



福州大学  
FUZHOU UNIVERSITY



# 高频磁性元件与磁性材料

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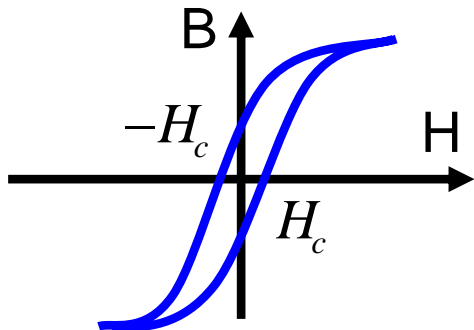


- 磁性材料的分类
- 软磁材料的主要参数和特性
- 高频磁性元件对磁材特性的要求
- 主要的高频磁性材料及其特点
- 磁性材料的损耗测量
- 磁性材料的发展



# 磁性材料的分类

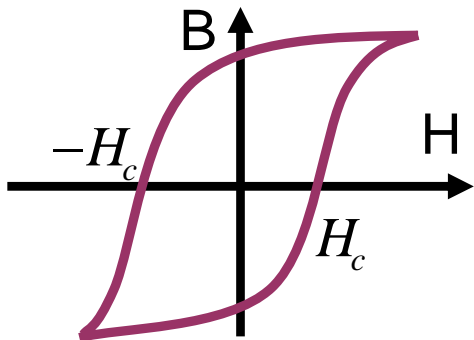
## 软磁材料



$\mu_r$ 大，易磁化、易退磁（起始磁化率大）。饱和磁感应强度大，矫顽力( $H_c$ )小，磁滞回线的面积窄而长，损耗小 ( $HdB$ 面积小)。

导磁作用，用于继电器、电机、以及各种功率变换器高频磁件的磁芯。

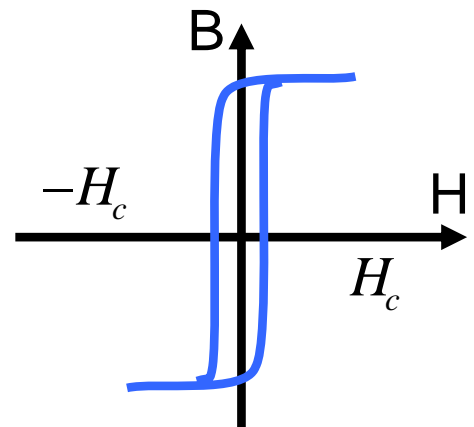
## 硬磁材料



矫顽力( $H_c$ )大 ( $>10^2\text{A/m}$ )，剩磁 $B_r$ 大，磁滞回线的面积大，损耗大。

偏磁作用，磁电式电表、扬声器和永磁电机中永磁铁。

## 矩磁材料



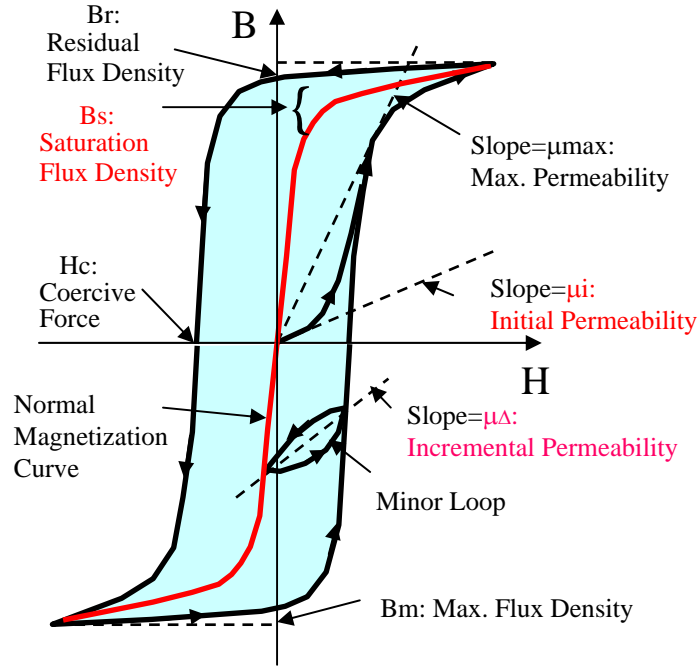
$B_r$ 接近 $B_s$ ， $H_c$ 小，磁滞回线呈矩形，损耗小。

用于两态记忆元件， $+/-$ 脉冲 $H > H_c / H < -H_c$ ，使得磁芯呈 $+B / -B$ 态，可做为二进制的两个态。

做磁放大器(Magamp)磁芯。

# 磁材料的基本参数

## ◆ 电气参数



1) 起始磁导率:  $\mu_i$

$$\mu_i = \frac{1}{\mu_0} \left. \frac{\Delta B}{\Delta H} \right|_{\Delta H \rightarrow 0}$$

2) 幅值磁导率:  $\mu_a$

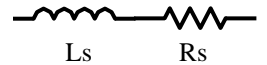
$$\mu_a = \frac{1}{\mu_0} \frac{\hat{B}}{\hat{H}}$$

3) 增量磁导率:  $\mu_{\Delta}$

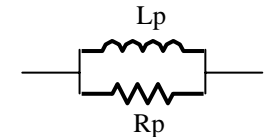
$$\mu_{\Delta} = \frac{1}{\mu_0} \left. \frac{\Delta B}{\Delta H} \right|_{H_{DC}}$$

4) 复数磁导率:  $\mu_s$

$$\mu_s = \mu'_s - j\mu''_s$$



$$\frac{1}{\mu_p} = \frac{1}{\mu'_p} - j \frac{1}{\mu''_p}$$



## ◆ 损耗参数

$$P_{CV} = K \cdot f^{\alpha} \cdot B^{\beta} \cdot (C_0 + C_1 \cdot T + C_2 \cdot T^2)$$

## ◆ 机械物理参数

弹性模量, 热伸缩系数, 导热系数等

## ◆ 磁滞伸缩系数

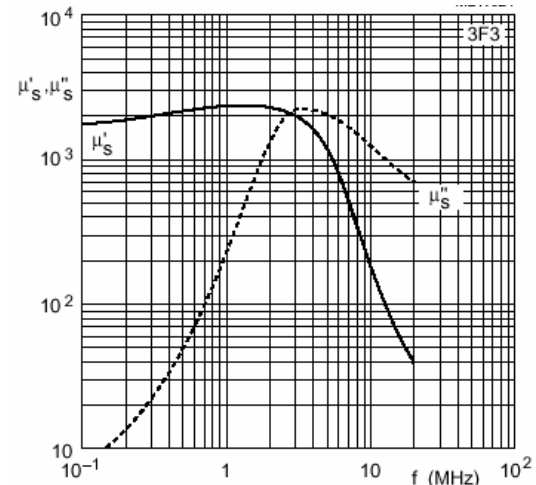
音频噪声的主要来源

# 磁性材料的电气特性参数

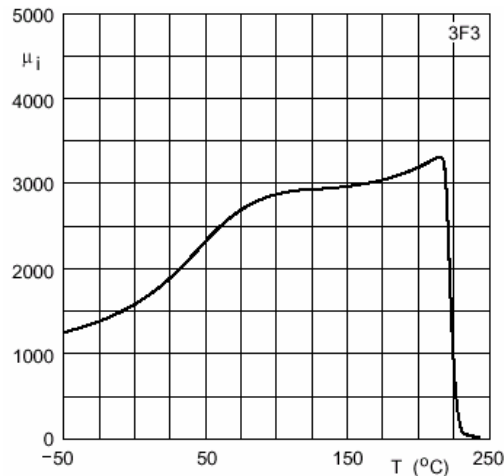
## Ferrite-3F3

### 3F3 SPECIFICATIONS

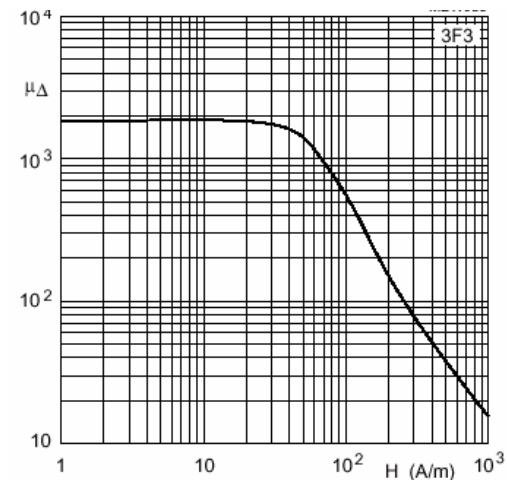
SYMBOL	CONDITIONS	VALUE	UNIT
$\mu_i$	25 °C; $\leq 10$ kHz; 0.1 mT	1800 $\pm 20\%$	
$\mu_a$	100 °C; 25 kHz; 200 mT	$\approx 4000$	
B	25 °C; 10 kHz; 250 A/m	$\geq 400$	mT
	100 °C; 10 kHz; 250 A/m	$\geq 330$	mT
$P_V$	100 °C; 100 kHz; 100 mT	$\leq 80$	kW/m <sup>3</sup>
	100 °C; 400 kHz; 50 mT	$\leq 150$	kW/m <sup>3</sup>
$\rho$	DC; 25 °C	$\approx 2$	$\Omega\text{m}$
$T_C$		$\geq 200$	°C
density		$\approx 4750$	kg/m <sup>3</sup>



Complex permeability with  $f_s$

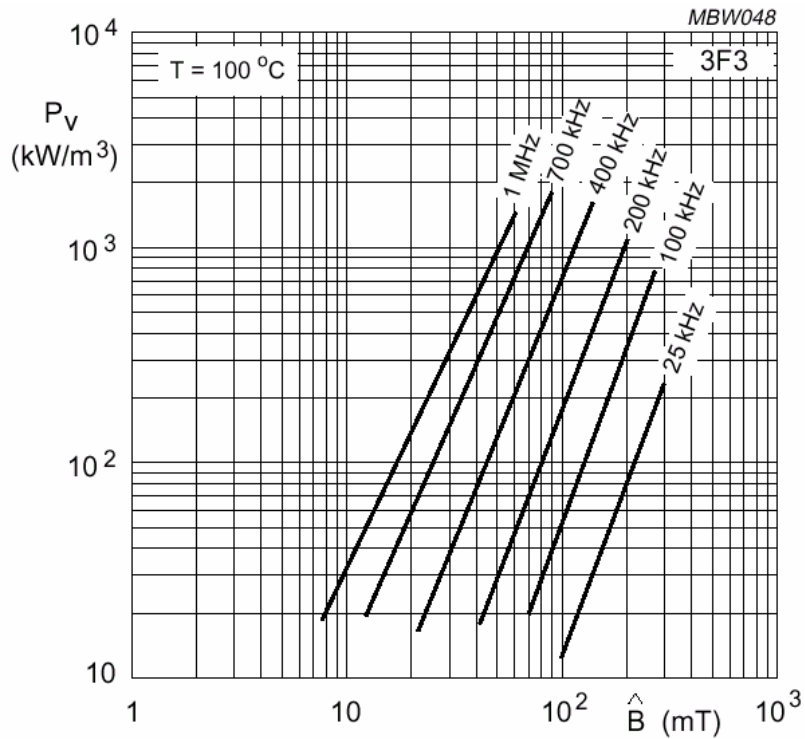


Initial permeability with  $T$

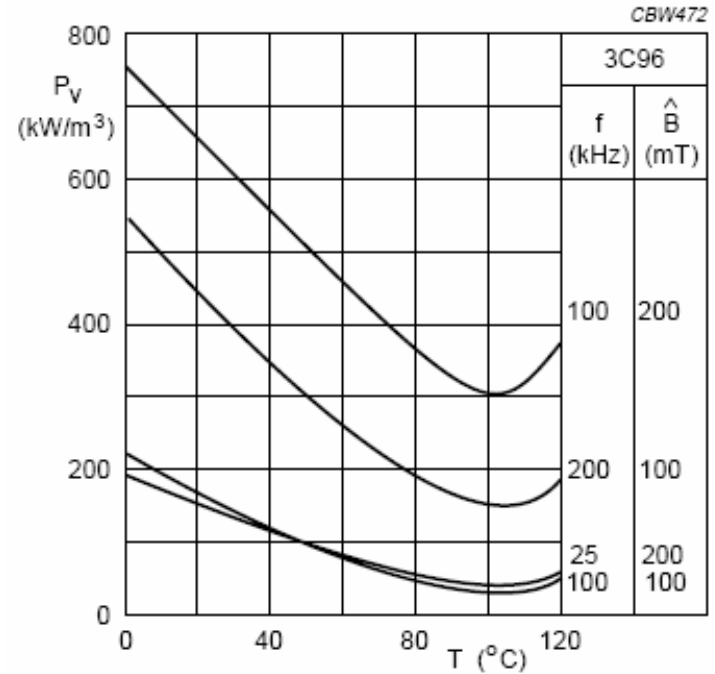


Incremental permeability with  $H_{DC}$

# 磁性材料的损耗特性参数

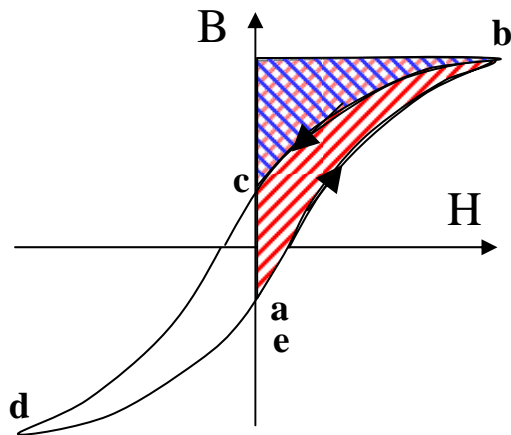


损耗的频率和磁密特性



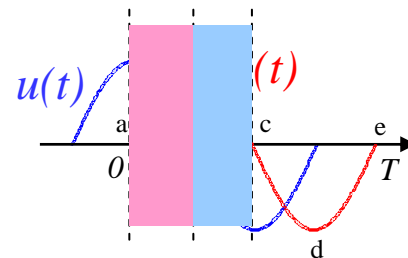
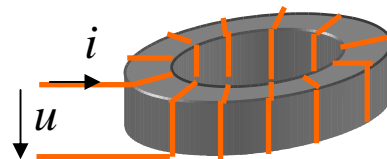
损耗的温度特性 (Ferrite)

# 铁芯的损耗 (磁滞损耗)



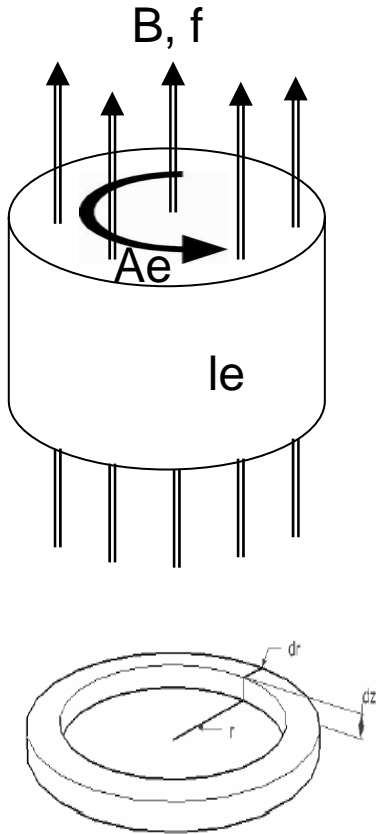
$$P_{in} = \int_a^b (i \cdot u) dt = \int_a^b \left( \frac{H \cdot l_e}{N} \right) \cdot \left( NA_e \frac{dB}{dt} \right) dt = A_e \cdot l_e \int_a^b H \cdot dB$$

$$= \int_b^c (i \cdot u) dt = A_e \cdot l_e \int_b^c H \cdot dB$$



- 磁滞损耗大小取决于铁磁材料本身的品质
- 磁滞损耗大小与激磁工作频率成正比
- 磁滞损耗大小与磁通密度大小的平方成正比

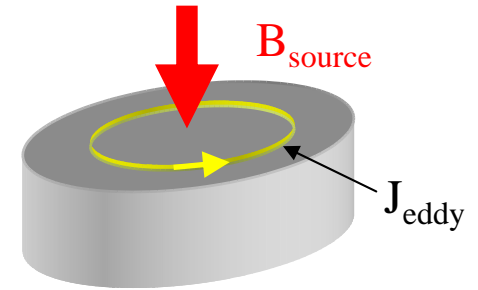
# 铁芯的损耗 (涡流损耗)



$$U_0 = \frac{d\phi}{dt} = 2\pi f * B * \pi r^2$$

$$dP = \frac{U_0^2}{dR_0} = \frac{4\pi^4 f^2 B^2 r^4}{\rho \frac{l_0}{S_0}} = \frac{4\pi^4 f^2 B^2 r^4}{\rho \frac{2\pi r}{drdz}}$$

$$= \frac{2\pi^3 f^2 B^2 r^3}{\rho} drdz$$



$$P_{eddy} = \iint \frac{2\pi^3 f^2 B^2 r^3}{\rho} drdz = \frac{2\pi^3 f^2 B^2}{\rho} \int_0^{r_{face}} r^3 dr \int_0^{le} dz$$

$$= \frac{\pi f^2 B^2}{2\rho} Ae^2 le = \frac{\pi}{2} f^2 B^2 le Ae^2 \sigma$$

$$P_{eddy} = \frac{\pi}{2} f^2 B^2 \cdot le \cdot Ae^2 \cdot \sigma$$

- 涡流损耗大小取决于铁磁材料本身的电导率
- 涡流损耗大小与激磁工作频率的平方成正比
- 涡流损耗大小与磁通密度大小的平方成正比

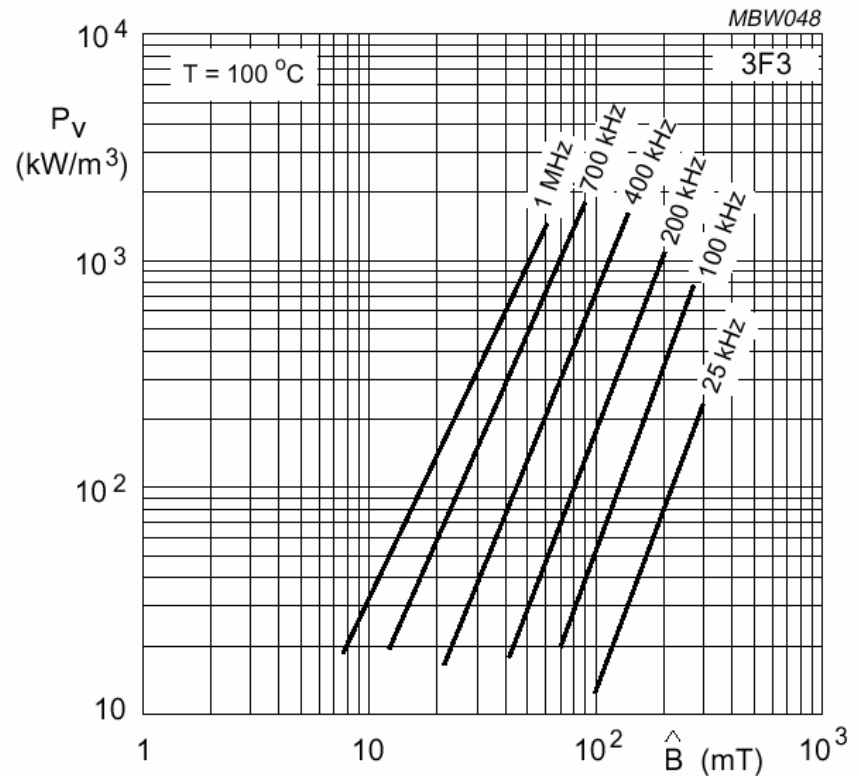


# 磁芯损耗模型-Steinmetz Model

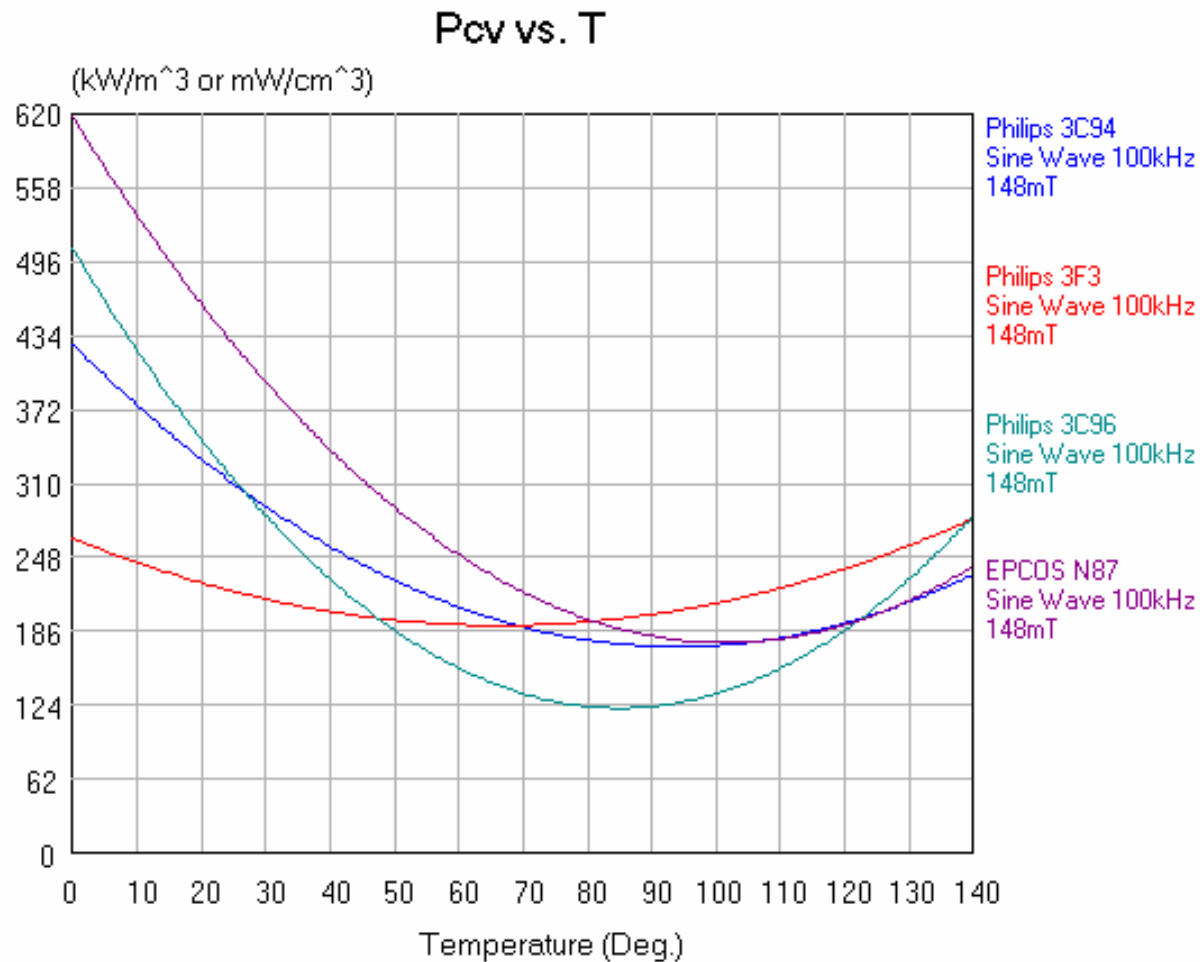
$$P_{CV} = C_m \cdot f^\alpha \cdot B^\beta \cdot (C_0 + C_1 \cdot T + C_2 \cdot T^2)$$

## Core loss is related to:

- ❖ Material grade
- ❖ Frequency
- ❖ Temperature
- ❖ Flux density
- ❖ DC bias
- ❖ Excitation waveform

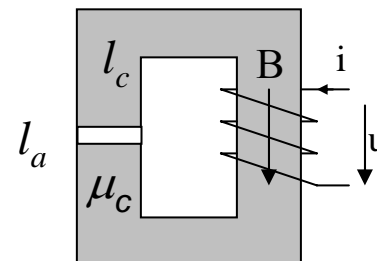
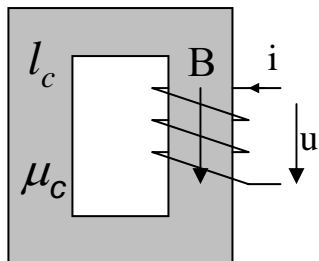


# 磁芯损耗的温度特性

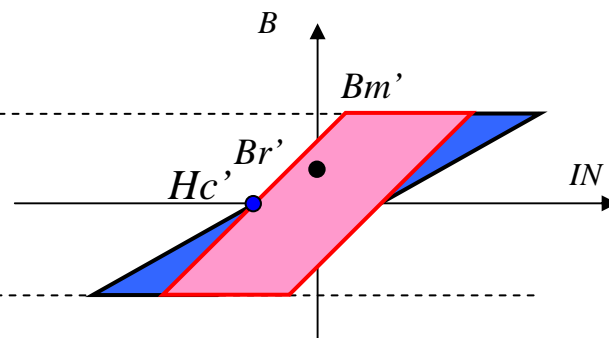
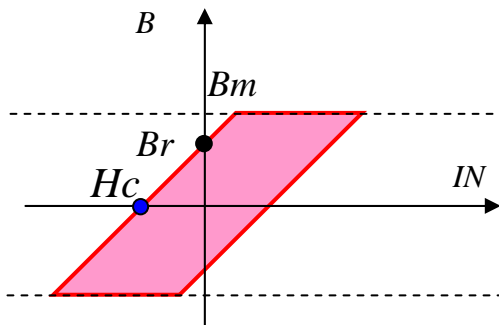


- ◆ 温度对铁氧体的损耗影响很大
- ◆ 不同材料有不同的温度特性曲线
- ◆ 注意设计工作温度的范围

# 磁芯带气隙特性



◆ 磁化曲线



◆ 磁导率

$$\frac{1}{\mu_c}$$

$$\frac{1}{\mu_e} = \frac{1}{\mu_c} + \frac{l_a}{\mu_a \cdot l_c}$$

◆ 剩磁密度

$$B_r$$

$$B_r' = \frac{1}{1 + \frac{l_a}{l_c} \frac{B_r}{H_c} \frac{1}{\mu_0}} = \frac{1}{1 + \frac{l_a}{l_c} \frac{\mu_c}{\mu_0}} = B_r \cdot \frac{\mu_e}{\mu_c}$$

# 磁性材料的性能因子与材料选择

$$P_{thr} = N_p \cdot A_e \cdot I_p \cdot (f \cdot B)$$

$f \cdot B$ : Material performance factor

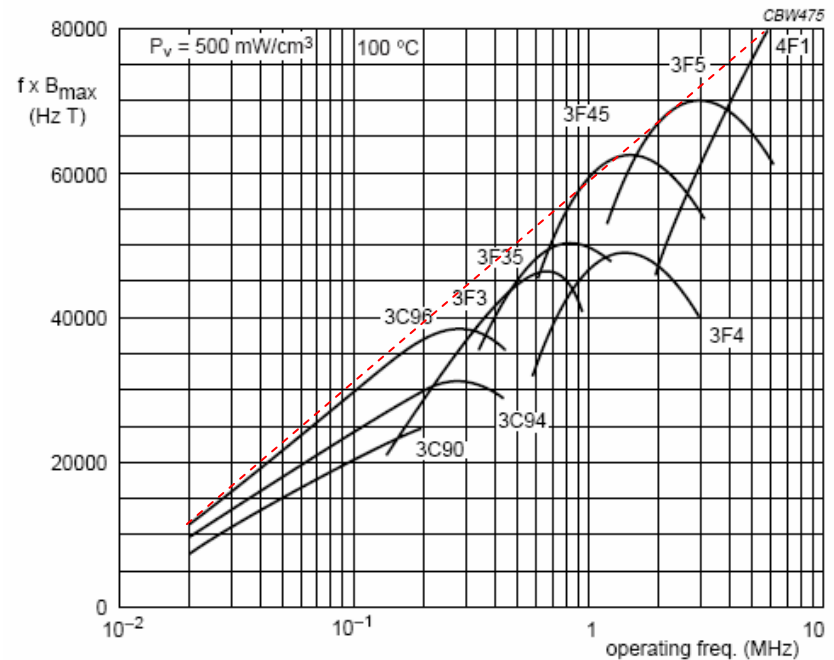
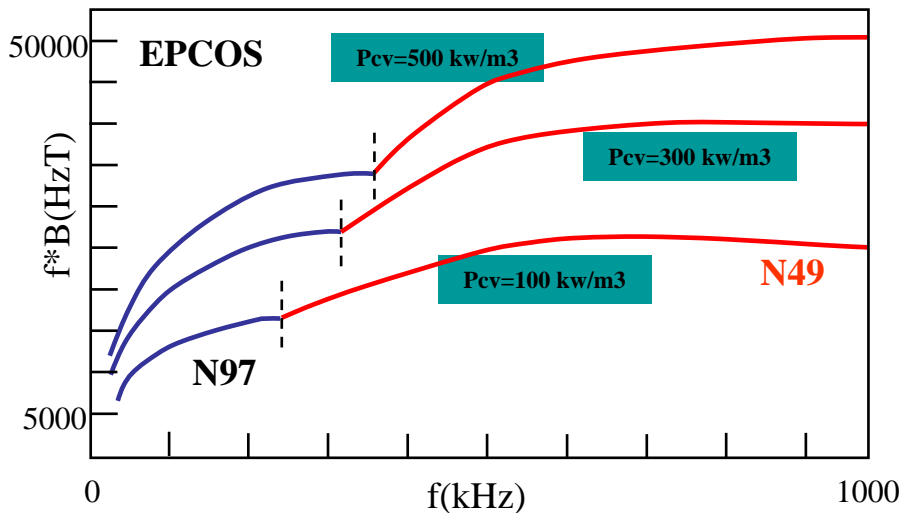
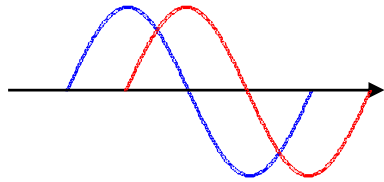


Fig.19 Performance factor ( $f \times B_{max}$ ) at  $P_v = 500 \text{ mW/cm}^3$  as a function of frequency for power ferrite materials.

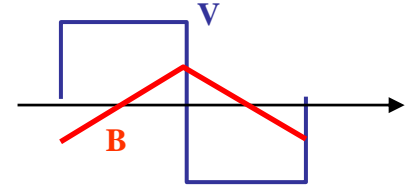


# PWM波形激励下的磁芯损耗



加权平均磁密变化率  $\bar{B}_w$

$$\bar{B}_w = \frac{1}{B_{\max} - B_{\min}} \int_T \left( \frac{dB}{dt} \right)^2 dt$$



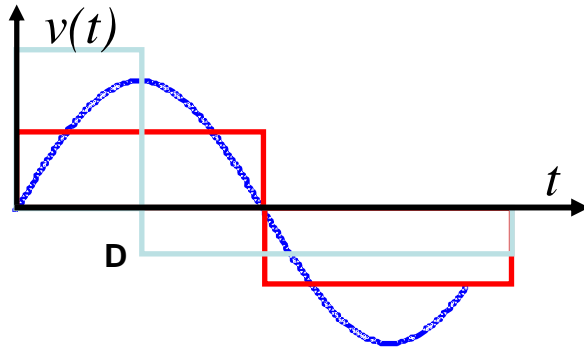
$$\bar{B}_{w \sin} = (B_{\max} - B_{\min}) \cdot \frac{\pi^2}{2} \cdot f_{\sin}$$



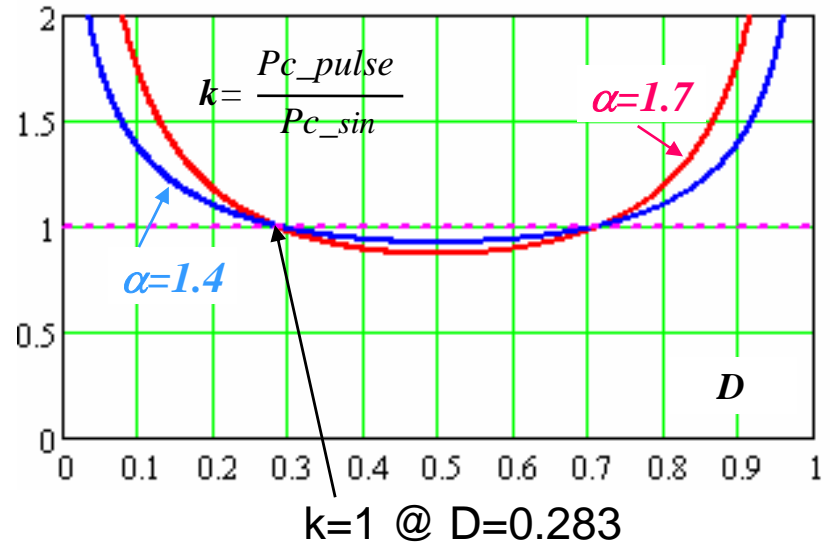
$$\bar{B}_{w \text{arb}} = \frac{1}{(B_{\max} - B_{\min})} \sum_k \frac{(B_{k+1} - B_k)^2}{t_{k+1} - t_k}$$

$$f_{\sin} = \frac{2}{\pi^2} \sum_k \left( \frac{B_{k+1} - B_k}{B_{\max} - B_{\min}} \right)^2 \cdot \frac{1}{t_{k+1} - t_k}$$

$$\Rightarrow P_c = f_s \cdot C_m \cdot f_{\sin}^{\alpha-1} \cdot B_{ac}^{\beta} \cdot (C_{t0} + C_{t1} \cdot T + C_{t2} \cdot T^2) \cdot V_e$$



Power loss factor,  $k$ , with same  $B_m$  and  $f_s$

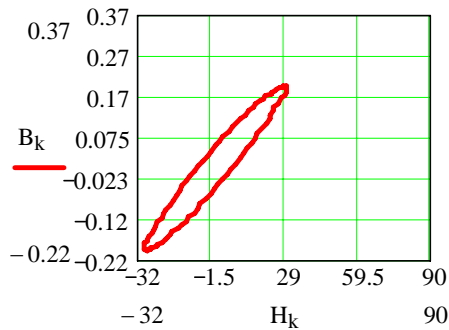


# 直流偏磁对磁芯损耗的影响

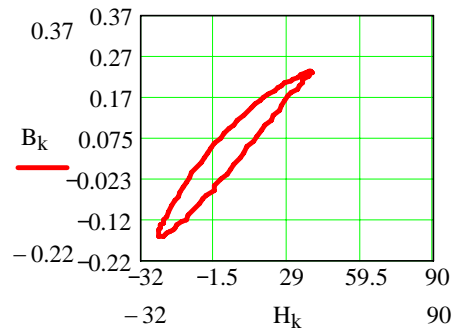
## Core loss model

$$P_c = (1 + K_{1dc} \cdot |B_{dc}| \cdot e^{\frac{|B_{ac}|}{K_{2dc}}}) \cdot K_{1ac} \cdot |B_{ac}|^{K_{2ac}} \cdot f_s^{K_{3ac}} \cdot (K_{t1} \tau^2 + K_{t2} \tau + K_{t3})$$

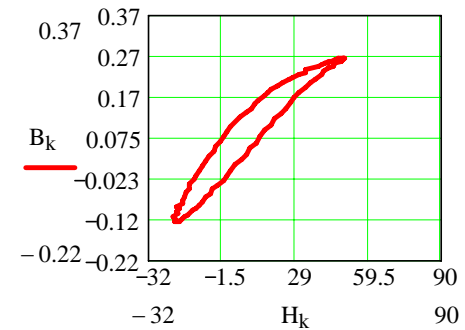
**B-H Loop @ fs=100kHz, Bac=200mT, To=100°C**



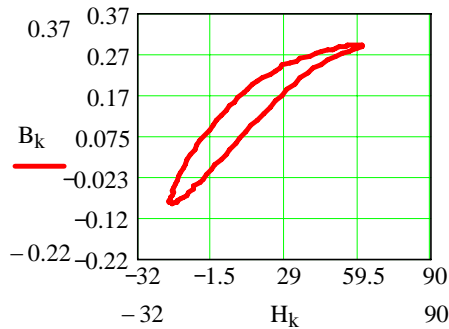
Hdc=0, Pc=504 (kw/m<sup>3</sup>)



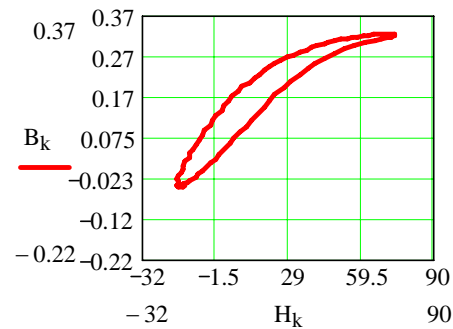
Hdc=6.93A/m, Pc=506 (kw/m<sup>3</sup>)



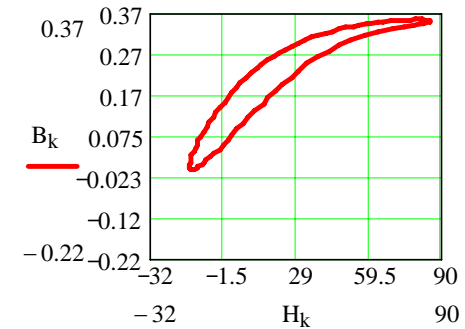
Hdc=13.85A/m, Pc=526 (kw/m<sup>3</sup>)



Hdc=20.77A/m, Pc=584 (kw/m<sup>3</sup>)



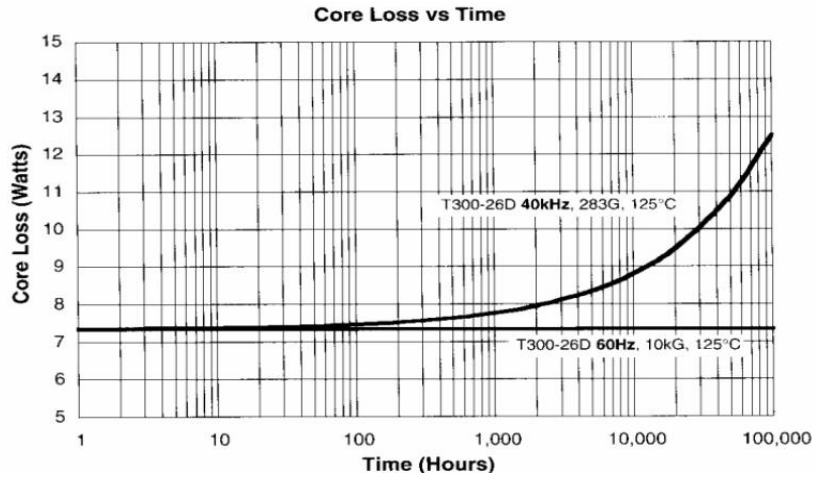
Hdc=27.69A/m, Pc=605 (kw/m<sup>3</sup>)



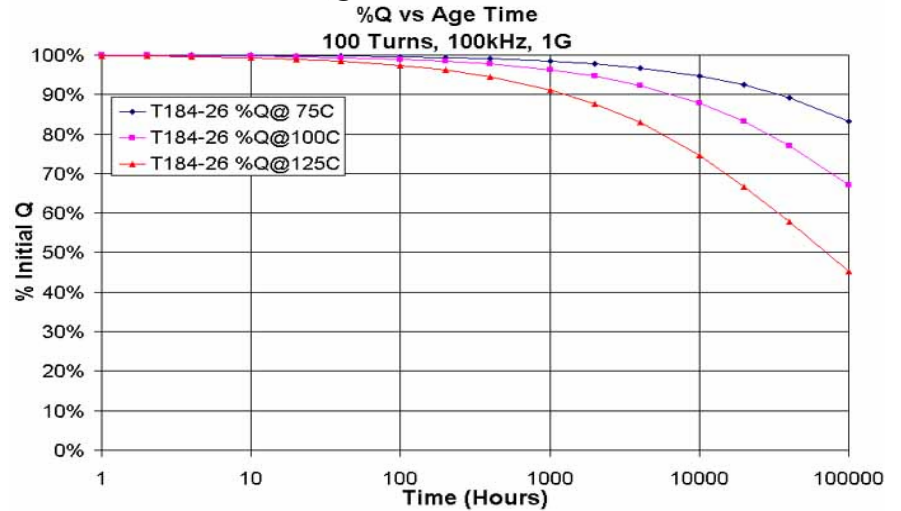
Hdc=34.62A/m, Pc=647 (kw/m<sup>3</sup>)

# 铁粉芯的老化问题

## 铁芯损耗随时间的变化曲线



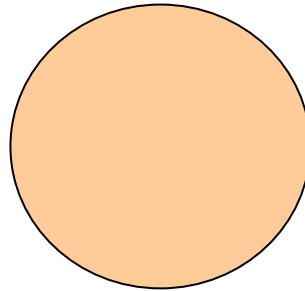
## %Q 随时间变化曲线



## 电感失效



Micro eddy currents  
in each particle



Macro eddy currents  
among particles

