Optimum Corrosion Protection of Nd-Fe-B Magnets

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For a long time, the successful application of Nd-Fe-B magnets was jeopardized by their poor corrosion resistance. At first, coatings alone were thought to provide adequate protection. We now know that correctly applying the best-suited coating and optimizing the microstructure of the magnet are both necessary for outstanding performance. This article reviews the present state-of the art, with guidance on best practices.

In the design of magnetic circuits using Nd-Fe-B magnets, the magnetic properties are usually the primary focus. Often minimal attention is paid to the subject of corrosion resistance. Yet in applications with long lifetimes and/or harsh environments, the magnets may fail due to corrosion, which may be preventable. We examine the subject with the goal of avoiding the high cost of failure.

Historical background

Early in the development of Nd-Fe-B magnets, people recognized there was a problem with corrosion. Compared to other common permanent magnet materials (i.e. samarium cobalt, ferrite and alnico), unprotected Nd-Fe-B magnets typically react with their environment, frequently with disastrous results [1].

Since one of the first large series applications was in disc drive voice coil motors, the oxidation and subsequent deterioration of Nd-Fe-B was initially an industry crisis until researchers could understand and ultimately control what was happening.

As we have now come to know, the corrosion process begins with the diffusion of oxygen, water vapor or hydrogen along grain boundaries inside the magnet, as shown in Figure 1. While oxygen and water vapor are naturally found in air, hydrogen arises as a by-product of the corrosion reaction, as oxygen is stripped from water vapor by the Nd-rich phases. Ironically, the other potential source of hydrogen is the acid treatment used to prepare the surface for plating or from electrolysis if the magnets are plated.

In general, gas atoms diffuse through grain boundaries much faster than they move through the main or matrix phase. Also present in the grain boundaries are excess Nd and other ingredients rejected from the main $Nd_2Fe_{14}B$ phase. The main chemical reaction is the combination of one or more of the above-mentioned gases with the Nd-rich phase in the grain boundary, initially forming a complex Nd-oxyhydroxide. While the ultimate reaction product is Nd_2O_3, the damage is done long before the oxide appears, from the volume expansion that accompanies the initial reaction and from the loose powder that forms in the early stages of the reaction.

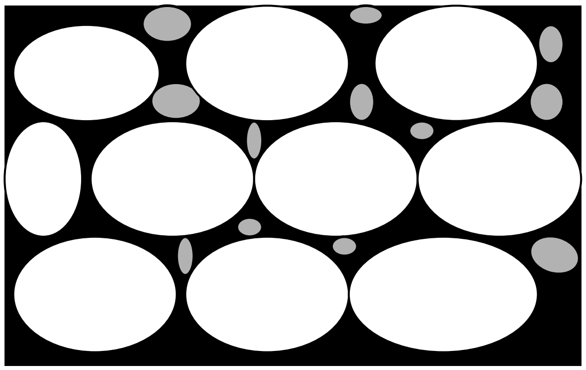

Figure 1. A schematic representation of the microstructure of an Nd-Fe-B magnet. The white phase is the main $Nd_2Fe_{14}B$ phase. The black region represents the grain boundaries; the small gray areas are neodymium oxide.

How to prevent corrosion

To control the corrosion of Nd-Fe-B magnets, researchers have focused on two distinct methods.

The first method is the use of coatings as a protective layer. Originally this technology was successfully introduced to samarium cobalt and ferrite magnets in disc drive applications to enable a residue free cleaning. Coatings can improve the corrosion resistance. Table I shows some of the coatings in use today with Nd-Fe-B magnets and some comments about possible application areas where each type of coating might be appropriate.

The second method tries to improve the intrinsic properties of the material. First, adding certain transition elements (e.g. Co, Ga, Nb, Mo and V) reduces the corrosion rate. [3, 4, 5, 6, 7, 8] Second, limiting the use of Nd to the lowest possible concentration cuts the corrosion rate. This discovery came as a surprise to many manufacturers. Early production methods typically used excess Nd, since the magnets were easier to make and the connection to corrosion behavior was not recognized. Unfortunately, some inexperienced manufacturers continue to use excess Nd in their process today, in spite of the well-documented problems with the approach. Unfortunately their magnets do not fare well in corrosion tests. And finally, keeping out undesirable impurities reduces the corrosion rate as well. Careful selection of raw materials and diligent handling of in-process materials can minimize levels of Ca, oxides, carbides, nitrides and the like found in the magnet. As we know today, three things are important in preventing corrosion of Nd-Fe-B magnets,

- Controlling the chemistry of the grain boundary in the magnet
- Preparing the surface for coating
- Applying the coating correctly

In other words, coating alone does not guarantee good corrosion resistance, as shown in Figures 2, 3 and 4. In extreme cases, the coating remains intact and undisturbed, while the magnet underneath completely disintegrates.

Figure 2. A sample with Ni-plating after 20 hours of a HAST at 130°C, 260 kPa and 95% humidity. Note that the plating has peeled away from the magnet.

Table I. Popular Coatings for Nd-Fe-B Magnets [2]

Coating	Thickness (μm)	Typical Applications
Al-Chromate	7 ~ 19	Motors & Sensors
Epoxy Resin Spray	40 ~ 80	VCM & MRI
Electrodeposition	20 ~ 30	VCM, Industrial
Nickel Plating	10 ~ 20	VCM, Motors & Sensors

Notes: VCM means voice coil motor in a disc drive
MRI means magnetic resonance imaging

Figure 3. A sample with an electrolytic zinc plating, as received from the manufacturer. It appears to be a good magnet.

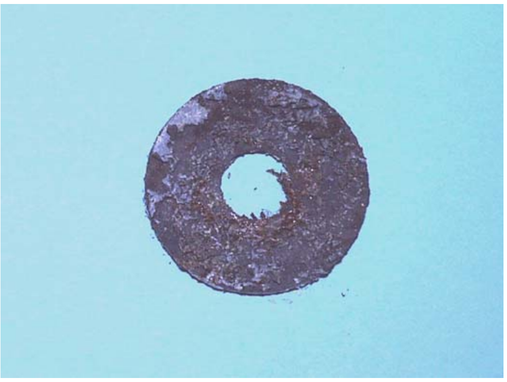

Figure 4. The same sample after 24 hours of a HAST at 130°C, 270 kPa and 100% humidity. The test demonstrates the plating was poorly applied.

Verification of corrosion control

The quality of a coating is usually tested by the magnet manufacturer. Characteristics such as coating thickness, porosity, and adhesion strength are checked as a way to verify the quality of the coating.

But for magnet users, performance is probably the better metric. The only true way to know the corrosion resistance of a magnet is to measure it in service, or in a similar environment. [3, 9] With several relevant tests available, a test, or a combination of tests, appropriate for the application should be selected. The popular tests are,

- HAST [9]
- Temperature and humidity
- Salt spray

HAST is an acronym for Highly Accelerated Stress Test, a combination of pressure, temperature and humidity, which evolved from the early use of pressure cookers and autoclaves to test Nd-Fe-B magnets for corrosion.

Testing is a final opportunity to identify any additional concerns, such as chemical compatibility among the various constituents, thermal expansion, thermal cycling or conductivity issues.

Caveat emptor

As Nd-Fe-B magnets have become more of a commodity item over the past few years, people have begun to think that Nd-Fe-B magnets are all essentially equivalent and that all suppliers are alike. From these assumptions, one might speculate that two Nd-Fe-B magnets with the same coating provide the same corrosion resistance. Be careful; this is not true!

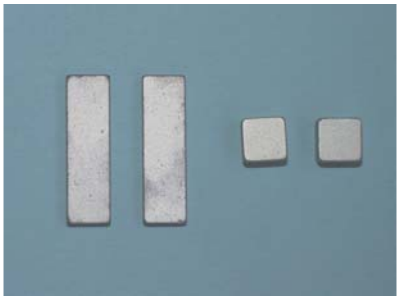

Figure 5. Samples with a spray coating after 12 days of a HAST at 130°C, 270 kPa and 100% humidity.

The manufacturer must control the microstructure of each magnet appropriately to control corrosion. Novices tend to make magnets with excess Nd, a serious mistake, inviting corrosion. Well-established manufacturers usually have better control of their process. Again, it is always best to confirm corrosion resistance by testing it thoroughly. Ideally, the magnets should fare as well as the ones shown in Figure 5.

Conclusion

To take full advantage of the extraordinary properties of Nd-Fe-B magnets and to avoid problems with corrosion, seek help from an experienced manufacturer early in the design cycle and test magnets to confirm their behavior in service.

Case studies

A few examples of the damage caused by corroded Nd-Fe-B magnets are given below:

Magnet: Axially oriented ring
Product: Hybrid Stepper motor
Function: X-Y table for a CNC machine
Failure: Table blockage
Root cause: The Ni plating just fell off the magnet and jammed the rotor inside the housing.

Magnet: Segment
Product: PM motor for elevator
Function: Hotel Elevator
Failure: The elevator stopped and could not be moved, even with a manual cranking device.
Root cause: A magnet came loose and damaged the elevator motor.

Magnet: Plated bread loaf magnet
Product: Magnet coupling
Function: Pump for hot, aggressive chemicals
Failure: Pump stopped
Root cause: Magnet corroded and disintegrated.

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