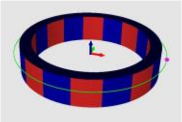

C: Working Point, Load Lines, Temperature and Stability

As stated in Part B in most cases the working points of a permanent magnet are located on the demagnetization curve. A working point is defined as a (B,H)-pair, which is related to the current magnetization of the magnet by eq. (A.7) or (A.8). When we have a magnet with internal field to be described or approximated by a demagnetization factor N as shown in part B, it follows together with eq. (A.7) and (B.8) that we have a constant B/H-relation, the so called load line, independent from the magnetic material, i.e.:

$$\frac{B}{-\mu_0 \cdot H} = \frac{1-N}{N} = \cot\beta \qquad \text{(C.1)}$$

When we use the H field in units $-\mu_0 H$, an angle ß like in (C.1) defines the steepness of this load line, which is different for different N, like e.g. the curves ending at locations A1 and B1. Having an increased demagnetization factor means that the load lines tends to have a larger angle ß, e.g. the load line with B1 instead of A1. The point where the load line meets the demagnetization curve provides the working point of the respective magnet. The relation $B/(\mu_0 H)$ in eq. (C1) is often called permeance coefficient.

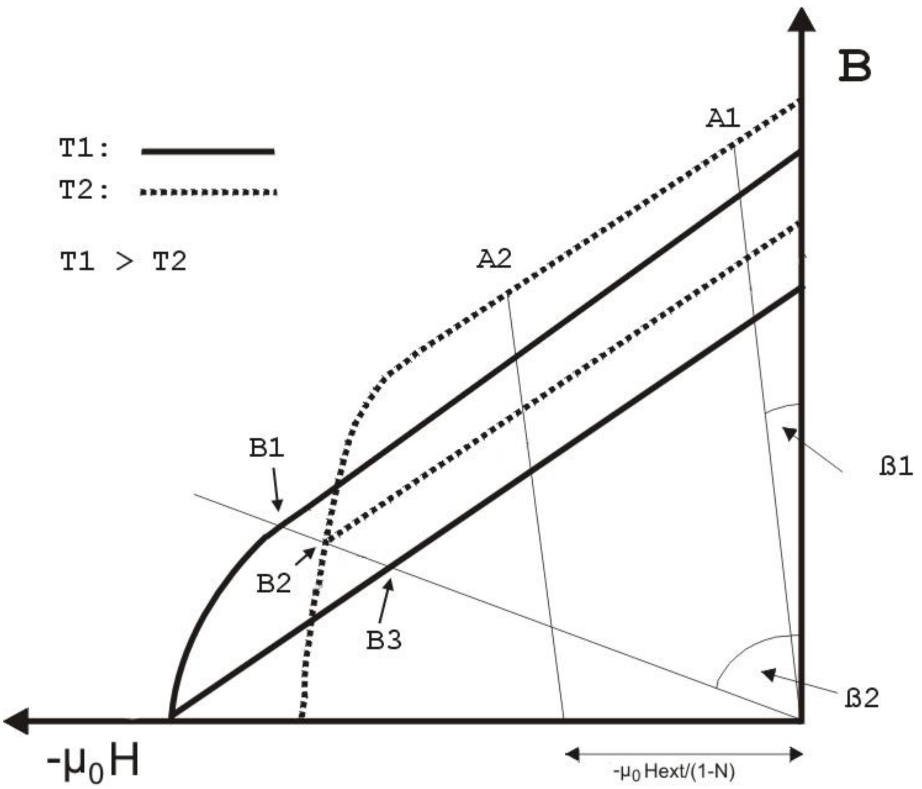

Fig. C1: Demagnetization curves with working points and load lines under different temperatures and external fields.

If in addition to the internal field H_i an external field H_{ext} is applied, instead of $H=H_i$ we now have $H= H_i + H_{ext}$ and the B/H ratio modifies to:

$$B = -\mu_0 H \cdot \frac{1-N}{N} + \mu_0 \frac{H_{ext}}{N} \qquad (C.2)$$

This means that the load line moves by an amount $\mu_0 H_{ext}/(1-N)$ along the horizontal axis as can be seen when setting B=0 in eq. (C2) and solving for H. When the internal field in a magnet can not be approximated by a single demagnetization factor, we can think of a bunch of load lines, which belong to the different demagnetizing fields at different spatial locations.

Up to now we treated magnetic hysteresis at one single temperature, e.g. at In the 20°C. When temperature changes generally the shape of hysteresis changes. Near room temperature the change of B_r and ${}_jH_c$ can be described by temperature coefficients, since the T dependence is nearly linear here for most cases. Generally the temperature coefficient of B_r is negative for all materials, which means that Br decreases when temperature increases. The coefficient of coercivity depends on the specific material. It is positive for Ferrites and some Alnico alloys, whereas being negative for the other common materials. The exact definition of both coefficients is given by the equations:

$$B_r(T) = B_r(20°C) \cdot (1 + T_{kBr} \cdot (T - 20°C)) \qquad (C.3a)$$

$$_jH_c(T) = {}_jH_c(20°C) \cdot (1 + T_{kjHc} \cdot (T - 20°C)) \qquad (C.3b)$$

In the following it should be explained what happens with different working points on a demagnetization curve when temperature changes. This will be done here for the case of a material which behaves like a Ferrite or Alnico. The behavior of other materials follows analogously.

Let's start with temperature T1 and let's imagine a magnet geometry which belongs to the load line with angle ß1 in Fig. C1. This means the working point is located on the upper solid demagnetization curve. When now temperature cools down the working point raises up to point A1, i.e. to the dashed demagnetization curve, which provides a larger B value. When we raise temperature again to the original state we move down on the load line again to the point where we have started at the beginning. So there is no net change of B after this temperature cycle. The behavior of the system is called reversible. Reversible changes always happen, when the load lines only touch the straight area of the demagnetization curves.

The situation is completely different when the steep area of the demagnetization curve is touched. Imagine a working point B1 at temperature T1. When we now cool down to T2, the respective working point that belongs to our load line moves to point B2 on the dashed demagnetizing curve, with a decrease of B. But when we raise up temperature to the original value T1, something odd happens. Instead of moving back to B1 the working point now settles down to B3. Since at B2 the working point has touched the steep part of the demagnetization curve, the working point is now bound to an inner branch of magnetic hysteresis. To be bound to that branch the working point now has to follow the temperature change of the inner curve and not that of the external curve. This results in a second decrease of B. The behavior of the system is called irreversible in this case, as the original state of the cycle is not met again.

Reversible and irreversible changes do not only occur when changes of temperature happen, but also when varying external fields are applied. I.e. when there is a change from load line A1 to A2 no steep part of any demagnetization curve is touched. When H_{ext} is released the working point again returns to the originalstate. But if H_{ext} were big enough to reach the steep part of the solid curve this also would mean an irreversible decrease of B after the final release of H_{ext}

Beside irreversible losses due to a transfer to an inner branch of hysteresis, additional losses by chemical changes inside the magnetic material can happen also. An irreversible magnetic loss as discussed above can be removed principally by a remagnetization process. But a chemical loss e.g. by oxidation or disintegration processes cannot be recovered. In this case even a remagnetization procedure does not restore the initial conditions.

Another effect which leads to a decrease of magnetic strength is the so called magnetic aftereffect or magnetic viscosity. When an operating point is located at the irreversible part of demagnetization curve, there can be a time dependent decrease of magnetization even if the field strength H is kept constant. The process often is described by a logarithmic function according to

$$\Delta M = -S \cdot \ln\left(\frac{t - t_0}{t_0}\right) \qquad \text{(C4)}$$

S is the magnetic viscosity and t_0 the starting time of observation. S is defined by

$$S = H_f \cdot \chi_{irr} \qquad \text{(C5)}$$

The fluctuation field strength H_f is a temperature and material dependent parameter. χ_{irr} is the irreversible part of susceptibility at the operating point. According to the specific material and especially at large temperatures the magnetic aftereffect can be of the same quantity as the above mentioned phenomena and is subject of a lot of publications these days. Pictorially it can be connected to an instability of magnetic structures. Thermal energy and its fluctuations lead these unstable structures to change so that M is declining with time.