概 念

主要概念与定义

1、磁场

电流产生磁场，在螺线管中，或在磁路中电流所产生的磁场为：

$$H=\frac{NI}{l}$$

在这个表式中，采用国际单位制，H单位为安培/米（A/m），N为匝数，I为电流，单位安培（A），L为螺线管或磁路长度，单位为米（m）。

在磁芯中，加正弦波电流，可用有效磁路长度Le来计算磁场强度：

$$H=\frac{\sqrt{2}IN}{le}\ (\mathrm{A/m})$$

$$1\mathrm{Oe}=\frac{1\times10^{3}}{4\pi}\approx79.58\mathrm{A/m}$$

2、磁通密度、磁极化强度、磁化强度

在磁性材料中，加强磁场H时，引起磁通密度变化，其表现为：

$B=\mu_0H+J$ 或 $B=\mu_0(H+M)$

B为磁通密度，亦称磁感应强度，J称磁极化强度，M称磁化强度，为真空磁导率，其值为

$4\pi\times10^{-7}$ 亨利/米（H/m）

B、J单位为T，H、M单位为A/m，1T=104Gs

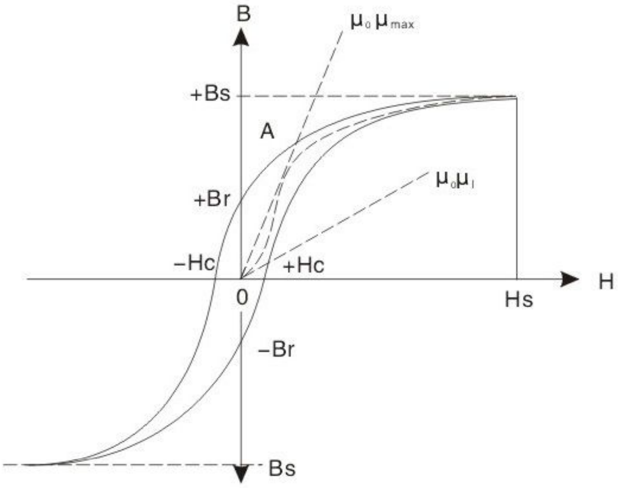
在磁芯中可用有效面积Ae来计算磁通密度：

正弦波为：$\hat{B}=\frac{0.225V}{fNAe}$

电压单位为V，频率单位为Hz，N为匝数，B 单位为T；Ae单位为m^2。

3、饱和磁通密度、剩余磁化强度、矫顽力

B和H的关系除在真空中和在磁性材料中小磁化场下具有线性关系外，一般具有非线性关系，即具有所谓磁滞回线性质：



Bs为饱和磁化强度，Br为剩余磁化强度，Hc为矫顽力。

Hs为饱和磁化场，不同磁性材料产生的磁滞回线表现形式不一样，Bs、Br、Hc、Hs都不一样。

4、磁导率

1）$\frac{B}{H}=\mu_0(1+\frac{M}{H})=\mu_{absolute}$ 称绝对磁导率，是有量纲的。

2）$\frac{B}{H}=\mu_0\mu_{r,}\mu_r$ 称相对磁导率，是无量纲的，是一个数值。

我们平常用的大都是相对磁导率，且把脚标r省去。

3）$\frac{1}{\mu_0}\frac{\triangle B}{\triangle H_{(\triangle H-0)}}=\mu_i$ 称初始磁导率，它与温度、频率有关。测量时在一定温度、一定频率、很低的磁通密度（或很小的磁场）、闭合磁路中进行。在实际测量中，规定：磁化场H所产生的磁通密度应小于1mT，一般B为0.1mT，但也有许多特殊情况，应加以注意。

4）在磁路中存在气隙，即非闭合磁路条件下，测得的磁导率为有效磁导率：

$$\frac{\mu_i}{1+g\mu_i/le}=\mu_e$$

g是气隙长度，le是有效磁路长度。这一表示，仅是小气隙g下的一种近似。在大气隙下，磁通要穿过气隙的外部，其有效磁导率将大于按上式计算所得之值。

5）在没有偏置磁场的情况下，磁场H较大时，该磁场H产生磁通密度B，则这时，

$\frac{1}{\mu_0}\frac{B}{H}=\mu_a$ 称振幅磁导率。

6）在具有直流偏置磁场时，再加上一个交流磁场，这时测得的磁导率 $\frac{1}{\mu_0}\left[\frac{\triangle B}{\triangle H}\right]_{H_{DC}}=\mu_\triangle$ 称为增量磁导率。在直流迭加状态下测得的电感，计算出的磁导率近似于增量磁导率。

7）上述1）~6）的磁导率都是频率较低，或接近直流状态下测得的磁导率，在频率较高时，其磁导率表现为复数磁导率。

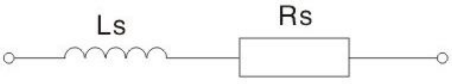
在串联电路中为 $\mu=\mu'_s-j\mu''_s$

在并联电路中为 $\frac{1}{\mu}=\frac{1}{\mu_p}-\frac{1}{j\mu_p}$

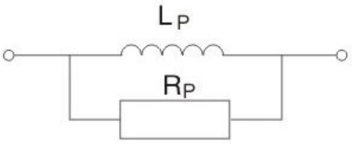
μ_s，μ_p，都是频率的函数。

5、阻抗

电感产生感抗 $X_L=j\omega L$，电容产生容抗 $X_C=\frac{1}{J\omega C}$，二者总称为电抗，纯电阻R。三者总称阻抗，在磁性器件讨论中，相对低的频率下，我们忽略容抗，只讨论电阻和感抗，且有串联电路和并联电路之分。



串联电路



并联电路

串联电路中阻抗 $Z_s=R_s+j\omega Ls$

并联电路中阻抗 $Z_P=\frac{1}{1/(j\omega Lp)+1/Rp}$

Zs、Zp都与频率有关，其特性称为阻抗频率特性，它与磁性材料频率特性有关。另外，它们与绕组参数有关。在复数磁导率中，其频率特性表现为 μ'，μ'' 的频率特性。阻抗频率特性，实际上是磁性器件的特性，非是材料的特性。

6、损耗因子

表示小信号下材料的损耗特性。由于磁芯损耗，引起信号相移，其表示为：

$$\mathrm{tg}\,\delta m=\frac{Rs}{\omega Ls}=\frac{\mu's}{\mu''s} \text{ 或 } \mathrm{tg}\,\delta m=\frac{\omega Lp}{Rp}=\frac{\mu'p}{\mu''p}$$

tgd_m 称为损耗因子，表示的是损耗功率与贮能的比值。因磁芯损耗包括磁滞损耗、涡流损耗、剩余损耗，所以损耗因子可表示为：

$\mathrm{tg}\,\delta_m=\mathrm{tg}\,\delta_h+\mathrm{tg}\,\delta_e+\mathrm{tg}\,\delta_r$，分别称为磁滞、涡流、剩余损耗因子。

7、比损耗因子

$\frac{\mathrm{tg}\,\delta_m}{\mu_i}$ 或 $\frac{\mathrm{tg}\,\delta}{\mu_i}$ 称比损耗因子，与材料几何尺寸无关，表示小信号下材料的损耗特性。

8、气隙的影响

当磁路中有气隙时，其损耗因子为带气隙损耗因子，（$tg\delta$）$_{gap}$它与无气隙时损耗因子关系为：

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

因 $\mu_e\ \mu_i>>1$，所以有：

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

由于 $\mu_e<\mu_i$，所以开气隙后，损耗因子减小，Q值增加。

磁芯开制气隙后，磁芯内部磁场强度H，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是绕组通以电流后产生的磁场（$He=\frac{NI}{le}$），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和温度的稳定性。

9、品质因素Q

磁性器件作滤波器的电感时，通常用品质因素（Q）来表示它的质量，

品质因素 $Q=\frac{1}{Tg\delta}=\frac{\omega L}{R_{tot}}$，$R_{tot}$表示总电阻，它是线圈和磁芯的总电阻。$R_{tot}$表示损耗，包括磁芯损耗、铜线损耗。Q与频率和绕组参数有关。

10、大信号场下的功率损耗

大信号场下，磁芯损耗用下式表示：

Pm=Ph+Pe+Pr,Ph、Pe、Pr,分别表示磁滞损耗、涡流损耗、剩余损耗。

11、温度系数与比温度系数

温度系数为 $\alpha_{\mu i}=\frac{\mu_{i2}-\mu_{i1}}{\mu_{i1}}X\frac{1}{T_2-T_1}$

μ_{i1}，μ_{i2} 分别表示温度 T_1, T_2 时的初始磁导率。

比温度系数：

$\alpha_{\mu ir}=\frac{\alpha_{\mu i}}{\mu_{i1}}=\frac{\mu_{i2}-\mu_{i1}}{(\mu_{i1})^2}X\frac{1}{T_2-T_1}$，$\alpha_{\mu i}$，$\alpha_{\mu ir}$ 均表示磁导率的温度稳定性。

12、减落因子与比减落因子

减落因子为$DA=\frac{\mu_{i1}-\mu_{i2}}{\mu_{i1}}\times\frac{1}{lg(t_2/t_1)}$

μ_{i1}，μ_{i2} 表示同一温度下，t_1,t_2 时刻的初始磁导率。

比减落因子，$D_F=\frac{D_A}{\mu_{i1}}=\frac{\mu_{i1}-\mu_{i2}}{(\mu_{i1})^2}\times\frac{1}{lg(t_2/t_1)}$

D_A，D_F 都表示 μ_i 经磁扰动或机械冲击后的经时变化。比减落因子，一般用DF表示，有时简称减落因子。

13、电感系数AL

一个电感或变压器，绕有N匝线圈，其电感值为L，则定义 $AL=\frac{L}{N^2}$，当 AL单位为 $\frac{nH}{N^2}$ 时。$AL=\frac{L}{N^2}\cdot10^9$ 这里L的单位为亨利，一般N取100，当N取得很大磁芯又是闭路时，不宜采用AL来表达，因可能进入谐振区或接近饱和区。

在设计中，知道AL值和设定要求的电感（nH），则导线圈数：

$$Ts=\left[\frac{\text{设定}L(nH)}{AL(nH/N^2)}\right]^{1/2}$$

在无气隙情况下，$\mu_i=\frac{C_1}{4\pi}A_L$ ，这里 C_1 为磁芯常数，单位为 mm^{-1}，AL 为 $\frac{nH}{N^2}$

Al值与气隙大小有关、磨削面精度有关。

14、静磁场影响一直流迭加

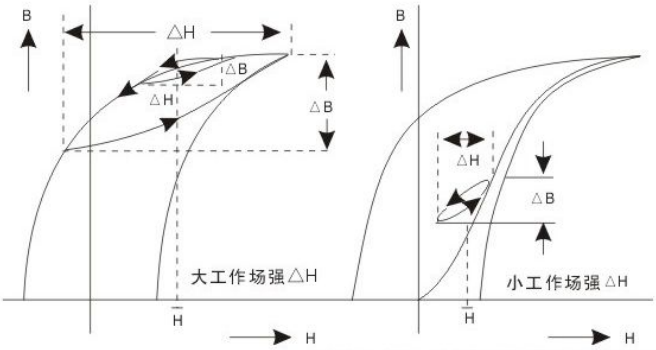
当交流磁场与直流磁场同时作用于磁芯时，称为静磁场的影响，有时简单地称为直流迭加。当磁芯有一个恒定的直流磁场 H_{DC}，并在其上迭加一个幅度为 $\frac{\triangle H}{2}$ 的正弦磁场时，则表示为：$H=H_{DC}+\frac{\triangle H}{2}\sin\omega t$

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（前已述过）。

$$\mu_{\triangle}=\frac{1}{\mu_0}\left[\frac{\triangle B}{\triangle H}\right]_{H_{DC}}$$

这里，正弦场叫工作场，直流场叫偏磁化场或偏置场。增量磁导随偏置场而改变。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。

由于交流磁场值大小不同，小回线有二种代表性的状态，如：



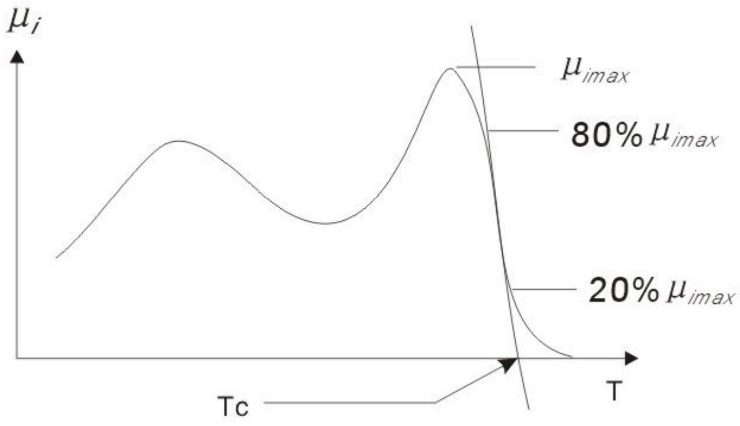
直流磁场H叠加一个幅度为△H/2的交流磁场后的磁滞回线

从中可推知迭加特性与材料特性的关系。

由于许多电路中，往往存在直流电成份，这相当于加了一个直流偏置场，而它会影响增量磁导率的大小，所以迭加特性很重要。

15、居里温度

居里温度是磁性材料从铁磁性（亚铁磁性）到顺磁性的转变温度，或称磁性消失温度，表示方式有多种，材料标准中规定居里温度的方法如下图：



随温度升高，磁导率下降到最大值的80%、20%时，这二点联线，延长到与温度轴的交点，即为居里温度。

Concepts

Main concepts and definitions

1.Magnetic field

Current induces magnetic field.In spiral coils,the magnetic field (H)induced by current can be expressed as:

$$H=\frac{NI}{l}$$

Where all parameters are in SI unit system and N is turn number,I (A) is current,l(m)is the length of the spiral coils.In magnetic core,the field strength H induced by alternate current can be calculated in term of the effective length le of the spiral coils:

$$H=\frac{\sqrt{2}IN}{le}\ (\mathrm{A/m})$$

$$1\mathrm{Oe}=\frac{1\times10^{3}}{4\pi}\approx79.58\mathrm{A/m}$$

2.Magnetic flux density,magnetic polarizability,magnetization.

In magnetic material,the magnetic flux density varies as applied field H. It behaviors as:

$$B=\mu_0H+J \quad \text{or} \quad B=\mu_0(H+M)$$

Where B is magnetic flux density also called magnetic induction,J magnetic polarization,M magnetization, and μ_0 vacuum permeability with the value of $4\pi\times10^{-7}$ H/m,The units of B and J are Tesla (T) and those of H and M are A/m.

1 Tesla = 10^4 Gauss

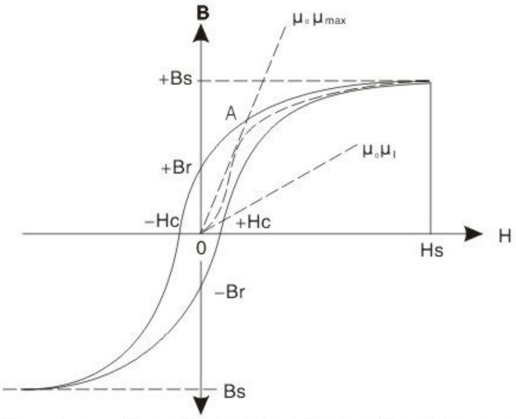
In magnetic cores,the magnetic flux density can be calculated using effective area Ae:

$$\hat{B}=\frac{0.225V}{FNAe} \quad \text{For sine wave}$$

Where V is electric potential in Volt,f frequency in Hz,N turn number,B in mT and Ae in m^2.

3.Saturation magnetization,remanent magnetization, and coercivity.

Besides the linear relation between B and H in vacuum, B behaviors a nonlinear relation as H in magnetic materials displaying the hysteresis shown in the figure.



In the figure, Bs is saturation induction, Br residual induction, Hc coercivity, and Hs saturation field. Different magnetic materials display various hysteresis, leading to different Bs, Br, Hc, and Hs.

4.Permeability

1) $\frac{B}{H}=\mu_0(1+\frac{M}{H})=\mu_{absolute}$ called absolute permeability with dimension.

2) $\frac{B}{H}=\mu_0\mu_r,\ \mu_r$ where μ_r is called relative permeability, which is a pure number without dimension.

Usually we use the relative permeability, neglecting the footnote r.

3) $\frac{1}{\mu_0}\frac{\triangle B}{\triangle H_{(\triangle H-0)}}=\mu_i$ is called initial permeability. It depends on temperature and frequency. The measurement of μ_i should be made in a closed magnetic circuit at certain temperature and frequency in a very weak applied field. In measurement, it requires that the change of magnetic flux density (△B) induced by △H should be less than 1mT, generally B=0.1mT.

4)For unclosed magnetic circuit with a gap, measured permeability is called effective permeability expressed as: $\frac{\mu_i}{1+g\mu_i/L_e}=\mu_e$

where g is the length of the gap, and L_e the effective length of the magnetic circuit. It notes that this equation only an approximation of μ_e for the small gap. For large gap, the effective permeability will larger than that calculated using above equation.

5)when an applied field H is larger without a DC bias field, it induces the magnetic flux density B, in which $\mu_a=\frac{1}{\mu_0}\frac{B}{H}$,is called amplitiude permeability.

6)In an alternate field with a DC bias field, the permeability. $\mu_\triangle=\frac{1}{\mu_0}\left[\frac{\triangle B}{\triangle H}\right]_{H_{DC}}$ is called incremental permeability. For the electric inductance measured in the AC field superposed with a bias DC field, the permeability is probably also the incremental permeability.

7)The permeability in above 1)—6) are all obtained in the low frequency or near to DC situation. When the frequency is high, the permeability is complex.

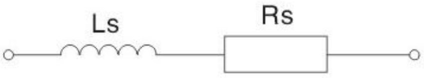
In serial circuit, $\mu=\mu'_s-j\mu''_s$

In paralles circuit, $\frac{1}{\mu}=\frac{1}{\mu_p}-\frac{1}{J\mu_p}$

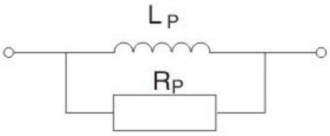
μ_s, μ_p, are all the functions of frequency.

5.Impedance

Inductive impedance in an electric inductance is $X_L=j\omega L$,and condenser impedance in a condenser is $XC=\frac{1}{J\omega C}$,These two are generally called electrical impedance. Adding pure resistance R,they are in all called impedance.In magnetic devices, we only consider inductive impedance and pure resistance for the issue of relative low frequency,neglecting condenser impedance.There is the difference between serial and parallel circuit.



Series representation



Parallel reparesentation

Series representation $Z_s=R_s+j\omega Ls$

Parallel reparesentation $Z_P=\frac{1}{1/(j\omega Lp)+1/Rp}$

Zs and Zp depend on frequency,and their characteristics are called impedance frequency characteristics and related to the frequency characteristics of magnetic materials, and they are connected with winding parameters.In complex permeability,its frequency characteristics is determined by the frequency characteristics of both μ and μ ,Actually,the impedance frequency characteristic is the characteristic of the magnetic device but the characteristic of material.

6.Loss factor

Loss factor indicates the loss property of material in small signal. It induces phase shift of signal due to magnetic core loss, which can be expressed as:

$$\mathrm{tg}\,\delta m=\frac{Rs}{\omega Ls}=\frac{\mu's}{\mu''s}\text{ 或 }\mathrm{tg}\,\delta m=\frac{\omega Lp}{Rp}=\frac{\mu'p}{\mu''p}$$

where $\mathrm{tg}\,\delta m$ is called loss factor indicating the ratio of loss power and input power. Because magnetic core loss induces hysteresis loss, eddy loss,and residual loss, the loss factor can be expressed as: $\mathrm{tg}\,\delta m=\mathrm{tg}\,\delta_h+\mathrm{tg}\,\delta_e+\mathrm{tg}\,\delta_r$,Where $\mathrm{tg}\,\delta_h$, $\mathrm{tg}\,\delta_e$,and $\mathrm{tg}\,\delta_r$ is called hysteresis loss factor, eddy loss factor, and residual loss factor respectively(see the following Figure).

7.Specific Loss factor

$\frac{\mathrm{tg}\,\delta_m}{\mu_i}$ or $\frac{\mathrm{Tg}\,\delta}{\mu_i}$ is called specific loss factor,which is independent of geometrical size of material, indicating small signal loss characteristic of the material.

8.The influence of gap

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

$$\frac{(\mathrm{tg}\,\delta)_{gap}}{\mu_e-1}=\frac{\mathrm{tg}\,\delta}{\mu_i-1}$$

Because μ_e μ_i>>1,the above equation becomes

$$\frac{(\mathrm{tg}\,\delta)gap}{\mu_e}=\frac{\mathrm{tg}\,\delta}{\mu_i}\quad,\quad \text{i.e } (\mathrm{tg}\,\delta)_{gap}=\frac{\mathrm{tg}\,\delta.\ \mu_e}{\mu_i}$$

where $\mu_e<\mu_i$,It is clear that $(\mathrm{tg}\,\delta)_{gap}>\mathrm{tg}\,\delta$, Q value increasing

After the gap is made,the internal magnetic intensity of core decreases in large scale,form the formula Hi=He−Hd=He−NM, we could see when demagnetising factor N increases,Hi will decrease on the contrary. Here He is the magnetic field produced by the winding with current $(He=\frac{NI}{Le})$,m is intensity of magnetization,demagnetising factor is 0~4π,if magnetic circuit is closed,N=0,when the gap is bigger, demagnetising factor is bigger,and it is the same on the contrary. Gap-making will increase the stability of magnetic field and temperature.

9.Quality factor Q

When magnetic device is used as electric inductance in wave filter,its property is usually characteriaed using quality factor Q.

$$Q=\frac{1}{\mathrm{tg}\delta}=\frac{\omega L}{R_{tot}}$$

When Rtot is total resistance including coil and core resistance.Rtot indicates loss including magnetic core loss and copper wire loss.Q value is cloesly related to frequency and coil parameters.

10.Power loss in large signal field

In large singnal field,magnetic core loss can be expressed as:

$$Pm=Ph+Pe+Pr,$$

When Ph、Pe、and Pr indicate hysteresis loss,eddy loss and residual loss respectively.In power ferrite, Pm is often used to analyze power loss,interpreted as dividing the total power loss and then analysing the cause and cores of power loss.

11.Temperature coefficient and specific temperature coefficient.

Temperatuer factor is: $\alpha_{\mu i}=\frac{\mu_{i2}-\mu_{i1}}{\mu_{i1}}\mathrm{X}\frac{1}{T_2-T_1}$

where mi1,mi2 indicate initial permeability at T1,T2 respectively.

Sepcific temperature factor is: $\alpha_{\mu ir}=\frac{\alpha_{\mu i}}{\mu_{i1}}=\frac{\mu_{i2}-\mu_{i1}}{(\mu_{i1})^2}\mathrm{X}\frac{1}{T_2-T_1}$

ami and amir all indicate temperature stability of permeability.

12.Dropping coefficient and Specific dropping coefficient.

Dropping coefficient is: $D_A=\frac{\mu_{i1}-\mu_{i2}}{\mu_{i1}}\times\frac{1}{\lg(t_2/t_1)}$

Where μ_{i1}, μ_{i2} indicate initial permeability at the same temperature at different time t_1,t_2 respectively.

Sepcific dropping coefficient is: $D_F=\frac{D_A}{\mu_{i1}}=\frac{\mu_{i1}-\mu_{i2}}{(\mu_{i1})^2}\times\frac{1}{\lg(t_2/t_1)}$

Both D_A and D_F indicates the change under the influence of magnetic interference and mechanical lash.

13. Electric inductance factor AL

The inductance value of an electric inductance or a transformer with N turn coils is L. It defines that $AL=\frac{L}{N^2}$,When the unit AL is $\frac{nH}{N^2}$,taking N=100 commonly,but sometimes the parameter of AL is not used,because when the turns of winding are too many and in circumstance of closed magnetic circuit the magaetic flied is likely to enter resonance area or approach saturation area.

$$Ts=\left[\frac{\text{Set L(nH)}}{\text{AL(nH/N}^2\text{)}}\right]^{1/2}$$

When without the gap , $\mu_i=\frac{C_1}{0.4\pi}AL$,where C_1 of core parameters is mm^{-1}, AL is $\frac{nH}{N^2}$.

AL value is related to the size and surface roughness of the gap. If known AL value and magnetic core size , one can easily obtain permeability mi used material.

14. Static field effect-DC superposition

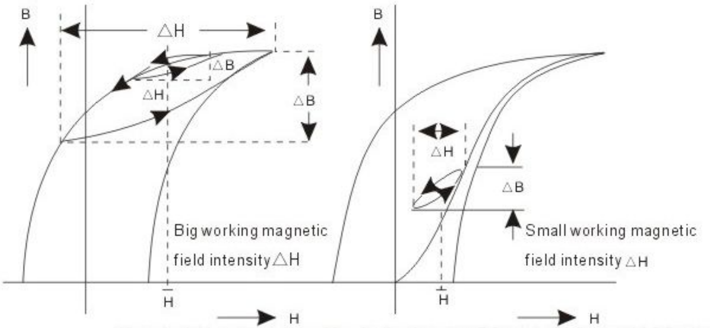
When an alternate field and a DC field act on a magnetic core simultaneously,it is called static magnetic influence. Sometimes it is call DC superposition.

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 $H=H_{DC}+\frac{\Delta H}{2}\sin\omega t$

Due to sine field,the change of magnetic flux density shows a small hysteresis loop in the large one and its peak value is △B/2(See the following figures). The average slope of the small hysteresis loop is incremental permeability (as mentioned above):

$$\mu_{\Delta}=\frac{1}{\mu_0}\left[\frac{\Delta B}{\Delta H}\right]_{H_{DC}}$$

Where the sine field is called applied and field DC field called displacing field or bias field. The incremental permeability 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. There are two typical small hysteresis loops for different alternate fields (shown in the following figures).

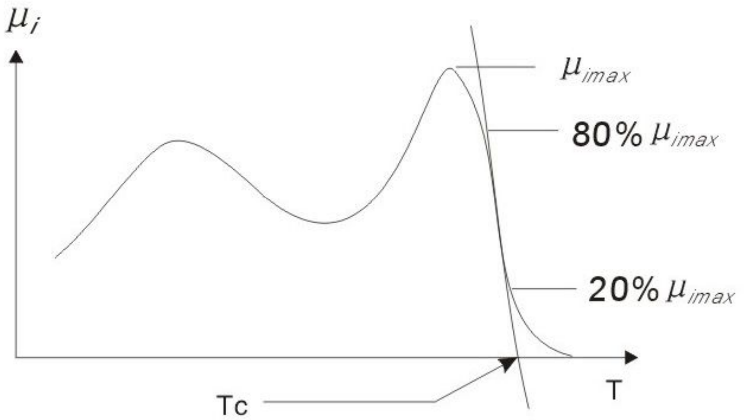


Where is the hysteresis loop,After folding between DC magnetic field and AC field with △H/2

From them one can know the relationship between the superposing characteristic and materialproperty. The superposing characteristic is very important due to the existence of DC in many electric circuits.

15.Curie temperature

Curie temperature is the transition temperature of magnetic materials from ferromagnetism to paramag-netism.There are several methods to determine Curie temperature.The method used by Tiantong Elec.Co.,Ltd.is shown as the following figure.



As temperature increases,one can find the two points with the permeability falling down to 80% μ_{imax} and 20% μ_{imax} respectively. Connecting the two points and extrapolating the line to T axis,the point of intersection is Curie temperature.