Comparison of two Magnetizing Fixture Designs to Achieve Radial Magnetization Profile for Isotropic Bonded Neo Magnets

Angara, Raghu C. S. Babu[1], *Member IEEE*, Hsu, Kirk Wei[1], Villar, Paul John [1], Sheth, Nimitkumar K.[1], *Member IEEE*
[1]R&D Magnequench Neo Powders Pte Ltd, Singapore, 117525, Singapore

This paper compares the performance of inner-only and inner-outer type of magnetizing fixture designs to achieve the radial magnetization profile in an isotropic bonded neo magnet. In inner-only fixture the magnetization coils are located on only one side of the magnet circumference and inner-outer fixture uses magnetization coils on either side of the magnet circumference. For both fixtures the finite element analysis based performance is presented and compared with the experimental validation. The effect of misalignment between the inner and outer coils in an inner-outer fixture is discussed using the finite element analysis as well as experimental results and a limit on the misalignment angle resulting in negligible reduction in mid airgap flux density integral per pole is arrived at.

***Index Terms*— Bonded Neo, Inner-only fixture, Inner-Outer Fixture, Isotropic Bonded Nd-Fe-B, Magnetic Flux, Magnetization Process.**

I. Introduction

The requirement of stringent environment and fuel efficiency target on automotive demand the use of lighter, smaller and efficient accessory motors. The advantages like higher magnetic properties than ferrite, near net shape magnet production, and no use of heavy rare earth elements makes the use of bonded neo magnet in an automotive accessory motor very attractive. 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]. An optimally designed magnetization fixture is needed to fully utilize the potential of bonded neo magnets. To magnetize the magnet used for the brushed DC motor and external rotor permanent magnet brushless (PMBL) DC motors a magnetizing fixture with coils located next to the magnet inner circumference is used. When the radial magnetization is desired, a double sided magnetization in which a fixture comprising of coils near to the inner and outer circumference of the magnet can also be used [2]. The use of double sided magnetization helps in enhancing the motor performance [3].

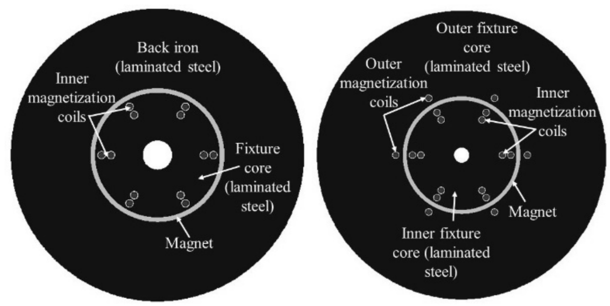
In this paper two magnetizing fixture designs namely inner-only and inner-outer is presented. The performance of both fixtures have been compared using the finite element analysis (FEA) and the results are validated by experimental measurements. The importance of manufacturing tolerance for the inner-outer fixture is also explained using the FEA and experimental results.

II. Finite Element Analysis

Using commercially available Opera Vector Fields 2-D FEA software, both inner-only and inner-outer fixtures were designed for magnetization of magnet given in Table I. Fig.1 shows the cross section of the designed magnetization fixtures. To achieve the full saturation of the magnet, the fixtures are designed to get a minimum of 30kG magnetizing field throughout the magnet thickness [4].

TABLE I
MAGNET DIMENSIONAL DETAILS

Symbol	Parameter	Value
ID	Magnet inner diameter (mm)	42
OD	Magnet outer diameter (mm)	45
H	Magnet height (mm)	11
	Magnet grade	MQ1™
	Number of poles	6
	Flux orientation	Radial



(a) Inner-only (b) Inner-Outer
Fig. 1. Designed magnetization fixtures

A. Magnetization Energy and Peak Conductor Current Density

Table II gives the magnetization energy needed to fully saturate the magnets and the corresponding peak current density in the conductor of magnetizing coil. From the Table, it is observed that the magnetization energy needed to saturate the magnet and the peak current density in the conductor is 39% and 22% lower for inner-outer fixture compared to inner-only fixture. In case of inner-outer fixture, the presence of magnetization coils and hence the application of magnetization energy on both sides of magnet surface leads to lower energy requirement to fully saturate the magnet. The lower energy required will lead to reduction in peak magnetizing current and hence the peak current density in the conductor. The reduction in the peak current leads to lower copper losses and thermal stress. The thermal stress is the foremost cause of the fixture failure and hence its reduction leads to the improvement in fixture reliability.

TABLE II
ENERGY REQUIRED FOR MAGNET SATURATION

Fixture type	J (kA/mm^2)	Energy (kJ)
Inner-only	6.9	3.5
Inner-outer	5.4	2.1

B. Mid Airgap Flux Density

The fully saturated magnet model for each case is imported to a closed circuit flux scan and motor model [5]. Fig. 2 shows the closed circuit flux scan set-up used to evaluate the mid airgap flux density from a fully saturated magnets. Fig. 3 shows the mid airgap flux density waveform when the magnets are fully saturated. The application of magnetization field on both sides of the magnet when inner-outer fixture is used leads to flat-topped mid airgap flux density waveform. Fig. 4 shows the flux density distribution for both fixtures when the peak magnetizing current is applied. From this figure it can be observed that in an inner-outer fixture the flux generated by the inner and outer magnetization coils counter each other in the magnet region between the slots in which inner and outer coils are located. This leads to the increased width of the transition zone, making the mid airgap flux density waveform less radial compared to inner-only fixture as seen in Fig. 3.

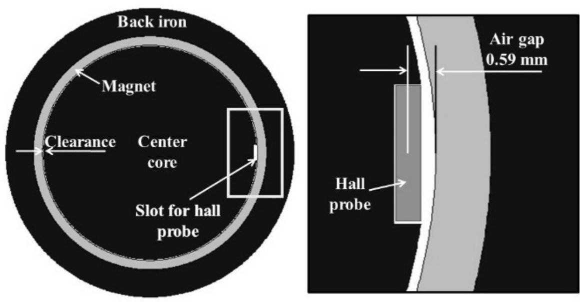


Fig. 2. Closed circuit flux scan set-up

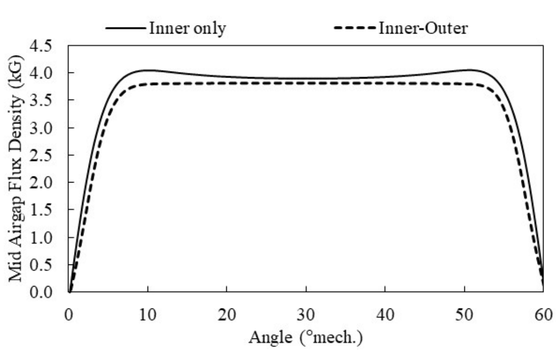
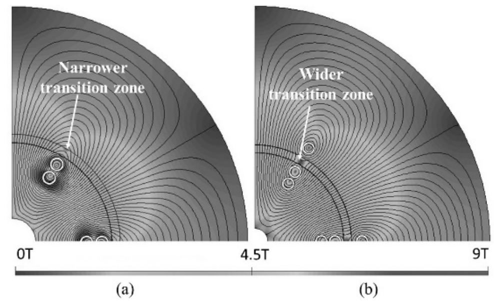


Fig. 3. Mid airgap flux density

TABLE III
COMPARISON OF MID AIRGAP FLUX DENSITY INTEGRAL

Fixture type	Mid airgap flux density integral per pole (kG-°mech)
Inner-only	218.57
Inner-outer	206.14



(a) Inner-only (b) Inner-Outer
Fig. 4. Flux density distribution at peak magnetizing current

Table III gives the mid airgap flux density integral per pole for the waveforms shown in Fig. 3. From Table III, it is observed that the mid airgap flux density integral per pole is 6% more when the magnet is magnetized using the inner-only fixture compared to inner-outer fixture.

C. Effect of Coil Misalignment in Inner-Outer Fixture

The fabrication and manufacturing tolerances leads to misalignment between the outer and inner coils and hence affects the performance of the fixture [6]. Based on the manufacturing and fabrication tolerances, a maximum misalignment of ±5° between the magnetization coils is possible. The positive sign represent the misalignment in counter clockwise (CCW) direction and vice versa in clockwise (CW) direction.

To understand the effect of misalignment, various degrees of misalignments between the inner and outer coils is simulated in CCW direction. Fig. 5 (a) and (b) shows the applied field lines and applied flux density when the inner and outer coils are aligned. From Fig. 5 (b), it can be observed that under aligned condition the flux generated by the outer and inner coils counters each other and create transition zones along the axes of the slots in which inner and outer coils are located. Fig. 5 (c) and (d) shows the applied field lines and applied flux density when the inner and outer coils are misaligned by 5°. It can be observed from Fig. 5 (c) that during misalignment the magnetization flux from the outer coil aids the flux from inner coil on the trailing edge of pole-1 and counters the flux on leading edge of pole-2. This results in shifting of the transition zones by half the misalignment angle as shown in Fig. 5 (d).

Using the closed circuit flux scan set-up shown in Fig. 2, the mid-airgap flux density profiles obtained for various misalignment conditions are shown in Fig. 6. As the outer coil is rotated in CCW direction, the pole leading edge shows a drooping wave shape with increasing misalignment due to the opposing magnetizing field by inner and outer coils. Simultaneously the trailing edge of the pole shows a hump due to aiding magnetization field generated by inner and outer coils. Table IV gives the mid airgap flux density integral per pole for various misalignments. It can be seen from the Table IV, that the increase in misalignment reduces the flux density integral. The reduction in integral is less than 0.5% for misalignment up to 2° and beyond which there is an appreciable reduction.

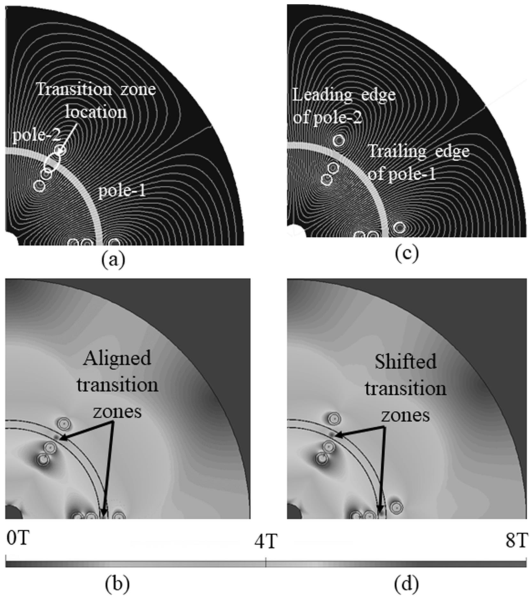


Fig. 5. Inner-outer fixture (a) Magnetization flux, (b) Flux density in aligned position (c) Magnetization flux, (d) Flux density in case of 5° misalignment

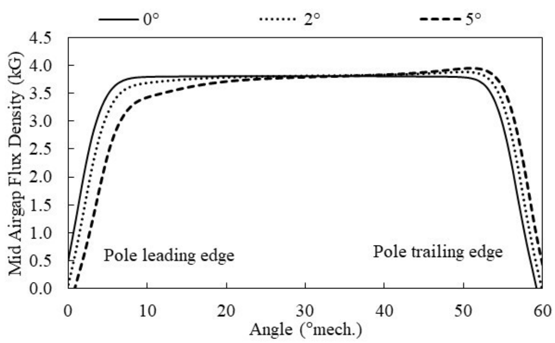


Fig. 6. Simulated mid airgap flux profile for various misalignment angles

TABLE IV
MID AIRGAP FLUX DENSITY INTEGRAL AT VARIOUS MISALIGNMENT POSITIONS BETWEEN INNER AND OUTER MAGNETIZATION COILS

Misalignment Angle	Mid airgap flux density integral per pole (kG-°mech)	Change in integral
0°	206.14	0%
1°	205.98	-0.1%
2°	205.33	-0.4%
3°	204.43	-0.8%
4°	203.21	-1.4%
5°	201.56	-2.2%

III. EXPERIMENTAL VALIDATION

The designed inner-only and inner-outer magnetizing fixtures are fabricated. Fig. 7 shows the fabricated fixtures. Using both the fixtures, a magnet saturation test [4] is performed and minimum energy required to saturate the magnets are arrived at. Using the set-up shown in Fig. 8, the closed circuit mid airgap flux density is measured on the fully saturated magnets magnetized by both inner-only and inner-outer fixtures.

Fig. 9 shows the saturation curves measured during the saturation test and Table V gives the energy needed to fully saturate the magnets. It can be observed from Table V that the energy required to saturate the magnet using inner-outer fixture is 27% less than the saturation energy for inner-only fixture. The reduced demand on energy for magnet saturation in an inner-outer fixture improves its reliability and durability. It will also help in reducing the magnetization cycle time.

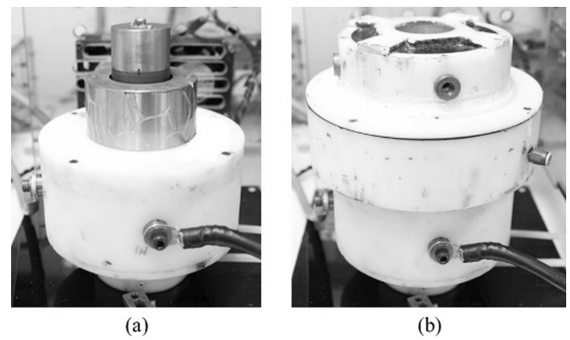


Fig. 7. Fabricated fixtures (a) Inner-only (b) Inner-Outer

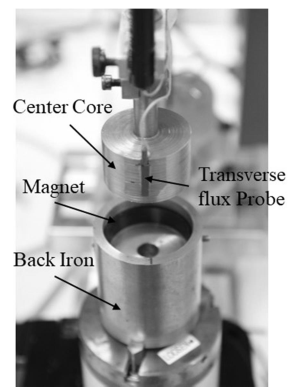


Fig. 8. Closed circuit flux scan measurement set-up

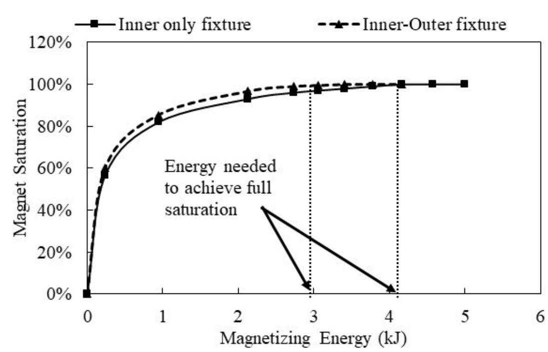


Fig. 9. Saturation test results for inner only and inner-outer magnetization fixtures

TABLE V
ENERGY REQUIRED FOR MAGNET SATURATION

Fixture type	Energy (kJ)
Inner only	4.2
Inner-outer	3.1

During fabrication of magnetization fixtures, various fixture components have gone through the mechanical processes like cutting and stacking. These processes leads to higher actual core loss [7] compared to the ideal value mentioned on the data sheet and used during simulation. The difference in ideal and actual core loss for soft magnetic parts of fixture leads to the higher energy requirement to saturate the magnet than the energy requirement estimated based on simulation. During simulation, the magnetizer inductance, switching and capacitor losses, eddy currents induced in steel parts as well as skin effect of conductors is neglected, leading to under estimation of the energy required for saturation than the actual energy needed.

Fig. 10 shows the mid airgap flux density for the fully saturated magnets magnetized using the inner-only and inner-outer fixtures. From this figure it is seen that when magnets are magnetized using the inner-only fixture the mid airgap flux density has saddle shape compared to the flat topped shape when it is magnetized using inner-outer fixture. Table VI gives the mid airgap flux density integral per pole for the waveforms shown in Fig. 10. From this table it can be seen that the magnetization using the inner-outer fixture results in 3.3% more flux per pole compared to magnetization with inner-only magnetization, this is due to the saddle shaped waveform in case of inner-only magnetization.

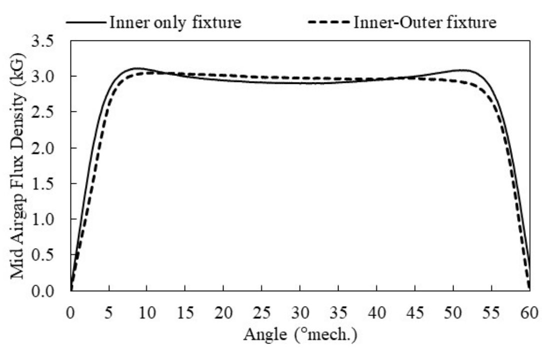


Fig. 10. Measured mid airgap flux density.

TABLE VI
COMPARISON OF MID AIRGAP FLUX DENSITY INTEGRAL

Fixture type	Mid airgap flux density integral per pole (kG-°mech.)
Inner only	162.32
Inner-outer	167.62

The effect of misalignment between inner and outer magnetization coils during magnetization is evaluated by creating various misalignment positions in CW and CCW directions with respect to aligned position. The magnets are magnetized using the inner-outer fixture with various degrees of misalignment. Fig. 11 shows the closed circuit mid airgap flux density of the magnetized magnets measured using the set-up shown in Fig. 8. It can be seen from Fig. 11 that for positive misalignment angles the drooping effect is on the pole leading edge and vice versa. This is in agreement with the observation from the simulation.

Table VII gives the flux integral per pole for measured closed circuit mid airgap flux density profiles under various misalignment positions between the inner and outer coils. From Table VII, it is observed that for misalignment angle up to ±2° the reduction in flux is up to 0.5% and misalignment angles more than 2° leads to the appreciable reduction in flux. It can also be seen that the effect of misalignment is symmetric about the aligned position.

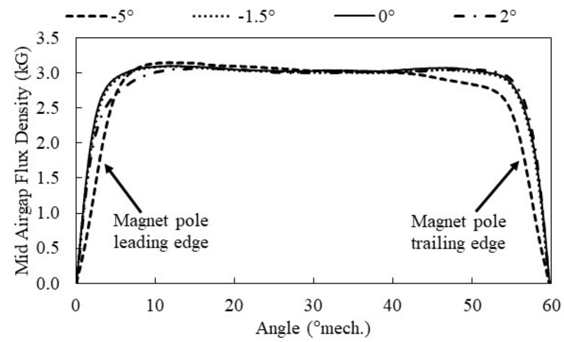


Fig. 11. Measured mid airgap flux for various misalignment positions for a single pole

TABLE VII
MID AIRGAP FLUX DENSITY INTEGRAL AT VARIOUS MISALIGNMENT POSITIONS BETWEEN INNER AND OUTER MAGNETIZATION COILS

Misalignment Angle	Mid airgap flux density integral per pole (kG-°mech)	Change in integral
-5°	166.55	-3.8%
-3°	168.49	-2.7%
-1.5°	172.68	-0.3%
0°	173.17	0%
1°	172.99	-0.1%
2°	172.35	-0.5%

IV. CONCLUSION

For radial magnetization orientation, inner-outer fixture requires less magnetization energy for magnet saturation compared to inner-only type of fixture which will lead to improved fixture reliability. The inner-only magnetization results in a saddle shaped closed circuit mid airgap flux density waveform compared to the flat topped wave shape in case of inner-outer fixture. The alignment between inner and outer magnetization coils in an inner-outer fixture is critical to optimally magnetize the isotropic bonded neo magnets. A misalignment more than 2° will lead to appreciable reduction in mid airgap flux density integral per pole.

REFERENCES

[1] Seok-Myeong Jang, Han-Wook Cho, Sung-Ho Lee, Hyun-Sup Yang, and Yeon-Ho Jeong, “The influence of magnetization pattern on the rotor losses of permanent magnet high-speed machines,” *IEEE Trans. Magnetics*, vol. 40, no. 4, Jul. 2004.

[2] C. D. Riley, G. W. Jewell, and D. Howe, “Design of impulse magnetizing fixtures for the radial homopolar magnetization of isotropic NdFeB ring magnets,” *IEEE Trans. Magnetics*, vol. 36, no. 5, Sep. 2000.

[3] Jaenam Bae, Seung-Joo Kim, Sung-Chul Go, Hyung-Woo, Yon-Do Chun, Cheol-Jick Ree, and Ju Lee, “Novel configuration of the magnetizing fixture for a brushless permanent-magnet motor,” *IEEE Trans. Magnetics*, vol. 45, no. 6, Jun. 2009.

[4] Nimitkumar K. Sheth, Raghu C. S. Babu Angara, “Effect of partial saturation of bonded neo magnet on the automotive accessory motor,” in *AIP Advances*, vol. 7, issue 5, 2016.

[5] Yuriy Zhilichev, Peter Campbell, and David Miller, "*In Situ* magnetization of isotropic permanent magnets," *IEEE Trans. Magnetics*, vol. 38, no. 5, Sep. 2002.

[6] C. J. Lee, C. I. Lee, and G. H. Jang, "Source and Reduction of Uneven Magnetization of the Permanent Magnet of a HDD Spindle Motor," *IEEE Trans. Magnetics*, vol. 47, no. 7, Jul. 2011.

[7] Silas Elfgen, Simon Steentjes, Stefan Bohmer, David Franck, and Kay Hameyer, "Influences of Material Degradation Due to Laser Cutting on the Operating Behavior of PMSM Using a Continuous Local Material Model," *IEEE Trans. Industry Applications*, vol. 53, no. 3, May/Jun. 2017