Empirical Implementation of the Steinmetz Equation to Compute Eddy Current Loss in Soft Magnetic Composite Components

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Recent efforts on reduction CO_2 emissions drive forward the electrification and the ultimate goal is to achieve more sustainable future. Highly efficient and sustainable electric propulsion and its sophisticated power electronic components are quite dependent on magnetic materials. Traditionally, the most common method for manufacturing of electrical machines is laminating the magnetic cores to overcome the losses due to Faraday's magnetic induction. Soft magnetic steels are the basis of laminated cores and with the recent developments in material science and manufacturing, high performance laminated iron cores including silicon-iron (SiFe), nickel-iron (NiFe) and cobalt-iron (CoFe) alloys are still the most common materials in electrical machines and similar magnetic devices such as transformers and inductors. Laminated electric steels are being produced over 140 years.

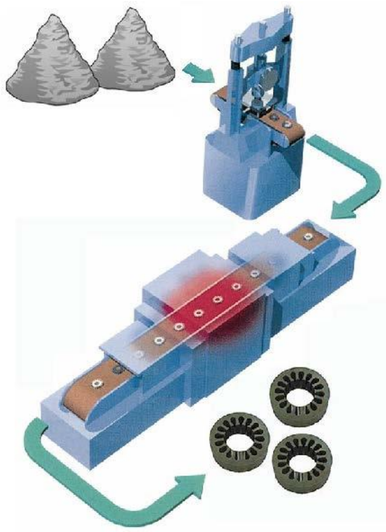

Fig. 1: Parts production in soft magnetic composites: powder, compaction and heat treatment

In the last two decades, soft magnetic composites (SMC) also attract many researchers working on low frequency magnetic components with the applications of electrical machines, actuators, transformers etc. According to Future Market Insights, the automotive and power generation are the key industries for SMC manufacturers and in 2018 the SMC worth of US$ 13Bn was sold and is anticipated to rise more than double over the next decade. SMC utilizes iron powder metallurgy and composed of high purity iron powders and surface coating for electrical insulation and mechanical bonding. The iron particles have a diameter of about 100 µm with an insulation thickness less than 1 µm. The coated iron powders are pressed into a solid magnetic core after several manufacturing steps including die pressing, heating and curing treatment as illustrated in Fig. 1.

One of the key parameters in SMC is powder to insulation ratio affecting resistivity of the composite. If the insulation is reduced in SMC, the electrical conductivity increases and thus the Joule losses will make it unfeasible for many applications such as motors and actuators where the efficiency is eminent. Multi-national powder metallurgy companies such as Höganas AB, GKN, Hitachi Metals Ltd, and Sumitomo Metal Mining Co., Ltd offer different types of SMC materials. This is because some SMC grades address high mechanical strength applications while some address the applications requiring higher magnetic permeability and lower power losses.

Although it is not possible to highlight a unique SMC material giving the best mechanical strength and magnetic properties in parallel, the isotropic nature of SMC offers various three-dimensional (3D) magnetic design solutions and the advantages of the SMC over conventional laminated steels can be summarized as follows:

- Simplified manufacturing process due to reduced number of parts to be assembled in electrical machines

- Applicable to higher frequency applications and demands lower losses
- Due to coated iron powder particles, the electrical resistivity is high that help prevents the formation of eddy currents in alternating field applications.
- Extremely low remanence
- Realization of novel 3D designs such as axial and transverse flux machines, claw pole designs, high performance inductor cores etc., due to unique 3D flux properties
- Easy to recycle
- Improved and more isotropic thermal conductivity in comparison to laminated machines

Soft magnetic composites significantly differ from laminated electric steels in terms of computational loss modelling. Electric machine designers mostly use material library in electromagnetic FE simulations to compute the power losses via available Watts/kg loss data. Even if this approach usually will not cause a mis-prediction of losses in laminated machines, in SMC based electrical machines, this approach causes inaccurate power loss results. Accurate prediction of power losses including hysteresis, eddy currents and ohmic losses needs further attention by researchers and design engineers in case where SMC is the main core material for the machine under investigation.

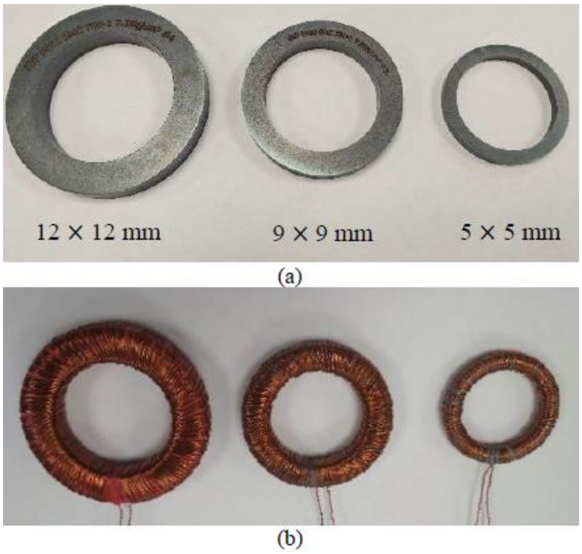

Fig. 2: Fabricated Soft Magnetic Composite (SMC) ring samples in different sizes for loss measurements

Furthermore, electrical resistivity measurements (in bulk material) in Soft Magnetic Composites (SMC) usually end up with not a unique resistivity value but a range of resistivity values with a high standard deviation depending on the size and production of SMC. Unlike finite element (FE) electromagnetic modelling of conventional laminated iron cores, SMC based 3D flux electrical machines require an accurate value of electrical resistivity value in the FE software for accurate iron loss results. There are several factors causing uncertainties in electrical resistivity of SMC components such as material grade, applied pressure and bulk dimensions. In the study, a set of test rings given in Fig. 2 have been fabricated to characterize the specific core losses and material resistivity. Main aim of the measurements is to compare the actual electromagnetic losses to those predicted through FE modelling. Traditional Steinmetz equation for loss calculations in SMC components are given in equation (1).

$$P_{total} = K_h f^{\alpha} B^{\beta} + K_{ep} f^2 B^2 + \frac{B^2 f^2 d^2}{1.8 \times \rho \times resistivity \times 1000} \quad (Watts/kg) \tag{1}$$

where K_h and K_{ep} are hysteresis and eddy current loss coefficients respectively; α and β are parameters to be determined from Steinmetz equation curve fitting; B and f are peak magnetic flux density (T) and electrical frequency (Hz) respectively and lastly d and ρ stands for the component's smallest cross-sectional dimension (mm) and mass density (g/cm^3), respectively. The unit of resistivity in (1) is $\mu\Omega m$.

In our collaborative research with SG Technologies, Rainham, UK, we propose a robust, empirical Steinmetz equation to reduce the uncertainties due to material resistivity. Non-linear regression of eddy current loss coefficients, K_{ep} as given in Fig. 3 for different size ring samples allows us to set up an empirical, modified Steinmetz equation. This equation is given in (2) below. These coefficients have been obtained after measurements on the SMC ring samples. As an example, the specific power loss measurements of 12 mm × 12 mm SMC ring sample (Somaloy 700 1P by Höganäs) are given in Fig. 4 below.

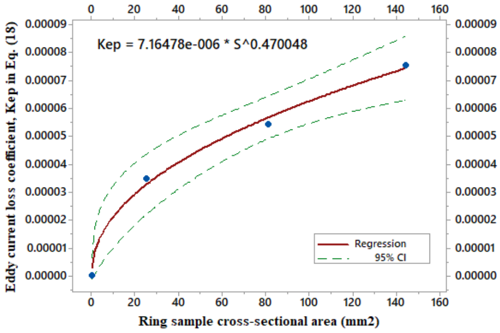

Fig. 3: Non-linear regression analysis for the varying K_{ep} values in the experiments

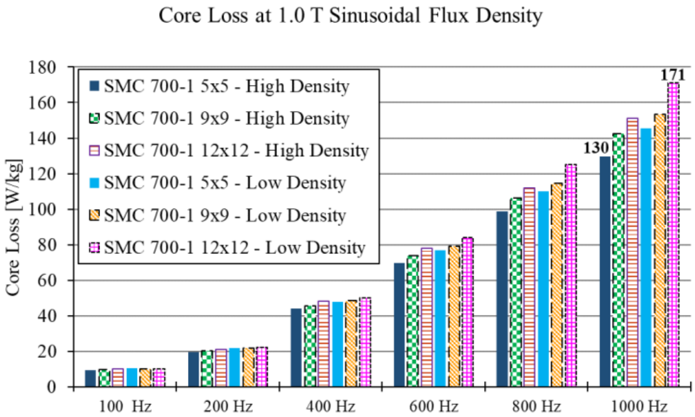

Fig. 4: Somaloy 700 1P core loss results in Watts/kg for the test ring samples with the cross-sections of: 5mmx5mm, 9mmx9mm, 12mm x12mm

$$P_{total} = K_h f^{\alpha} B^{\beta} + \theta_1 \times S^{\theta_2} f^2 B^2 \ (Watts/kg) \tag{2}$$

where K_h, α, β, θ_1 and θ_2 are the parameters to be determined via a surface curve-fitting for varying cross-sectional area, S of the ring samples where $S \in [0\ mm^2 - 144\ mm^2]$

Dimensional factor and material resistivity in SMC are the main sources of error in loss computations and the proposed empirical approach to estimate the eddy current loss in SMC would be a better option with improved loss computation accuracy since it avoids electrical resistivity of the SMC component under investigation. Thus, E-machine designers dealing with Soft Magnetic Composites can obtain more accurate numerical loss models in early stages of the design through the proposed approach.