The Straight Attraction

PART TWO

Tony Morcos
The Magnequench Technology Center

Direct-drive linear motors are gaining popularity with motion control system designers and are rapidly replacing traditional rotary-to-linear-motion conversion technologies such as motor/lead screw and belt-drive systems. Linear motors provide distinct advantages over these established techniques: higher speed and acceleration, greater accuracy, and elimination of backlash. DC permanent magnet motors comprise almost exclusively the new generation of linear motors, with the great majority incorporating neodymium-iron-boron (NdFeB) permanent magnets.

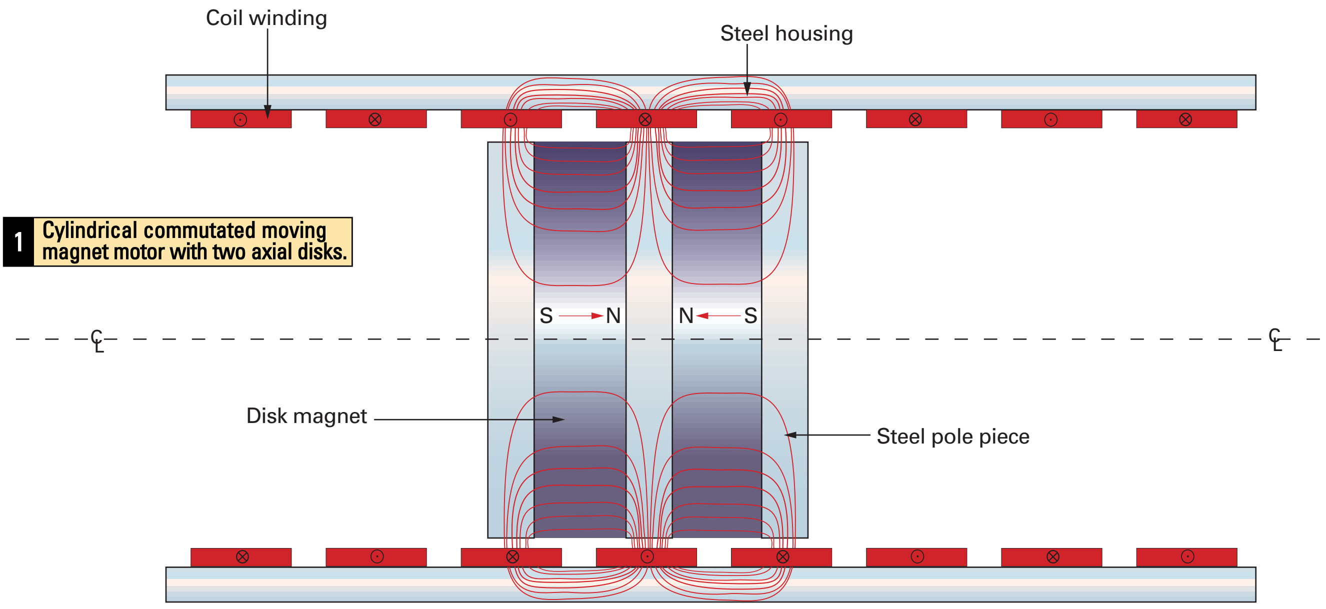
Direct-drive linear motors are benefiting from the use of NdFeB permanent magnets.

Editor's note:
Last month, we examined advances in high-energy permanent magnets. This issue, we'll see more of the impact they've made on linear motors.

Unfortunately for designers, available magnet shapes usually dictate the magnetic circuit designs for linear motors—not vice versa. We'll continue to look at how the many available grades and geometries of NdFeB magnets are most effectively applied to a variety of linear motor designs. I'll also resume our discussion of which magnets are best suited to specific linear motor geometries.

Linear Motor Designs: Commutated

Simply taking the same magnetic circuits and replicating either the coil windings or the permanent magnets along the stroke axis can overcome the inherent stroke limitations of voice coil motors (VCMs) and moving magnet actuators (MMAs). The coils must be commutated using brushes, Hall-effect sensors, or feedback from some other position sensor (e.g., a linear encoder) to switch the coil currents. The following is a sampling of commutated linear motor designs.



1 Cylindrical commutated moving magnet motor with two axial disks.

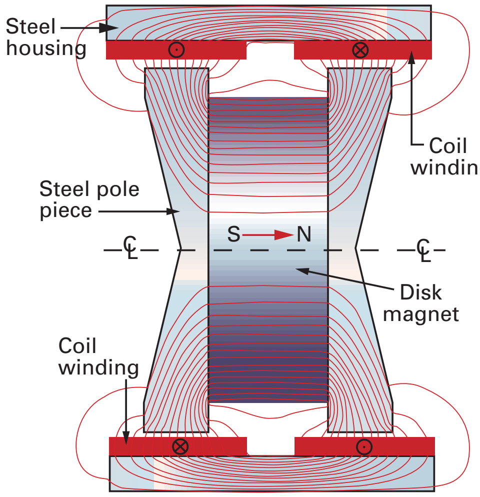
Cylindrical Moving Magnet Linear Motor

The magnetic circuit of the cylindrical moving magnet linear motor, shown in Figure 1, is quite similar to that of the MMA shown in Figure 2. The difference is that the coils are replicated to increase the stroke, and the moving assembly usually consists of two high-energy NdFeB axial disk magnets with three pole pieces. Magnetic flux is squeezed through the pole piece between the oppositely polarized magnets, yielding a very high magnetic field (0.6–1.2 times the magnet material's B_r value). The coil winding typically comprises three phases, with trapezoidal brushless commutation using Hall-effect switches.

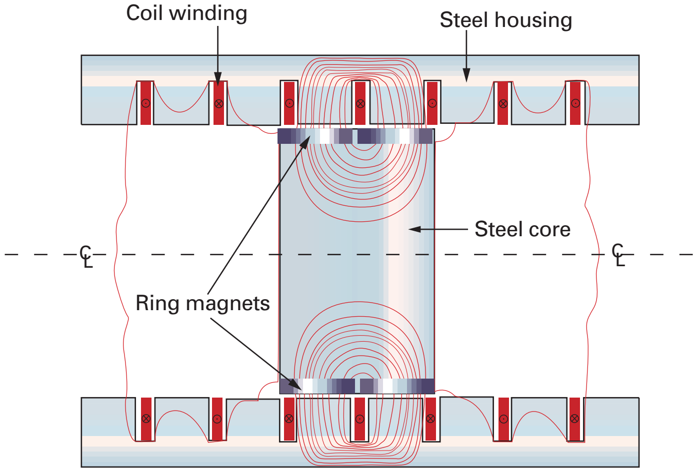
A different version of the cylindrical moving magnet linear motor is shown in Figure 3. It typically employs radial ring NdFeB magnets of MQ1 (bonded), MQ2 (hot-pressed isotropic), or extruded MQ3 (anisotropic). The coil winding is embedded within the outer steel housing. The working magnetic air gap is very small because it no longer contains the winding. This small air gap yields higher forces via a higher magnetic field: 0.6–0.8 times the magnet material's B_r value. The coil winding typically comprises two or three phases, with trapezoidal brushless commutation using Hall-effect switches.

Rectangular Ironless Moving Coil Linear Motor

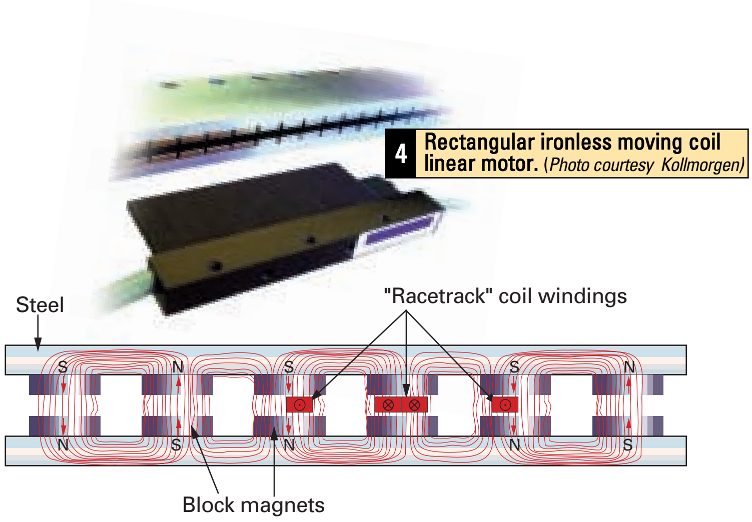
The rectangular ironless moving coil motor's magnetic circuit (Figure 4) is identical to that of the VCM shown in Figure 5, except that the magnets and coils are replicated to provide for the increased (and virtually unlimited) stroke. Typically, the racetrack coil winding is three phases, with either sinusoidal or trapezoidal brushless commutation. The commutation scheme dictates the smoothness of the force versus stroke profile (i.e., force ripple). Like a VCM, this type of linear motor has no cogging or attractive forces between the moving coil and the permanent magnets, and the ironless coil assembly has a rather low mass, allowing for very high acceleration. Because of the rectangular block geometry of the magnets, MQ3 and sintered NdFeB are usually the materials of choice. The tightest magnet tolerance—the magnetic length—is in the pressing direction, which may allow for the use of an as-pressed MQ3 block with no secondary operations required.



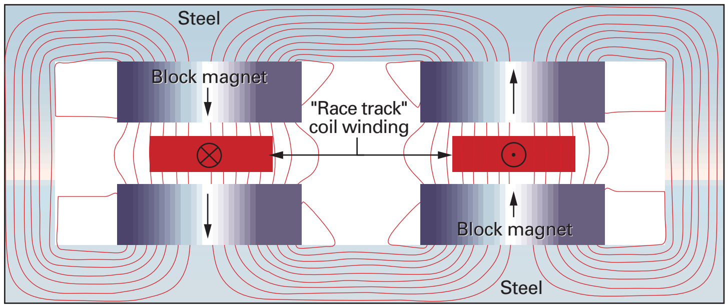
2 Cylindrical MMA with single axial disk.



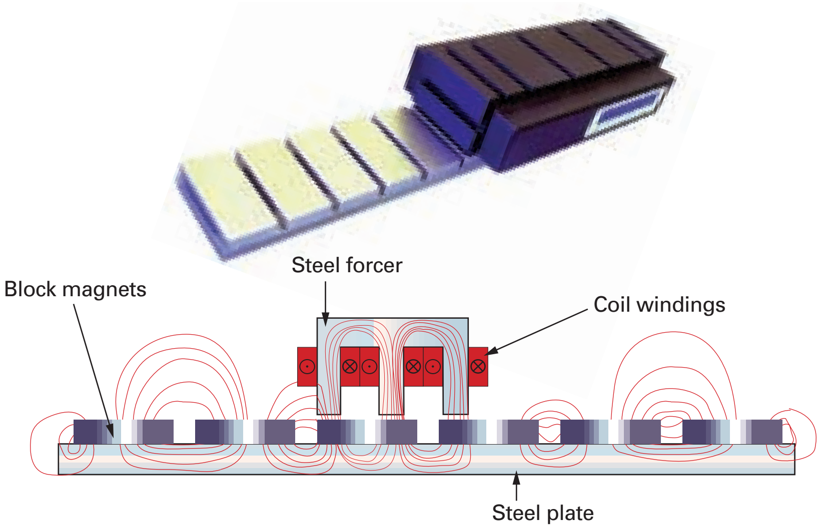
3 Cylindrical commutated moving magnet motor with radial rings and embedded winding.



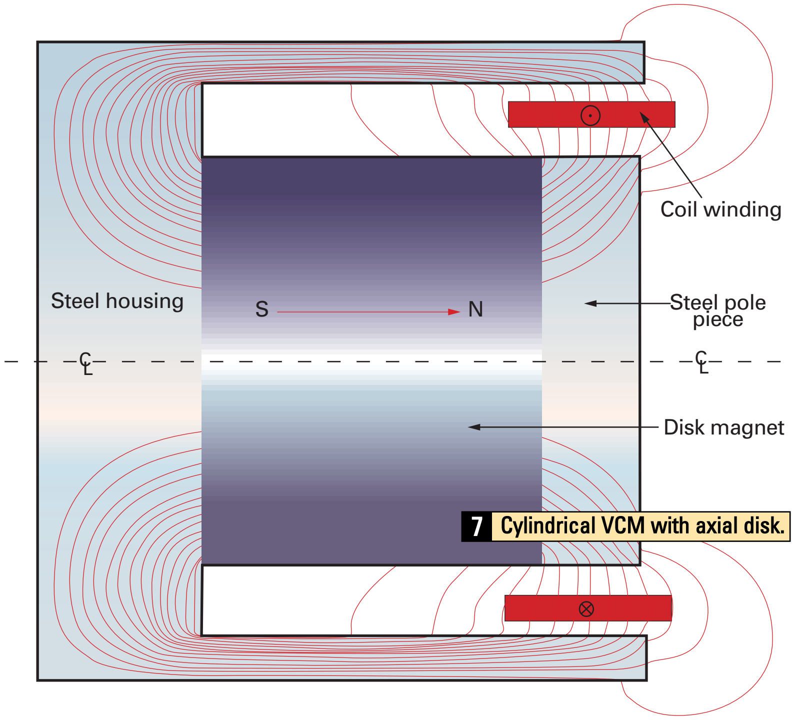
4 Rectangular ironless moving coil linear motor. (*Photo courtesy Kollmorgen*)



5 Short-stroke rectangular VCM without core.



6 **Rectangular iron core linear motor.** (*Photo courtesy Kollmorgen*)



7 **Cylindrical VCM with axial disk.**

Rectangular Iron Core Linear Motor

In a rectangular iron core linear motor (Figure 6), the multiphase coil windings are inserted into a steel structure to create the moving armature assembly. Typically, such motors are three-phase brushless with either sinusoidal or trapezoidal commutation. While the moving armature assembly is more massive than that of the ironless design described above, the iron core significantly decreases the working magnetic air gap. The small air gap yields higher forces via a higher magnetic field: 0.6–0.8 times the magnet material's B_r value. There is a strong attractive force between the iron-core armature and the stationary permanent magnet assembly—this can be used advantageously as a preload for the bearing system. There will also be cogging forces, which can be reduced by skewing the magnets. As is the case with most rectangular cross-section linear motor designs, the magnets are rectangular blocks, preferably made from MQ3 or sintered NdFeB.

Manufacturing Considerations

Several NdFeB magnet characteristics can dictate the manufacturing methods employed in linear motor assembly. The extremely high energy of such magnets, though desirable from a motor-efficiency point of view, leads to two primary difficulties in the manufacturing process: they require very high magnetic fields to magnetize, and their high fields generate large magnet-to-magnet and magnet-to-steel forces. Furthermore, they lose magnetic strength when exposed to high temperatures, and the fully dense varieties (i.e., sintered NdFeB, MQ2, and MQ3) are mechanically glassy and brittle. They're also prone to oxidation (especially the sintered variety), and must be coated to prevent rusting.

Magnetization

NdFeB magnets require a very high magnetic field of 20–40 kOe to magnetize fully. A large pulse magnetizer provides this field, where a bank of capacitors is rapidly discharged over a period of a few milliseconds, dumping several thousand amperes of current through a magnetizing coil to provide the necessary magnetic field. *In situ* magnetization, where the magnet is magnetized after assembly onto its back iron structure, provides the simplest manufacturing solution.

Unfortunately, *in situ* magnetization has several difficulties that make it impractical, or even impossible, in many instances. Eddy currents will be generated in any electrically conductive materials (e.g., steel, aluminum, and copper) in the assembly during the transient pulse-magnetizing field. These eddy currents significantly reduce and re-direct the magnetizing field. In addition, it's quite difficult to design magnetizing coils with sufficient field strength to magnetize the multi-pole magnetic circuit designs of most commutated linear motors (or of all designs employing radially oriented magnets, commutated and non-commutated). If there's sufficient magnetizing field in reserve to overcome the eddy currents, the best linear motor candidates for *in situ* magnetization are VCMs or non-commutated moving magnet motors employing either axially-magnetized disks (Figures 2 and 7) or rectangular blocks (Figure 8).

In most linear motor designs, NdFeB magnets must be magnetized prior to assembly. If the magnet vendor performs magnetization, special precautions must be taken in packaging, shipping, storing, and handling the "hot" magnets. In any event, handling after magnetization should be minimized for safety reasons. Most linear motor manufacturers will have a high-energy pulse magnetizer with several magnetizing coil fixtures that allows them to magnetize the magnets at the latest possible point in the assembly process.

Assembly Techniques

Magnetized NdFeB magnets generate large magnet-to-magnet and magnet-to-steel forces, which are proportional to the magnet's energy product and surface area and can be extremely dangerous. Magnets will suddenly accelerate to seek the nearest piece of steel, crushing any fingers that might get in the way! Adjacent magnets will jump to find each other's opposite pole, slamming together (usually shattering and destroying the magnets). It's critical that carefully practiced and documented safety procedures are employed, and that assembly personnel be experienced in dealing with these magnets.

In most linear motors, the NdFeB magnets are bonded onto the back iron using an adhesive. There's a wide range of suitable materials, including thermosetting epoxies, cyanoacrylates, phenolics, and structural adhesives. In fact, many adhesives are designed expressly for bonding magnets to steel. Below are several general bonding tips:

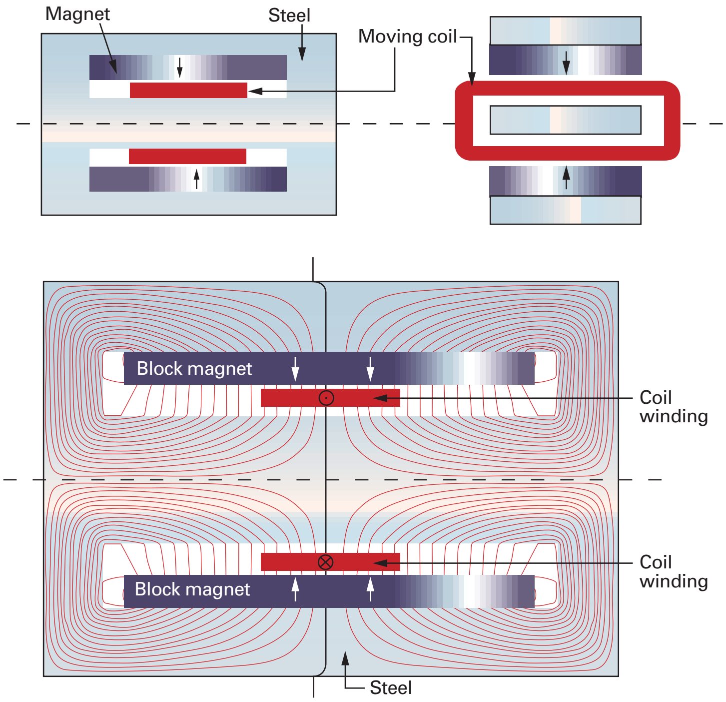
- The bondline strength is directly proportional to the bonding surface area, which you'll want to maximize.
- Ideal bonding surfaces are virgin metal with any coating removed. The bondline strength is only as strong as its weakest link, which may be the base metal to the coating.
- Magnetized magnets will compress the bondline and force adhesive out of the gap. Grooves in the steel, roughened bonding surfaces, bead-filled epoxies, and spacer pins can help ensure that an adequate amount of adhesive stays in the gap.
- To avoid demagnetization, the maximum adhesive cure temperature should be kept below 100°C when bonding pre-magnetized NdFeB magnets to steel. This temperature can be increased significantly if the adhesive is cured prior to magnetization.
- Tremendous forces are applied to the magnets during *in situ* magnetization, so the adhesive chosen in such linear motor designs should be able to withstand this shock load.
- When bonding magnetized rings to steel, the diametrical tolerances must be loose enough to allow for adhesive, yet tight enough to minimize radial runout. This eccentricity always yields a worst-case tolerance stackup, because the magnetized magnet will tend to suck up against one side of the steel ring or hub.
- Worst-case bondline forces occur when multiple blocks of like polarity are placed side-by-side. The individual magnets will want to jump off the steel plate and flip over to attract an opposite pole. *In situ* magnetization is recommended for such linear motor designs (e.g., the rectangular VCM shown in Figure 8).

With the exception of MQ1, NdFeB magnets are mechanically brittle and glassy. They should not be threaded, and they should never be employed as structural or load-bearing members in a linear motor design. Still, in some cases, mechanical assembly methods such as sheathing, staking, or swaging can be employed to augment, or even supplant, adhesive bonding forces.

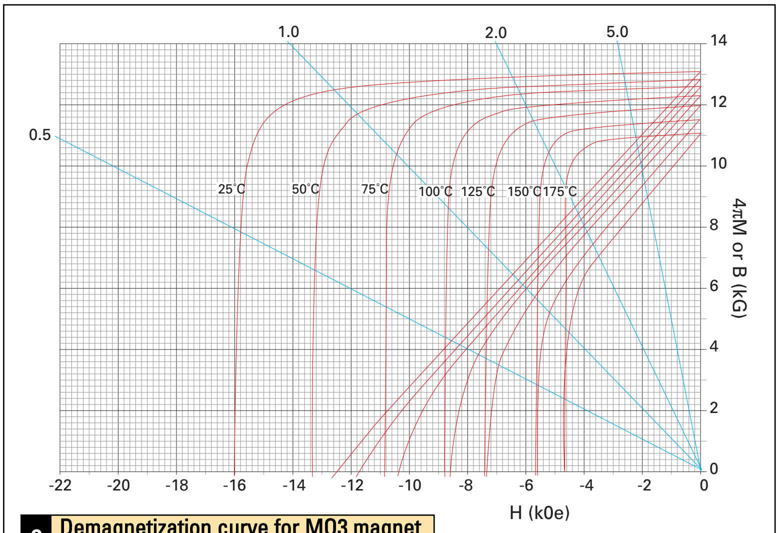
Stability and Thermal Limitations

Flux losses in NdFeB magnets can be classified as reversible or irreversible, and depend on the magnet's temperature, grade, operating load line, and the demagnetization field it sees. Figure 9 (page 28) shows the second quadrant demagnetization curves at various temperatures for a typical grade of MQ3 NdFeB magnet. Figure 10 (page 28) graphically represents the flux losses with respect to magnet temperature for a typical grade of MQ1, operating under load in a DC motor.

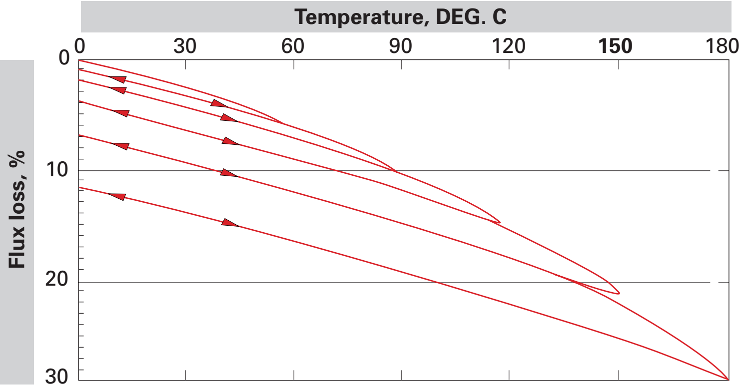
Up to a certain temperature—ranging from 100–220°C, depending on the type and grade—the magnetic field of the magnets will decrease in a somewhat linear fashion with respect to temperature. Assuming the magnets' temperature rise is small, and the load line excursion due to demagnetizing current is slight, this loss of field will lead to a temporary performance reduction in the linear motor. The magnetic field will return to normal when the magnet's temperature normalizes. Such losses are referred to as *reversible*. When the magnets' temperature rise is large, and/or the motor's demagnetizing current is high, the losses will be more severe and *irreversible*. The magnets must then be re-magnetized to regain full properties.



8 Long-stroke rectangular VCM with steel core.



9 Demagnetization curve for MQ3 magnet material at various temperatures.



10 Flux loss vs. temperature for MQ1 magnet material.

Linear motor engineers must carefully design the magnetic circuit to ensure an adequate magnet load line of operation to prevent demagnetization from large motor currents. These problems become more prevalent as the magnets' temperature increases. It's strongly recommended that prior to shipment, a linear motor be operated under worst-case loading conditions at maximum temperature. This process stabilizes motor performance by knocking down the magnets' flux to minimize any further *irreversible* losses. NdFeB magnet grades with the highest intrinsic coercive force (H_{ci}) ratings will provide the most robust linear motor designs with respect to thermal demagnetization and operational stability.

Corrosion of and Coatings for NdFeB Magnets

Sintered NdFeB magnets are highly prone to oxidation and must be coated. This instability arises from these magnets' extremely fine particle size, approximately the size of a single magnetic domain. Magnets made from melt-spun ribbon (i.e., MQ1, MQ2, and MQ3) are considerably more stable because each particle contains hundreds of magnetic domains, and thus the majority of domain walls aren't exposed. Still, most melt-spun varieties should also be coated, if for no reason other than to prevent surface discoloration.

There are a variety of suitable coatings available. The most common is e-coating, wherein a charged mist of epoxy is electrodeposited onto an oppositely charged NdFeB magnet. Nickel, zinc, tin, and aluminum chromate (ion vapor deposition) are candidate metallic coatings. Epoxy and phenolic spray coatings are also quite effective in preventing oxidation.

Magnet vendors have extensively tested these and other coatings for suitability in various harsh environments. The most common test is a 240-hour exposure to 85°C and 85% relative humidity. An accepted accelerated aging test is the autoclave test, where the magnet is placed in a pressure chamber under high temperature and pressure. Typical autoclave test conditions are 125°C and 15 psig for 120 hours. Perhaps the most severe qualification is salt-spray testing, which is often required by automotive industry manufacturers. Different coatings are best suited for different environments. Linear motor designers should work closely with their magnet vendors to choose the optimum coating for the specific application.

NdFeB magnets have been the enabling technology to make direct-drive linear motors a viable commercial product. Their high energy product and stiff intrinsic coercivity allow high magnetic flux densities to be pushed across the large air gaps inherent in most linear motor designs, while withstanding the demagnetizing fields generated by the motors' coil windings. There are two fundamental metallurgical formulations for NdFeB magnets: sintered and melt-spun ribbon (i.e., MQ1, MQ2, and MQ3). These formulations and their associated fabrication techniques dictate the magnets' available shapes and magnetic orientations. Unfortunately, linear motor magnetic circuit designs are confined to these magnet shapes and orientations.

Linear motor designs can be non-commutated (single-phase) or commutated (multi-phase), cylindrical or rectangular, and several different linear motor magnetic circuits employ the range of available NdFeB magnet shapes.

The properties of NdFeB magnets dictate many of the assembly steps in the manufacture of linear motors. They require very high magnetic fields to magnetize, and this will determine whether or not the magnet can be magnetized in the motor assembly (*in situ*) or must instead be magnetized prior to assembly. Their high fields generate large magnet-to-magnet and magnet-to-steel forces, thereby complicating the bonding and fixturing process. They lose magnetic strength when exposed to high temperatures, thus limiting the adhesive cure temperatures during the assembly process. NdFeB magnets, especially the sintered variety, are prone to oxidation and are usually coated to prevent rusting.

Make Contact!

Anthony C. Morcos is a senior applied scientist for the Magnequench Technology Center. He is responsible for the design and analysis of various permanent magnet devices, including motors, actuators, and sensors. Contact him at 9000 Development Drive, P.O. Box 14827, Research Triangle Park, NC 27709-4827; tel: (919) 993-5510; fax: (919) 993-5501; amorcos@mqii.com; www.magnequench.com.