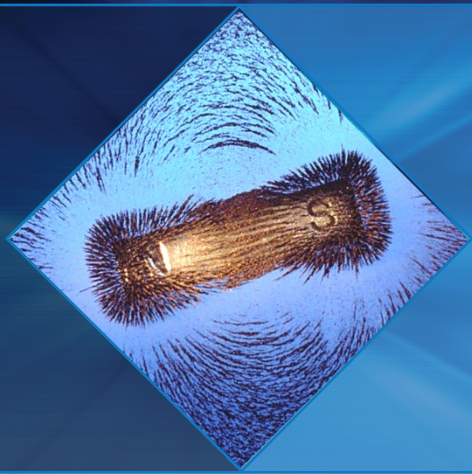
Magnetic Properties of Permanent Magnets & Measuring Techniques



Abstract

This White Paper describes the characteristics of permanent magnet materials and the properties of individual permanent magnets. The second part of this document deals with the mostcommon measuring techniques used by the magnet industry.

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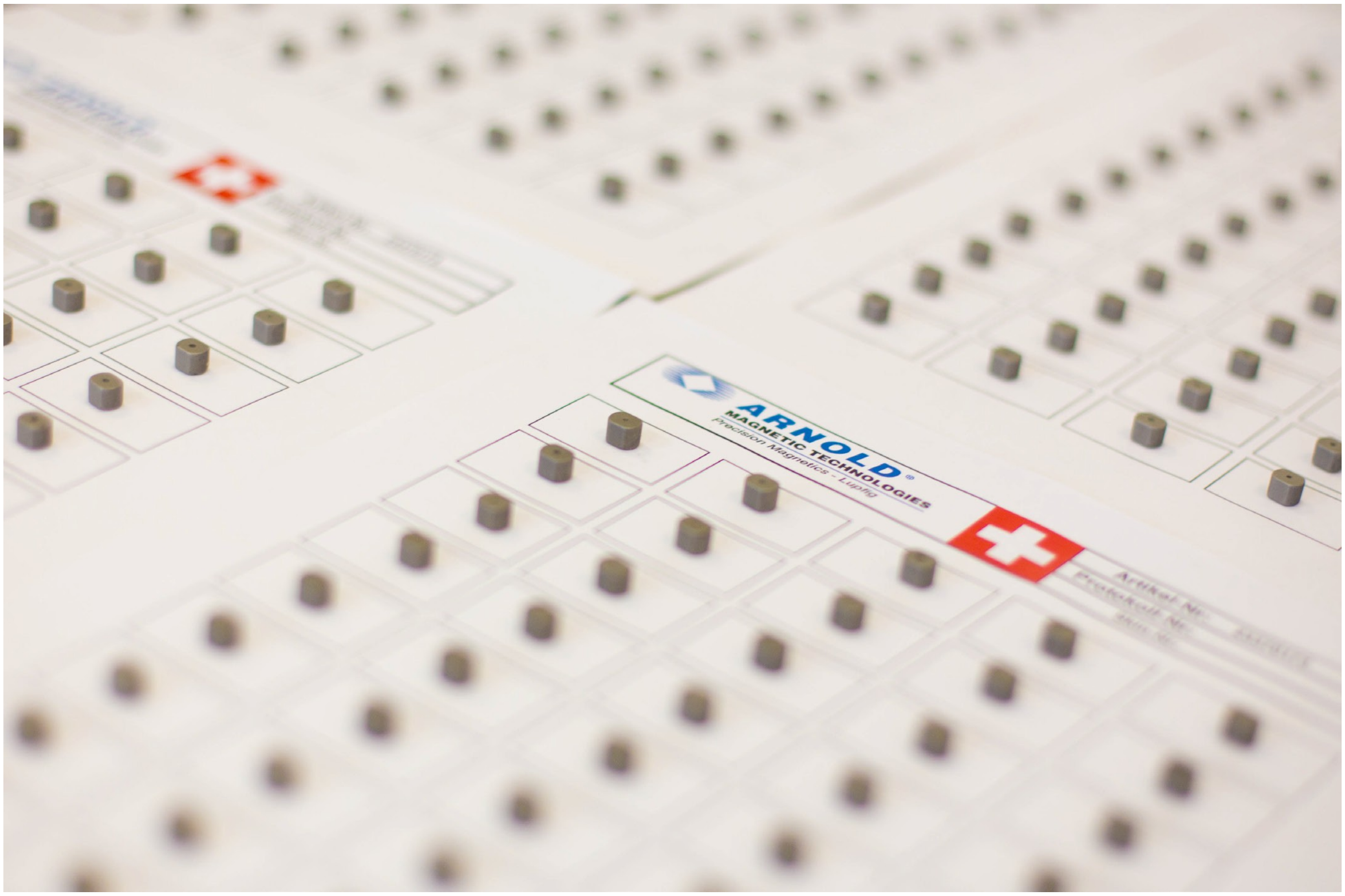


1 Permanent Magnet Properties

This chapter represents the basic properties of permanent magnets. Subchapter 1.1 discusses the properties of the materials, which do not depend on the magnet shape, while subchapter 1.2 discusses the properties of a magnet piece, which are dependent both on material, and shape and size of the magnet.

1.1 Material properties

The properties of hard magnetic materials are typically described by showing the second quadrant of the saturated material hysteresis curve. Figure 1 shows a typical curve. There are several quantities that can be read from this kind of curve. These key figures are described below.

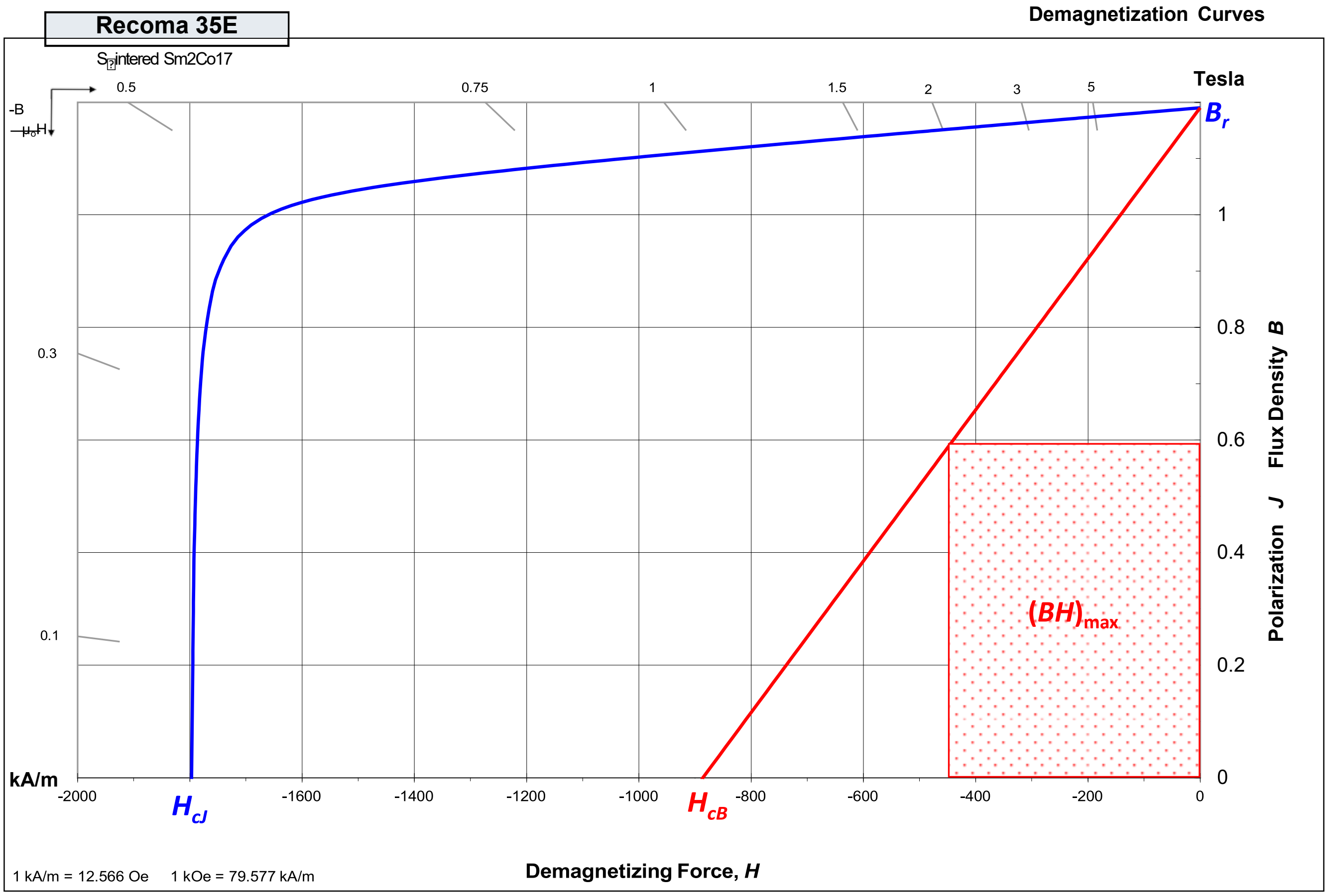


Figure 1. A typical 2nd quadrant hysteresis curve of a high performance Sm_2Co_{17} material at room temperature showing remanence B_r, intrinsic coercivity H_{cJ}, normal coercivity H_{cB} and maximum energy product $(BH)_{max}$.

1.1.1 Remanence B_r

Remanence is the magnetic polarization J_r that remains in the material because of hysteresis after the material has been fully saturated. Remanence is the intersection point of the hysteresis curve and vertical axis (*B*-, or *J*-axis).The unit of remanence is Tesla (T) or Gauss (G).

1.1.2 Energy Product $(BH)_{max}$

$(BH)_{max}$ is the maximum energy that a magnetic material can supply to an external magnetic circuit. For linear materials $(BH)_{max}$ is a function of B_r as follows:

$$(BH)_{max} = B_r^2 / (4 \mu_0 \mu_r)$$

In BH-diagram the point of $(BH)_{max}$ is represented by the maximum rectangular area that can be drawn under a corresponding BH-curve. The unit of $(BH)_{max}$ is kJ/m^3 or MGOe.

1.1.3 Coercivity H_{cB}

Coercivity, or normal coercivity or coercive field strength is the magnetic field value opposing the magnetization direction that is strong enough to reduce the flux density through the magnet to zero. Coercivity is the intersection point of B-curve and the horizontal H-axis. The unit of magnetic field and thus the unit of coercivity is A/m or Oersted (Oe).

1.1.4 Intrinsic coercivity H_{cJ}

Intrinsic coercivity represents the ability of a magnetic material to resist demagnetization. It is defined as the magnetic field strength which is strong enough to reduce the magnetic polarization J to zero. Intrinsic coercivity is the intersection point of J-curve and the horizontal H-axis. The unit of intrinsic coercivity is A/m or Oersted (Oe).

1.1.5 Squareness factors H_k and H_{D5}

A perfect theoretical hysteresis curve showing magnetic polarization J as a function of opposing magnetic field H would have a sharp angle in its upper left corner. In reality, the curve is always round in its upper left corner. This shape is called “roundness” or “squareness” of the curve and it can be described with the parameters H_k and H_{D5}. If the magnet is used in this round area, it will suffer irreversible losses in magnetic polarization.

The demagnetization curves in rare earth magnets typically start at H = 0 A/m as straight lines with a small slope initially. This small and gradual decrease of magnetization is assumed to be essentially reversible. When the field approaches H_{cJ}, the curves start to decline more rapidly. This drop indicates the onset of severe irreversible losses, and both H_k and H_{D5} give a suitable indication for the field value where a significant drop occurs. H_k and H_{D5} are defined in terms of the polarization curves $J(H)$:

- H_k is sometimes called the “knee field”. It is defined as the field where the polarization J has dropped to 90 % of B_r. In magnets with very high coercivity, it may happen that 90 % of B_r is reached while the curves are still perfectly straight. In these cases, H_k obviously fails to correctly indicate the drop in the curves.

- H_{D5} takes into account the (reversible) slope of the demagnetization curve and thus avoids the problem of H_k in magnets with very high H_{cJ}. A straight line is drawn in parallel to the demagnetization curve, extending from a point at 95 % of B_r towards the curve. The intersection with the curve is H_{D5}.

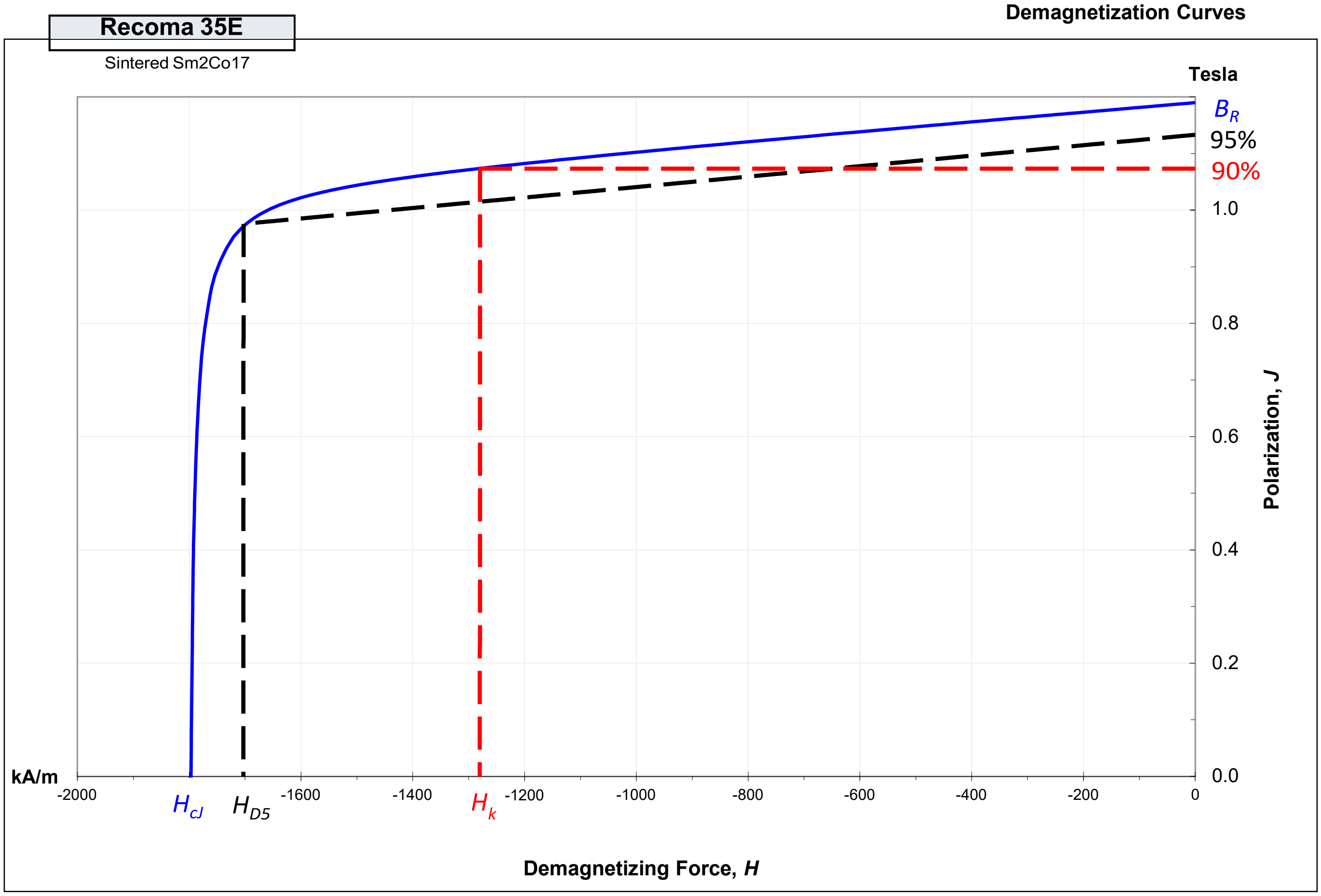


Figure 2. Definition of H_k and H_{D5}. The slope of the black line is set according to the slope of the blue curve between *H*-values -20 % H_{cJ} ... -70 % H_{cJ}.

1.1.6 Permeability

The general expression for the magnetic fields interacting with magnetic material

$$B = \mu_0 H + J,\ \text{or}\ \ B = \mu_0 (H + M)$$

is sometimes replaced by the linear relation

$$B = \mu H.$$

The permeability μ is often separated into two terms as

$$B = \mu_0 \mu_r H,$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ Vs/Am is the permeability of free space, and the dimensionless factor μ_r is called *relative permeability*.[1]

[1] In cgs units, the permeability of free space is equal to 1 "G/Oe". The permeability μ in cgs thus has the same value as μ_r in SI.

The permeability defined as $B = \mu H$ is useful for magnetization curves, which pass through the origin, showing zero coercivity and remanence. It applies to paramagnetic, diamagnetic and, as an approximation, to soft-magnetic materials.

For permanent magnets with approximately straight demagnetization curves, it is common to represent the 2nd quadrant demagnetization curve as a straight line connecting the points of the curve given by H_{cB} and B_r:

$$B(H) = B_r + \mu H, \qquad with\ \mu = \frac{B_r}{H_C}\ or\ \mu_r = \frac{B_r}{\mu_0 H_C}$$

In this case, the quantities μ and μ_r refer to the *differential permeability* $\mu = \Delta B/\Delta H$, rather than the permeability $\mu = B/H$, which is commonly used with soft-magnetic materials.

In sintered rare earth magnets with sufficient coercivity, the values for the relative permeability according to this definition are usually in the range of $\mu_r = 1 \ldots 1.1$.

1.1.7 Recoil Permeability μ_{rec}

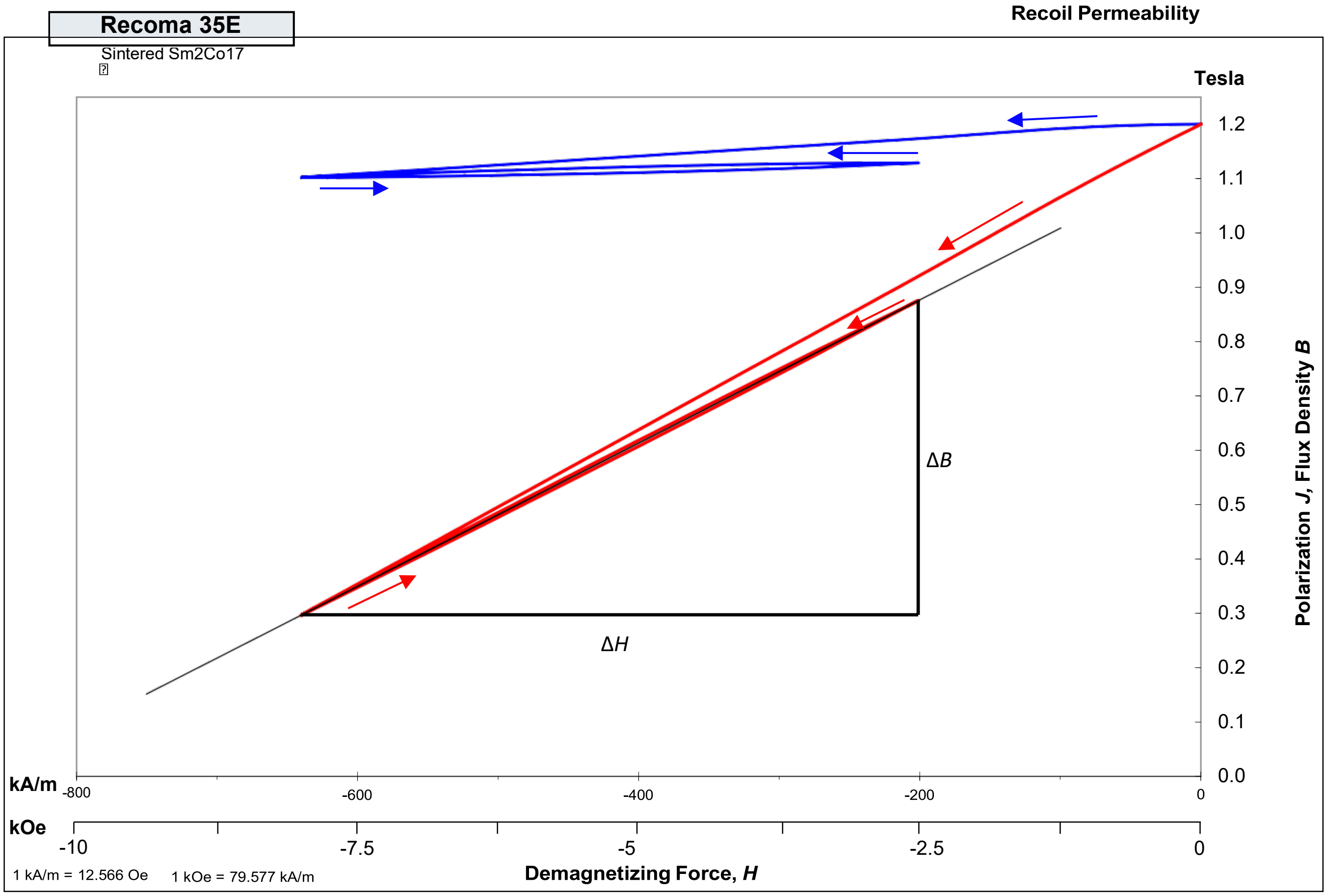


Figure 3. Recoil loop and recoil permeability μ_{rec} of a high remanence Sm_2Co_{17} magnet between *H*=-640 kA/m and *H*=-200 kA/m.

The recoil permeability μ_{rec} is often used for the designing of permanent magnet applications. The recoil permeability is defined by the mean slope of the recoil loop $\Delta B/\Delta H$. Since the shape of the recoil loop depends slightly on the start and end point of the loop the value of the recoil permeability depends on the measuring conditions.

Although the recoil permeability μ_{rec} and the relative permeability μ_r are very similar for sintered rare earth permanent magnets it is always given that $\mu_{rec} < \mu_r$

1.1.8 Temperature coefficients of magnetic properties

All magnetic properties are temperature dependent. In the Rare Earth magnets both remanence and intrinsic coercivity drop with increasing temperature. The drop is reversible until a certain point, above which the magnet starts to demagnetize.

Usually, linear temperature coefficients are given, although the temperature dependence is not linear over a wide temperature range. The temperature dependence of B_r is often called alpha α and the temperature coefficient of H_{cJ} is often called beta β.

For a temperature interval $T_0 \dots T$, the temperature coefficient for B_r is usually defined as

$$\alpha(B_r) = \frac{B_r(T) - B_r(T_0)}{B_r(T_0) \cdot (T - T_0)}$$

T_0 is usually defined as 20 °C. This is a linear approximation over a defined temperature range.

The temperature coefficient of a non-linear behavior can also be defined in a different way. The example above shows the definition between the two end-points of the range. It can be also set to minimize the average error over the range.

Note: temperature coefficient is not given to normal coercivity H_{cB}, which has similar, but not the same temperature dependence as remanence.

1.2 Properties of individual magnets

The properties of an individual magnet piece depend both on the properties of the material and also on the shape and size of the magnet piece.

1.2.1 Working point and permeance coefficient

Magnetic permeance describes how well the surroundings of a magnet is capable to carry magnetic flux. A very useful quantity related to permeance is the permeance coefficient

$$P_c = -\frac{B_m}{\mu_0 H_m}$$

where B_m and H_m refer to the flux density and the magnetic field in the magnet.

P_c is determined solely by the shape of the magnet and of the magnetic circuit surrounding it, independent of the size. If a magnet is in a fully closed circuit, its permeance coefficient is infinite. If the magnet is in a circuit with an air gap, the permeance coefficient will drop when the air gap is increasing. If the magnet piece is alone in the air, its permeance coefficient is related to the demagnetizing factor *N*

$$P_c = 1 - \frac{1}{N}$$

Once the value of P_c or *N* is known for a given magnetic circuit or magnet shape, it can be used in conjunction with the demagnetization curve to determine the "working point" of the magnet, as illustrated in Figure 4. A line with a slope equal to -P_c through the origin is called a working line or load line. Figures for the permeance coefficient are often shown on the top and left edges of the diagrams, facilitating the drawing of the working line. The intersection point of the working line and the BH-curve is the working point (H_m, B_m). It expresses the flux density inside the magnet B_m, and the demagnetizing field H_m the magnet is experiencing. Once the demagnetizing field H_m is determined, the magnetic polarization of the magnet J_m in that working point can be read from the *JH*-curve.

Note that, in most practical situations, the magnetic polarization in a working point is lower than the remanence B_r of the magnet. Also, the flux density through the magnet B_m is usually significantly smaller than the remanence B_r.

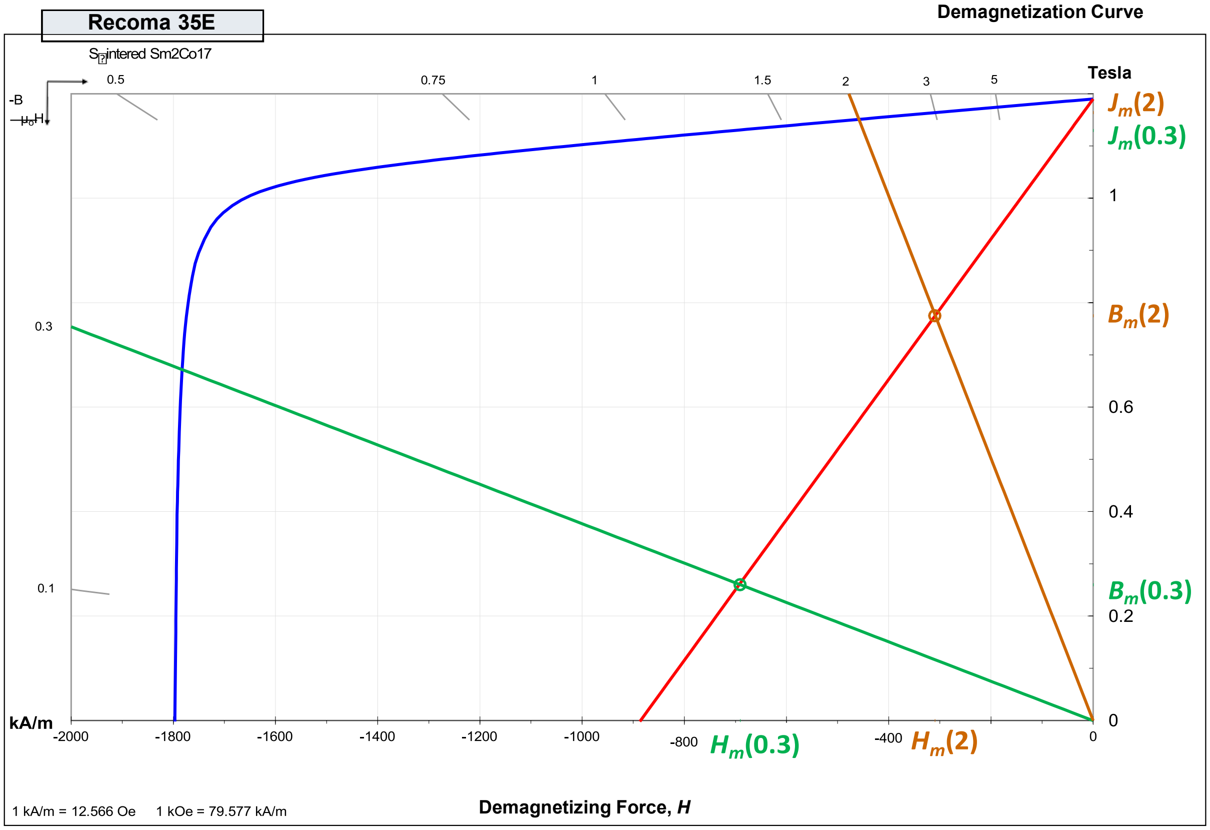


Figure 4. A hysteresis curve showing also two working lines (for permeance coefficient values of 2 and 0.3), and the values (H_m, B_m, J_m) in the working points (shown by circles) of the magnet.

1.2.2 Magnetic moment

The magnetic moment *m* is the product of magnet volume *V* and the magnetic polarization *J* of the magnet:

$$m = J \cdot V.$$

According to this definition, the unit of the magnetic moment is T·m^3 = V·s·m = Wb·m. There is an alternative definition of the magnetic moment: $m = M \cdot V$, where *M* is the average magnetization. Depending on whether *J* or *M* is used, the magnetic moment m will be given in Wb·m or A·m², respectively. Conversion from A·m² to Wb·m is achieved by multiplying with μ_0, as in

$$J = \mu_0 M.$$

The magnetic polarization *J* is dependent on the material properties, but also on the magnet piece shape. This means that magnetic moment *m* depends on material properties, shape and size (volume).

If a magnet with a magnetic moment *m* is put into a homogenous magnetic field *H*, the magnet experiences a torque *T*:

$$\vec{T} = \vec{m} \times \vec{H}.$$

1.2.3 Magnetization direction

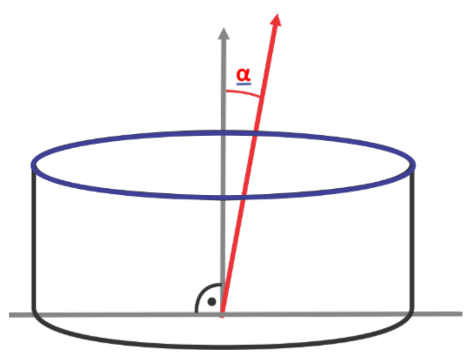


Figure 5. The difference between the magnetization direction and the geometric axis of a magnet.

The geometric and the magnetization direction can deviate from each other in a real magnet. The angle between the geometric axis and the magnetization direction is called angular deviation. The angular deviation depends strongly on the chosen process routes. With near net shape pressing angular deviations < 1° are possible. With certain process routes, angular deviations > 15° are possible.

1.2.4 Field distribution and pole strength difference

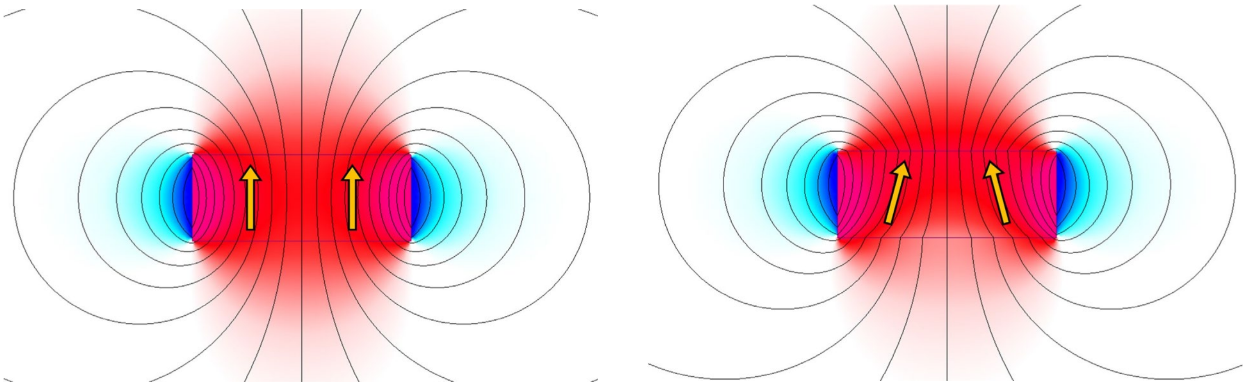
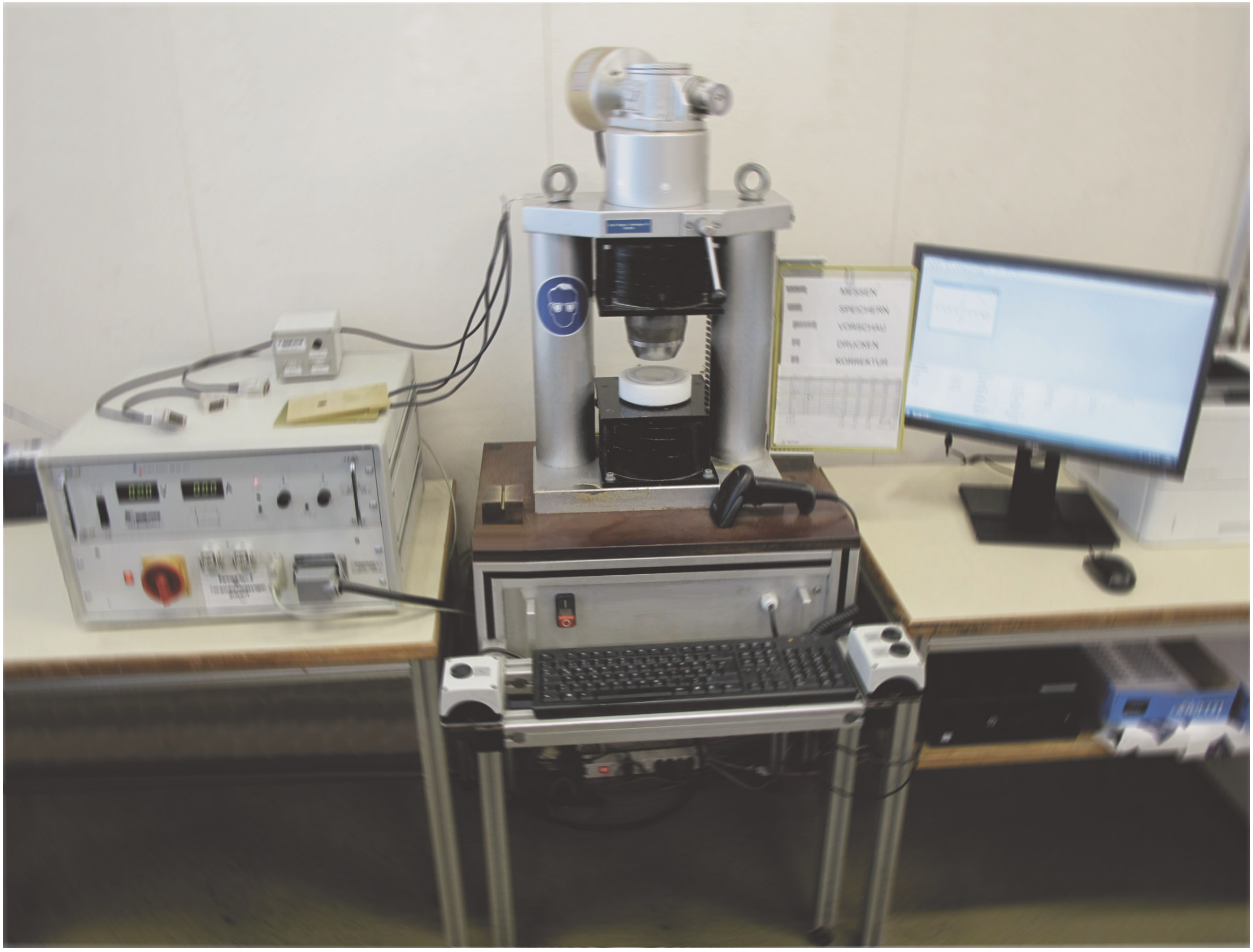


Figure 6. Pole strength difference is caused by non-symmetric alignment of the magnet. The colors indicate the vertical component of the flux density for a magnet with uniform magnetization (left) and non-uniform magnetization. The flux densities at the upper pole are stronger on the right picture.

In a real magnet, the alignment of the crystal structure is not uniform. This can cause an inhomogeneity of the flux density in a field scan or a difference of the flux density between the North and South poles. This difference is called pole strength difference (PSD) or North-South-Difference. Similar to the angular deviation, the PSD depends on the chosen process route. PSD < 2 % is possible, but also PSD values > 20 % can be seen.

Manufacturers usually aim to achieve a uniform magnetization and thus minimize the PSD. In some cases, however, a PSD may be useful for concentrating the field at the location of a sensor, or creating stronger forces and torques in electrical machines. Special production techniques are applied for manufacturing "shaped field magnets[2]", with non-uniform magnetization patterns tailored to give optimum performance in a given application.

[2] Shaped Field Magnets (SFMs) are patented by Arnold Magnetic Technologies.



2 MEASUREMENT TECHNIQUES

This chapter describes the measurement methods that can be used to study the properties of the magnetic material and the properties of an individual magnet piece. The methods can be divided in open circuit and closed circuit measurements.

2.1 Closed circuit measurement: Hysteresisgraph

Hysteresisgraph (or a permeameter) is a set of devices consisting of a controllable electromagnet forming a closed magnetic circuit, two fluxmeters and the measurement coil set. A magnet sample is placed in a homogenous field between the poles of the electromagnet. During the measurement the field between the poles is increased and the magnetic field strength and the flux through the magnet are measured in hundreds of data points. The output of the measurement is a set of points, where the magnetic flux density *B* in the magnet and the magnetic polarization *J* of the magnet are given as a function of the external field *H*. In practical terms, the measurement gives a curve shown in Figure 1 at the measurement temperature.

The hysteresisgraph measurement is well liked, because it gives the result in a form of a curve, which is visually easy to understand. However, the accuracy of the hysteresisgraph measurement is quite sensitive to sample thickness, sample and measurement coil centering in the device and drifting of the calibration. The hysteresisgraph measurement also sets some limits to the sample shape and size: the sample must have two flat parallel surfaces within some reasonable distance apart and parallel sides of arbitrary shape perpendicular to the flat surfaces. A typical sample is a cylinder with thickness of 2.5…10 mm and diameter of 5…20 mm.

A basic problem in accuracy is also the material of the pole pieces. Normally the pole pieces are made of iron, which saturates around 2 T. After the pole pieces are saturated, the field between the poles is not homogenous any more. This can be seen in the curve shape of the measurements when *H*-axis value exceeds 1600 kA/m. Pole pieces can also be manufactured of CoFe to increase the saturation up to 2.4 T. Pole pieces made of CoFe allow measurements with higher accuracy also for magnets having higher intrinsic coercivity. Still, there are magnets with such high intrinsic coercivities that they cannot be reliably measured at room temperature up to the field strength corresponding to their intrinsic coercivity H_{cJ}.

Some hysteresisgraphs have heated pole shoes or a heated sample holder making it possible to make measurements at elevated temperatures up to +200^{o}C.

Pros:

- Visual and easily understandable result

Cons:

- Special requirements for the sample shape
- Limited accuracy on higher magnetic field values
- Limited temperature range

Figure 7. A magnet sample (in the center) between the pole pieces in a hysteresisgraph. The sample is surrounded with a flat coil set.

2.2 Open circuit measurements

Measurements in an open circuit do not rely on the sample being sandwiched between pole pieces. Therefore, the samples do not need parallel surfaces and may, in principle, have an arbitrary shape. Since there is no need for pole pieces which could saturate, the applied fields can be quite large. Fields of 9 T or more are not uncommon in vibrating sample magnetometers or pulse field magnetometers. Complete demagnetization loops can therefore be measured even in materials with very high coercive fields.

In the open circuit measurement, the magnetic field in the samples is different from the externally applied field. The inner field is determined by correcting the applied field for the self-demagnetizing fields of the sample, which depend on the sample's shape. The correction uses a demagnetization factor or permeance coefficient, which, in most cases, is not a perfect representation of the spatially inhomogeneous fields. In modern magnet materials with high coercive fields, the small errors in determining the inner field are usually of minor importance.

2.2.1 Vibrating sample magnetometer

The vibrating sample magnetometer measures the magnetic moment of a sample by moving it between pick-up coils and measuring the AC voltage induced by the oscillating motion. An external field is provided by large electromagnets (as shown in the image), or by superconducting coils surrounding the pickup coils. The setup may also include a small chamber where temperatures can be varied over a large range in a protective atmosphere.

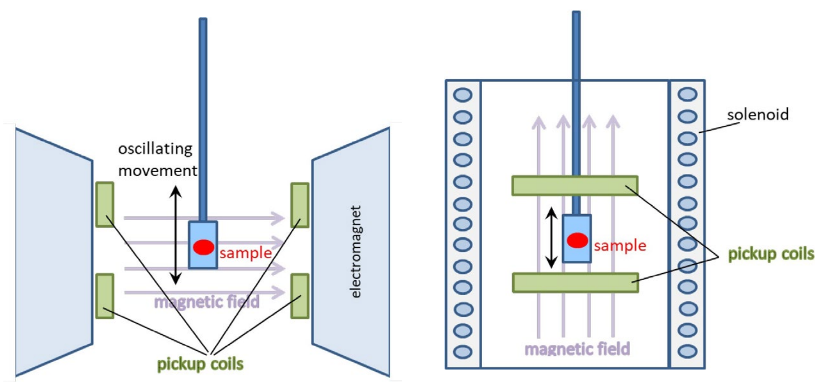


Figure 8. Schematic of a vibrating sample magnetometer (VSM). In the right figure, a (superconducting) solenoid is used to create the applied field.

Pros:

- Equipment with superconducting coils can apply fields large enough for measuring the complete hysteresis loop of rare earth magnets
- Curves can be measured over a wide temperature range, including low temperatures down to 4K

Cons:

- Time-consuming and expensive, in particular if the applied fields require using superconducting coils
- Sample size is limited to a few millimeters

2.2.2 Pulse field magnetometer

A pulse field magnetometer (PFM) measures the demagnetization curve not with a slow increase of a demagnetization field but with a few short field pulses in an open circuit measurement. This allows the fast characterization of magnets with a high H_{cJ}, which would not be possible with a hysteresisgraph. The short pulses are created by a fast discharge of a capacitor bank through a magnetizing coil.

The pickup coils have to distinguish the field generated by the magnet and the magnetizing coils. This can be done by a reference measurement without a sample at the beginning of each measurement sequence or with special compensating coil arrangement.

The short pulses cause eddy currents in metallic magnets, which have to be compensated. The influence of the eddy currents can be calculated by the use of two pulses with different frequencies.

Unlike in a hysteresisgraph a PFM measurement needs some calculation at the end of the measurement to create a demagnetization curve in which the reference measurement and the eddy current correction is fulfilled.

Since B_r is detected by measurement of the full hysteresis loop, the pulses must be strong enough to completely remagnetize the magnet. Otherwise a too small B_r would result.

A PFM can measure the magnetic properties in a temperature range of -40 to 220 °C (depending on the manufacturer).

The PFM method is described in the IEC TR 62331 standard.

Pros:

- Fast
- Samples can be saturated in the PFM itself
- Capable of measuring at very high fields
- More freedom in shape of magnets than a hysteresisgraph or a VSM

Cons:

- No initial curve possible
- Metallic magnets need correction for eddy currents
- Material with extremely high coercivity like good $SmCo_5$ can show some errors in curve shape and remanence
- Open circuit measurement

2.2.3 Helmholtz coil

This type of measurement is typically used for testing finished magnets, as it can be applied to magnets of almost any size and shape. The samples are placed into the coil system, and the magnetic moment of the magnet is derived from the voltage induced in the coil while the magnet moves. The voltage is read and processed by an “integrating fluxmeter”, which delivers the time integral of the voltage. The result is independent of the speed of the movement. It indicates the change in magnetic flux through the coil between the initial and the final positions of the sample. The reading is taken by:

- Placing the magnet into the coil center, from a position far away from the coil, or
- Removing it from the coil center, to a position far away from the coil, or
- Turning the sample over in the coil, flipping the orientation of the magnetization from parallel to antiparallel with the coil axis. (This procedure will result in reading twice the value of the previous options.)

The reading of the fluxmeter is a measure for the magnetic moment *m*

$$m = J \cdot V$$

where *V* is the volume of the magnet and *J* is the average polarization of the magnet.

Since no external field is applied during the measurement, it is tempting to assume that the polarization determined in a Helmholtz coil is equal to the remanent polarization J_r. However, this is not exactly true: As the magnet creates a self-demagnetizing field, the field in the magnet is not equal to zero during the measurement. The Helmholtz coil actually measures the polarization in the working point, J_m, as indicated in Figure 4.

In an accurate measurement the resistance of the coil must be taken into account. Some Helmholtz coil systems can do it automatically. Neglecting the resistance might cause an error up to several per cents in extreme cases.

Pros:

- Simple and fast
- Non-destructive
- Can be used for magnets of arbitrary size
- Excellent reproducibility, traceable to international standards
- Measured values can be predicted by theoretical calculations
- Measurement of the magnetization angle

Cons:

- No externally applied field
- The use of integrating fluxmeters requires a certain degree of care and experience (time-drift)

Measuring magnetization angle by Helmholtz coil

The magnetic moment is a vector quantity. If the sample is measured with the magnetization oriented at an angle to the coil axis, the result will give the component of magnetic moment that was parallel to the axis of the coil. It is thus possible to determine not only the absolute value, but also the direction of the average magnetization by measuring the same sample with different orientations:

- Performing three individual Helmholtz coil measurements, with the sample oriented in three different (orthogonal) directions with respect to the coil axis. This is usually achieved by mounting the magnet in a rectangular sample holder, or by providing three orthogonal surfaces in the coil, holding the same magnetsurface against each surface in consecutive measurements.
- Some suppliers offer a system of three Helmholtz coils, with orthogonal axes. In this case, all three componentscan be read at the same time. This is obviously attractive, if many angle measurements are performed on aroutine basis. There are some drawbacks, however:
    - The measurement requires three fluxmeter readings in parallel. The equipment is therefore moreexpensive than a simple fluxmeter.
    - Designing three coils with orthogonal axes, where the location for placing the sample should still be easily accessible, usually requires compromises in the shape and size of the coil. The resulting systems are often tailored for a limited range of sample sizes and shapes and thus less versatile. Or they tend to be rather large in comparison to the sample size.
- Very precise measurements can be performed by rotating the sample in the coil, while monitoring the fluxmeter reading and analyzing the complete “flux vs. angle” curves.

Estimating the magnetic moment of a magnet by theoretical calculation

One advantage of measuring the magnetic moment in a Helmholtz coil is the possibility to theoretically predict the result for a given magnet, as characterized by its demagnetization curve and dimensions. It is thus possible to specify limiting values prior to production and verify if the results are consistent with the specified demagnetization curves and magnet dimensions.

The magnetic moment is given as

$$m = J_m \cdot V$$

where J_m is the average polarization in the working point, as described in the section "Working point and permeance coefficient".

A prediction of *m* is obviously possible by numerical simulation, using finite element or similar modeling methods. The model just needs to include the magnet geometry in a sufficiently large air space. The magnetization curve can usually be implemented as a point by point table. For most permanent magnet users, however, this will not be an option. An alternative approach follows the traditional route for estimating J_m as the intersection of the working line with the demagnetization curve as described in Figure 4. This approach requires:

- the permeance coefficient for the magnet shape in question,
- a numerical representation of the demagnetization curve,
- the magnet volume

The averaged permeance coefficient P_c (or the demagnetizing factor *N*) can be found in literature, in the form of analytical equations or tabulated values for many different magnet shapes. Once the value for P_c is determined, the working line is given as

$$B = -P_c \cdot H$$

The demagnetization curve can often be approximated by a single straight line with a slope (permeability) as given by section "permeability":

$$B(H) = B_r + \mu H, \qquad with\ \mu = \frac{B_r}{H_C}$$

From the intersection of this curve with the working line, J_m can be read, as illustrated in Figure 4. Multiplying J_m with the magnet volume *V* gives the magnetic moment *m*.

2.2.4 Hall probe and scanning

A Hall probe measures the flux density at a certain place using the Hall-Effect. Usually the Hall probe is connected to a Gaussmeter (also called Teslameter), which can read calibration information and temperature compensation factors from the Hall probe. The flux density is measured in Tesla (T) or Gauss (G).

While the measurement itself is fast and easy, the method has some difficulties, which have to be noticed: Most important is the fact that the flux density itself heavily depends on the distance to the magnet. Therefore a certain distance of the Hall probe to the magnet is recommended to get a good repeatability of the measurement. Please be aware the active area in a hall probe is not at the outermost tip of the Hall probe but often multiple millimeters below. The distance of the active area to the tip of the probe can be found in the specification of the Hall probe supplier. The active area is also not an infinite small point, but an electronic chip of a certain area, which automatically averages the flux density over this area.

A Hall probe measures usually only one component of the flux density vector. Therefore an axial Hall probe detects only the axial field, while a transversal probe measures the field in one perpendicular direction. There are 2- or 3-axis Hall probes available, which can measure 2 or all 3 components of a magnetic field vector.
Since the measurement can be pretty fast it's possible to move the Hall probe over the measured magnet. Depending on the speed of the measurement and the required precision this scanning can be done stepwise or continuously.

But a Hall probe measurement delivers almost no information about the measured material. Therefore it's not often used by magnet producers, which prefer the above described hysteresis or magnetic moment testing.

Pros:

- Simple and fast
- Non-destructive

Cons:

- Low repeatability due to positioning
- No material information