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Investigative study on the properties of magnetic materials for electrical machines

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ABSTRACT

The paper attempts to investigate the properties of the magnetic materials used in the construction of rotating electric machines, with a view to arrive at the appropriate choice for the induction motors in particular. Measurement of magnetic properties for rotating electrical machines are more important to both machine designer and operator. This paper discusses the influence of magnetic properties of electrical steel on performance of electrical machine. Here properties like BH curve, core loss, permeability and other vital parameters are measured using 400×400 Epstein tester over wide range flux density and frequency up to 50 Hz and 400 Hz. The results measured in terms of the core loss, BH curve and permeability showcase the benefits to decide on the suitability of the material for use in practice.

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1. INTRODUCTION

Huge efforts to reduce the toxic gas emissions from fossil fuels coupled with the constant push to increase the renewable energy production seem to be the order of the day. The magnetic materials invite applications in almost every field of the modern technology. The total energy consumption worldwide continues to increase dramatically [1] especially in Asia and third world countries, where there exists a need to improve the energy infrastructure. The energy framework demonstrates the significance of the electrical energy and promotes it to be the most valuable form of energy with its prominence in the areas of generation and utilization.

The electrical machines consume about three quarters of the electrical energy generated from the various sources [2]. It appears to be a possibility of saving about 15% to 30% of the energy consumed if the machines can be operated on a variable speed framework [3]. Although it may not allow an increase in the system's energy density, in practice it can reduce the efficiency of the electrical machine. Improving the design specifications to achieve higher efficiency and/or higher energy density relates to a close dependence on the present technology [4]–[6]. The use of new topologies and better electrical steels for the rotor and/or stator stack has been envisaged in [7]. The effect of the silicon content on the iron loss of the non-oriented electrical steel sheets has been investigated by Oda *et al.* [8] on an interior permanent magnet motor made using different Si steel sheets and at a high core flux density. It has been seen that the performance of the machine designs depends significantly on material selection and the operating point of the core.

A comparative analysis of the influence of the alloying elements on magnetic properties of several grades of electrical steels has been reported by Lorenzo *et al.* [9]. A higher power magnetic tester has been designed to measure the magnetic hysteresis properties, permeability, harmonic and core loss and the performance compared with the traditional Epstein frame and single sheet tester by Li *et al.* [10]. The experimental results have been presented to bring out the difference of the magnetic properties for silicon steel sheets between the laminated and the rolling direction. The study has been oriented to provide dynamic and comprehensive data for designing and evaluating the performance of the electrical machines and the power transformers. The influence of a wide range of magnetizing frequencies and peak flux densities on the magnetic properties of the electrical steels have been reported by Hamzehbahmani *et al.* [11]. The samples have been magnetized with a time-varying magnetic field of magnetizing frequencies from 10 Hz up to 1000 Hz and the peak flux densities of 1.3, 1.5, and 1.7 T. The results have been highlighted to show that the magnetizing frequency and the peak flux density remain the two determinant factors with significant effect on the magnetic properties of the electrical steels. The experimental data for the frequency dependence of the magnetization curves that include the coercive force, the permeability, and of the magnetic losses for non-oriented electrical steels with thicknesses in the range of 0.10 mm up to 0.50 mm has been reported by Schneider *et al.* [12].

A different character of the dynamic magnetization behaviour at increasing frequency of the applied external field compared to the thicker materials has been observed for thin electrical steels. The performance of soft magnetic materials used for the manufacturing of the magnetic cores of energy-efficient electric motors has been investigated by Hanene *et al.* [13]. The properties of the materials have been compared and their prospective influence on iron loss and efficiency of electric motors discussed. On an analysis the properties of the chosen magnetic materials, the appropriate magnetic material may be selected for the construction of the electrical machine and augur to arrive at the strict energy efficiency regulations. The main problem identified based on literature; the efficiency of the electrical motors has been improved through significant mechanisms to scale down the losses in the electrical machines through feasible materials. The efforts lay a need to experimentally study the properties and analyze the characteristics for reaching out to the choice of the material.

2. PROPOSED METHOD

The focus owes on the myriad of options that emerge to determine the best materials for being used in the cores of electrical machines. It gathers appropriateness to reflect from the characteristics, thickness of the lamination, the saturation flux and permeability together with the cost of the materials under study. The investigations include a detailed view of the losses that depend on the operating frequencies and influence the performance of the machine. The iron losses occur primarily in several parts of the stator and rotor of any rotating electric machine. It augurs to be an important component of the loss, especially in high-speed electric machines. However, its prediction poses challenges because it relies heavily on the materialistic properties. The magnetic materials that include iron (Fe), nickel (Ni) and cobalt (Co) constitute to be the basic types used in the manufacture of the cores for electrical machines. The saturation of the core of any electrical machine depends upon the relation between the magnetic flux to the magnetizing force being referred to as the magnetic permeability of the particular core. The physical properties can be improved by alloying with the other minerals and including alloy materials to offer cold- rolled motor lamination steel in the form of thin-gauge silicon steel and non-oriented electrical steel.

The cold rolled steel belongs to the very low carbon category with approximately 0.06% carbon, 0.5% silicone and 0.6% manganese, and 0.46 mm-0.79 mm [14]. It finds its use when designing drives and require higher saturation or permeability flux values [15]. It exhibits low primary loss characteristics despite the very fact that contemporary grades of cold rolled motor lamination (CRML) steel [16] show competitive loss properties with certain degrees of non-directed silicon steel. The lack of intrinsic alloy materials and abrasive insulating paints extend the lifetime of the fabric, leading to additional cost savings in manufacturing. The thin-gauge silicon steel, generally 0.25 mm thinner allows reducing the thickness and resistance of wheeled vehicle to scale back eddy current losses [17] and thus the general basic losses during a given roll. It forges to be split into two categories, those with atypical silicon content slightly below 3% and that with a silicon content of about 6.5%. The characteristics make it attractive for being used in the motors and special power generation applications, especially those operating at high rotational speeds. The standard chemical steels find an area where lower losses become imminent to result in lower costs [18]. The 6.5% of silicon steel, although costly, offers lower losses and really low magnetic friction properties because of its high silicon content [19]–[21].

The non-directed silicon steel relates to be characterized by being a mild steel of up to 2.7% of silicon and provides uniform longitudinal and transverse magnetic properties [22]. It inherits an increased permeability [23] and low average heat loss [24] combined with cold finishing that permits a smooth surface and reduces buckles and ripples in order to enjoy flatness and a high stacking factor [24]. With moderate silicon content, it allows an extended lifetime of the tool to enjoy a wide range of applications for engines [25] and generators including servo motors for motion control systems and space accessories. The electric traction systems [26], industrial vehicles, generators and public service, although include fewer grades to settle on from its magnetic properties on being manipulated slightly during the annealing cycle after stamping, serve to provide a number of features.

3. TEST BENCH DESCRIPTION

The Epstein tester constitutes to be a standardised measuring device used for measuring the magnetic properties of the electrical steel. The Epstein framework shown in the Figure 1 includes a 16-bit microcrystalline sine wave generator, which provides 25 Hz to 450 Hz and equipped with an amplifier with peak values of 40 amps and 110 volts. The Figure 2 to Figure 27 represents the graphical outline of the magnetization and core loss properties of the commonly used lamination materials. It provides a closer look at the core loss properties of each class of material at 50 Hz and at lower and higher values of 0.1 and 1.6 T respectively.

Figure 1. Epstein frame test bench

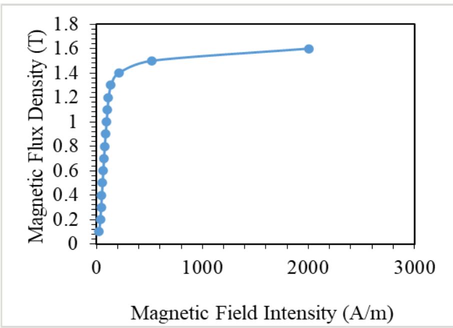

Figure 2. B-H curve of CRML semi processed grade Q core-0.64 mm

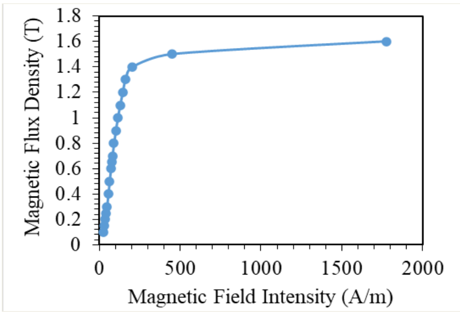

Figure 3. B-H curve of CRML semi processed grade Q core-II 0.46 mm

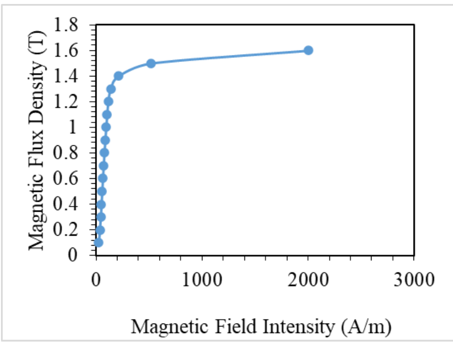

Figure 4. B-H Curve of CRML semi processed grade Q core-II 0.56 mm

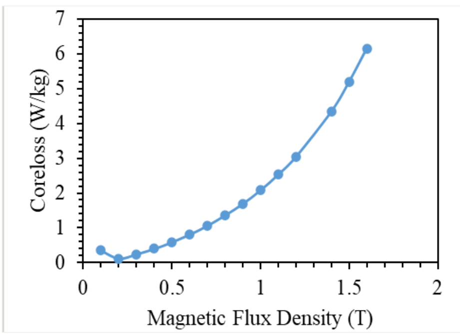

Figure 5. Core loss curve of CRML semi processed grade Q core-0.64 mm

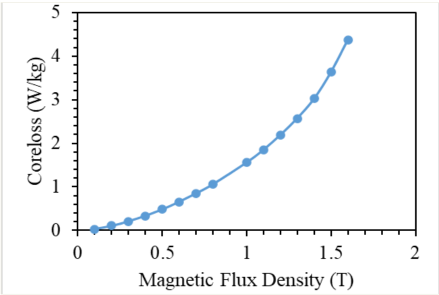

Figure 6. Core loss curve of CRML semi processed grade Q core-II-0.46 mm

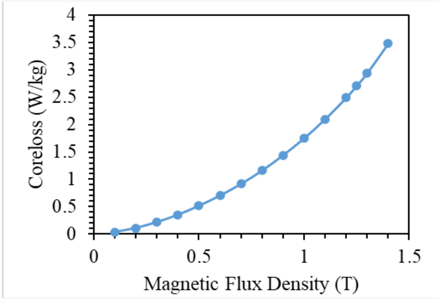

Figure 7. Core loss curve of CRML semi processed grade Q core-II-0.56 mm

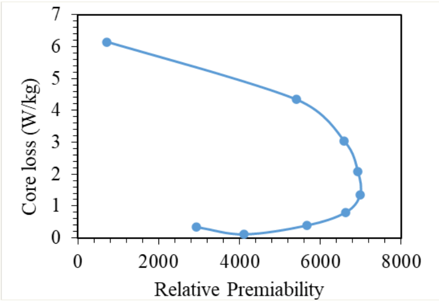

Figure 8. Relative permeability and core loss curve of CRML semi processed grade Q core-0.64 mm

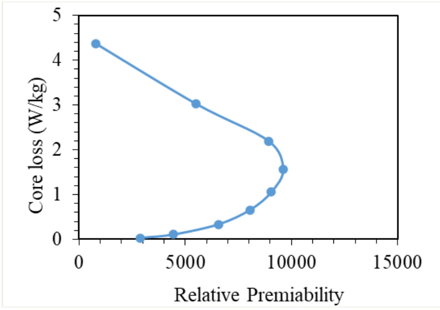

Figure 9. Relative permeability and core loss curve of CRML semi processed grade Q core-II 0.46 mm

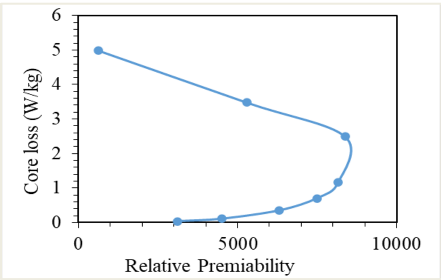

Figure 10. Relative permeability and core loss curve of CRML semi processed grade Q core-II 0.56 mm

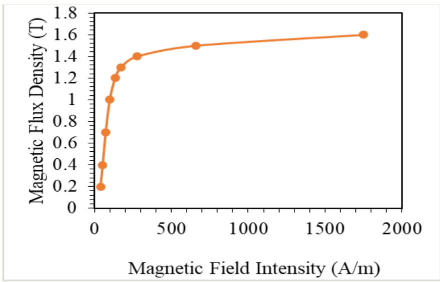

Figure 11. B-H curve of non-oriented steel DI-MAX-M15-0.36 mm

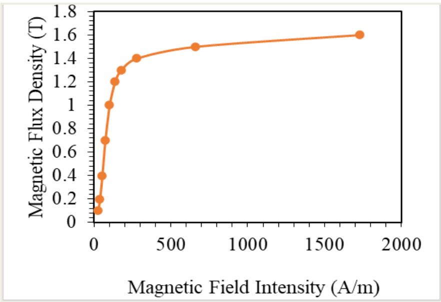

Figure 12. B-H curve of non-oriented steel DI-MAX-M19-0.36 mm

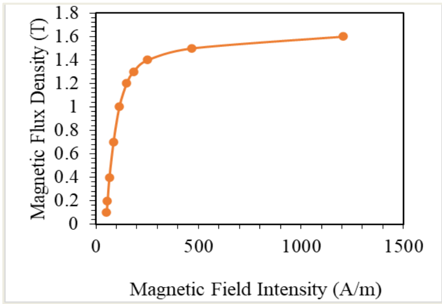

Figure 13. B-H curve of non-oriented steel DI-MAX-M36-0.36 mm

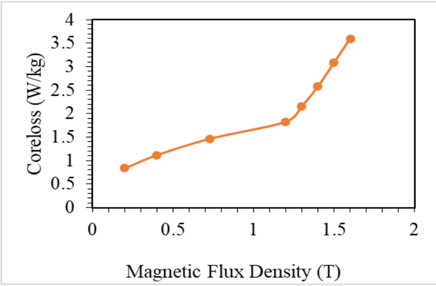

Figure 14. Core loss curve of non-oriented electrical steel-DI-MAX-M15-0.36 mm

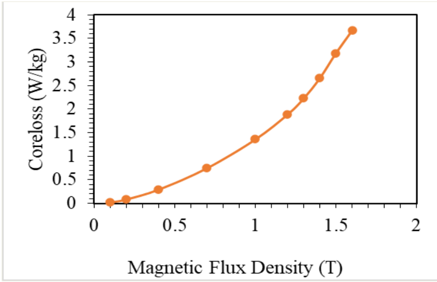

Figure 15. Core loss curve of non-oriented electrical steel-DI-MAX-M19-0.36 mm

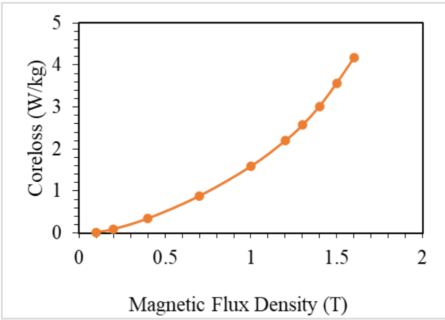

Figure 16. Core loss curve of non-oriented electrical steel-DI-MAX-M36-0.36 mm

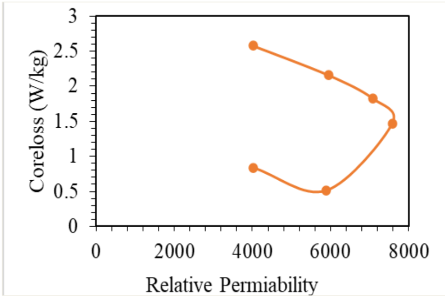

Figure 17. Relative permeability and core loss curve of non-oriented electrical steel-DI-MAX-M15-0.36 mm

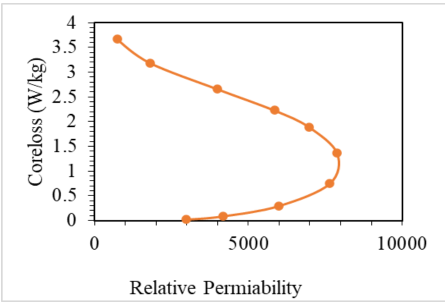

Figure 18. Relative permeability and core loss curve of non-oriented electrical steel-DI-MAX-M19-0.36 mm

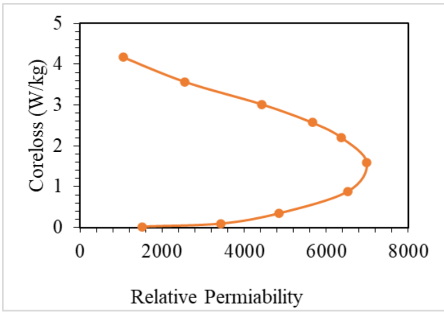

Figure 19. Relative permeability and core loss curve of non-oriented electrical steel-DI-MAX-M36-0.36 mm

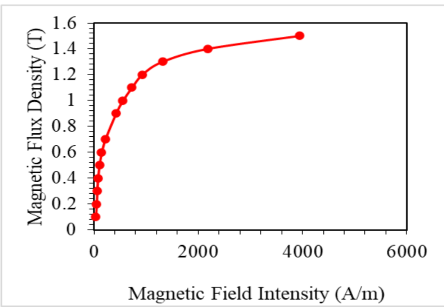

Figure 20. B-H curve of non-oriented thin gauge silicon steel-JNHF-CORE10JNF600-0.1 mm

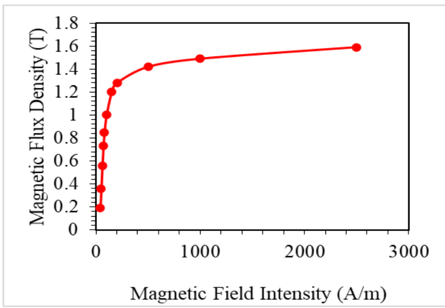

Figure 21. B-H curve of non-oriented thin gauge silicon steel-JNHF-CORE20JNEH1500-0.2 mm

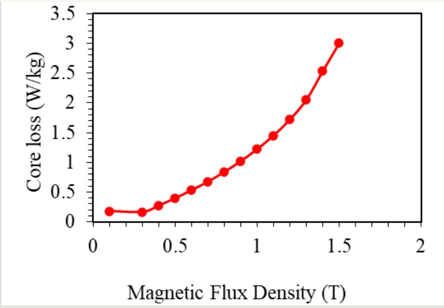

Figure 22. Core loss curve of non-oriented thin gauge silicon steel-JNHF-CORE20JNEH1500-0.2 mm

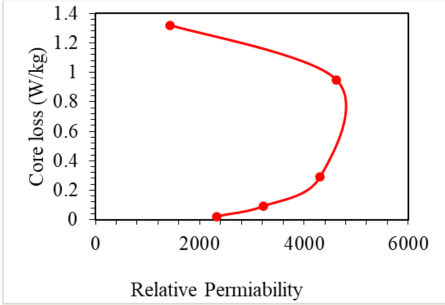

Figure 23. Relative permeability and core loss curve of non-oriented thin gauge silicon steel-JNHF-CORE10JNHF600-0.1 mm

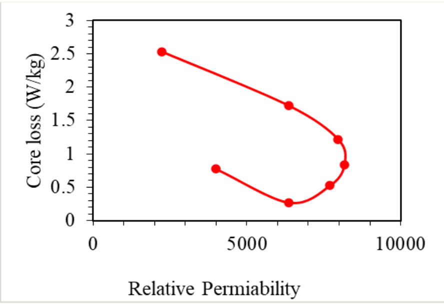

Figure 24. Relative permeability and core loss curve of non-oriented thin gauge silicon steel-JNHF-CORE20JNEH1500-0.2 mm

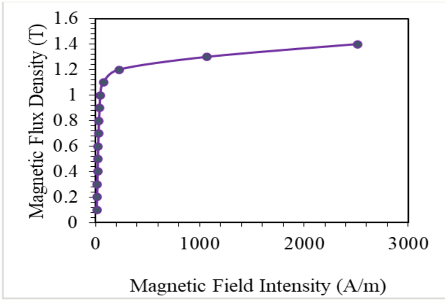

Figure 25. B-H curve of non-oriented thin gauge super silicon steel-JFEXJNEX-CORE10JNEX900-0.1 mm

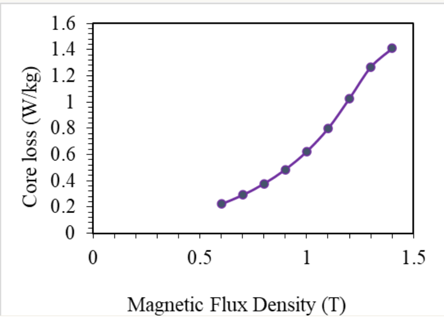

Figure 26. Core loss curve of non-oriented thin gauge super silicon steel-JNHF-CORE10JNHF600-0.1 mm

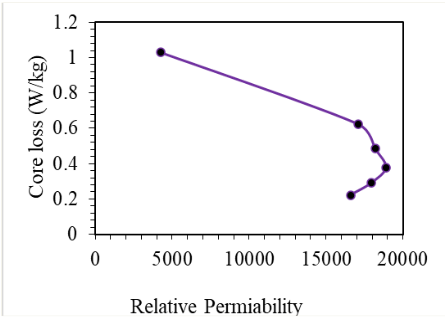

Figure 27. Relative permeability and core loss curve of non-oriented thin gauge super silicon steel -JFEXJNEX-CORE10JNEX900-0.1 mm

Figure 2 to Figure 4 shows the magnetic flux density (B) and the magnetic field intensity (H) curves of the chosen CRML steel. The magnetic field required to attain a flux density of 1.2 T turns out to be 107 A/m in grade Q core-II semi processed CRML steel (0.46 mm) and about 145 A/m and 114 A/m in grade Q core semi processed CRML steel (0.64 mm) and grade Q core-II semi processed CRML steel (0.56 mm). It follows from the study that grade Q core-II semi processed CRML steel (0.46 mm) requires a lower magnetic field intensity when compared with the other grade Q core semi processed CRML steel (0.64 mm) and grade Q core-II semi processed CRML steel (0.56 mm). The Figure 11 to Figure 13 shows the magnetic flux density (B)-magnetic field intensity (H) curves of the chosen non oriented electrical steel, wherein the magnetic field required to attain the flux density of 1.2 T turns out to be 135 A/m in DI-MAX-M-15 while, it reads as 137 A/m and 150 A/m for DI-MAX-M-19 and DI-MAX-M-36 respectively. The quality of the magnetic material plays an important role in enhancing the efficiency of the electrical device and may be achieved by ensuring a higher saturation level and magnetic permeability. The Table1 shows the relative properties of the magnetic materials under study in terms of the core loss, saturation flux density and the magnetic flux density.

Table 1. Relative properties of magnetic materials

Material type		Thickness (mm)	Core loss	Saturation flux density	Magnetic flux density
Grade Q core-II semi processed CRML steel		0.56	Poor	Good	Good
Non oriented silicon steel	DI-MAX-M-15	0.36	Good	Good	Good
	DI-MAX-M-19	0.36	Good	Good	Good
	DI-MAX-M-36	0.36	Poor	Good	Good
Thin guage super silicon steel JFEXJNEX-CORE10JNEX900		0.1	Fair	Good	Good
Non oriented thin gauge silicon steel JFE Steel	JNHF-CORE 10JNHF600	0.1	Fair	Good	Good
	JNHF-CORE 20JNEH1500	0.2	Fair	Fair	Good

The Figure 20 and Figure 21 show the magnetic flux density (B) and the magnetic field intensity (H) curves of the non-oriented thin gauge silicon steel. The magnetic field required by the JNHF-CORE 10JNHF600 (0.1 mm) material to the attain flux density of 1.2 T turns out to be 923 A/m where as in the JNHF-CORE 20JNEH1500 (0.2 mm), it relates to 150 A/m, indicating that the JNHF-CORE 20JNEH1500 requires lower magnetic field intensity when compared with the others. The Figure 25 depicts the magnetic flux density (B) magnetic field intensity (H) curves of the thin gauge super silicon steel to extradite that it needs 224 A/m to attain a magnetic flux density of 1.2 T. The Figure 5 to Figure 7 project the core loss curve of the CRML steel, where the core loss of grade Q core-II semi processed CRML steel at 1.2 T turns out to be 2.19 W/kg where as it indicates to be 3.04 W/kg and 2.49 W/kg for the grade Q core semi processed CRML steel (0.64 mm) and grade Q core-II semi processed CRML steel (0.56 mm) respectively. Thus, the core loss of grade Q core-II semi processed CRML steel (0.46 mm) reduces by 28% of the grade Q core-II semi processed CRML steel (0.64 mm). Owing to the fact that the core loss strongly affects the performance of the rotating electrical machines, it fosters the need to select the material which results in lower core loss. The Figure 14 to Figure16 explain the core loss curves of the non-oriented electrical steel, where the core loss at 1.2 T in DI-MAX-M-15 steel becomes equal to 1.83 W/kg whereas, it shows it to be 1.89 W/kg and 2.2 W/kg for DI-MAX-M-19 and DI-MAX-M-36 respectively, indicating a 14 percent reduction for DI-MAX-M-19. The core loss of DI-MAX-M-15 steel becomes less when compared with that of DI-MAX-M-19 and DI-MAX-M-36.

The Figure 22 and Figure 26 shows the core loss curve of the non oriented thin gauge silicon steel and thin gauge super silicon steel. The core loss of the JNHF-CORE 10JNHF600 (0.1 mm) steel at 1.2 T indicates to be 1.72 W/kg while it turns out to be 1.03 W/kg for the JNHF-CORE 20JNEH1500 (0.2 mm), claiming a reduction of 40 percent for the JNHF-CORE 10JNHF600 (0.1 mm). In order that the silicon content in the core material influences the saturation flux density and the core loss, it becomes significant to use a higher grade for the core material. The energy loss in an electromagnetic core may be reduced by using thinner laminations. However, it necessitates to be weighed against the other factors, especially the cost in choosing the best steel for a particular machine. With ever-increasing requirements for low-cost machinery, including those with advanced performance, it brings in a requirement to combine the performance problems with the value of the ultimate machine. A detailed reading of the magnetic properties of rolling materials provides the bet information about their individual properties and a construal of the overall characteristics of the variants of the electrical steel. The Table 2 represents the magnetic material properties of the core material at 50 Hz frequency. Despite the adhesion that every class of the fabric includes strengths and weaknesses that require to be addressed, the consideration of the quandaries strives to avail the electrical steel that fortifies the performance and marketing requisites.

Table 2. Magnetic material properties of used core material @50 Hz frequency

Material		Thickness (mm)	Core loss (W/kg) @1.2 T	Relative permeability
Grade Q core -II semi processed CRML steel		0.56	2.49	8165.93
Non oriented silicon steel	DI-MAX-M-15	0.36	1.83	7077.14
	DI-MAX-M-19	0.36	1.89	6973.82
	DI-MAX-M-36	0.36	2.2	6369.42
Thin Guage super silicon steel	JFEXJNEX-CORE10JNEX900	0.1	1.03	4265.24
Non oriented thin gauge silicon steel JFE Steel	JNHF-CORE 10JNHF600	0.1	1.76	1032.88
	JNHF-CORE 20JNEH1500	0.2	1.72	6369.42

4. CONCLUSION

A comprehensive study has been extradited to permit the choice of the magnetic materials suitable to be used in the electrical machines. The analysis has been enabled using the Epstein tester to spotlight the effect of the magnetic parameters on the losses in the magnetic materials. The efforts have been strengthened by opening up the diverse influence of the factors that account to arrive at the appropriate choice of the material. The investigations have been presented from an experimental perspective and hence the claim from the results adds a new dimension in exploring the best choice of the magnetic material for being used in rotating machines.

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