Effect of partial saturation of bonded neo magnet on the automotive accessory motor

Nimitkumar K. Sheth and Raghu C. S. Babu Angara

Citation: AIP Advances **7**, 056611 (2017); doi: 10.1063/1.4973496
View online: http://dx.doi.org/10.1063/1.4973496
View Table of Contents: http://aip.scitation.org/toc/adv/7/5
Published by the American Institute of Physics

AIP ADVANCES **7**, 056611 (2017)

Effect of partial saturation of bonded neo magnet on the automotive accessory motor

Nimitkumar K. Sheth[a] and Raghu C. S. Babu Angara
R&D, Neo Performance Materials Pte Ltd, Singapore 117525, Singapore

(Presented 4 November 2016; received 23 September 2016; accepted 10 October 2016; published online 27 December 2016)

In this paper the effects of using a partially magnetized bonded neo (NdFeB) magnet in an automotive accessory motor are presented. The potential reason for partial saturation of the bonded neo magnet is explained and a simple method to ensure saturation of the magnet is discussed. A magnetizing fixture design using the 2-D Finite element analysis (FEA) is presented. The motor performance at various magnet saturation levels has been estimated using the 2-D FEA. Details of the thermal demagnetization test adopted by the automotive industry is also discussed and results of the motor performance for four saturation levels are detailed. These results indicate that the effect of demagnetization is more adverse in a motor with partially saturated magnets. [http://dx.doi.org/10.1063/1.4973496]

I. INTRODUCTION

Bonded neo magnet based motors are fast gaining popularity in automotive accessory applications as they offer substantial weight/size reduction and efficiency improvement over the traditional ferrite based motors. The weight reduction and efficiency improvement helps in achieving the stringent fuel efficiency improvement and CO_2 emission reduction targets. The partial demagnetization or the irreversible flux loss at high temperature and/or at load is the major concerns with the permanent magnet motors.[1] Different magnet needs different energy level to achieve full saturation, and hence their full potential. Figure 1 show the typical magnetizing fields required to saturate isotropic bonded neo and ferrite magnets. It is evident from Fig. 1 that isotropic bonded neo magnets need a stronger field for saturation than the ferrite magnets. For the ferrite based motor the verification of post assembly magnetization is proposed in literature.[2] Bonded neo magnets are isotropic in nature compared to the anisotropic nature of ferrite magnets and hence need special attention for the magnetizing fixture design to achieve the desired magnetization profile and full saturation. Ferrite magnets have been the traditional choice for the automotive accessory motors, leading to the possibility that during the magnetization of bonded neo magnet one uses the magnetizing energy needed to saturate the ferrite magnet by mistake. In such a case, application of insufficient magnetizing field and/or inappropriate magnetizing fixture will lead to a partially saturated bonded neo magnet.

In this paper, using two dimensional (2-D) finite element (FE) analysis, the effects of demagnetization on the performance of an automotive accessory motor with a partially saturated bonded neo magnet is presented in Section–II. A magnetization fixture designed for *in-situ* magnetization of bonded neo magnet is also presented. In Section III, the motor demagnetization test followed by automotive industry is discussed. Motor performance for different saturation level of bonded neo magnets before and after the demagnetization test is presented and the effect of partial saturation is quantified.

[a]Author to whom correspondence should be addressed. Electronic mail: n.sheth@neomaterials.com.

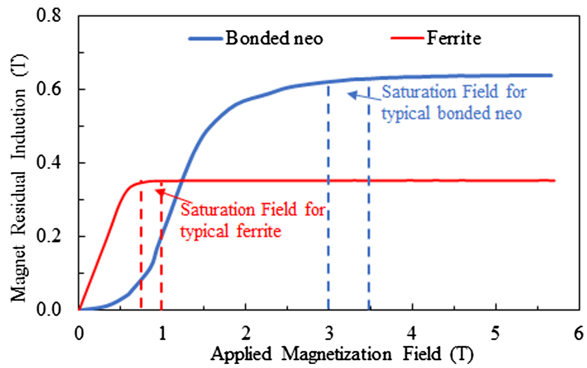

FIG. 1. Saturation field for ferrite and bonded neo magnets.

II. FINITE ELEMENT (FE) ANALYSIS

An Isotropic bonded neo magnet needs to be fully saturated to utilize its complete potential. As indicated in the previous section, the magnetization of bonded neo magnet requires special attention to the fixture design and the total energy required for saturation. Table I gives the specifications of the automotive accessory motor used for analysis. For the bonded neo magnet given in Table I, a magnetization fixture is designed using commercially available Opera Vector Fields 2-D FEA software, for *in-situ* magnetization in which the magnet is inserted into the motor pole housing before magnetization.

A. Magnetization of magnet

To ensure full saturation of a permanent magnet, a saturation test needs to be performed during the magnetization of the magnet. In the saturation test the applied magnetizing energy is increased in appropriate steps and the magnet flux per pole is measured after magnetization at each step. The magnet is considered saturated if the change in magnet flux per pole between consecutive energy steps is less than 2%. Figure 2 shows the cross section of the designed magnetizing fixture. Figure 3 shows the result of the saturation test on a typical bonded neo magnet. The generated magnetizing field is about 1 T when the applied energy is 560 J, which represents the energy required to fully saturate the ferrite magnet as seen from Fig. 1 or 60% saturation of bonded neo magnet as seen from Fig. 3. As Ferrite magnets are widely used in an automotive accessory application, the applied energy or saturation limit of 60% is considered as lower limit in this study.

The magnets are virtually magnetized for 60%, 80%, 90% and 100% or full saturation of the bonded neo magnets. The magnetized magnet data is imported in to the motor model shown in Fig. 4 and the motor performance is simulated.[3] Figure 5 shows the no-load air-gap flux distribution in the motor. The area under the curve is calculated using the trapezoidal rule for definite integral. Table II gives the calculated no-load air-gap flux integral for motors with different satura-

TABLE I. Specifications of the automotive accessory motor.

Parameter	*Value*
Number of slots	10
Number of poles	4
Air gap	0.375 mm
Motor outer diameter	30.5 mm
Motor length	43 mm
Magnet grade	MQP 15-9HD-20178
Magnet residual induction, B_r	0.693 T
Magnet coercivity, H_c	448 kA/m

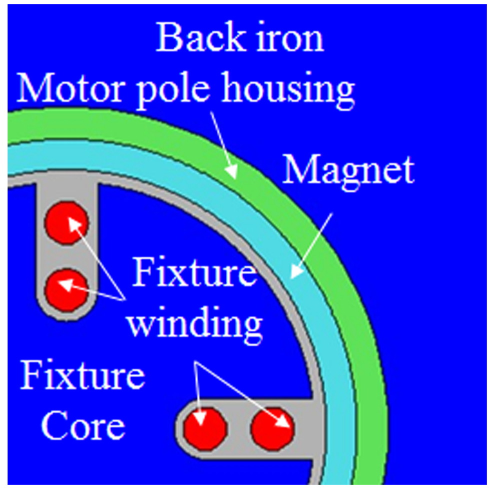

FIG. 2. Cross section of the magnetizing fixture for bonded neo magnets.

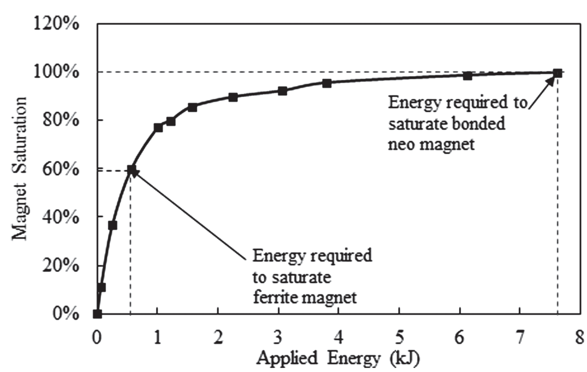

FIG. 3. Saturation test plot for a typical bonded neo magnet.

tion levels. From Table II it can be seen that the calculated no-load air-gap flux integral per pole in the motor with 60% saturation magnet is 32% less compared to the motor with fully saturated magnet.

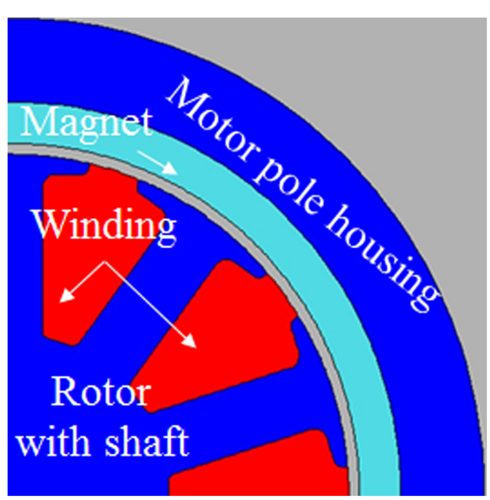

FIG. 4. Motor cross section for 2-D FE analysis.

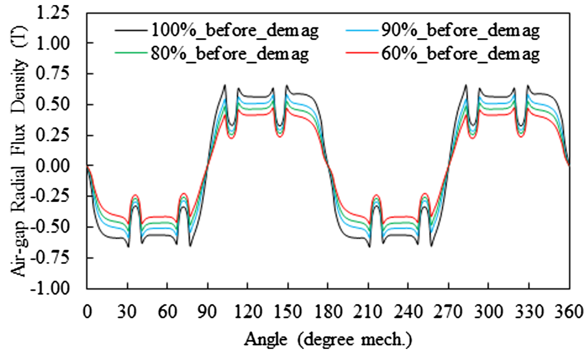

FIG. 5. Effect of magnet saturation level on the motor no-load air gap flux.

TABLE II. Comparison of air-gap flux integral before and after thermal demagnetization test.

Parameter	*100%*	*90%*	*80%*	*60%*
Before demagnetization (T-rad)	3.06	2.62	2.36	2.07
After demagnetization (T-rad)	2.98	2.55	2.27	1.96

B. Demagnetization analysis

Figure 6 shows the first and second quadrant major and minor magnetization curves, the load lines and operating points of the motor at no-load and stall conditions for a typical bonded neo magnet motor at room and high temperatures. At a given operating temperature, the motor operates along the major curve when the magnet is fully saturated and if the magnet is partially saturated then the operating point shifts to the minor curve at the same temperature.[4]

In Fig. 6, point ‘a’ represents the no-load operating point at room temperature in a motor with fully saturated magnet. When the motor temperature increases the operating point shifts to point ‘b’ along the same load line. As the motor is loaded, the load line moves along the negative Y-axis with the same slope by a distance proportional to the applied load, resulting in the operating point moving from point ‘b’ towards point ‘c’. Under stall conditions, the slope of the load line decreases due to low permeance coefficient resulting in operation of motor at point ‘c’. When

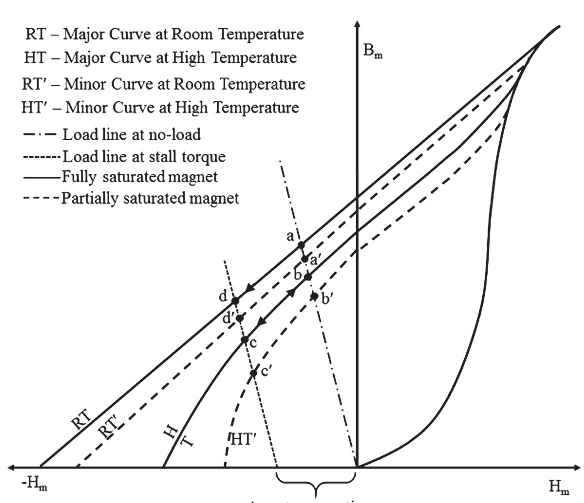

FIG. 6. Motor operating point at different magnet temperatures and loads.

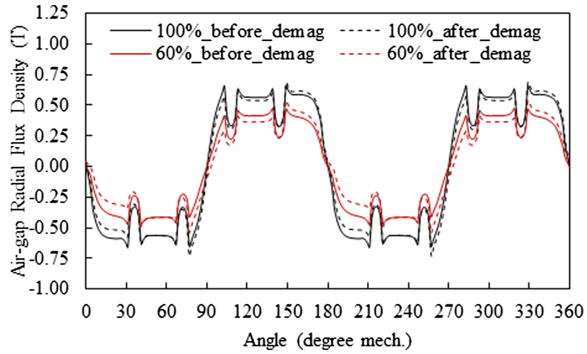

FIG. 7. Comparison of air-gap flux at no-load and after thermal demagnetization test in motors with 100% and 60% saturated bonded neo magnet.

a motor has partially saturated magnet the no-load operating point at room temperature starts at 'a′' and moves to point 'b′' at high temperature. Under load conditions at high temperature, the operating point shifts along line 'b′c′'. The increased load or stall torque condition may result in shifting of the load line such that the operating point falls below knee point resulting in irreversible demagnetization.

The typical demagnetization test for the automotive accessory motors is performed with the motor being subjected to an elevated temperature of 100°C to 120°C. To understand the effect of partial saturation on the motor performance, the same motor models have been analyzed for the magnet temperature of 120°C. Figure 7 shows the air-gap flux distribution when a demagnetization field is applied in a motor with a fully saturated magnet and a motor with 60% saturated magnet. Table II gives the air-gap flux integral after demagnetization in the motors with different levels of magnet saturation. From this table, it is observed that the air-gap flux integral is only reduces by 2.6% for motor with fully saturated magnet compared to 5% in a motor with 60% saturated magnet.

Figure 8 shows the magnet flux density and flux lines in the magnet after applying the demagnetization field while magnet exposed to 120°C for both the fully saturated and 60% saturated magnets. It is observed from Fig. 8, that the demagnetization under load is very severe in a partially saturated magnet and is prominent near transition zone between two magnetic poles.[5] The magnetic domains in the transition zones are tangential to the magnet's orientation, the energy required to demagnetize the region near the transition zone is less, leading to severe demagnetization near transition zone. In the analyzed motor the demagnetization effect is the maximum for 60% saturated magnet.

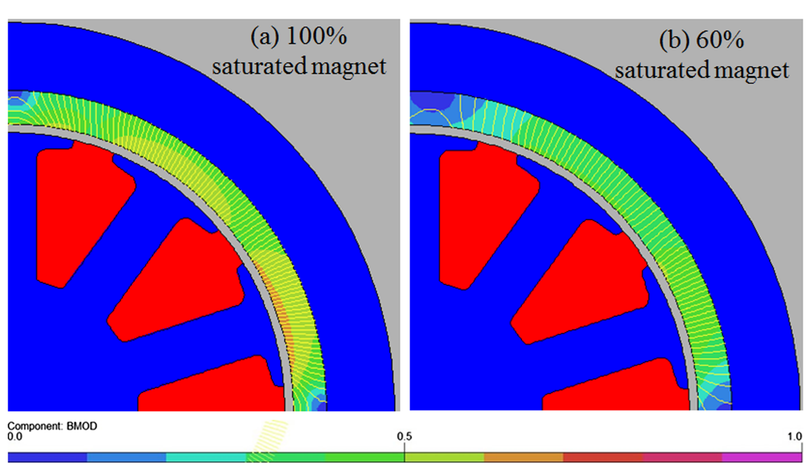

FIG. 8. Flux distribution in magnet at 120°C magnet temperature and stall current.

III. MOTOR EVALUATION

Figure 9 shows a typical procedure followed by the automotive industry to evaluate the magnet demagnetization and automotive accessory motor reliability. The test includes both the effect of armature reaction when motor is loaded and also magnet working at high temperature. A magnetizing fixture based on the design shown in Fig. 2 is fabricated. The magnetized bonded neo magnet samples are prepared for 60%, 80%, 90% and full saturation. The motors are assembled using these magnets and the motor back-emf and performance are measured before thermal demagnetization. Figure 10 shows the speed-torque characteristics before thermal demagnetization for motors with magnets at 100% and 60% saturation. Table III gives the no-load speed, stall torque and back-emf values for motors at different saturation levels.

After the load performance evaluation, the prototype motors are subjected to the thermal demagnetization process explained in Fig. 9. The motor back-emf and the performance are measured after demagnetization. Figure 10 also shows the speed-torque characteristics after demagnetization for the motors with 100% and 60% saturated magnets. Table III gives the measured no-load speed, stall torque and back-emf after thermal demagnetization process.

It is observed from Fig. 10 that after demagnetization the no-load speed of the motor increases and the stall torque reduces due to reduction in magnet flux. From Table III it is observed that before thermal demagnetization, the motor with 60% saturated magnet has 70% more no-load speed and 56% less stall torque compared to the motor with fully saturated condition. After thermal demagnetization, the increase in no-load speed is 3.8% and reduction in stall torque is 8.8% in case of motor with fully saturated magnet compared to 4.5% increase in no-load speed and 13.4% reduction in stall torque for motor with 60% saturated magnet. The reduction in back-emf after demagnetization is almost

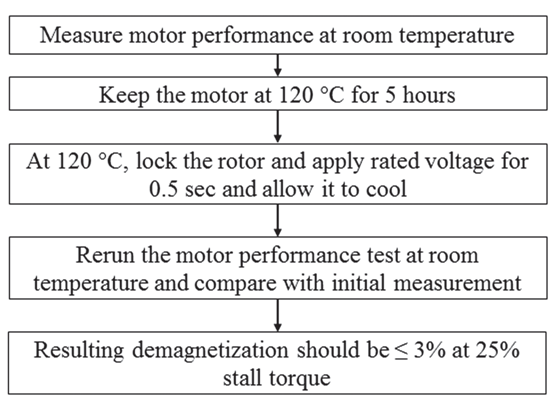

FIG. 9. Procedure for motor thermal demagnetization test.

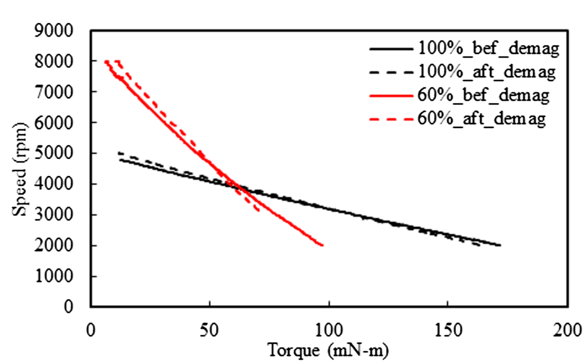

FIG. 10. Effect of thermal demagnetization on Speed-Torque characteristics of the motors with magnets at different saturation levels.

TABLE III. Comparison of motor performance before and after thermal demagnetization test.

Parameter	*100%*	*90%*	*80%*	*60%*
Back-emf before demagnetization (V)	8.3	7.7	6.6	4.4
Back-emf after demagnetization (V)	8.3	7.3	6.2	4.1
No-load speed before demagnetization (rpm)	4892	5446	6370	8340
No-load speed after demagnetization (rpm)	5077	5758	6640	8717
Stall torque before demagnetization (mN-m)	287	251	210	125
Stall torque after demagnetization (mN-m)	262	227	193	109

negligible in case of motor with fully saturated magnet compared to 6.5% reduction for motor with 60% saturated magnet.

From the motor performance evaluation results, it is evident that the partial saturation of the magnet will lead to severe magnet demagnetization and hence poor motor performance.

IV. CONCLUSION

In this paper the potential effects of using partially magnetized bonded neo magnet in an automotive accessory motor are presented. About 60% of the energy required to saturate a bonded neo magnet is sufficient to saturate a ferrite and hence the magnetization fixture and/or the magnetization energy needed to saturate ferrite magnet should not be applied to bonded neo magnetization as it will lead to partially saturated bonded neo magnet. The performance measured for automotive accessory motors with different saturation levels indicate that after thermal demagnetization, the stall torque is reduced by 4.5% and no-load speed increased by 13.4% for the motor with 60% saturated magnet compared to 3.8% increase in no-load speed and 8.8% reduction in stall torque when the magnet is fully saturated. To avoid the adverse effects of thermal demagnetization and to utilize the complete potential of the bonded neo magnet, full saturation of the magnet must be ensured.

[1] K. C. Kim, K. Kim, H. J. Kim, and J. Lee, "Demagnetization analysis of permanent magnets according to rotor types of interior permanent magnet synchronous motor," IEEE Transactions on Magnetics **45**, 2799–2802 (2009).

[2] K. W. Lee, J. Hong, S. B. Lee, and S. Lee, "Quality assurance testing for magnetization quality assessment of bldc motors used in compressors," IEEE Transaction on Industry Applications **46**, 2452–2458 (2010).

[3] Y. Zhilichev, "Analysis of permanent magnet demagnetization accounting for minor B-H curves," IEEE Transaction on Magnetics **44**, 4285–4288 (2008).

[4] S. Ruoho, E. Dlala, and A. Arkkio, "Comparison of demagnetization models for finite-element analysis of permanent magnet synchronous machines," IEEE Transaction on Magnetics **43**, 3964–3968 (2007).

[5] G. Sawczuk and J. Junak, "Finite element analysis of permanent magnet synchronous motor considering magnetization process," International Conference on Electrical Machines and Systems 7–12 (2013).