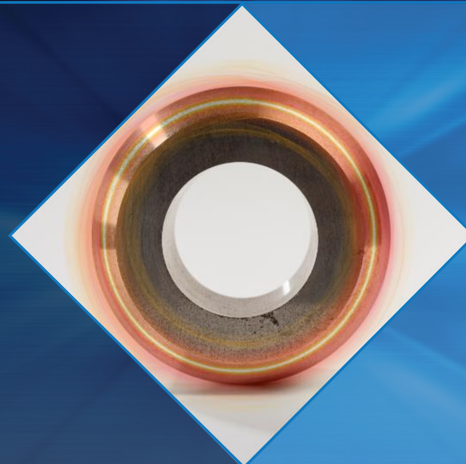
Magnetization Losses in Rare Earth Permanent Magnets



Abstract

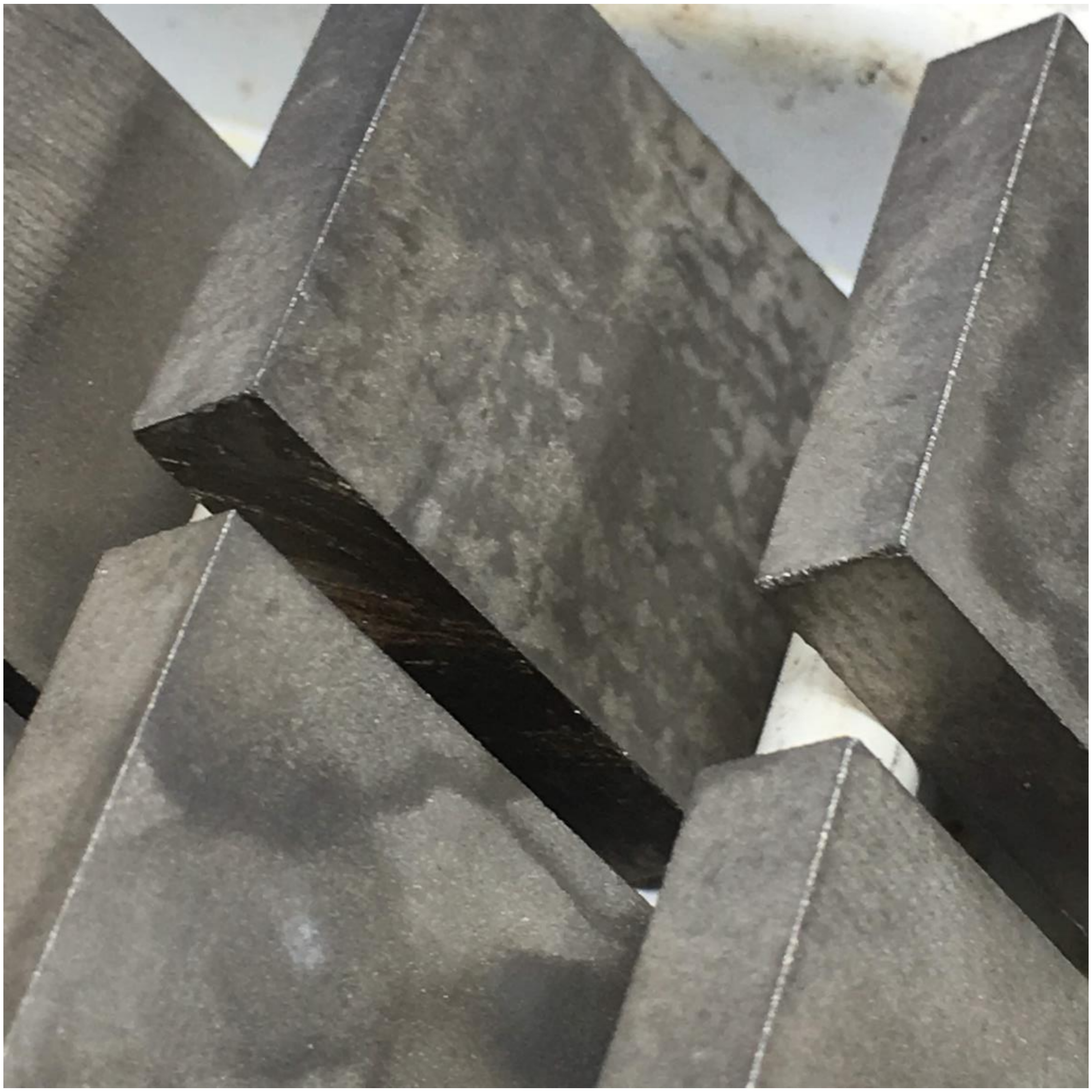
This paper describes the magnetization losses that are possible in SmCo and NdFeB permanent magnet materials. Reversible losses are first discussed followed by irreversible losses, which can be caused by temperature, external fields or radiation. Losses over time by magnetic viscosity are also discussed. Finally, permanent losses caused by corrosion, hydrogen, high temperatures and radiation are considered.

Gerhard Martinek, Sami Ruoho, Urs Wyss
Arnold Magnetic Technologies

ARNOLD®
MAGNETIC TECHNOLOGIES

Losses in Rare Earth Permanent Magnets

Contents



1 Introduction

When permanent magnets are used in any application, it is important to consider also the long-term behavior of the magnets. The choice of the magnet grade and design depends on the expected losses and required long-time stability. When magnets are used in too difficult magnetic environment, irreversible losses may occur. And if the magnet is used in challenging atmospheric conditions there might be a risk of permanent losses due to corrosion.

2 Reversible Losses

The reversible loss of a magnet is the change of the magnetization of a magnet with changing temperature, if the magnetization completely returns to the original magnetization after returning to the original temperature. The reversible loss can be characterized by the reversible temperature coefficient (RTC). In a closed circuit, a standard Sm_2Co_{17} magnet has between room temperature and 200°C a reversible temperature coefficient of about -350ppm/K (-194ppm/F). $SmCo_5$ has a RTC(Br) of about -450ppm/K and NdFeB has a RTC(Br) from 950 to 1250ppm/K. These values can change in an open circuit, especially for Sm_2Co_{17} magnets.

As can be seen in the following diagram the changes of the polarization with temperature are not perfectly linear but slightly parabolic.

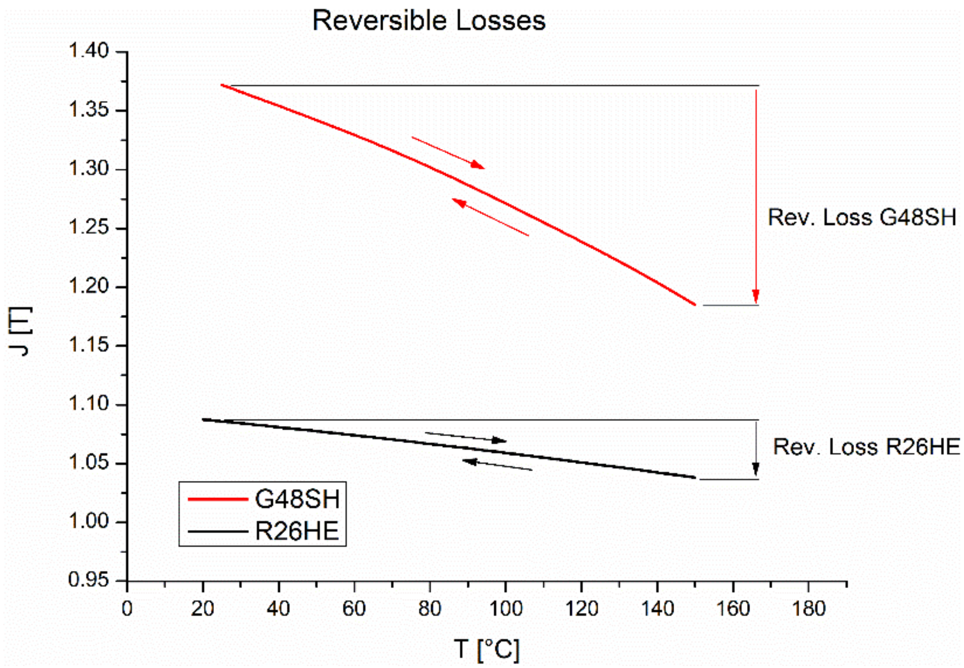


Figure 1. Reversible loss of a NdFeB and a Sm_2Co_{17} magnet.

3 Irreversible Losses

Irreversible losses in magnetization can happen due to several reasons, which are discussed in further subsections. They depend on the shape of the demagnetization curve, the load line of the application, and the temperature behavior of a magnet. Irreversible losses can be recovered by magnetizing the magnet again: In the context of permanent magnets, irreversible losses do not refer to changes in the material itself or in its microstructure. Only the state of magnetization is changed.

3.1 Demagnetization by Field

A permanent magnet causes into itself a self-demagnetizing field, which is opposite to the magnetization direction. The strength of the self-demagnetizing field depends on the magnet shape. A demagnetization factor *N* depending on the magnet shape can be defined. The demagnetization factor *N* is related to the permeance coefficient:
$P_c = 1 - \frac{1}{N}$.

When an external field H_{ext} is applied to a magnet, the resulting internal field in the magnet is comprised of the self-demagnetizing field at the magnets load line and the external field: $\mu_0 H_{int} = \mu_0 H_{ext} - N \cdot J(H)$. If the resulting internal field is too large, a magnet will lose a part of its magnetization.

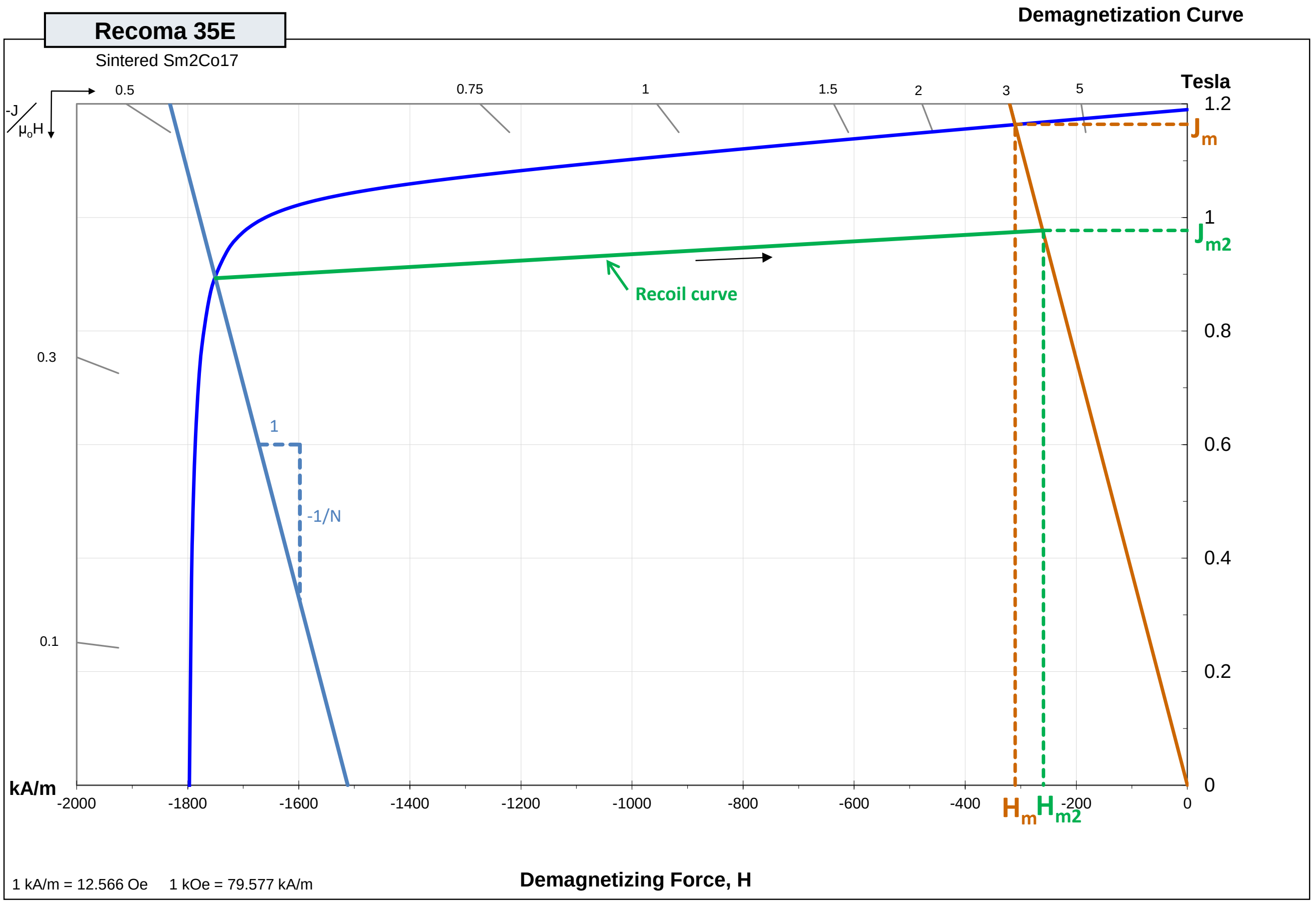


Figure 2. Irreversible loss $J_m - J_{m2}$ of a magnet with $P_c = 3$ after an applied external field of -1510 kA/m (-1.9 T)

3.2 Demagnetization by Temperature

Irreversible losses by temperature are caused by the shortening of the demagnetization curve with increasing temperature. The losses depend on the load line of the magnet as can be seen in Figure . The magnet with high load line (cyan in color) survives the temperature change, while magnet with lower load line (light green) suffers an irreversible loss.

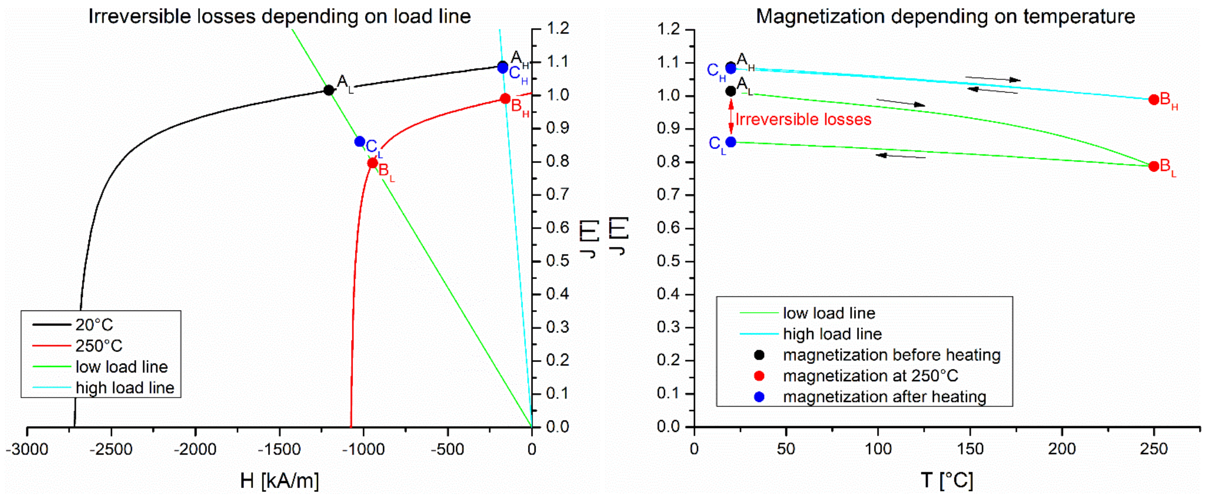


Figure 3. The points A_L and A_H describe the magnetizations at 20°C for magnets operating on two different load lines. B_L and B_H show the magnetizations at 250°C. After cooling to 20°C, the two magnets have the magnetizations C_L and C_H. While the magnet working on a high load line has almost the same magnetization as before, the magnet on a low load line now has a much lower magnetization. Irreversible losses have occurred.

3.3 Magnetic Viscosity

The irreversible losses, as introduced in the preceding sections, essentially happen instantaneously. After applying a demagnetizing field at a given temperature, the losses as expected from the demagnetization curve (fig. 3) occur within a time span too short to be observable in the usual hysteresis curve measurements. However, after the initial instantaneous drop, there is an additional contribution of losses “slowly” developing with time. This phenomenon is called magnetic viscosity, sometimes also referred to as “after-effect” or magnetic creep.

3.3.1 Basic description

The basic behavior is illustrated in figure 4:

- After applying a moderate field (point “A” in fig 4), the magnetization is very stable. Keeping the magnet at point “A”, no significant change will occur with time, even after many years.
- If the magnet is exposed to a stronger field, where substantial irreversible losses are imminent or have already occurred (point “B” in fig. 4), magnetization losses with time will occur. The rate of losses will be faster initially, followed by a continuous reduction in speed.
- If, at some point in time, the demagnetizing field is increased again, the magnetization does not react to the increasing field until the original curve is met (from “C” to “D” in fig. 4). Beyond point “D”, it follows the

original curve.

These observations suggest that the effect of time (waiting at a constant field, “B” to “C”) is very similar to applying a small additional demagnetizing field H_f (reading magnetization at “D” rather than “B” on the original curve).

Although the actual measurements of magnetic viscosity are difficult to perform and interpret, understanding the basic behavior allows deriving some simple general rules for avoiding/limiting magnetization losses:

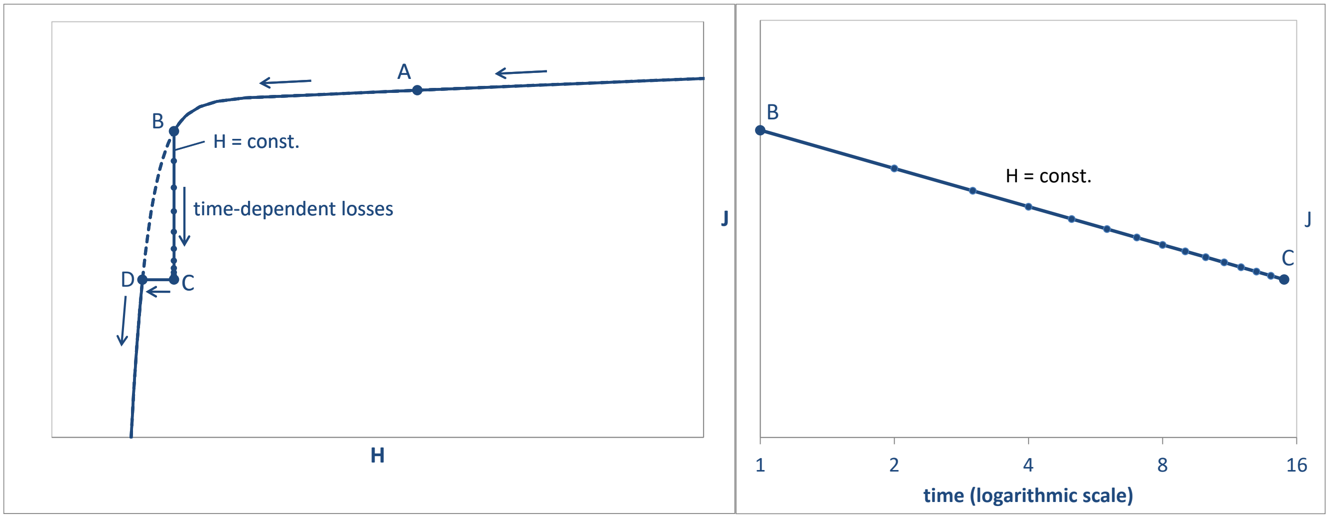


Figure 4. Idealized representation of magnetic viscosity.

3.3.2 Material selection

In order to avoid irreversible losses, the designers of a permanent magnet application generally need to determine the worst conditions in terms of temperature and demagnetizing field, which may occur in the magnets. They will then choose a material with sufficiently high intrinsic coercive field at the given temperature, making sure that the magnet’s working point (load line) remains in the straight part of the curve and does not approach the “knee”. This is the traditional procedure for avoiding irreversible losses according to sections 3.1 and 3.2. Accounting for magnetic viscosity just means adding an extra safety margin in terms of the demagnetizing field considered. Reviewing published results of viscosity measurements, viscosity losses over 10 years are found to be equivalent to an additional demagnetizing field of no more than +200 kA/m. In many cases, even less of a margin will be required, a more detailed analysis is presented below in 3.3.4.

3.3.3 Avoiding irreversible losses by aging

The rate of viscosity losses decreases dramatically with time, since the phenomenon is logarithmic in its nature. During the first 2 hours after applying a demagnetizing field at a given temperature, the losses will be the same as in the following 5 months under the same conditions. Aging the magnets in more challenging conditions than during the actual operation (higher temperature and/or stronger demagnetizing field) will guarantee stability over their lifetime.

3.3.4 Detailed analysis

The equivalence of time losses with applying a small field H_f, as introduced in 3.3 / fig. 4, is a very useful concept: If H_f is known, the viscosity losses can simply be estimated from the static demagnetization curve. Fortunately, H_f does not change dramatically with temperature or applied field. And the dependence of H_f on time follows a well-established curve: H_f grows with the logarithm of time,

$$H_f = S_v \ln(\frac{t}{t_0})$$

S_v is typically found to be about 2…10 kA/m in rare earth magnets, over the technically interesting range of temperatures and demagnetizing fields. This relation allows predicting the magnetization loss during a time interval between a first observation at t_0 and a later time t. Published demagnetization curves are usually measured over time intervals of many seconds (hysteresisgraphs) or minutes (vibrating sample magnetometers). The "initial" readings of the magnetization are thus taken at $t_0 \approx 1\ s$.
If the application time is assumed as 10 years (≈ 3.15x 10^8 s),

$H_f = S_v \cdot 19.6$, or ≈ 39…196 kA/m.

These values will dramatically overestimate the losses in most cases, as they refer to a constant exposure to the given temperature and field. However, the demagnetization curves will be analyzed for "worst-case" conditions, which will usually be present for much shorter periods. Most of their lifetime, the magnets are subjected to substantially lower temperature or field, where losses are negligible. If only the time t spent at or near the worst-case conditions is considered, H_f is usually well below 100 kA/m.

3.4 Irreversible losses by Radiation

Numerous experiments have been performed about magnetization losses under ionizing radiation. Unfortunately, there are many parameters (type of radiation, energy, dose, dose rate, magnet material, temperature, demagnetizing fields…) affecting the losses. Each (not exactly simple and inexpensive) experiment will only consider just one instance (or an extremely limited range) of these parameters. Therefore, a comprehensive list of losses for different radiation types and conditions does not exist.

For perfect safety, each application case will ultimately need testing in the actual working environment and conditions. However, some general trends and observations can help to design the application in a way to start these final tests with a certain confidence: Radiation losses are similar to losses induced by temperature, practically meaning that more temperature resistant materials are more radiation resistant, and SmCo is considerably more stable than NdFeB. High H_{cJ} grades of NdFeB are more stable than those with lower H_{cJ}. Magnets working near the limit in terms of temperature and field are much more susceptible to additional radiation losses.

4 Permanent Losses

Unlike irreversible losses, permanent losses are not recoverable by magnetizing the material again. Permanent losses are caused by chemical changes, changes in microstructure or loss of material by corrosion.

4.1 Corrosion

Corrosion causes permanent losses by both changing the material chemically and causing material to detach from the base material. Since the diffusion reactions are much higher in polymer bonded magnets, they are most susceptible to corrosion, but also SmCo and NdFeB magnet are as rare earth magnets affected by corrosion.

4.1.1 SmCo High Temperature Corrosion

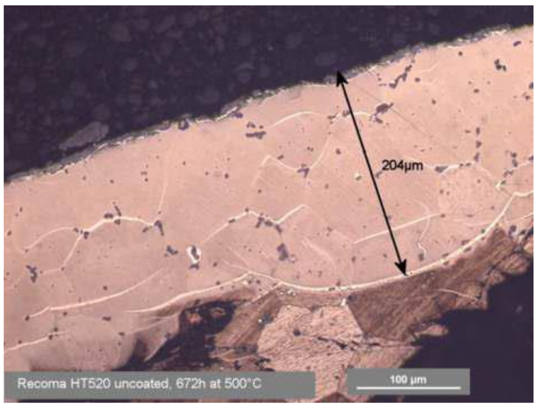


Figure 5. Corrosion after 672h at 500°C

While SmCo is quite stable at normal ambient conditions, it has to be protected at temperatures above 400°C. Depending on the oxidation conditions external Sm-oxide-layers or internal Sm-oxides were reported. In both cases the microstructure of the outermost regions is disturbed and the coercivity is strongly reduced.

4.1.2 NdFeB Corrosion

There are two significant corrosion mechanisms of sintered NdFeB magnets called white corrosion and red corrosion.

The white corrosion takes place in Nd-rich grain boundaries, and it used to be a more serious problem in the earlier days of NdFeB magnets, when the grain boundaries and the microstructure were not so well optimized. In white corrosion, Nd-oxides react with atmospheric moisture and form Nd-hydroxides, which require more volume. This process causes grains of $Nd_2Fe_{14}B$ and $Nd(OH)_3$ particles to get loose of the material, forming a layer of white powder on the magnet.

Roughly two thirds of the weight of NdFeB magnet material is iron. If the magnet gets wet, the iron forms rust (or iron hydroxides) on the surface.

4.1.3 Hydrogen

All rare earth magnets are susceptible to the influence of hydrogen. They can absorb significant amounts of hydrogen and can form rare earth hydrides, which can lead in the worst case to a complete disintegration of the magnet. Generally, it can be said, that NdFeB magnets are much more vulnerable than SmCo magnets. While NdFeB crumbles to powder already at room temperature and low hydrogen partial pressures, SmCo magnets are usually stable at room temperature and 1 bar hydrogen. But since the formation of hydrides is often only kinetically hindered, it's necessary to look at the individual case.

4.1.4 Vibration

Vibrations or deformation are not relevant for the rare earth magnets. Obviously, the brittle rare earth magnets can break with excessive mechanical stresses, which of course causes a similar effect as corrosion: particles detach from the base material.

4.2 Metallurgical Changes

Like most industrial alloys, rare earth magnets are in a metastable state. This means that long-time exposure at higher temperatures can lead to changes of the microstructure even if the magnets are protected from corrosion. Since the usual operation temperature of NdFeB magnets is relatively low, a significant change of the microstructure, except corrosion, is not expected.

SmCo magnets are often used at higher temperatures. Long-time exposure to high temperatures can lead to noticeable diffusion reactions. For example, a slight reduction of the coercivity of Sm_2Co_{17} magnets after an exposure above 400°C may happen. The last heat treatment step typically leaves the magnets in a state of thermodynamic equilibrium at 400°C, where the copper atoms collect in favorable locations in the $SmCo_5$ cell boundaries. After an exposure above 400°C the distribution of the copper changes slightly, creating another stable state with a slightly lower coercivity. A subsequent heat treatment at 400°C appears to restore the former coercivity completely.

Other metallurgical changes like grain growth or dysprosium diffusion in grain boundary diffusion material are conceivable at very long-time exposure, but have not been reported yet.

4.3 Permanent losses by Radiation

The experiments with ionizing gamma, electron or proton radiation, so far, have not been found to cause permanent structural damage. The magnets could be remagnetized to the original values after exposure. However, there are cases where permanent radiation damage can plausibly be expected. In the majority of cases studied, the radiation interacts with the electrons (ionizing radiation). These changes are likely to be of temporary nature, as missing or excited electrons will be replaced and return to their original state within short times. In contrast, if interaction occurs with the nuclei, these can be permanently displaced, or transformed into other elements by nuclear reactions. Permanent losses were actually observed in the case of irradiation with argon ions.

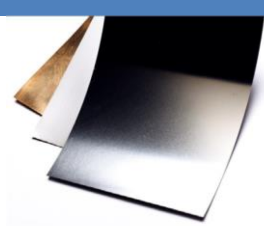
Finally, it is a well-known fact that thermal neutrons interact with cobalt nuclei. This reaction results in a radioactive cobalt isotope. While this may not cause permanent magnetization loss, “activating” the magnet is certainly undesirable in most cases. Avoiding SmCo or Alnico magnets is an obvious recommendation in these situations. However, Cobalt is usually present in NdFeB magnets as well, but in much smaller concentrations.

ARNOLD®
MAGNETIC TECHNOLOGIES
ENGINEERING SOLUTIONS TOGETHER

LEARN MORE ABOUT ARNOLD MAGNETIC TECHNOLOGIES

PRODUCTS


Permanent Magnets


Precision Thin Metals


Flexible Composites


Electromagnetics


Electric Motors

LOCATIONS

Rochester, NY	Greenville, OH	Sheffield, UK	Ogallala, NE	Marietta, OH
Madison, WI	Lupfig, CH	Shenzhen, CN	Marengo, IL	Norfolk, NE