The Initial and Four-Quadrant BH-Curve of Soft Magnetic Materials

Both the initial and four-quadrant BH-curves are used to characterize soft magnetic materials. This application note describes the initial and four-quadrant BH-curves, and explains how these curves are used to characterize soft magnetic materials.

The Initial BH-Curve

Applying a magnetic field (H) to a demagnetized sample generates the initial curve. The magnetic induction (B) is measured as the magnetic field is increased from zero to its maximum value. An initial BH-curve of 1010 Steel is shown below.

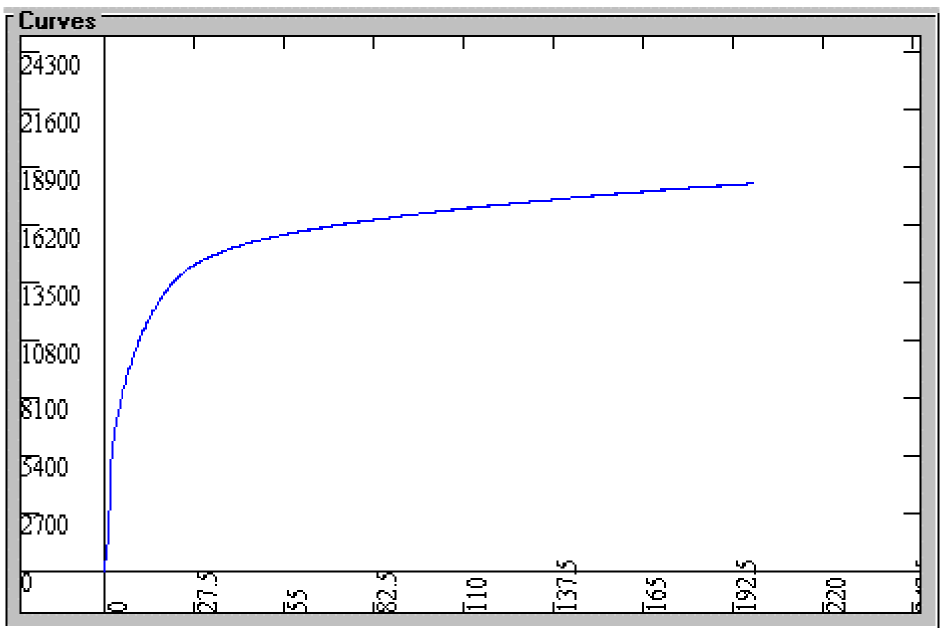

Figure 1: Initial BH-curve of 1010 steel. The horizontal axis is the applied field, H and the vertical axis in the magnetic induction, B.

As the applied magnetic field (horizontal axis) increases, the magnetic induction (vertical axis) of the material increases as well. Note that the magnetic induction has a nonlinear dependence on the magnetic field in the initial BH-curve.

The initial BH-curve is used to determine a parameter of soft magnetic materials called permeability. Permeability is defined as the change in magnetic induction (B) for a given change in magnetic field (H).

Mathematically, permeability, μ is expressed as:

$$\mu = \frac{\Delta B}{\Delta H}.$$

The size of the field increment and the point on the curve from where B and H are measured has not been standardized for all materials. Many different permeability specifications exist which call out for different field increments. Following is a brief review of some commonly found permeability parameters.

Maximum Permeability

The maximum permeability is defined as the largest slope of a line which starts at B, H=0 and ends on a point of the initial curve. Below is a table of typical values of maximum permeability for various materials.

Material	Permeability (Gauss/Oested)
1010 Steel	2,500
1045 Steel	900
Electrical Steel	17,500
50% Ni, 50% Fe	40,000

Incremental Permeability

The incremental permeability is the instantaneous slope of the BH-Curve at a specific point on the curve. In effect, the permeability is determined in the limit as ΔB and ΔH approach zero.

Initial Permeability

For some applications, most notably magnetic shielding, the permeability at very low magnetic fields is of interest. The permeability of a material near the origin is sometimes referred to as the initial permeability. One definition of the initial permeability is to determine the slope of the initial BH-curve where the magnetic induction at 3% of its maximum value.

The Four-Quadrant BH-Curve

A four-quadrant BH-curve is generated by immediately magnetizing the sample at a maximum magnetic field value, called Hmax, reducing the magnetic field through zero field to –Hmax, and then increasing the magnetic field back up again to Hmax. As with initial curves, the applied magnetic field is plotted on the horizontal axis, and the magnetic induction is plotted on the vertical axis. The magnetic induction is measured over the full range of magnetic field values and the resulting S-shaped curve is called a four-quadrant BH-curve, as shown below.

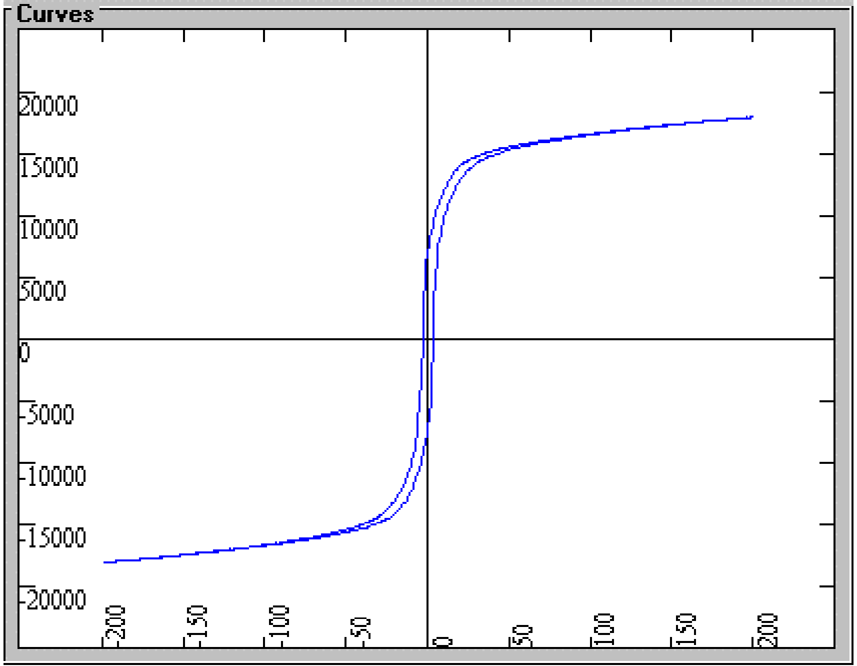

Figure 2: The four-quadrant BH-Curve of 1010 Steel

Four-quadrant BH-curves are also known as hysteresis curves. The curve is called four-quadrant because it occupies all four quadrants in the BH-plane. Note above that the curve is open in the middle. This is a consequence of the magnetic microstructure of the material. It is this microstructure, and changes to this microstructure through alloying, impurities, and heat-treating that determine the magnetic performance of soft magnetic materials.

The speed at which the magnetic field is changed will affect the result of the BH-Curve for most materials. For materials used static field applications, the magnetic field is swept very slowly, over a period of at least 20 seconds, and in some cases for several minutes. Curves generated in this manner are called DC BH-Curves, even though the applied magnetic field is not technically a constant field.

In contrast to static situations, it is instructive to oscillate the magnetic fields at the AC current frequency to investigate how the material will perform in the device. These curves are called AC BH-curves.

Remanence

The magnetic remanence is defined as the absolute value of the magnetic induction of the material at zero applied magnetic field. It is therefore, the $H = 0$ intercept of the BH-curve. Remanence can be thought of the “remaining” magnetization when there is no longer any magnetic field.

Coercivity

The coercivity is defined as the absolute value of the applied magnetic field to bring the magnetic induction to zero. It is somewhat the opposite of remanence, as it is the $B = 0$ intercept of the BH-curve. Coercivity describes the width of the BH-Curve, and is often an indicator to measure stress and impurity levels in steels.

Core Loss

As the magnetic field is cycled in a material, energy is lost due to the magnetic hysteresis of the material. From electromagnetic energy considerations, this energy loss of a single cycle can be shown to be equal to

$$\int HdB$$

integrated over the BH-curve. This is equal to the area inside the BH-curve. This energy loss is dissipated through heat, acoustic vibrations (transformer hum), and other processes. Core loss is specified in units of Watts per mass of material, rather simply the energy lost in a single cycle. As power loss is energy lost over time, the core loss is then expressed as

$$\frac{f}{d}\int HdB$$

where f is the excitation frequency, d is the density of the material, and $\int HdB$ is the area enclosed by the BH-curve.

AC permeability

AC permeability is another commonly used parameter to specify soft magnetic materials for AC applications. As permeability is expressed as $\Delta B/\Delta H$, the AC permeability is the peak induction level divided by the AC field amplitude. AC permeability is usually defined at a given induction level and AC frequency. For example, the AC permeability at 4,000 Gauss induction at 60 Hz is equal to 4,000 Gauss divided by the AC magnetic field amplitude required to achieve a 4,000 peak induction level at a 60 Hz frequency. AC permeability tends to be used to specify powder cores, and other low permeability materials where the core loss is very difficult to measure.