INDUCTION CORE PERFORMANCE*

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Abstract

Large masses of magnetic core material are required for many of the induction accelerator-based projects currently under study; the quantities required exceed 10^7 kg for a linear heavy-ion fusion driver, so core performance and cost are critical issues. We have evaluated cores of amorphous alloys from AlliedSignal and MRTI (Moscow Radio Technical Institute) and nanocrystalline alloys from Hitachi and Vacuumschmelze. The cores were of moderate size, between 1 and 11 kg. We characterized the materials in terms of the flux swing ΔB from $-B_{remanent}$ to $+B_{saturation}$, and the energy loss versus dB/dt. We found sources for each material that could coat, wind, and then anneal the cores. This required the development of thin coatings that withstand 350-550^o C anneal temperatures. The result is core performance near the ultimate small sample performance of each material, with higher ΔB and lower losses than the earlier approaches of using as-cast material or rewinding after anneal, in both cases usually cowinding with thin mylar (~4μm thick). We are beginning system code studies of tradeoffs between ΔB and losses.

1 INTRODUCTION

In a previous paper[1] we showed that tape wound magnetic induction cores, processed by annealing after winding, produced superior performance to cores wound of as-cast material and not annealed, or to cores wound with previously annealed material. Annealing after winding is advantageous both to gain the full flux swing, and to wind while the material is still ductile. With annealing after winding, we achieved performance near the ultimate small sample performance[2]. The major technical challenge in annealing cores after winding is providing an interlaminar insulation[3], that reduces eddy current losses at high magnetization rates. The insulation must withstand annealing temperatures the order of 360^o C without applying mechanical stress to the amorphous metal ribbon, and must meet other requirements related to cost, lifetime and packing fraction which have been described in greater detail [1]. Two insulation techniques were used, mica paper in ribbon form of 18 μm thick, and inorganic coatings of <1 μm thick.

In this paper, we extend the previous work with measurements on cores manufactured from alloys produced by four manufacturers: the amorphous alloys 2605SC and 2605SA1 from AlliedSignal (USA), 9KCP, 30KCP, 2HCP, and 7421 from Amet (Russia); and the nanocrystalline alloys FT-1H from Hitachi (Japan), and VitroVac 800 from Vacuumschmelze (Germany). The 2605SC was insulated with mica paper, wound and annealed by LLNL (USA) [1]. The other materials were coated, wound, and then annealed: FT-1H by Hitachi (Japan), the four Amet alloys by MRTI - Moscow Radiotechnical Institute (Russia), 2605SA1 and VitroVac 800 by National-Arnold Magnetics (USA).

2 RESULTS

Our experimental methods for measuring core parameters have been discussed previously [1]. Briefly, we discharge a 1 μfd capacitor bank through a thyratron switch into 1 to 32 primary turns wrapped around the minor cross section of the toroidal cores. The core has been reset to $-B_{remanent}$. We measure the current through the primary and the voltage across a 1-turn secondary. The flux swing ΔB and the losses u(J/m^3) are referenced to the area and volume of alloy, determined by weight, not the geometrical area and volume of the core, i.e., we correct for the packing factor. The digital oscilloscope calibration was checked by the manufacturer to be within specifications (errors<1% of full scale), the voltage probe attenuation was adjusted to be within 1% over the range of time bases used (10-100 ns resolution), and the current transformer/terminator were also checked to be within 1%.

We summarize our findings in Table 1. We list each alloy by the manufacturers designation, and each core with an abbreviation of its manufacturers labeling. Each row represents a different core, except for 2605SA1, where data from one core is analyzed at 4 different flux swings, to allow direct comparison of the losses at the same flux swings as other alloys can achieve. We note that the loss increases more rapidly than the square of the flux swing (see scaling in Eq. 1 below) so that one can tradeoff increased core capital costs for reduced pulser capital and operating costs.

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Table 1: Core flux swing and loss for various alloys, all annealed after winding.

Alloy	Core No.	ΔB_{max}(T) (1 μs dur.)	ΔB_u(T)	C_1	C_2	u(J/m3) (1 μs dur.)	ID(m)
2605SC	C-12	2.46	2.30	171	583	651	0.125
2605SC	C-13	2.30	2.20	130	612	609	0.125
2605SC	C-14	2.39	2.30	144	591	633	0.125
2605SA1	NA-97	2.84	2.70	144	1341	1720	0.125
"	"	"	2.50	136	1158	1294	0.125
"	"	"	2.30	129	1068	1023	0.125
"	"	"	2.00	123	993	734	0.125
FT-1H	982-1	2.03	1.95	41.5	355	248	0.06
FT-1H	982-2	1.97	1.90	25.0	367	231	0.06
FT-1H	982-3	2.06	2.00	27.5	354	249	0.06
FT-1H	982-4	1.99	1.90	28.0	354	226	0.06
VitroVac800	NA-1	2.28	2.15	18.4	304	241	0.102
VitroVac800	NA-2	2.21	2.10	39.7	240	203	0.102
VitroVac800	NA-3	2.14	2.10	27.6	284	224	0.102
9KCP	06-01	2.40	1.85	84.6	773	486	0.327
9KCP	06-02		2.25	78.2	934	827	0.327
9KCP	08-01	2.79	1.75	-30.3	807	374	0.336
30KCP	00-01	2.69	2.60	221	848	1147	0.115
30KCP	01-01	2.53	2.45	139	1027	1123	0.110
30KCP	05-01	2.30	2.25	65.5	1032	895	0.326
2HCP	03-01	2.49	2.3	137	530	575	0.110
2HCP	03-02	2.59	2.30	263	440	614	0.110
2HCP	07-01	2.26	2.15	77.3	756	626	0.327
7421	04-01	2.07	1.90	128	843	584	0.110

The usable flux swing ΔB_u is slightly smaller than $\Delta B_{max} = B_{saturation} - (-B_{remanent})$. It is obtained by applying four criteria to a sampling of the 20-70 data records of primary current and secondary voltage for each core, each record at a different level of pulser charge or number of primary turns. The four criteria are:

(1) The primary voltage is dropping;

(2) The current is beginning to rapidly increase above its average level;

(3) The loss per unit flux change approximately doubles; and

(4) The core impedance drops to 0.1-0.25 of peak value.

While these criteria are only semi-quantitative, the uncertainty in the flux swing is usually within 0.1 T. A more precise, engineering, determination of the usable flux swing depends on the design of the pulser and the requirements on the precision of the core voltage output. The values listed in Table 1 are a reasonable match to the assumptions of the systems code[4] with which we are evaluating accelerator architectures and components. This code assigns portions of the flux swing to the rise and fall of the pulse voltage, before and after the beam passes, while the central portion of the pulse must accurately match the desired pulse form in order to properly accelerate and shape the beam. The sag in the voltage can then be assigned to the fall time. For comparison, ΔB_{max} and the loss u(J/m3) for a 1 μs pulse duration are also listed. We note that ΔB_{max} in Table 1 is generally less than published small sample values; this may indicate that further development is needed in core manufacturing technologies.

The losses are fit with the 2-term loss criterion of Faltens' [1],

$$u\left(\frac{J}{m^3}\right) = C_1\left(\frac{\Delta B}{2.5T}\right)\left(\frac{t}{25\mu m}\right) + C_2\left(\frac{\Delta B}{2.5T}\right)^2\left(\frac{1\mu s}{\tau}\right)\left(\frac{t}{25\mu m}\right)^{1-2}$$

where τ(μs) is the pulse duration, and t(μm) is the thickness of the ribbon with an exponent of 1 or 2 (an exponent of 1 is used in here). We set t = 25 μm to compare cores made with alloys of unknown thickness. The ultimate capabilities of the different materials would be more fairly compared if the tape thicknesses were used in Eq. 1. C_1 (which represents dc hysteresis losses) and C_2 (which represents the fast-pulsed losses due to eddy currents and domain wall motion) are determined by a least-squares fit to the data.

The data and fit are shown in Figs. 1-3 for 2605SC, 2605SA1, and VitroVac 800 respectively. The fit is seen to be best for the VitroVac 800, but lies above the data

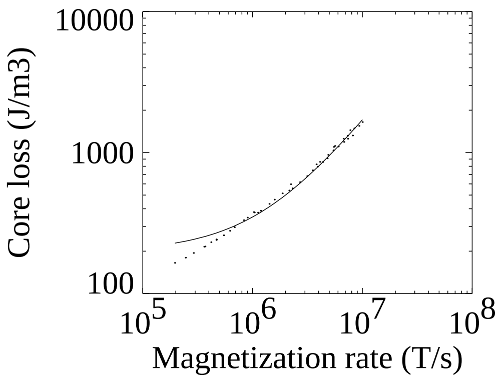

Fig. 1. 2605SC C-14 data shown by dots, fit by line, $\Delta B = 2.3$ T.

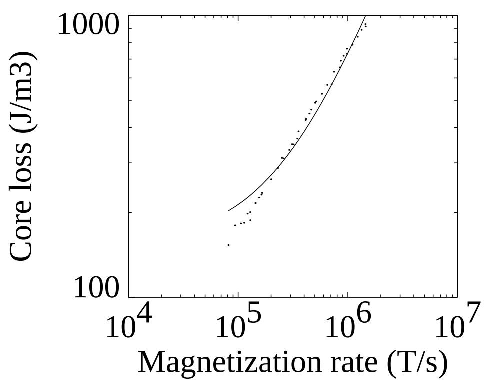

Fig. 2. 2605SA1 NA-97 data, $\Delta B = 2.7$ T.

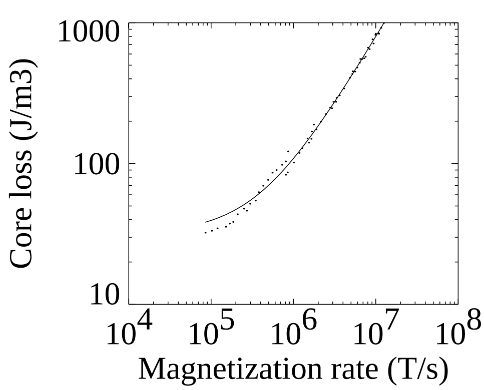

Fig. 3. VitroVac 800 NA-2 data, $\Delta B = 2.1$ T.

for low magnetization rates in each example. In some cases, the fit is very poor, e.g. core 08-01 where C_1 is negative. We are looking at alternative models with which to better characterize the data.

The consistency of amorphous metal cores has been an area of concern, see for example, Ref. [5] where the standard deviation in loss per volume ranged from 14-29% for 3 sizes of 38 cores of 2605SC. While we don't have sufficient cores of any one alloy to obtain reliable standard deviations, we compute 3% with 2605SC and we find three other alloys that also have <10% standard deviations of loss: FT-1H, VitroVac800, and 2HCP. The first two are nanocrystalline alloys. The MRTI cores (the bottom 10 rows) come in three geometries: The inside diameter of the cores is listed in the last column of Table 1. Cores with diameters near 0.1 m have masses between 1.6 and 2.3 kg. Cores with diameters near 0.3 m have masses between 5.4 and 6.1 kg. All of the MRTI cores use 0.020 m wide ribbon, except for 08-01 that uses material slit to 0.009 m wide and weighs 2.5 kg. We see that cores with a similar geometry are grouped more closely than those of different geometry.

The capital cost of cores is minimized with 2605SA1, which is manufactured in large quantities for use in 60 Hz transformers. Its cost varies from \$20/kg in small quantities to an estimated <\$4/kg in lots larger than 10^5 kg. It also has the largest flux swing, which minimizes the amount of core material needed. However it has the highest loss per pulse, at the same flux swing its losses are about 1.5-2 x that of 2605SC, and at maximum flux swing they are near 3x that of 2605SC. And compared with nanocrystalline, the losses are 3-7x higher.

The operating costs of an accelerator are minimized with the nanocrystalline alloys: the losses are down a factor of 7 compared with 2605SA1 at maximum flux swing. However, more material is needed, by at least the ratio of the flux swings (2.7/(1.9-2.15) = 1.25-1.4), and by more if a large build-up is needed. The material is also more expensive: most of the components are similar to those in the amorphous alloys 2605SC and 2605SA1, the major difference is the addition of 3% niobium. The niobium will increase the ultimate cost of the materials in large quantities by ~\$1/kg of alloy. The additional capital costs will be partially offset by the reduced cost of pulsers. These and other tradeoffs are being investigated with a systems code [4].

3 REFERENCES

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