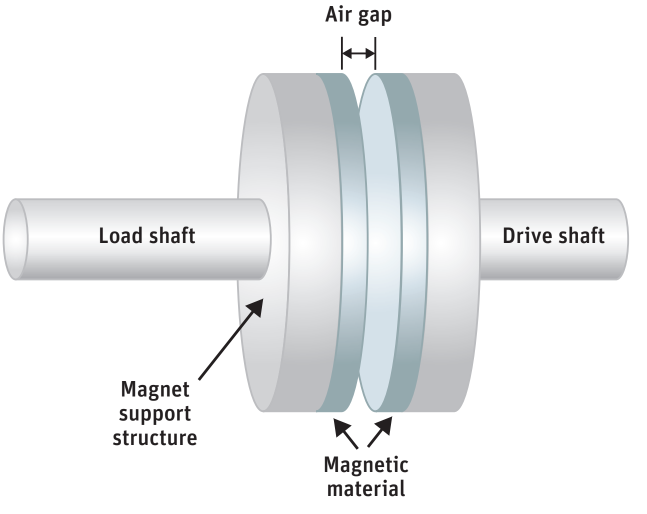
MAGNETIC ATTRACTION

Simulation aids a revolutionary magnetizing machine to produce magnets with precision-tailored magnetic fields, forces and behaviors.

By Scott Evans, Director, Product Development and R&D Programs, and
Ron Jewell, Vice President, Sales and Marketing, Correlated Magnetics Research, Huntsville, U.S.A.

Magnets have a large number of commercial applications in a variety of devices, such as clutches, bearings, gears, fasteners, motors, sensors, security devices, pointers, scopes and optics, to name a few. The material in conventional high-field magnets is typically oriented, or magnetized, in a single direction, a condition that results in fields that are far from ideal for many electromechanical applications. Manufacturers of magnetic devices have been addressing this limitation by creating complex magnetization fixtures or by assembling groups of smaller magnets. Both of these methods increase fabrication challenges and result in field losses in the gaps between magnetic pieces.

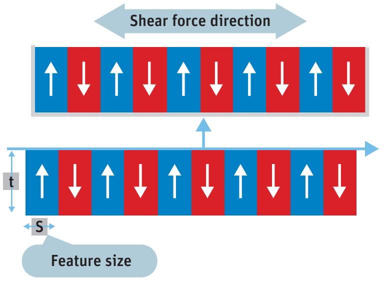
The latest advancement in this field, correlated magnetics, involves precise and rapid magnetization of materials a small volume at a time, making it possible to optimize the emission of fields from magnetic materials — and even to create field profiles that were not previously possible. This breakthrough ability to accurately shape magnetic fields increases device efficiency, enables savings in assembly and integration, and establishes whole new areas of application for magnets. Furthermore, the technology permits material size and weight reduction by reducing any overdesign intended to compensate for alignment errors in assembly and integration of magnetic materials. These correlated magnets are created using an innovative new machine, called a MagPrinter™, that renders complex magnetic structures in bulk magnetic materials. One of the first areas of application is improving the design of magnetic clutches.



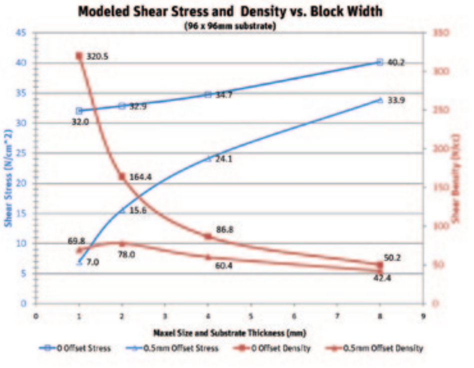
Typical magnetic linkage

Magnetic clutches are used in equipment in the aerospace, marine, medical and chemical industries, among others, and in devices including industrial ovens, pumps, compressors, metering devices, controllers and hydraulic machines. Magnetic torque-transfer devices are often used in applications in which it is difficult to maintain alignment between driving and driven shafts. The devices also play a role replacing dynamic seals for lower torque applications within chemical or high-pressure processes. In the marine industry, one application is connecting electric motors to pumps on ships. A ship's hull interacts with waves, which causes flexing in the frame and makes it difficult to keep shafts aligned. If the shafts go out of alignment, wear on bearings and shafts increases substantially. Ship engineers then must spend a considerable amount of time maintaining alignment and addressing problems caused by misalignment.

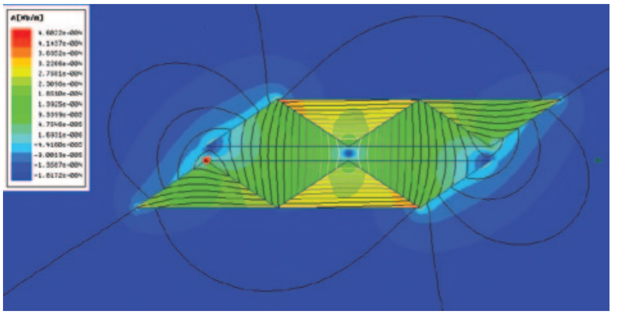
During the operation of a typical two-plate magnetic coupling device, torque is transferred by shear forces between magnetic materials interacting across an air gap. Transferring torque without physical contact means that alignment is much less of a concern; the process also eliminates wear while providing a barrier to vibration, torque overloads, electricity and heat. This type of device traditionally uses several sections of uniformly magnetized material arranged as alternating



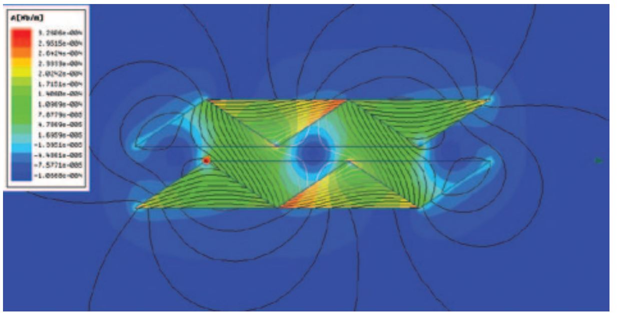
▲ Alternating blocks of magnetic material are used to produce magnetic shear forces.



▲ The effect of block width on measured shear stress and density



▲ Magnetic field emitted by one-sided structure under zero shear condition. The triangles are magnetic blocks, and the rest of the image is air. The highest field intensity is orange, and the lowest is dark blue. The lines that travel across the gap illustrate attractive forces.



▲ Magnetic field emitted by one-sided structure in a maximum-shear condition. The highest field intensity is orange, and the lowest is dark blue. The lines that travel across the gap illustrate attractive forces.

stripes or as pie pieces to form the surfaces facing the air gap. But the shear forces generated by conventional designs are relatively weak, so conventional magnetic torque transfer devices must be many times heavier and larger than direct mechanical couplings to deliver the same torque. In other words, they have a low torque density, which is directly proportional to the shear forces between magnets.

Correlated Magnetics Research (CMR) is developing multipole magnetic structures that offer higher torque-transfer performance from smaller, lighter magnets. The company is also exploring techniques for eliminating the non-torque-producing tensile forces between the magnets. CMR has two key innovations: the application of signal processing methods and coding theory to guide the production of complex patterns of magnetic elements and resulting magnetic fields, and the MagPrinter™ that is capable of rendering very complex magnetic structures rapidly and inexpensively in bulk magnetic material. The CMR R&D team found that ANSYS Maxwell electromagnetic field simulation software played a key role by assisting in the design of these complex magnetic structures that deliver shear forces 40 percent higher than previously known magnetic structures and, at the same time, halving magnetic material requirements.

BASIC RESEARCH INTO MAGNETIC LINKAGES

CMR engineers use Maxwell to investigate the shear force generated by various magnetic structures. For example, in the early stages of research and development, the team performed an investigation to determine how shear force varies with respect to the aspect ratios — thickness to width — of the magnetic blocks facing the gap between the two correlated magnetic structures. The model showed that an aspect ratio of 1:1 yielded the highest shear force per surface area and shear force per volume of magnetic material.

Next, square regions, 96 mm per side, were assembled in the software from magnetized blocks: 8 mm, 4 mm, 2 mm and 1 mm wide. The thickness of each block was equal to its width; each substrate had the same area. Simulation showed that with a zero displacement across the gap between the magnetic blocks, as the blocks are reduced in width from 8 mm to 1 mm, the shear per area decreases modestly and the force per volume of material rises sharply. So, while the highest forces come from larger blocks, the best use of magnetic material comes from many small blocks.

When the simulation was repeated with a small 0.5 mm gap between the substrates, the results were very different. The shear force per area falls more rapidly as the blocks are halved in size; the maximum shear per volume occurs with a 2 mm block width. Smaller blocks confine the field more strongly near the surface, so the best use of magnetic material comes when the blocks have a width that is about four times the gap between the substrates. Other architectures will have different ratios, but the team anticipates that the basic relationship will apply. Generally, by knowing the gap that can be used in a particular application, engineers can estimate both the best feature sizes for the magnetic structure and the maximum shear force per magnet volume that is achievable. Maximizing the shear force, in turn, makes it possible to increase torque density and reduce the size and weight of a magnetic clutch with a given torque capacity.

WORKING WITH ONE-SIDED MAGNETS

To obtain guidance into scaling and design issues in more complex magnetization patterns, researchers examined magnetic structures that emit magnetic fields predominantly on one side with several models. An example of a one-sided structure is a Halbach array, which uses a spatially rotating pattern of magnetization to augment the magnetic field on one side of the array while cancelling the field to near zero on the other side. The first model was an array of triangles whose bases face the opposing substrate and that have magnetization vectors that alternate toward and away from the opposing magnetic structure. The triangles with bases facing away from the opposing substrate are magnetized to the left and right with respect to the opposing magnetic structure. Magnetic fields were plotted with the opposing magnets aligned at zero shear and maximum shear conditions. This arrangement generated large forces between the opposing magnetic structures. When the two sides are aligned, those forces are attractive or repulsive. When the two patterns are offset, a shear force is developed, while attractive or repulsive forces are reduced. At a maximum shear force condition, the attractive and repulsive forces are zero.

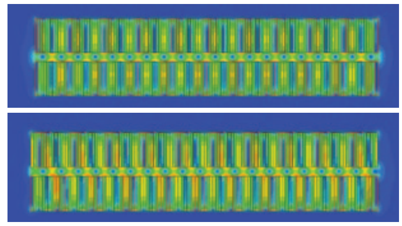
CMR examined shear force generation between magnetic materials that had smoothly and continuously varying magnetization. This type of magnetization profile also creates a strongly one-sided field emission; this is possible only theoretically (so far). The shear forces generated by smoothly varying magnetization followed the same patterns identified with the triangle array described above. When two continuously varying substrates are aligned, there is a large attractive force. If the pattern in the upper magnet is shifted to the side, a maximum shear force condition occurs. The simulation with smoothly varying magnetization also established an upper limit to shear forces that can be generated between magnetic materials. In effect, the simulations using Maxwell help to quantify achievable performance gains as manufacturing enhancements make it feasible to magnetize smaller regions of material and to render more complex magnetic patterns into magnetic materials.

DEVELOPING A WORKING PROTOTYPE

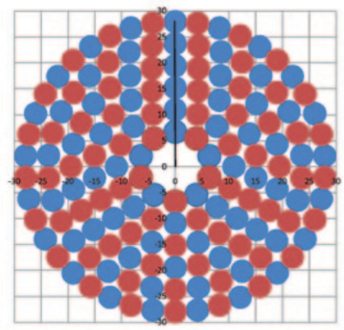
CMR's MagPrinter includes a unique electromagnetic coil that is placed near a magnetizable material and energized with a very short high-current electric pulse. The energized coil emits a very intense magnetic field in a confined region of space, magnetizing a small region of the adjacent material. Each of these small regions is called a maxel (much like a pixel, a shortened form of magnetic element). An array of maxels forms a complex magnetization profile and, likewise, emits a complex magnetic field. Guided by the results of the simulation studies, CMR conducted a series of experiments to find the best combination of magnetic patterns and pulse energies for producing shear forces. The knowledge from simulation efforts and shear force experimentation was applied to fabricating a magnetic clutch. The magnetization energies and geometry of those codes were adapted to create a high-torque maxel code.

The team divided a 3-inch outside diameter magnet into tracks, and each track was printed to have an alternating magnetization that approximated the continuously varying pattern. Magnetization was accomplished in about three minutes with the fourth-generation CMR MagPrinter machine. The system features a computer-controlled platform that moves a magnetic material substrate relative to a specialized print head that imparts a focused magnetic field onto the substrate, resulting in a single, well-defined maxel at a prescribed location. The fifth-generation machine, which is now the standard, performs the same task in about 15 seconds. The tracks and their partner tracks on the opposing magnet were oriented so that each track reached a maximum torque condition at the same orientation of the magnets.

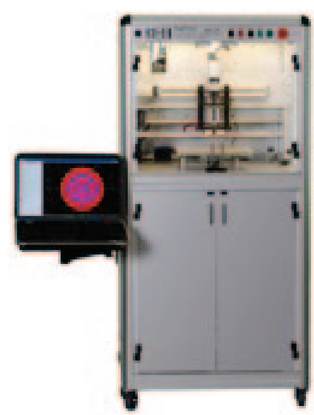
With two 3-inch magnets, each one-eighth inch thick, this pattern withstood 27 Newton-meters (N-m) of torque. At a gap of 1 mm, this clutch produced about 300 N-m per liter of torque density, about half the torque density of a large-scale planetary gearbox, and triple that of the highest-performing commercial magnetic gear, which also has a gap between magnets of about 1 mm. These results helped to convince the Office of Naval Research to award CMR a Phase II Small Business Innovation Research (SBIR) grant to develop high-torque magnetic gears and clutches utilizing CMR's Polymagnet™ technology. The two-year contract is a collaborative effort between CMR and MagnaDrive, Inc.



▲ Two continuously varying substrates aligned have a large attractive force (top). The pattern in the upper magnet has been shifted to the side and illustrates a maximum shear force condition (bottom).



▲ Pattern of tracks printed on magnet to produce high-performance magnetic clutch



▲ The MagPrinter creates customized magnetic materials that can be widely employed in industry.