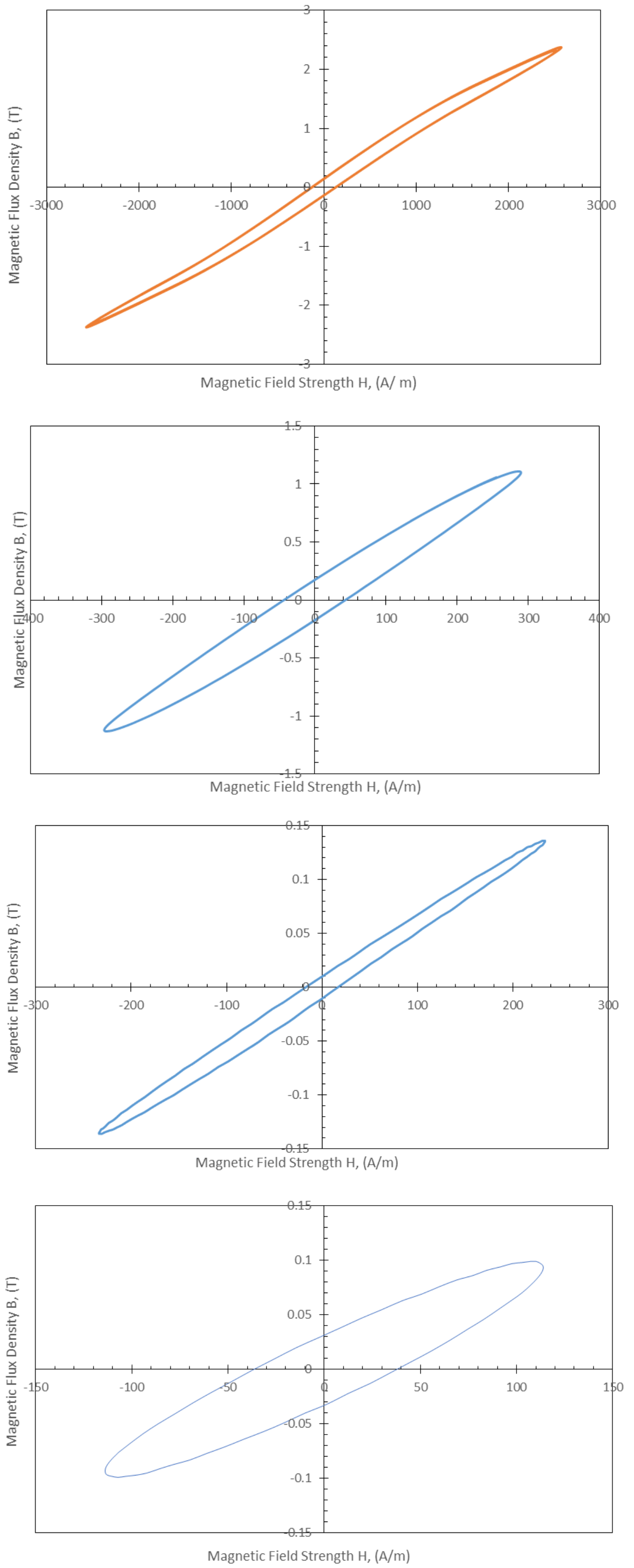

Fig. 8. The hysteresis loops of SOMALOY 700 (5P) in the x-axis at (a) 50 Hz (b) 100 Hz (c) 500 Hz and (d) 1000 Hz.

Figs. 8 (a), (b), (c) and (d) show that the loop area is getting bigger with the frequency. This explains that the ability of the 3-D tester to magnetize the SOMALOY 700 (5P) material is decreased when the frequency is setting to be higher. Based on figure that exhibits the measurement at 50 Hz, it shows that the recorded magnetic flux density is 2.3 T. However, the saturation magnetic flux density is around 2.45 T [19] that will cause the loop is flatted at both end in representing the saturation condition of magnetic material. The saturated magnetic flux density of SOMALOY 700 (5P) is higher than SOMALOY 500 which is saturated at 2.03 T as reported by Guo in 2006 [20]. The condition of the 3-D tester has affected the experimental work in measuring the magnetic properties of SOMALOY 700 (5P) material at very high saturation magnetic flux density.

At 100 Hz, the recorded magnetic flux density is 1.1 T as expressed in Fig. 8 (b). However there is 0.14 T recorded as the highest magnetic flux density when the measurement has been done at 500 Hz as shown in Fig. 8 (c), whereas the highest magnetic field strength at the same frequency is 231 A/m.

For core loss measurement at 1000 Hz, the peak magnetic flux density of the outer loop is 0.1 T and the corresponding magnetic field strength is 114 A/m. As stated in [21], the possible magnetic field can be generated at 1000 Hz by the original 3-D tester is only 0.1 T.

B. *Core Loss under 1-D Alternating Magnetic Field*

Three magnetic properties measurements have been conducted along the x-, y- and z-axes by experiencing the alternating magnetic flux experimental. Fig. 9 exhibits the plotted graphs which express the total core loss of SOMALOY 700 (5P) material when there is a magnetic flux excitation in the x-, y- and z-axes and the core loss curve of SOMALOY 500 material which has been provided by the manufacturer. It can be seen that the SOMALOY 500 core loss is higher than SOMALOY 700 (5P) core loss along all axes.

The figure visibly illustrates that the curve lines for all axes are quite similar and they have been plotted up to 2.3 T. The similarity is due to the isotropic characteristic that reflects the condition of the SOMALOY 700 (5P) with the identical values of property in all directions.

However, the core loss along z-axes is slightly higher due to the stress induced during the manufacturing process [4] [4.5]. As illustrated by the curve, the core loss of sample is proportional to the squared of magnetic flux density. There was a significant increase in the production of core loss from the low *B* to the high *B* due to the changes of magnetic flux passing through the magnetic material that makes the core loss getting larger when the magnetic flux density is increased to the right as shown in graph.

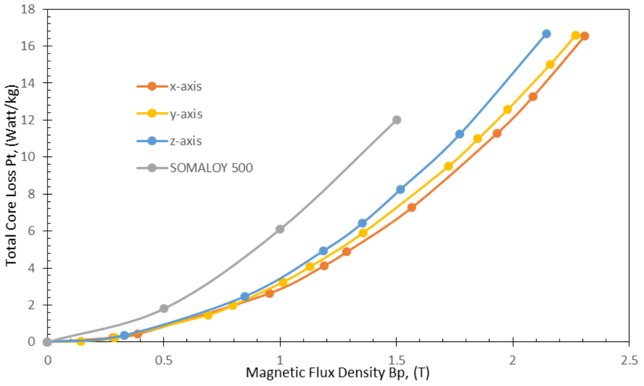

Fig. 9. Loss curve of SOMALOY 700 (5P) at 50 Hz for three different axes.

Fig. 10 explains the alternating core loss at 50 Hz when there is a variation of magnetic flux density which is up to 2.76 T. As illustrated by the figure, the curve is gradually risen from the start. However, it then becomes flat at 2.45 T and it shows that the SOMALOY 700 (5P) saturated at this value.

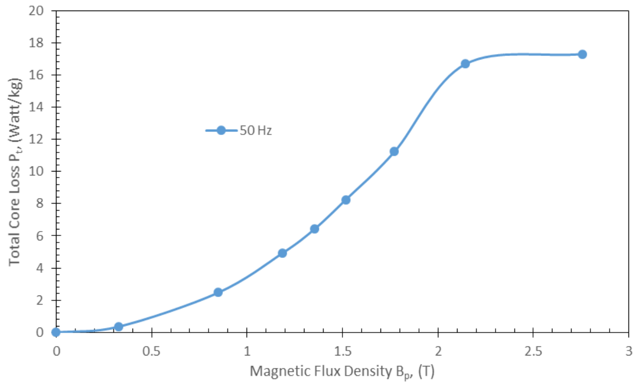

Fig. 10. The alternating core loss of SOMALOY 700 (5P) at 50 Hz.

Fig. 11 illustrates the core loss of SOMALOY 700 (5P) material versus peak magnetic flux density. There are four graphs that represent the core loss curve at 50 Hz, 100 Hz, 500 Hz and 1000 Hz. As can be seen from the graph, all curves dramatically increased with the magnetic flux density at the end after the slowly risen in the beginning. The measurement at 1000 Hz is recorded as the highest in contributing the core loss and it has been followed by measurement under 500 Hz, 100 Hz and 50 Hz. As expressed in equation (1), it describes that the core loss is proportional to the operating frequency and it is proved in this study.

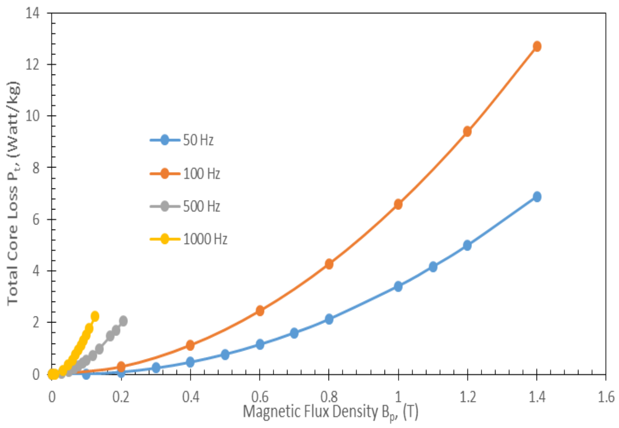

Fig. 11. Loss curve of SOMALOY 700 (5P) material at 50 Hz, 100 Hz, 500 Hz and 1000 Hz.

C. *Core Loss Coefficients*

In order to obtain the core loss coefficients, curve fitting method is considered. By fitting to the measured data, the coefficients C_h, C_e, C_a, and n are deduced as 0.063, 9 x 10^{-10}, 2.9 x 10^{-5} and 1.75, respectively. In this method, the determined coefficients are based on measurements at different frequencies with different magnetic flux densities. Squared error tool is used to fit both calculated and measured core losses in order to calculate the loss coefficients which will be used in determining each component of core loss in the next study.

V. Conclusions

The 3-D tester has measured the magnetic properties of the SOMALOY 700 (5P) material under alternating magnetic flux density at certain range of frequency. The characteristic of the SOMALOY 700 (5P) is compared to the SOMALOY 500, the magnetic material, which has been studied for over 15 years. Due to the new features that have been offered by the SOMALOY 700 (5P), the core loss dissipation is much lower. The magnetic properties have been further discussed by conducting core loss measurement at 50 Hz, 100 Hz, 500 Hz and 1000 Hz of operating frequency. The higher frequency will increase the vibration of the magnetic material during the magnetization process which will cause extra heat dissipation. The current is flown in forward and reverse directions to complete the hysteresis cycle within the magnetic core which will increase the core loss of the material. By obtaining the core loss curve of the magnetic material, the core loss coefficients can be known after fitting the measured data using the Excel software.

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