it keeps the stack it is attached to from locking to the stack immediately below it. In that way, stacks can be produced sequentially and continuously, keeping the choke station constantly filled with parts, essential to generating the consistent back-pressure needed to interlock parts together.

The Varilok process can produce extremely accurate part geometries. The peripheries of each lamination are die-cut, so close tolerances and high repeatability are a given. All part dimensions that run perpendicular to the pass line of the tool (for example the part's overall height) are, to some extent, dependent on the stack-up of stock thickness. Coil stock on the thin side of its range produces shorter stacks, while thick stock produces taller stacks. This fact does not mean that nothing can be done to mitigate the accumulation, plus or minus, of stock thickness variance.

Sophisticated die controllers have basic features to match the complexity of the tool to be run, and handle important matters such as part recipes, die protection, diagnostics, die I/O for all actuable die features, servo motor operations, production scheduling, and even stock measurement. Therefore, in many instances part stack-height adjustments (add a lam, leave out a lam) can be made that improve the dimensional accuracy of the finished product. This can be done with a stock measuring system in place, or simply by adjusting the lamination counts.

It should also be noted that while both Autolok and Varilok technologies were initially employed in tools for the production of electromagnetic components, laminated structures produced with these methods can be used for purely mechanical reasons, in substitution for machined or cast parts. The die-cut edges are extremely accurate and repetitive, and even the features whose depth or height is determined by lamination stack-up dimensions are generally as accurate as can be attained by other more common manufacturing methods. — *Tom Neuenschwander*

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Neo Magnets

High-energy magnets improve DC motors and add value to appliances.

While most corded appliances are driven by induction and universal motors, cordless battery-powered appliances typically employ permanent magnet DC motors as primary movers. Until recently, DC motors for cordless appliances have continued to use conventional sintered ceramic ferrite permanent magnets. This article describes how neodymium-iron-boron ("Neo") can be used in place of ferrite magnets to improve the performance of a DC motor, while simplifying its manufacture.

In comparison to ferrite, Neo magnets have a significantly higher energy product which, when properly incorporated in a motor's design, can provide the motor with an increased power output, an improved efficiency, or some combination of the two. Higher power density allows for increased torque and output power in the same motor package size, or it enables a smaller, lighter motor with the same performance as a larger ferrite motor. Higher motor efficiency reduces the electrical current draw from the battery of the appliance, thereby extending battery life. The boost in motor performance provided by Neo magnets will improve the functionality and value of the appliance.

Recent improvements in the magnetic, mechanical, and thermal properties of neodymium-iron-boron ("Neo") magnetic materials, together with the evolution of low cost, high volume manufacturing processes, have made the replacement of traditional ferrite permanent magnets attractive in appliance applications. While the development of Neo magnets has had a significant technical and economic impact on the traditional electric motor industry, these advancements have been slow to gain acceptance from the appliance sector. The reason for this has been the higher cost of Neo compared to ferrite, while ignoring the added value that Neo can provide to most applications. Continual price reductions in both Neo magnets and the powders from which they are made are finally enabling the replacement of ferrites in many battery-powered appliances. The cost difference between a Neo and ferrite magnet solution is narrowing, the value of which will be evident in improvements to motor production and performance.

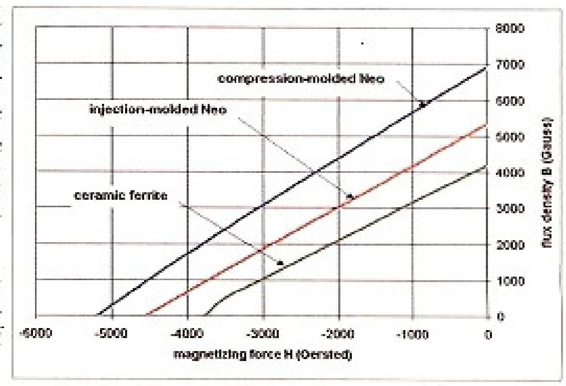

Fig. 1. Demagnetization curves of motor magnets at 25°C.

Bonded Neo properties

The measure of a permanent magnet's performance is demonstrated by its *demagnetization characteristic*, a few of which are shown in *Fig. 1.* Ceramic ferrite magnets have the lowest magnetic properties, compared to injection-molded and compression-molded bonded Neo magnets. The higher the *remanence* (B_r) of a magnet, the better it can be utilized to increase the power density and efficiency of a DC motor. The product of a magnet's operating *flux density* (B) and its *magnetizing*

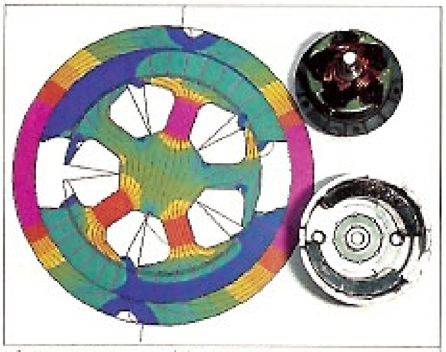

Fig. 2. Disassembled 24V cordless power tool motor and a magnetic flux contour plot of the motor cross-section.

force (H) is a direct measure of its energy density, the maximum of which $(BH)_{max}$ is a characteristic *energy product* which is commonly used as a figure of merit for a permanent magnet material.

Bonded Neo magnets are fabricated by mixing Neo powder with an epoxy and compression molded, or mixed with plastic binder and injection molding the magnet to shape. Approximately 80 percent magnet-to-epoxy volume loading can be achieved in compression-molded bonded Neo, while 60 percent volume loading is typical for injection-molded Neo. Thus, compression molding yields higher magnetic properties, but injection molding allows for a wider variety of shapes and more efficient manufacturing techniques.

Many appliance motors are designed to run relatively hot, and the maximum magnet temperature during motor operation will determine both the type of Neo powder and the binder to be employed in the bonded magnet. There is a tradeoff between the B_r of the Neo powder and its maximum operating temperature. Other ingredients can be added to the Nd-Fe-B blend to improve its high-temperature stability, and there is a wide variety of Neo powders available to meet a broad range of magnetic, thermal and environmental requirements. The Nylon binder employed in injection-molded bonded Neo magnets is good up to approximately 150°C, so higher-temperature injection-molded magnets should utilize PPS binder, which is good up to 180°C. The thermosetting epoxy resin employed in compression-molded Neo magnets can survive temperatures in excess of 200°C.

Optimizing performance

A typical appliance DC permanent magnet motor is shown disassembled in *Fig. 2.* This particular motor is employed in a 24V cordless power tool. Also shown in this figure is the magnetic flux density distribution, as calculated by finite element analysis (FEA), in the cross-section of the motor while running at full current load. The spokes of the rotor are made from laminations of silicon steel, and the coil is wound around the teeth in the armature slots. The current in the 5-slot armature is mechanically commutated via brushes. The 2-pole motor stator is comprised of

Magnet Type	Stack Length
Ceramic Ferrite	48.0 mm
Injection-Molded Neo	36.9 mm
Compression-Molded Neo	33.8 mm

Table 1. Power tool motor length reduction with bonded Neo.

Magnet Type	Motor OD
Ceramic Ferrite	48.0 mm
Injection-Molded Neo	43.0 mm
Compression-Molded Neo	41.5 mm

Table 2. Power tool motor diameter reduction with bonded Neo.

a steel housing into which two sintered ceramic ferrite magnet arcs are either glued or clipped in place.

If one directly replaces a ferrite magnet with Neo, there is the risk that greater flux from the Neo material can drive the housing and armature laminations into saturation, increasing iron losses and limiting the potential gain in efficiency. The red regions of the FEA flux density distribution shown in *Fig. 2* do indeed indicate areas of magnetic saturation in the steel laminations and outer housing, even with the ferrite magnets. In this specific case, the direct substitution of higher-energy Neo for the ferrite magnets will drive the motor further into saturation and will not yield the expected benefits in motor performance. To alleviate saturation when converting to the use of bonded Neo magnets, the magnet should be made thinner in the radial direction to allow for a thicker outer steel housing. Also, the spokes of the armature teeth should be widened to accommodate the extra flux, and the slots may need to be reshaped to allow sufficient space for the winding.

The 2-pole/5-slot power tool motor of *Fig. 2* was redesigned accordingly with both compression-molded and injection-molded Neo magnets. The increased power density of bonded Neo was employed to create a smaller, lighter motor with the same output power as a larger ferrite motor. The baseline ferrite motor is 48 mm in outer diameter with a 48 mm armature stack length. Table 1 shows the reduction in stack length—with a corresponding reduction in motor axial length and weight—afforded by the use of Neo magnets. Table 2 shows the reduction in motor diameter that bonded Neo can provide. Note that for all of the Neo redesigns, the magnet radial thickness (L_m) was reduced and the lamination spoke width was increased to optimally utilize the higher energy product of bonded Neo.

A cordless leafblower-vacuum was chosen as another demanding application worthy of a motor optimization exercise with bonded Neo magnets. The blower motor for this home and garden appliance, shown in *Fig. 3*, is a 4-pole, 16-slot DC brush machine using sintered ceramic ferrite arc segments. The 1.3 kg motor has a 100 mm outer diameter and a 60 mm axial length. Such a device must operate at 100 percent duty cycle for a prolonged period: the present ferrite motor allows for only 12 min. between charges with a 12V X 3.8 Amp-hr rechargeable nickel-cadmium battery. The goal was to achieve 15 min. between battery charges by increasing the efficiency of the motor with bonded Neo magnets.

The blower motor was redesigned with injection-molded and compression-molded Neo, and *Fig. 4* shows the FEA flux distributions for both Neo designs at a motor current of 10 Amperes. Comparison of the injection-molded vs. the compression-molded Neo motor designs of *Fig. 4* clearly shows the adjustments to magnet and housing thickness, lamination spoke width, and the rotor hub required to accommodate the added flux of the higher-energy magnets.

When comparing similarly-sized motors, a *motor constant* K_m is often used as a figure of merit, and a higher K_m generally translates to higher motor efficiency. K_m is equal to K_t/sqrt(R), where K_t is the motor's *torque constant* (Newton-meters/amp) and R is its armature winding *resistance* (ohms). The increased air gap magnetic flux density provided by bonded Neo yields a higher K_m, which in turn can be utilized either to increase K_t while retaining an identical winding, or to retain K_t while reducing R, or to both increase K_t and reduce R by lesser amounts. The latter approach was chosen in order to reproduce as closely as possible the original ferrite motor's torque versus speed characteristic. This was accomplished by rewinding the armature with fewer turns of thicker wire. The higher energy available from bonded Neo magnets improves the efficiency of the blower motor, allowing for a reduction in armature current for any given out-

Fig. 3. 12V blower motor.

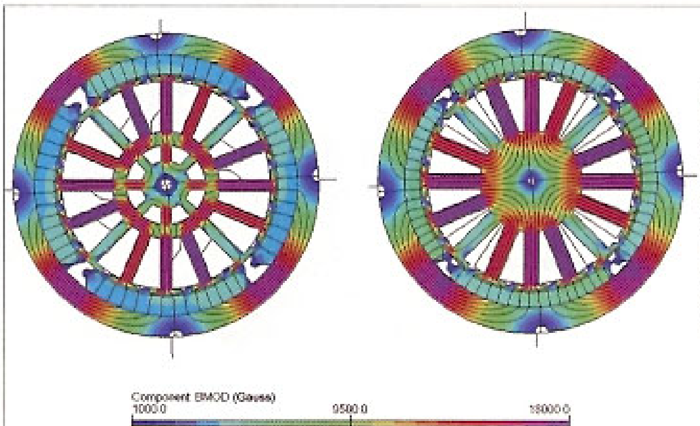

Fig. 4. Magnetic flux contour plots of injection-molded (left) and compression-molded (right) Neo redesigns of the blower motor.

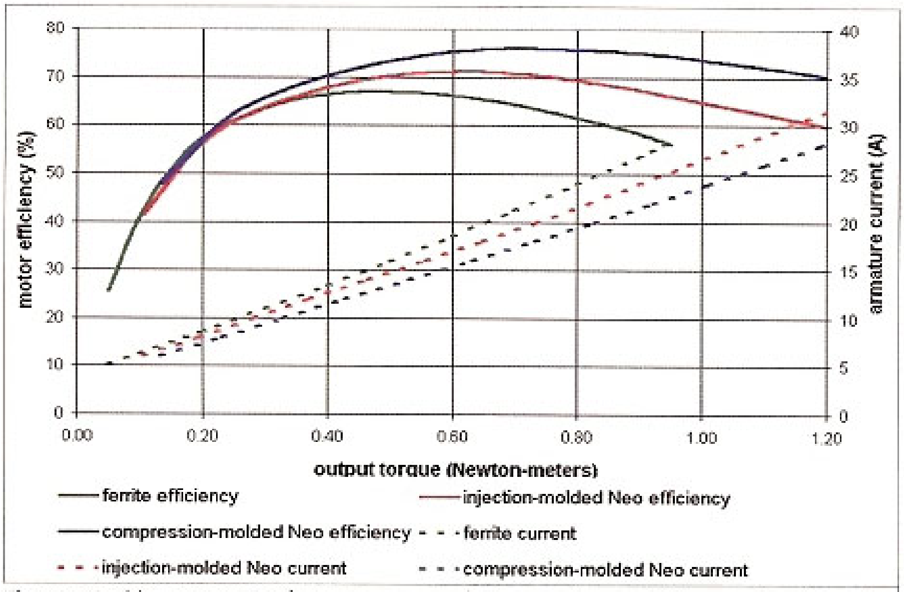

Fig. 5. 12V blower motor performance curves: efficiency vs. torque (solid curves) and current vs. torque (dashed curves).

put torque. The comparative efficiency vs. torque and current vs. torque curves are shown in *Fig. 5*.

Table 3 summarizes the results of the cordless leafblower study. The higher magnet properties of the two selected bonded Neo materials in comparison to ceramic ferrite enabled an increase in *motor constant* K_m. At the motor's normal continuous operating torque of 0.6 Nm, there is a 2.0 amp (10 percent) reduction in current draw by replacing ferrite with injection-molded Neo, and a 4.0 amp (21 percent) drop in current by using compression-molded Neo. The battery life of the cordless leaf-blower-vacuum is inversely proportional to the current drawn from the motor at its operating torque. Therefore, the leafblower incorporating compression-molded Neo magnets will last over 20 percent longer between battery charges than a device with a ferrite-magnet motor, thereby meeting the design goal of 15 min. between battery charges.

Simplified manufacturing

The ceramic ferrite magnets shown in the stators of the DC motors of *Fig. 2* and *Fig. 3* are attached to the steel motor housing using either glue or clips. Such attachment methods com-

Parameter	Unit	Ferrite	Injection-Molded Neo	Compression-Molded Neo
Remanence - Br	Gauss	4200	5200	6950
Intrinsic Coercivity - Hci	Oersted	4000	9500	9500
Energy Product - (BH)max	MGOe	4.0	5.4	10.4
Torque Constant (Kt)	N-m/A	0.0357	0.0397	0.0444
Winding Resistance (R)	Ohms	0.177	0.143	0.113
Motor Constant (Km)	N-m/W^.5	0.085	0.105	0.132
Maximum Motor Efficiency	%	66.7	71.3	76.2
Current draw @ 0.6 N-m	Amperes	19.0	17.0	15.0
Battery life (3.8 Amp-hours)	minutes	12.0	13.4	15.2

Table 3. Summary of bonded Neo motor performance improvements for 12V leafblower.

promise the reliability and the structural integrity of the motor, and both methods add time and cost to the motor manufacturing process. The use of bonded Neo magnets, when properly implemented, can alleviate these reliability and cost issues.

While both injection and compression molded magnets can be provided as individual arcs like ceramic ferrite, the preferred solution is to make the magnets as complete rings for direct mounting within the motor housing. A compression-molded ring can be inserted into the motor housing and locked in place with tabs. While compression molding yields higher magnetic properties, injection molding allows for a wider variety of shapes and more efficient manufacturing techniques.

Ceramic ferrites are fabricated via pressing and sintering, yielding brittle magnets that must be ground with diamond wheels to achieve the tight tolerances required for motors. In most applications, bonded Neo magnets can be employed "as-pressed" with minimal secondary operations required.

Conclusion

There are many ways in which bonded Neo magnets can improve motors and add value to the appliances in which they are employed. A Neo-magnet DC motor will have an increased energy density, which can provide a combination of a higher output power and torque, a higher efficiency, a reduced current draw from the battery, and a reduction in size. Minor redesign of the magnetic circuit of the motor is typically all that is required to reap the benefits of the higher energy product of bonded Neo in comparison to ferrite magnets.

Bonded Neo magnets also simplify the manufacture of DC motors. A single compression-molded Neo ring can replace multiple ferrite arcs. Clearly, bonded magnets allow for greater flexibility in production and assembly of the motor. As the price differential between a Neo and ferrite motor solution narrows, bonded Neo magnets will continue to penetrate more deeply into the appliance motor market.

—Anthony C. Morcos

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Winning with Winding

Automation speeds production without sacrificing flexibility.

Over the past 10 years, there has been a frantic rush by companies to move manufacturing facilities to regions with lower labor and material costs. While these moves often provide a significant improvement in shareholder value, they are accompanied with a number of costs that are often not accounted for. These include: increased scrap rate, increased