Influence of Soft Magnetic Material type in Fixture Components on the Magnetization of Bonded Neo Magnet and Motor Performance

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In this paper the effects of using laminated steel and solid steel for the magnetizing fixture components on the magnetization energy needed for saturation, magnetization profile and motor performance are presented. Three combinations of fixture core and back iron materials have been analyzed using 2-D Finite element analysis as well as experiments. The potential issues with the use of solid steel as fixture components have been explained. The results indicates that the magnetization fixtures made with solid steel components requires higher energy to generate the magnetization field needed for magnet saturation and in most practical cases leads to partially magnetized magnet and poor motor performance. The use of laminated steel for all soft magnetic components in the magnetization fixture is highly recommended.

***Index Terms*— Fixture, Isotropic Bonded Nd-Fe-B, Laminated steel, Magnet, Magnetization, Solid steel.**

I. Introduction

The advantages like higher magnetic properties than ferrite, near net shape magnet production, and no use of heavy rare earth elements makes the bonded neo magnet very attractive in motors used for automotive accessory, home appliance and office automation. The isotropic nature of bonded neo magnets offers a feasibility to obtain wide range of magnetization profiles. The magnetization of the magnet influences the air-gap flux distribution and hence the motor performance [1]. Magnetizing fixture comprising of copper coils embedded in soft magnetic material is used to magnetize the magnet. When radial magnetization profile is desired, a back iron made up of soft magnetic material is also used to reduce the amount of magnetizing energy needed to saturate the magnet. Laminated steel is the preferred material for the magnetizing fixture as well as back iron, but at times solid steel is also used in place of laminated steel. In this paper, the simulated and experimental results are presented on the influence of soft magnetic material type used in magnetizing fixture components on the magnetization performance of the magnets and also on the performance of motor namely motor back-emf, no-load speed, stall torque and cogging torque (which is the torque generated due to magnet flux only without any motor current), when these magnetized magnets are assembled in it.

II. Finite Element Analysis

Using the commercially available finite element analysis (FEA) software OPERA Vector Fields a magnetizing fixture is designed to achieve full saturation for the magnet given in Table I. The fixture is designed such that 30 kG magnetizing field is applied at the magnet circumference farthest from the fixture conductors [2]. Fig. 1 shows the cross section of the designed fixture. The fixture is designed with fixture core and back iron made of laminated steel 1010 (LCLB). The magnetizing performance of the designed fixture is evaluated using 2-D FEA. To evaluate the influence of soft magnetic material type used in fixture components two more combinations; (i) fixture core made of laminated steel but the back iron is made of solid steel (LCSB) and (ii) both fixture core and back iron made of solid steel (SCSB) are simulated. During the simulation the solid steel conductivity of 7.146e6 S/m is considered.

TABLE I
MAGNET DIMENSIONAL DETAILS

Symbol	Parameter	Value
ID	Magnet inner diameter (mm)	24
OD	Magnet outer diameter (mm)	27
H	Magnet height (mm)	29
	Magnet type	MQ1™
	Number of poles	4
	Magnetization	Radial

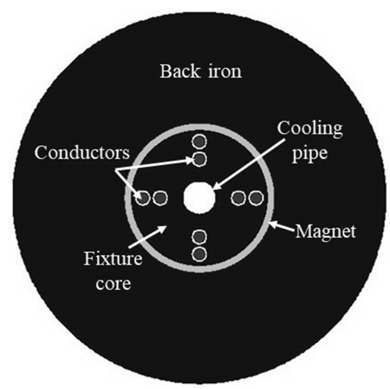

Fig. 1. Magnetization fixture cross-section

A. Magnetization

For the designed fixture when both the core and back iron are made of laminated steel, the energy needed to generate 30 kG field at the magnet outer diameter (OD) is 5.44 kJ. Fig. 2 shows the flux due to applied magnetization field and the eddy currents generated for various combinations. It can be observed from Fig. 2(a) that no eddy currents are generated in LCLB combination.

From Fig. 2(b) and (c) it can be observed that the use of solid steel components leads to the generation of eddy currents leading to reduction in effective thickness of back iron. The presence of eddy current also reduces the magnetization field at the magnet OD to 17.59 kG and 14.5 kG respectively for LCSB and SCSB combinations.

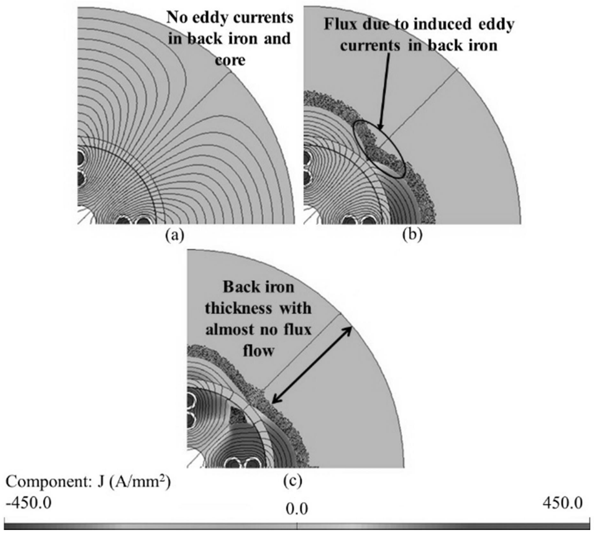

Fig. 2. Flux due to applied magnetization field and induced eddy currents in the fixture (a) LCLB (b) LCSB and (c) SCSB

To achieve the full magnet saturation the applied magnetizing energy and current density in the conductor is increased for LCSB and SCSB combinations as given in Table II. The increase in magnetizing energy and current density in the conductor results in higher thermal stress on the fixture and reduces the fixture reliability. Fig. 3 shows the applied magnetization field plotted at magnet OD considering the mechanical angle. From this figure it is observed that the use of solid steel components leads to the generation of hump at the center of the pole due to the generated eddy currents. In SCSB combination, the eddy currents in the fixture core distorts the flux near the pole area pushing the field slightly towards the conductors creating a waveform with a trough at the center.

TABLE II
SIMULATED ENERGY REQUIRED FOR MAGNET SATURATION

Fixture Component Combination	Energy (kJ)	Current density (kA/mm^2)
LCLB	5.44	7.85
LCSB	34.02	19.64
SCSB	68.28	27.79

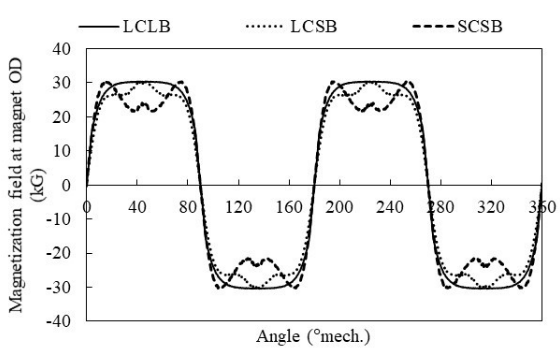

Fig. 3. Applied magnetization field measured at magnet OD

B. Estimated Magnet Flux and Motor Performance

The magnets are magnetized to full saturation by applying the energy indicated in Table II for all three LCLB, LCSB and SCSB combinations. The fully saturated magnet model for each case is imported to a closed circuit flux scan and motor model [3]. Fig. 4 shows the closed circuit flux scan set-up used to evaluate the mid airgap flux density from a fully saturated magnet. As shown in the figure, the effective airgap is the sum of the probe clearance and half the thickness of hall probe. Fig. 5 shows the mid airgap flux density waveform when the magnets are fully saturated. It is observed from Fig. 5 that the flux density waveform for LCLB is radial and is near to sinusoidal (Halbach) [1] in case of both LCSB and SCSB combinations. Table III summarizes the flux integral per pole for the waveforms shown in Fig. 5. From Table III, it is seen that the presence of solid steel component (LCSB and SCSB) leads to lower flux integral per pole. This is due to the sinusoidal nature of the flux waveform.

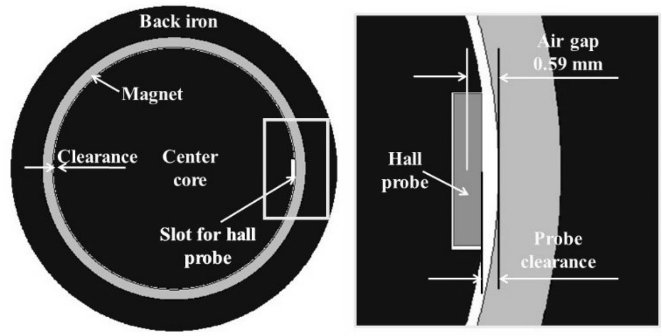

Fig. 4. Closed circuit flux scan set-up

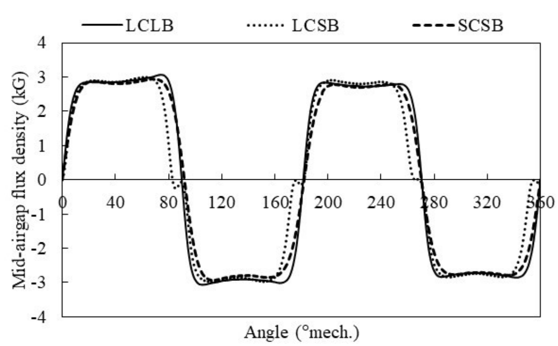

Fig. 5. Simulated mid airgap flux density using closed circuit model

TABLE III
COMPARISON OF SIMULATED MAGNET FLUX INTEGRAL

Fixture Component Combination	Flux integral per pole (kG-°mech)
LCLB	289.5
LCSB	241.8
SCSB	237.8

Table IV gives the simulated motor back-emf and cogging torque for various combinations of materials for fixture components. The reduced flux per pole and near sinusoidal airgap flux wave shape resulted in lower cogging torque when solid steel components are used during magnetization. The reduced mid airgap flux also resulted in lower motor back-emf when the solid steel components are used. Compared to LCLB combination the motor back-emf at 3300 rpm is reduced by 2.4% and 6% respectively for LCSB and SCSB combinations.

TABLE IV
COMPARISON OF SIMULATED MOTOR PERFORMANCE

Fixture Component Combination	Peak-peak Cogging Torque (mN-m)	Back-emf (V)
LCLB	47.04	10.2
LCSB	6.19	10.0
SCSB	5.15	9.6

III. EXPERIMENTAL VALIDATION

The designed magnetizing fixtures have been fabricated. Fig. 6 shows the fabricated fixture components. Using the fabricated fixtures the magnets have been magnetized for LCLB, LCSB and SCSB combinations. The estimated energy needed to achieve full magnet saturation in LCSB and SCSB combination exceeds the capability of most of the commercially available magnetizers. Based on the capability of the available magnetizer a maximum of 6kJ energy is applied during magnetization process.

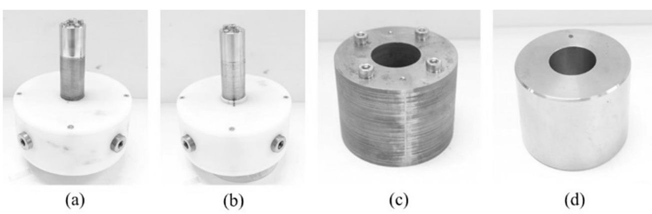

Fig. 6. Fabricated fixture components (a) Laminated fixture core (b) Solid steel fixture core, (c) Laminated back iron and (d) Solid steel back iron

A. Magnetization Process and Magnet Performance

The magnets are magnetized at applied energy levels in initial steps of about 0.5kJ up to 3.5kJ followed by 0.2kJ up to 6kJ. For each magnetization level the mid airgap flux density is measured using the closed circuit flux scan measurement set up shown in Fig. 7 and flux integral per pole is arrived at.

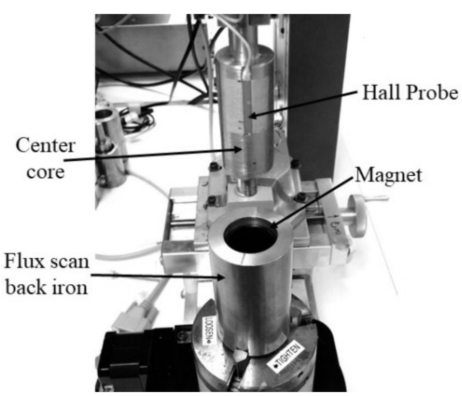

Fig. 7. Closed circuit flux scan measurement set-up

Fig. 8 shows the mid airgap flux density profile for different combinations when magnet is magnetized at the maximum energy of 6 kJ. It can be seen from Fig. 8, that the mid airgap flux density profile for LCSB combination has a small notch near the transition zone. This is due to the presence of eddy current only in back iron. For the waveforms shown in Fig. 8, the flux integral per pole is derived as shown in Table V. It is observed from the Table V, that the LCLB combination has the highest flux integral due to its radial waveform and LCSB has the least flux integral due to the presence of notch near the transition zone.

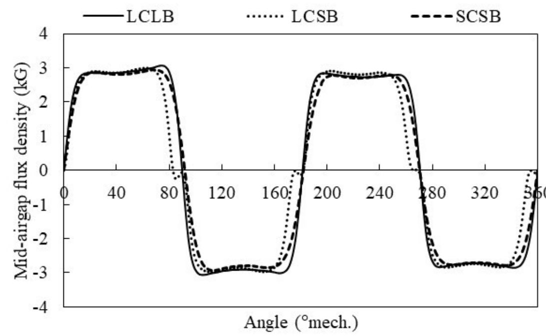

Fig. 8. Comparison of mid airgap flux density for various combinations.

TABLE V
COMPARISON OF MEASURED MAGNET FLUX INTEGRAL

Fixture Component Combination	Flux integral per pole (kG-°mech.)	Difference
LCLB	233.5	-
LCSB	207.6	-11.1%
SCSB	218.1	-6.6%

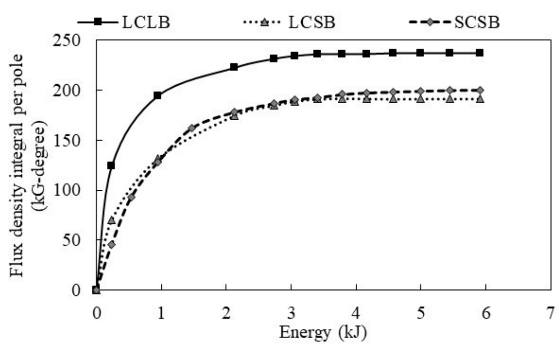

Fig. 9. Magnetization test results for various combinations

Fig. 9 shows the flux integral per pole for different applied energy. Table VI summarizes the applied magnetization field at the magnet OD when the 6 kJ magnetization energy is applied. The presence of solid steel components results in induced eddy current opposing the applied magnetization field and hence partially saturated magnet in LCSB and SCSB combinations. The magnetization field generated in LCSB and SCSB combinations is 48% and 54% less respectively than the required magnet saturation field of 30 kG. Difference in material used for steel during simulation and fabrication have contributed to the difference between simulated and measured values of energy needed for saturation.

The material used for the fixture components influences the transition zone on the magnet surface. Fig. 10 shows the transition zone on the magnet surfaces for various combinations. From the figure it can be observed that the presence of solid steel component leads to the unwanted secondary transition zones. Although the magnet flux per pole in SCSB combination is higher than the LCSB combination, the magnetization field at the magnet outer diameter is less in SCSB combination as given in Table V. This is due to the presence of eddy currents on both fixture core and the back iron which results in a blurred transition zone on the magnet outer surface as shown in Fig. 10(c). The blurred transition zone is an indicator of partially saturation of magnet during magnetization.

TABLE VI
MEASURED FIELD GENERATED DURING MAGNETIZATION

Fixture Component Combination	Field at magnet OD for 6kJ applied energy (kG)
LCLB	29.4
LCSB	15.6
SCSB	13.7

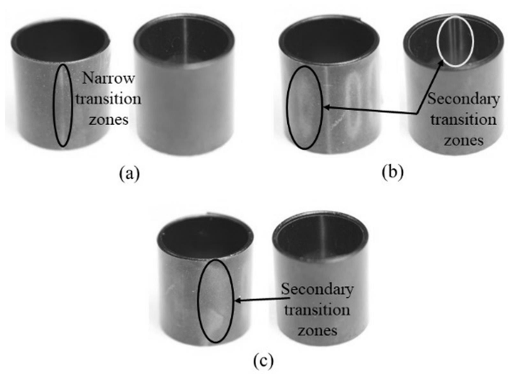

Fig. 10. Magnet pole transition zone (a) LCLB (b) LCSB (c) SCSB

IV. EFFECT ON MOTOR PERFORMANCE

Magnets magnetized by applying 6 kJ energy and for various combinations of fixture components during magnetization are assembled in a 10-slot motor and motor performance is evaluated.

A. *Cogging Torque and Motor Back-emf*

Table VII gives the peak to peak cogging torque and motor back-emf measured at 3300 rpm for various combinations. The highest flux due to the radial wave shape in LCLB combination leads to the highest back-emf and also contributed to the highest cogging torque for LCLB combination. Compared to the estimated values of cogging torque from simulation, the measured values in LCSB and SCSB combinations are higher due to the presence of the unwanted secondary transition zones.

TABLE VII
COMPARISON OF PEAK-TO-PEAK COGGING TORQUE AND MOTOR BACK-EMF

Fixture Component Combination	Peak-to-peak cogging torque (mN-m)	Motor back-emf at 3300 rpm (V)
LCLB	69.9	8.53
LCSB	25.2	7.82
SCSB	27.9	8.20

B. *No-Load Speed*

Table VIII gives the no-load speed for the motors. Compared to LCLB combination, the no-load speed is higher in SCSB and LCSB combinations due to lower magnet flux.

TABLE VIII
MEASURED NO-LOAD PERFORMANCE

Fixture Component Combination	No-load speed (rpm)	Difference
LCLB	5062	-
LCSB	5435	7.4%
SCSB	5220	3.1%

C. *Load Performance*

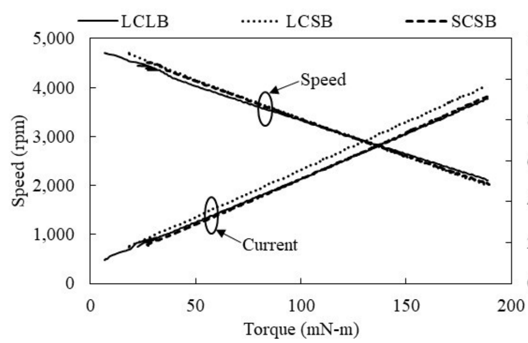

Fig. 11. Motor performance on load

Fig. 11 shows the measured torque-speed and torque-current characteristics for motors. From the measured speed-torque characteristics, the stall torque value is extrapolated for all three combinations and is given in Table IX. As the rotor is the same, the stall current, dependent on the rotor winding is almost equal. Due to highest airgap flux density, the LCLB combination offers highest stall torque.

TABLE IX
ESTIMATED STALL CONDITION PARAMETERS

Fixture Component Combination	Stall torque (mN-m)	Difference
LCLB	329	-
LCSB	297	-10%
SCSB	313	-5%

V. CONCLUSION

The magnetization fixtures made with solid steel components requires more energy to generate the magnetization field required for magnet saturation due to the eddy current induction in solid steel components. The presence of solid steel component results in prohibitively high energy required for magnet saturation and hence the magnets magnetized using most of the commercially available magnetizers result in a partially saturated magnets, leading to poor motor performance. Also use of solid steel magnetization components will lead to generation of secondary transition zones on the magnet and hence higher than expected cogging torque. Therefore use of laminated steel for all soft magnetic components in the magnetization fixture is highly recommended.

References

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