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 tend to a higher angle ß. The point where the load line meets the demagnetization curve, e.g. in point A1 of fig. C1, reveals the working point of the respective magnet.

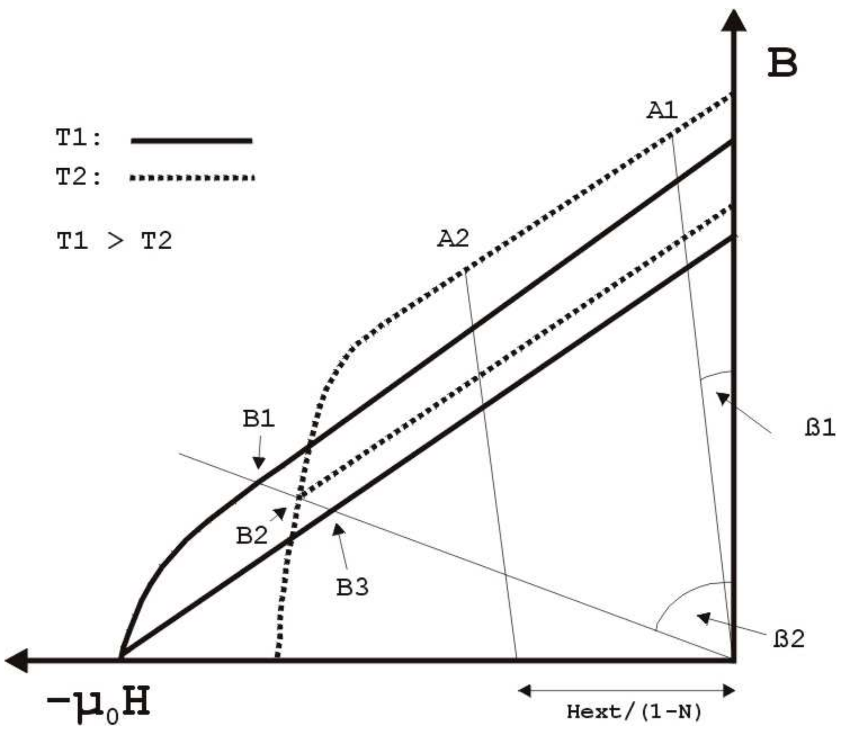

Fig. C1: Demagnetization curves with working points and load lines under different temperatures and external fields.

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:

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

This means that the load line moves by an amount $H_{ext}/(1-N)$ along the horizontal axis. When the internal field in a magnet can not be approximated by a single demagnetization factor, we can imagine a whole bunch of load lines, belonging to the different demagnetizing fields at different spatial locations.

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

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

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

In the following it should be explained what happens with different working points on a demagnetisation curve when temperature changes. This will be done for the case of Ferrites or Alnico, the behavior of the other materials follows analogously:

Lets start with temperature T1 and lets imagine a magnet geometry coupled to the load line with angle ß1 in Fig. C1. This means the working point is located on the solid outer demagnetization curve, where it is crossed by the load line which ends in A1. When now temperature cools down the working point raises up to this point A1, i.e. to the dashed outer demagnetization curve, which delivers a higher B. When we again raise up temperature to the original state we again move down on the load line to the preliminary 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 again cool down to T2, the respective working point belonging to our load line moves to point B2 on the dashed line, now with a decrease of B. But when we raise up temperature to the original value T1 again, something strange happens. Instead of moving back to B1 the working point now settles down to B3. Since at B2 the working point had touched the steep part of the demagnetization curve, the working point is now fixed to an inner branch of magnetic hysteresis. Being fixed to this branch the working point now has to follow the temperature change of the inner curve and not that one of the external curve, resulting in a second decrease of B. The behavior of the system is called irreversible in this case, for the original state of the cycle was not met again.

Reversible and irreversible changes not only occur under changes of temperature but also when changes of external fields happen. I.e. when there is a change from load line A1 to A2 no steep part of any demagnetization curve is touched. When Hext is released the working point again returns to the preliminary state. But if Hext 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 Hext .

Beside the described changes of B and probable irreversible magnetic losses, additional losses by chemical changes of the internal structure can happen. Whereas an irreversible magnetic loss in B as described above can be removed principally by a remagnetization process, a chemical loss is originated e.g. by an oxidation process. 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 on the irreversible part of the 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

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

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

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

with the fluctuation field strength H_f , which is a temperature and material dependent parameter. χ_{irr} is the irreversible part of susceptibility at the operating point. According to material and temperature 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.