High-precision systems using modern high-energy permanent magnet materials

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ABSTRACT

To satisfy the demands of miniaturized high-precision systems new designs and new materials are necessary. Especially, the disadvantages of classical configurations like friction, hysteresis, and stick-slip effects have a great influence on miniaturized systems and will decrease the capacity of small drive systems. Therefore, new principles for driving and guidance are necessary. One possibility to guide small moving parts of high-precision drives is the usage of magnetic field forces. We developed such a magnetic guidance integrated in an electromagnetic drive. We use new high-energy rare earth magnet materials with a flat shape and a multi-pole striped magnetization. These magnetic layers are made of sintered or polymer-bonded neodymium iron boron. The layers are homogenous and will be magnetically structured by a capacitor discharge magnetization process. Layers of sintered NdFeB were prepared by machining of commercially available plates. New polymer-bonded materials have been developed, too. The main focus was the development of new material mixtures with better magnetic parameters and good molding capabilities. Different molding processes for the preparation of magnetic films with a thickness in the range from 20 µm to 1 mm as well as an improved subsequent magnetization process have been developed.

This paper discusses the development of such new polymer-bonded permanent magnetic materials, the molding processes to manufacture thin film and the magnetization process. The presented application of such magnetic films is multi-coordinate drive with a magnetically lifted and moved aluminum sheet.

THE HIGH-ENERGY PERMANENT-MAGNET MATERIALS

Introduction

Permanent magnetic materials and the corresponding magnetic parameters have undergone a dramatic evolution during the past decades. Especially the discovery of the NdFeB-family of permanent magnetic compounds in 1984 and the development of suitable industry-scale preparation routes for these rare-earth magnets have led to a widespread use of such magnets in many applications. The introduction of this new class of permanent magnets opened new horizons with respect to the miniaturization of magnet components. If one compares the evolution of the maximum energy product (BH)max achieved with NdFeB-materials clearly demonstrates the new dimension for miniaturization and volume reduction of magnetic-microactuators. Potential fields of application of the high-energy permanent magnets in micro-systems, especially in micro- actuators, require such miniaturization of the components with a simultaneously large mechanical driving power. Consequently, magnetic components are needed which are able to provide magnetic forces large enough to serve in actuator systems. Magnetic thin films of NdFeB prepared by sputtering [4] usually have a thickness of the film in the order of 1-20 microns. These films are not able to generate the needed induction on the surface or at a given distance from the surface of the film to be applied in micro- actuators. To successfully operate as permanent magnetic component in micro-drives NdFeB-films with a thickness of 50-1000 µm are necessary. Those magnets are commercially not available; conventional methods of NdFeB- magnet production either by the powder metallurgical route, by hot-forming of melt-spun powders or injection molding of polymer-bonded powders yield magnets with a thickness larger than 1 mm. Machining and grinding operations to obtain small magnets are not effective and very cost-intensive. Therefore methods for the preparation of magnetic thick films with a thickness of 50-1000 microns have to be developed. In this contribution we report on the preparation of such thick films using several techniques and the application of the films in integrated multi-coordinate drives [5], [6], [7], [11] with parallel kinematics.

Printed films

The magnetic material is mixed with binder to give a magnetic ink or paste. Films with a thickness between 20-100µm can be printed on different substrates (iron, ceramics, glass). After curing the epoxy the films exhibit the magnetic properties as shown below.

	NdFeB-films:	*Ferrit-films*:
B_R:	350-450 mT	60-100 mT
${}_IH_C$:	300-700 kA/m	200 kA/m

Tape casted films

NdFeB powders, after wet milling, are dispersed in a special mixture of solvents and sequentially, this mixture is converted into a viscous casting slip through addition of binders and plasticizers. Shaping is realized by the doctor-blade method in a continuous casting machine with a stationary doctor-blade and a slowly moving casting surface. After removal of the solvent a flexible green tape is obtained. Annealing yields mechanically stable films of thickness between 100-1000 µm.

The remanent induction of the films ranges from 300 to 400 mT (depending on the volume loading of magnetic powder) while the coercivity varies between 300 - 700 kA/m (depending on grade of the magnetic powder used).

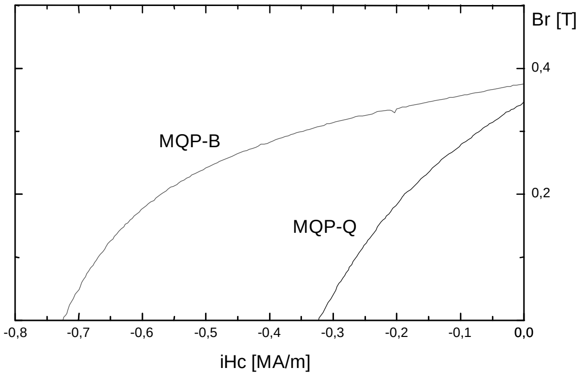

Figure 1: Demagnetization curve of tape casted films

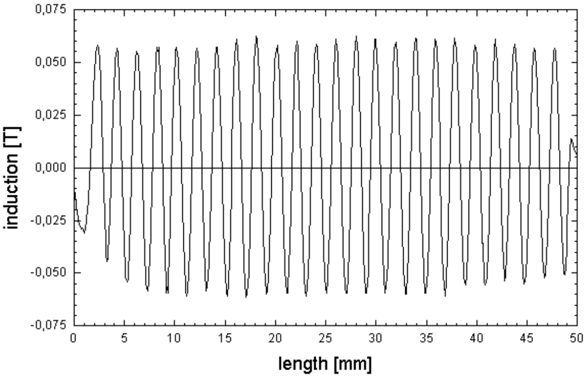

Figure 2: Typical curse of the surface-induction of tape casted films

Flexible foils

To prepare flexible magnetic foils NdFeB-powder (wet milled) is mixed (hot kneading, extrusion) with a polymer to form a composite material (compound). Subsequently the compound is transformed by calendering into a flexible foil with a thickness between 300-1000µm. The remanent induction of the foils 300 to 500mT are obtained with coercivities between 300-700kA/m.

Multi-pole magnetization

The films are magnetized with a multi-pole striped pattern with a pole distance of 2.0, 1.0 and 0.5 mm. A capacitor discharge magnetizer is used to produce a short current impulse. The magnetic film is placed on top of a copper wire wound fixture and the capacitor bank is discharged through the fixture. The obtained magnetic multi-pole pattern is measured by a Hall probe scanning the surface of the magnetic film.

APPLICATIONS

This kind of permanent magnetic film with a multi-pole striped pattern can be used for a widespread range of actuators like synchronous machines and hybrid stepper motors. Another possible kind of applications using permanent magnets with multi-pole striped pattern are linear drives [6], [7] and multi-coordinate drives as presented below.

Modeling of the magnetic field

To use this kind of permanent magnetic films for drives, we have to calculate the magnetic field generated by the film. The field strength depends on the material mixture and the maximum value of the magnetizing current. The field distribution depends on the geometry of the magnetizing coil. The magnetic field around the film was calculated by using the FEA software MAXWELL 2D. To model the magnetization of the film, we used the Halbach magnet array structure [9] (Figure 3).

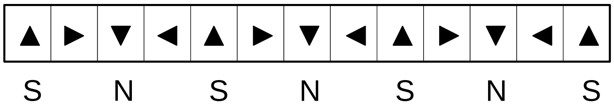

Figure 3: FEA model (Halbach magnet array)

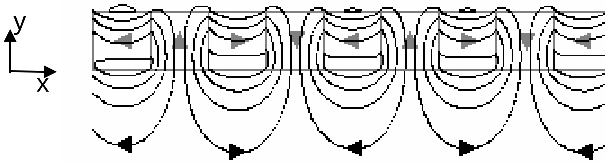

Figure 4: Magnetic field of the film

Figure 4 shows the simulated magnetic field. The field is concentrated below the film. In horizontal direction, the field strength changes sinusoidal. In vertical direction, the field strength amplitudes decreases with increasing distance from the skin of the film. Above the layer, there is nearly no magnetic field. The maximum induction of films with 2 mm wide magnetic stripes is about 0.12 T.

If a current carrying wire is arranged below the film, a force is exerted on the magnetic film depending on the current, the length of the wire and the position of the wire. Figure 5 shows the horizontal Force (F_x) and the vertical Force (F_z) at a current of 10 A.

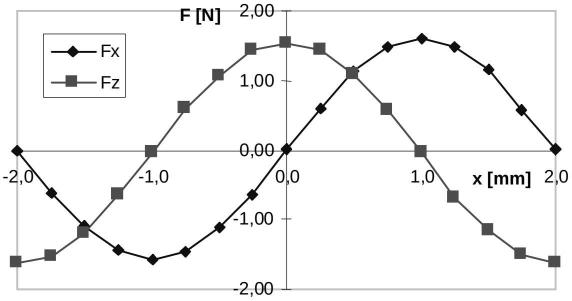

Figure 5: Force exerted on the film

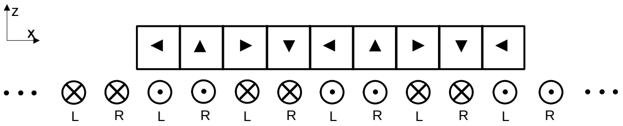

Figure 6: Drive design

To generate horizontal and vertical forces on the film at the same time, we arranged 2 wires multiple below the magnetic film (Figure 6). To distinguish between the wires, they are named with “L” and “R”. The distance between these wire is equal to the half of the pole distance of the magnetic pattern. By applying currents to the wires, we can set up the forces in horizontal and vertical direction independently. The currents can be calculated by

$$I_R = K_x \sin\varphi + K_z \cos\varphi \tag{1}$$

$$I_R = K_x \cos\varphi - K_z \sin\varphi \ . \tag{2}$$

with $K_x = \dfrac{F_x}{B(z) l_w}$ and $K_z = \dfrac{F_z}{B(z) l_w}$.

Whereby, $B(z)$ is the maximum flux density at the distance z from the film skin. F_x and F_z are the forces in horizontal and vertical direction. The wire length is named as l_w.

Our drive uses four coupled actuators (Figure 7). Two of them work in x-direction and the other two actuators work in y-direction. All four actuators are used to lift the sheet. The actuators are coupled by mounting the four magnetic films below an aluminum sheet. To measure the position of this sheet, we use an optical incremental position measurement system, which can measure the position in x- and y-direction and the rotation around the z-axis. Four sensors between the actuators are used to measure the z-position of the sheet and the rotation around the x- and the y-axes. A PC with a data acquisition board is used to control the drive.

A special design criterion is the weight of the sheet because it is lifted by magnetic forces. If the weight of the sheet increases, the needed vertical force and the current through the wires also increases proportional, and the power losses and the heat dissipation of the drive coils increases quadratic.

This sheet can be lifted by some tenth millimeters, can be move in x- and y-direction by 50 mm and can be rotated by some degrees around all 3 axes.

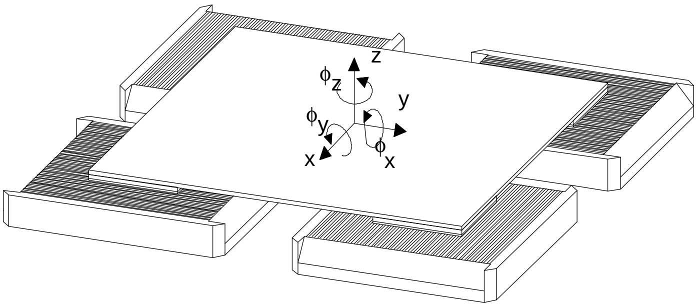

Figure 7: Multi-coordinate drive

CONCLUSIONS

This paper presents new polymer-bonded NdFeB permanent magnet materials which can be processed by film printing, calendring, and tape casting to manufacture films with a thickness of 50-1000 microns. The films are magnetized with a multi-pole striped pattern by the use of a capacitor discharge magnetizer. The pole distance of the magnetization can be 0.5, 1.0, or 2.0 mm. These films are used to design a electrodynamic multi-coordinate drive with a similar function principle to that one presented in [8] and [9]. The main advantages of our drive are the easier manufacturing of the magnetic film by batch processing and the shorter pole distance which leads to thinner permanent magnetic films. The short pole distance also gives the possibility to miniaturize these kind of drives, whereby the ratio between the generated forces and the mass of the lifted parts will become better.

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