主要概念与定义

● B–H曲线

当在软磁材料上加一个交变磁场时，磁感强度随磁场强度的变化如图1所示磁滞回线描述了H与B的联系，叫做磁化曲线。

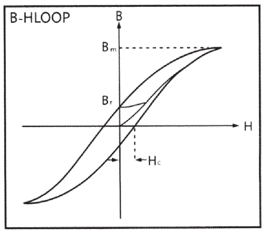


图1

初始磁导率，μi

它是B/H的极限值，在这里H（铁磁物质的原始磁化曲线中）值无限趋向于零，并且由以下几个因素决定：

$$\mu i=\frac{1}{\mu o}\lim_{H\to 0}\frac{B}{H}$$

μo：真空磁导率

H：交流磁场强度

B：交流磁感强度

（注）磁性材料的本征磁导率用一只绕着导线的圆环磁芯来测定，并由以下几个因素决定：

$$\mu i=\frac{L-Lo}{4\pi N^2}\times\frac{Le}{Ae}\times 10^9$$

L：带磁芯的线圈电感（H）

Lo：不带磁芯的线圈电感（H）

N：线圈匝数

Ae：磁芯有效截面积

Le：磁芯有效磁路长度

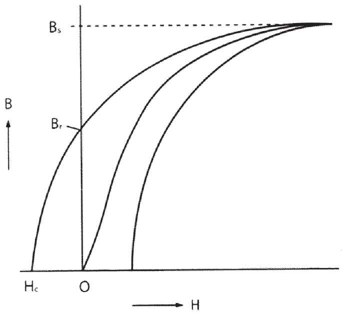


图 2

饱和磁感应强度，Bs

如图2（初始磁化曲线）所示，当完全退磁的磁芯周围的直流磁场强度增加时，磁感应强度将从最初的“0”开始增加。最后磁感应强度达到它的最大值，这个值就叫做饱和磁感应强度，在这里当H＝10Oe时B的值被定义为B_{10}。

剩余磁感强度，Br

它是直流磁场强度减小并最后变为零以后保留在磁芯中的剩余磁感应强度的值。

矫顽力，Hc

它是在反方向的直流磁场激化下剩余磁感应强度为零时的磁场强度。

● 损耗

损耗角正切，tan δ

磁芯损耗由三种不同类型的损耗组成：磁滞损耗，涡流损耗和剩余损耗。

$$\tan\delta=\tan\delta h+\tan\delta e+\tan\delta r$$
$$=h_1\sqrt{\frac{L}{V_1}}+e_1\times f+r_1$$

损耗系数tan δ 也可以表示为如下所示的阻抗与电抗的比值：

$$\tan\delta=\frac{Rm}{\omega L}=\frac{Reff-Rw}{\omega L}$$

tan δ h：磁滞损耗因子
tan δ e：涡流损耗因子
tan δ r：剩余损耗因子
L：带磁芯的线圈电感（H）
V：磁芯体积（cm^3）
i：电流（A）
h_1：磁滞损耗系数
e_1：涡流损耗系数
r_1：剩余损耗系数
f：频率（Hz）
Rm:磁芯的损耗电阻（Ω）
Reff:带磁芯线圈的损耗电阻（Ω）
Rw：线圈的损耗电阻（Ω）
ω：角频率（度/秒）

（注）h_1表示如下：

$$h_1=\frac{1}{\omega L}\times\sqrt{\frac{L}{V_1}}\times\frac{R_2-R_1}{i_2-i_1}$$

R_1=电流i_1的阻抗
R_2 = 电流i_2的阻抗

比损耗因子tan δ / μ i

它是每单位磁导率的损耗，表示如下：

tan δ / μ i（对磁芯材料）
tan δ / μ e(开气隙磁路）

品质因素Q

品质因素是损耗角正切的倒数。

$$Q=\frac{\omega L}{R_L}=\frac{1}{\tan\delta}$$

ω=2πf=角频率　　R = 带磁芯线圈的阻抗

● 功率损耗，Pc

功率损耗表示在高频，大磁场磁化条件下由电子变压器造成的损耗，例如开关电源变压器。工作磁感强度，B，通常表示如下：

$$B=\frac{V}{4.44fNAe}\times 10^8\ (\text{Gauss})$$

B:磁感强度（Gauss）
V：线圈端电压（V）
f：频率（Hz）

N：线圈匝数

Ae:有效截面积（cm^2）

●其他性质

电阻率，ρ（Ω·m）

通过磁芯单位截面在单位长度上的电阻

温度系数，αμ

它是在T_1到T_2这个温度范围内温度每变化1℃磁导率的变化量。

$$\alpha\mu=\frac{\mu_2-\mu_1}{\mu_1}\times\frac{1}{T_2-T_1}$$

μ_1：在温度T_1的磁导率

μ_2：在温度T_2的磁导率

比温度系数，αμr

它是每单位磁导率的温度系数，可表示为：

$$\alpha\mu r=\frac{\alpha\mu}{\mu i}$$

因此一个实际磁芯温度系数由下式决定：

$$\alpha\mu=\alpha\mu r\times\mu e$$

居里温度，Tc

如图3所示典型磁导率与温度特性曲线，居里点由磁芯从铁磁状态转向顺磁状态的温度决定。

它是0.8μmax.和0.2μmax.两点的连线与μ=1线的交点的温度。

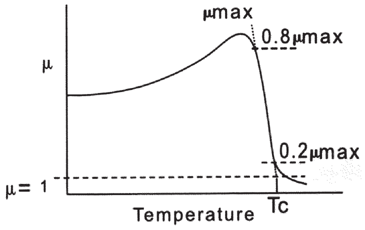


图3

密度，d（g/cm^3）它是每单位体积磁芯的重量，表示如下：

$$d=\frac{W}{V}$$

W：磁芯的重量（g）；V：磁芯的体积（cm^3）；

减落因子，DF

它是表示在恒温下磁芯完全退磁后磁导率随时间变化的因素。

$$DF=\frac{\mu_1-\mu_2}{\log\frac{t_2}{t_1}}\times\frac{1}{\mu_1^{2}}\quad(t_2>t_1)$$

μ_1：完全退磁t_1分钟后的初始磁导率

μ_2：完全退磁t_2分钟后的初始磁导率

（注）一般，t_1、t_2分别被设为10、100分钟。

气隙影响

当磁路中有气隙时，其损耗因子就变为带气隙损耗角正切，$(\tan\delta)_{gap}$它与无气隙时损耗角正切的关系为：

$$\frac{(\tan\delta)_{gap}}{\mu_e-1}=\frac{\tan\delta}{\mu_i-1}$$

因 μ_e、 $\mu_i >> 1$，所以有：

$$\frac{(\tan\delta)_{gap}}{\mu_e}=\frac{\tan\delta}{\mu_i}$$，即有$(\tan\delta)_{gap}=\frac{\tan\delta\ \mu_e}{\mu_e}$

由于$\mu_e < \mu_i$，所以开气隙后，损耗角正切减少，Q值增加。

磁芯开气隙后，磁芯内部磁场强度Hi大大减小，由Hi=He Hd=He–Nm可以看出，退磁因子N越大，Hi越小。这里He是绕组通过电流后产生的磁场（He=NI/le），M是磁化强度。退磁因子为0～4π，对闭路磁芯N＝0，气隙越大，N越大，反之亦然。开制气隙可增加磁场性能的温度稳定性。

电感因素，AL

电感因素由下式定义：

$$AL=\frac{L}{N^2}$$

L：带磁芯的线圈电感　　N：线圈的匝数

直流迭加

当交流磁场与直流磁场同时作用于磁芯时，称为直流迭加。

当磁芯有一个恒定的直流磁场H_{DC},并在其上迭加一个幅度为△H/2的正弦磁场时，则表示为：

$$H=H_{DC}+(\triangle H/2)\sin(\omega t)$$

当正弦磁场作用时，磁通密度形成小磁滞回线时，其峰值用△B/2表示，此时小磁滞回线在大磁滞回线内变化，小磁滞回线的平均斜率叫增量磁导率。

$$\mu_\triangle=\frac{1}{\mu_0}\times\frac{\triangle B}{\triangle H}$$

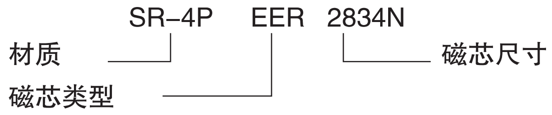
正弦场叫工作场，直流场叫偏磁化场或偏置场。增量磁导率随偏置场而改变。测直流迭加特性，就是在一定偏置场下加工作场，测其增量磁导率，并与无直流场时的磁导率作比较。

有效参数：

C_1：磁芯常数　Le：有效磁路长度　Ae：有效截面积　Acp：中心柱截面积

Ve：磁芯有效体积　Amin：最小截面积　Aw：磁芯线圈面积　W：磁芯毛重

标记示例：



Main concepts and definitions

● B–H curves

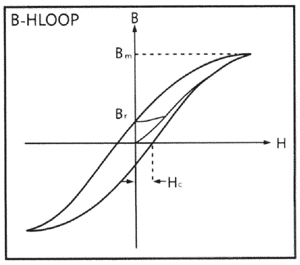


图1

If an alternating magnetic field is applied to a soft magnetic material,the magnetic induction(B) changes with the magnetic field (H) as shown in Fig.1 The hysteresis loop,describing the relation between Hand B,is called the magnetization curve.

Initial permeability, μ i

This is the limit value of B/H,where H is indefinitely close to xero(H≈O) at the virgin magnetization curve of ferromagnetic substance,and derived by the following equation:

$$\mu i = \frac{1}{\mu o} \lim_{H \to 0} \frac{B}{H}$$

μ o:permeability in vacuum　H：AC magnetic field strength　B：AC magnetic flux density

(Note)The essential permeability of a core material is measured us ing a toroidal core wound with a coil,and is represented by the following equatoion:

$$\mu i = \frac{L-Lo}{4\pi N^2} \times \frac{Le}{Ae} \times 10^9$$

L：self–inductance of core including coil(H)

Lo:self–inductance of coil(H)

N:number of turns

Ae:average cross–sectional area of toroidal core(cm^2)

Le:average magnetic path length of toroidal core(cm)

Saturation magnetic flux density,Bs

When the strength of a DC magnetic field H is intensified around a completely demagnetized magnetic core,the magnetic flux density Bincreases form the initial point "0" as shown in Fig.2.This is called an initial magetization curve,The magnetic flux density eventually reaches its upper limit,called the saturation magnetic flux density Bs,where the value of B is defined as $B_{10}$when H =100e.

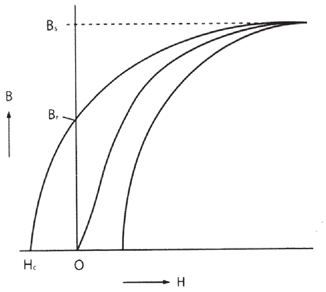


图 2

Residual magnetic flux density ,Br

This is the amount of residual magnetic flux density retained by the core after the DC magnetic field is weakned and finally removed to the level of H=0.

Coercive Force ,Hc

This is the strength of the magnetic field whereby the residual flux density becomes zero under the intensification,in the opposite direction,of the DC magnetic field.

● Loss

Loss factor tans δ

The core loss factors of three different types of losses:hysteresis loss,eddly–current loss and residual loss.

$$\tan\delta = \tan\delta h + \tan\delta e + \tan\delta r$$

$$= h_1\sqrt{\frac{L}{V_1}} + e_1 \times f + r_1$$

The loss coefficient tan δ can be also represented by the ratio of resistance to reactance as follows:

$$\tan\delta = \frac{Rm}{\omega L} = \frac{Reff-Rw}{\omega L}$$

tan δ h:hysteresis loss coefficient

tan δ e:eddy–current loss coefficient

tan δ r:residual loss coefficient

L: self inductance of core with coil (H)

i: current (A)

e_1: eddy–current loss coefficient

f: frequency (Hz)

Reff:resistance of coil (Ω)

ω: angular velocity(radian/sec.)

v: core volume(cm^3)

h_1: hysteresis loss coefficient

r_1: residual loss coefficient

Rm: resistance of magnetic core (Ω)

Rw: resistance of coil (Ω)

(Note) h_1 is expressed as follows:

$$h_1 = \frac{1}{\omega L} \times \sqrt{\frac{L}{V_1}} \times \frac{R_2-R_1}{i_2-i_1}$$

R_1=resistance for curren i_1 R_2 = resistance for curren i_2

Relative loss factor tan δ / μi

This is the amount of loss per unit permeability and is expressed as follows:

tan δ / μi (for magnetic materials) tan δ / μe(where gaps are added to the magnetic circuit)

Quality factor,Q

The quality factir Q,is defined as the reciprocal of loss angle tangent.

$$Q = \frac{\omega L}{R_L} = \frac{1}{\tan\delta}$$

ω=2πf=angular velocity R = loss resistance of coil with magnetic core

● Power loss,Pc

Power loss denotes the loss by an electrical transformer,such as a switching regulator,under a magnetization condition featuring a high frequency and a large amplitude.Operating magnetic flux density,B,is generally expressed as follows:

$$B = \frac{V}{4.44fNAe} \times 10^8 \text{ (Gauss)}$$

Where B:magnetic flux density (Gauss)

V: coil terminal voltage (V)

N: number of coil turns

f: frequency (Hz)

Ae: effective cross–sectional area (cm^2)

● Other characters

Electrical resistivity, ρ (Ω・m)

This is the electrical resistance per unit length and cross sectional area of a magnetic core.

Themperature coefficient, αμ

This is the fractional difference of permeability per 1℃ in a temperature range of forn T_1 to T_2

$$\alpha\mu = \frac{\mu_2-\mu_1}{\mu 1} \times \frac{1}{T_2-T_1}$$

Where μ_1: permeability at temperature T_1

μ_2: permeability at temperature T_2

Relative temperature coefficient, $\alpha\mu r$

This is the temperature coefficient per unit permeability and is represented by:

$$\alpha\mu r = \frac{\alpha\mu}{\mu i}$$

Thus, the temperature coefficient of an actual core is obtained as follows:

$$\alpha\mu = \alpha\mu r \times \mu e$$

Curie temperature,Tc

As shown by the typical temperature characteristic of permeability in Fig.3,the Curie temperature Tc is defined as the temperature at which the magnetic core changes from the ferromagnetic to the paramagnetic state,It is the temperature obtained at the intersection point of the horizontal line of $\mu=1$ and the line passing through the point 0.8 μ max.and 0.2 μ max.

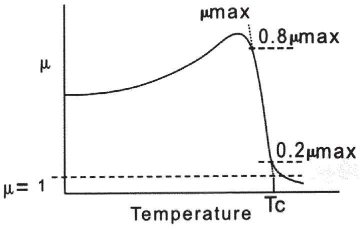


图3

Density,d(g/cm^3)

This is the weight per unit volume of a magnetic core as expressed bellow:

$$d = \frac{W}{V}$$

W: weight of magnetic body (g) ;

V: volume of magnetic body (cm^3)

Disaccomodation factor,DF

This is the factor representing the variation of permeability through time after a complete demagnetization of the core at a constant temperature.

$$DF = \frac{\mu_1 - \mu_2}{\log \frac{t_2}{t_1}} \times \frac{1}{\mu_1^2} \quad (t_2 > t_1)$$

μ_1:initial permeability t_1 minutes after complete demagnetization

μ_2:initial permeability t_2 minutes after complete demagnetization

(Note) Generally,t_1 to t_2 is set at 10 to 100 minutes.

Thein fluence of gap

When the magnetic circuit is unclosed with a gap,the loss factor is called gap loss factor ($\tan\delta$)$_{gap}$,The relation between gap loss factor and loss factor without the gap is:

$$\frac{(\tan\delta)_{gap}}{\mu_1-1} = \frac{\tan\delta}{\mu_1-1}$$

Because μ_e、$\mu_i >> 1$, the above equation becomes

$$\frac{(\tan\delta)_{gap}}{\mu_e} = \frac{\tan\delta}{\mu_i}$$, ie $(\tan\delta)_{gap} = \frac{\tan\delta\ \mu_e}{\mu_e}$

$\mu_e < \mu_i$, It is clear that$(\tan\delta)_{gap} > \tan\delta$,Q value increasing After the gap is made,the internal magnetic intensity of core decreases in large scale,from the formual Hi=He–Hd=He–Nm,we could see when demagnetizing factor N increases, Hi will decrease on the contrary,Here He is the magnetic field produced by the winding with current(He=NI/le),M is intensity of magnetization,demagnetizing factor is 0~4π,if magnetic circuit is closed,N=0,when the gap is bigger,demagnetizing factor is bigger,and it is the same on the contrary. Gap–making will increase the stability of magnetic field and temperature.

● Inductance factor,AL

Inductance factor,AL,is defined as the formula below:

$$AL = \frac{L}{N^2}$$

L: Inductance of the coil with magnetic core

N: Number of turns wound around magnetic core

● DC superposition

When an alternate field and a DC field act on a magnetic core simultaneously,it is called DC superstition.

When there is a sine field with the amplify of △H/2 acting on a DC field in the magnetic core,the applied fields is $H = H_{DC} + (\triangle H/2)\sin(\omega t)$

$$\mu_{\triangle} = \frac{1}{\mu_0} \times \frac{\triangle B}{\triangle H}$$

Where the sine field is called applied and field DC called displacing field or bias field.The incremental permebility changes as displacing field.The measurement of DC superposition characteristic is to measure the incremental permeability in DC displacing field and to compare it to that measured without DC displacing field.

● Effective parameters

C_1:Core constant

Ae:Effective cross–sectional area

Ve:Effective core volume

Aw:Winding area of core

Le:Effective magnetic path length;

Acp:Cross–sectional center pole area

Amin:Minimun cross–sectional area

W:Approx.weight of core

● Example of mark

SR-4P EER 2834N

Material

Core type

Core Size