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WIDE TEMPERATURE CORE LOSS CHARACTERISTICS OF TRANSVERSE MAGNETICALLY ANNEALED AMORPHOUS TAPES FOR HIGH FREQUENCY AEROSPACE MAGNETICS

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ABSTRACT

100 kHz core loss properties of sample transverse magnetically annealed, cobalt-based amorphous and iron-based nanocrystalline tape wound magnetic cores are presented over the temperature range of -150 C to 150 C , at selected values of B_{peak} . For B-fields not close to saturation, the core loss is not sensitive to temperature in this range and is as low as seen in the best MnZn power ferrites at their optimum temperatures. Frequency resolved characteristics are given over the range of 50 kHz to 1 MHz, but at $B_{\text{peak}}=0.1\text{ T}$ and 50 C only. For example, the 100 kHz specific core loss ranged from 50 mW/cm^3 to 70 mW/cm^3 for the 3 materials, when measured at 0.1 T and 50 C . This very low high frequency core loss, together with near zero saturation magnetostriction and insensitivity to rough handling, makes these amorphous ribbons strong candidates for power magnetics applications in wide temperature aerospace environments

INTRODUCTION

In most power converter and inverter circuits that utilize magnetic components, the inductors and transformers are a major contributor to mass and bulk. With internal operating frequencies of such aerospace power conditioners now being about 100 to 500 kHz, the magnetics losses nevertheless remain an order of magnitude below the total losses in the solid state switches and diodes. At this level, the magnetics losses detract less than 1% from an overall conversion efficiency that can reach 95%.

The concern to minimize losses at even the lowest levels arises from the multiplicative composition of the efficiencies of power processing blocks, chained in series and delivering a specified load power P_{load} . Thus the overall efficiency of a chain is $\epsilon \equiv (\epsilon_1 \cdot \epsilon_2 \cdot \dots \cdot \epsilon_n)$ and generates a power loss of $(\epsilon^{-1} - 1)P_{\text{load}}$. The loss power usually amounts to waste heat that adds to the size of the heat rejection apparatus in aerospace applications.

The input power $P_{\text{in}} (=P_{\text{load}}/\epsilon)$ is invariant under a permutation of the order of the processors in the chain. A

given perturbation of the efficiency of the i^{th} processor from the start of the chain (i.e., let $\epsilon'_i = \epsilon_i + \delta_i$) induces a reduction

$$\Delta P_{\text{loss}} = \Delta P_{\text{in}} = -\left(\frac{P_{\text{load}}}{\epsilon}\right) \frac{(\delta_i / \epsilon_i)}{1 + (\delta_i / \epsilon_i)} \quad (1)$$

in the total losses, or input power. The result is the same for any i as long as the fractional change (δ_i / ϵ_i) is the same. The overall efficiency ϵ will often be considerably less than unity, in effect amplifying the fractional increase (δ_i / ϵ_i) .

And this consideration is further constrained by a consensus that 'progress' requires both system mass and individual building block, i.e. converter, mass to be minimized. A percent efficiency gain is significant and valuable in advanced power conditioners, whereas a device that adds mass to achieve this is hard to sell. Thus in the context of aerospace applications, a magnetic material that can maintain a lower core loss over the applicable temperature range can provide a basis for nosing out the competition.

Amorphous ribbons of certain metallic alloys, usually based on Co and/or Fe, are well known to exhibit extremely low core loss [1, 2], that is as low as that of the best ferrites in the above frequency range and nowhere near as temperature sensitive. Moreover, their B-H characteristics can be controlled from highly square to linear by magnetic anneal and, in some cases, by partial recrystallization. Instability of magnetically interactive defects in the amorphous structure contributes to the very low coercivity [1]. Near zero ($\lambda_s < 0.1 \times 10^{-6}$) saturation magnetostriction can be obtained in the Co-based ribbons. And these amorphous materials have a plastic yield strength 5 to 10 times that of say the competing crystalline Ni-Fe magnetic materials (Permalloys, 50%Ni-Fe), making the magnetic properties of the amorphous tapes insensitive to rough handling. It has been recognized now for over a decade that these amorphous ribbons or tapes represent an advanced technology permitting new solutions for high frequency aerospace magnetics.

This work presents the core loss properties of a few sample amorphous and partially recrystallized

('nanocrystalline') tape wound cores. Most of the data was taken at 100 kHz (sinusoidal) over the temperature range of -150 C to $+150\text{ C}$, at selected peak B-fields (B_{peak} , or B_p). Specific core loss data is also presented as a function of frequency, but only for $B_p=0.1\text{ T}$ at 50 C . Although not exhaustive, this data provides an overview sufficient for first cut design decisions. It is also spans a wider temperature range than is available in the literature.

SAMPLE CORES

Unpackaged cores, listed in Table I, were obtained from Vacuumschmelze GmbH. They are representative of commercially available, competitive types and are not intended to be a specific endorsement. These cores fit in a nominal size group specified by height=0.25", ID=1.00" and OD=1.25", although their actual dimensions deviated slightly. Stated tape thickness for the 6025F and 500F materials was about $23\text{ }\mu\text{m}$ (0.91 mil) and about $17\text{ }\mu\text{m}$ (0.67 mil) for the 6030F material.

The 6025F is a Co-based, relatively low saturation induction (B_s), very low core loss, high permeability, transverse magnetically annealed type, intended for fast pulse transformers and common mode chokes. The 6030F is also a Co-based, low core loss, transverse magnetically annealed material, but with a lower permeability, a lower temperature sensitivity, better linearity and a higher B_s . The 6030F is intended for power and pulse transformers that require a low remanent induction. The 500F is a low core loss, Fe-based material of unspecified composition and anneal. Most likely it is an Fe-Si-B based, partially recrystallized metallic glass having a very fine grain structure of nanometer sized bcc Fe crystals throughout the bulk, that has been subjected to a transverse magnetic anneal. Its composition thus may be similar to that of the Hitachi Metals, Ltd. *Finemet* alloy ($\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$) [3], where the simultaneous presence of both Cu and Nb is known to enhance the soft magnetic properties of this optimally annealed, partially recrystallized amorphous, Fe-Si-B based alloy. Also, the possibility of extra surface recrystallization to induce a compressive stress magnetic anisotropy in the bulk, perpendicular to the surface of the ribbon, exists [4]. According to the manufacturer, the 500F is a high permeability, flat B-H loop material, having extra thermal stability and intended for high frequency inductor, transformer and common mode choke applications. The λ_s is specified to be less than 0.2 ppm for the 6025F and 6030F materials, and less than 0.5 ppm for the 500F.

MEASUREMENT TECHNIQUE

Bare cores were placed in thin walled aluminum cases that were closed on top by an insulating washer. cursory checks showed that the eddy current losses in these cases were negligible under the measurement conditions. This arrangement permits the cores to be tested over a wide temperature range without adverse effects from an encapsulant. The low value of λ_s ensures that buildup of magnetostrictive resonances is not a concern in these undamped cores.

Data consisting of waveforms of the current in a primary exciting winding and induced voltage in a secondary sense winding were recorded by a digitizing oscilloscope. The current sensor was a Pearson model 2877 current transformer and the oscilloscope was a Tektronix model TDS 540. The secondary voltage was sensed differentially, simply by channel subtraction. The driving amplifier was a push-pull arrangement of two Apex model 19A high power operational amplifiers. At times a parallel tuning capacitor was used to relieve the amplifier from handling reactive current. With 3 well matched oscilloscope probes, in most cases this setup provided data accuracy better than 5% to at least 1 MHz and losses of the order of 1 part in 100 of volt-ampere product could be resolved. Depending on the frequency and B_p , either 5-turn or 10-turn windings were used. This type of measurement setup has been reported in a NASA soft magnetic materials evaluation program [5], as well as in published literature [6]. A new variation was the use of a gated signal burst, either in a single shot or a repetitive averaging mode, to decrease the duty cycle. Core temperature then could be held accurately constant while measuring very high core losses.

CORE LOSS CHARACTERISTICS

Temperature resolved specific core loss data at 100 kHz is presented in Figure 1 for the 3 materials discussed above. At the selected values of B_p , the curves naturally fall into triplet groups. At low temperatures, the lowest curve in each group is for the 6025F material, the next higher being for the 6030F and the highest being for the 500F. Magnetic saturation eliminates the 6025F from the $B_p=0.7, 1.0\text{ T}$ groups and the 1.0 T group has only the 500F.

Several observations are apparent from this data. First, the core loss is rather constant with temperature over a span of 300 degrees C, at least at the lower B_p . This is

similar to the properties of low loss Ni-Fe crystalline materials, such as Supermalloy.

As the temperature increases, the core loss of a material can start to increase disproportionately. Presumably this is due to the onset of magnetic saturation and is very prominent in Figure 1 for the 6025F, which has the lowest Curie temperature T_c as well as the lowest B_s . As B_p is increased, the effect becomes prominent also for the 6030F, which has the next higher T_c and B_s . Thus, as concerns losses, temperature effects can significantly influence, or even reorder, the relative ranking of these materials at a given B_p .

A word about tolerable core loss is appropriate here. In previous NASA reports, a steady specific core loss exceeding about 1.7 W/cm^3 in metallic tape wound cores has been considered impractical, from the standpoint of heat removal. A number of points presented in the data above are far in excess of this value, having been taken by a low duty cycle, signal burst method. Such high loss operating points would likely be applicable to pulse power only. Moreover, long term operation of a 6025F core at 150 C would likely cause magnetic degradation, because magnetic anneals are usually performed at a temperature near T_c .

Finally, the 100 kHz core loss of these amorphous and partially amorphous materials is indeed low. For comparison to a lowest loss crystalline material, the 100 kHz specific core loss of $17 \mu\text{m}$ (0.67 mil) Supermalloy tape at 0.1 T is estimated to be 135 mW/cm^3 . The only competition comes from certain low loss MnZn type ferrites, which can have comparably low losses: about 50 mW/cm^3 at 100 kHz and 0.1 T . However, the losses in ferrites are very temperature dependent and the 50 mW/cm^3 value only holds over a narrow temperature range.

Due to project limitations, a frequency scan of the core loss was performed only at 50 C and a B_p of 0.10 T . Such data is of course valuable for broad band transformer applications and especially to evaluate the figures of merit of the material for resonant and filter inductor applications. Figure 2 shows the data obtained for the 3 materials to be the roughly straight lines usually seen for such log-log plots. Estimates of these specific core loss (\bar{p}_c) curves for other values of B_p can be made by a parallel shift of the curves in Figure 2, based on the data versus B_p at 100 kHz (Figure 1).

Using least squares fits to the data, the following estimates of \bar{p}_c were obtained:

$$6025\text{F: } \bar{p}_c = 2.44 B_p^{2.22} f^{1.76}$$

$$6030\text{F: } \bar{p}_c = 1.32 B_p^{2.08} f^{1.86}$$

$$500\text{F: } \bar{p}_c = 1.87 B_p^{2.09} f^{1.81}$$

Here \bar{p}_c is in mW/cm^3 , if B_p is in T and f in kHz . These estimates become poor for B_p approaching saturation.

SUMMARY AND CONCLUSIONS

100 kHz core loss data was obtained over the temperature range of -150 C to 150 C for two amorphous and one partially recrystallized core materials. All of the selected materials have low magnetostriction ($\sim 0.2 \times 10^{-6}$) and a flat magnetization characteristic induced by transverse magnetic annealing. Each of these was picked to be representative of a class of commercial products:

1. A relatively low saturation ($\sim 0.5 \text{ T}$), cobalt based, amorphous tape, having very low losses and a low frequency permeability of the order of 10^5 . (Such as type 6025F).
2. A higher saturation ($\sim 0.8 \text{ T}$), cobalt based, amorphous tape having low losses, a relatively low, but perhaps more stable, permeability ($\sim 3 \times 10^3$) and a higher Curie temperature. (Such as type 6030F).
3. A more recently developed, iron based, nanocrystalline tape, featuring some of the desirable soft magnetic properties of the cobalt based, amorphous tapes, but at a lower cost. (Such as type 500F).

As expected from the manufacturer's literature, the core loss of these materials was indeed very low. At 100 kHz and 0.1 T , the specific core loss was about 50 mW/cm^3 , and relatively constant from -150 C to 150 C , for the amorphous 6025F material. This is as good as the best MnZn power ferrites can do at their optimum temperatures. Under these conditions, the highest specific core loss seen was about 70 mW/cm^3 , for the nanocrystalline 500F material. As long as operation was at low B-fields, the specific core loss was rather insensitive to temperature in the above range, for all 3 materials. At higher B_{peak} , above say 0.2 T , the significant increase in specific core loss seen above a certain temperature may be attributed to onset of magnetic saturation, as the effect appeared to be ordered according to the Curie temperatures of these materials.

A frequency scan of the specific core loss of these materials showed the characteristics to be the usually seen, more or less straight lines on a log-log scale. This was done from 50 kHz to about 1 MHz, but only at 0.1 T and 50 C. The core loss frequency slope was somewhat less than for an f^2 dependence for all 3 of these materials, with the 6030F being the closest to f^2 .

All three types of materials characterized here are suitable for very low loss, flux ratcheting resistant, high frequency power transformers, but they are not suitable to make up high Q, or high current inductors, unless cut and gapped to lower their permeability. A parallel inductor-resistor circuit is used in reference [7] to model the linear magnetization properties of the above materials and to explore their applications to inductive elements.

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Table I. Physical Properties of the Core Materials Characterized.

Type	Composition	B_s (T)	T_c (C)	T_x (C)	ρ ($\mu\Omega\text{m}$)	δ (g/cm^3)	λ_s (10^{-6})
6025F	(CoFeMo) ₇₃ (SiB) ₂₇	0.55	210	540	1.35	7.70	< 0.2
6030F	(CoFeMnMo) ₇₇ (SiB) ₂₃	0.80	350	480	1.30	7.75	< 0.2
500F	(?)	1.2	600		1.15	7.35	< 0.5

B_s - saturation magnetic induction

T_c - Curie temperature

T_x - recrystallization temperature

ρ - electrical resistivity

δ - density

λ_s - saturation magnetostriction

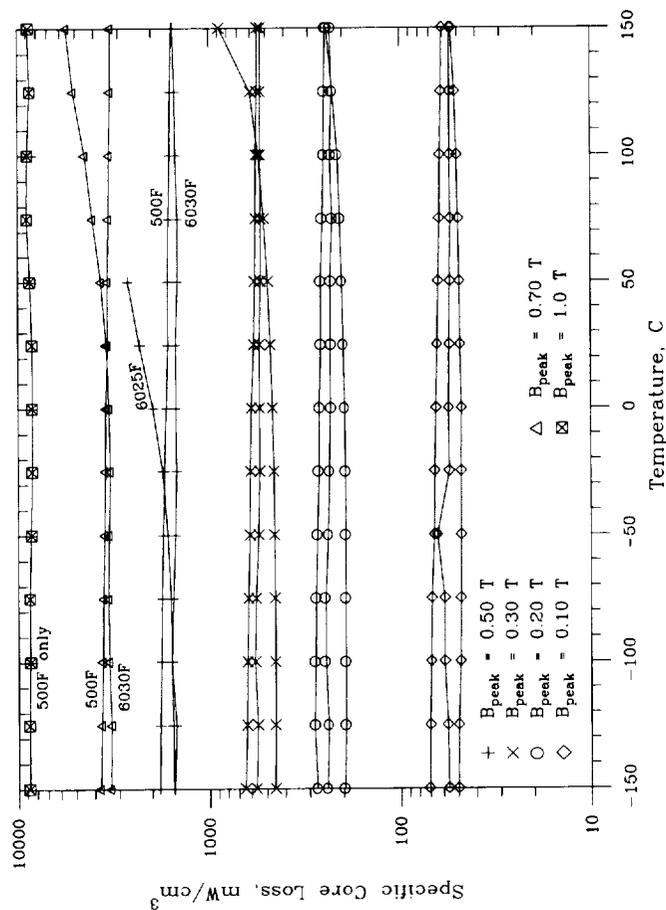


Figure 1. Losses in amorphous tape-wound cores at selected peak flux densities. Excitation: 100 kHz sine wave. Materials in each B_{peak} group, in order of decreasing losses at low temperature: 500F, 6030F, 6025F.

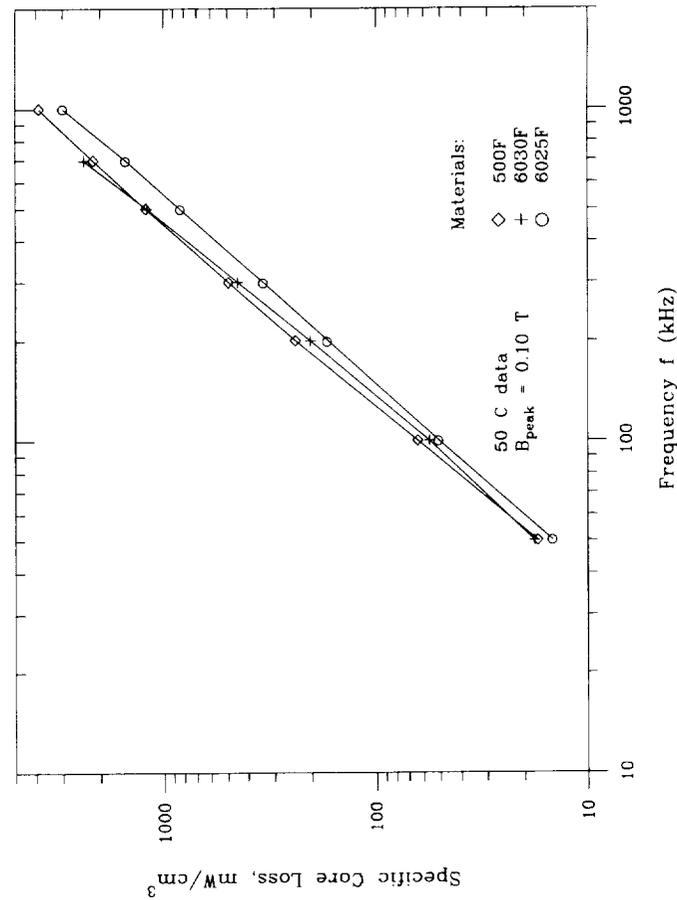


Figure 2. Frequency dependence of the specific core loss of the 6025F, 6030F and 500F tape materials at 50 C and 0.1 T.

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