# NEW NANOCRYSTALLINE CORE PERFORMANCE VERSUS FINEMET® FOR HIGH-POWER INDUCTORS

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## ABSTRACT

Advanced power electronic component development is critical for increasing power density for future military hybrid-electric ground vehicle systems. The design and development of compact, high-power, and high-temperature inductors for a 150 kW, DC-DC bi-directional converter is presented. The converter requires four 25 μH inductors, each rated for continuous operation at 37.5 kW. With goals of reduced component volume and improved thermal management, inductor performance for commercially available FINEMET® FT-3M and newly developed HTX-002 nanocrystalline core material is compared.

## 1. INTRODUCTION

Hybrid-electric vehicles (HEV) and their supporting technological advancements have been the subject of many research efforts over the past few years. One of these efforts has focused on the design and development of an interleaved, multi-phase, high-power, DC-DC bi-directional converter (Urciuoli and Tipton, 2006). In this application, reducing the volume and mass of the converter is critical to meet system goals. However, each phase of the converter requires a large inductor that must be capable of transferring 37.5 kW of power continuously and be able to provide in excess of 40 kW during peak demand.

The challenging design task of fabricating high-power inductors and the merits of using nanocrystalline core material has previously been reported (Salem et al., 2007). The primary advantage of using this advanced material is realized in the overall thermal management system, where the nanocrystalline material offers cooling system size and weight reduction compared to that required for other core materials. Further system level improvements in thermal management are examined by using a new nanocrystalline alloy (HTX-002) for the core material of the high-power inductor. Preliminary characterization of the HTX-002 core material indicated that it would exhibit greater loss than FINEMET® FT-3M in this application. However, it was anticipated that the higher saturation flux density, lower permeability, and higher operating temperature range of the HTX-002 material could provide overall performance benefits.

This paper begins with specifications of a commercially available nanocrystalline alloy (FINEMET® FT-3M). Next, the development of a new nanocrystalline alloy (HTX-002) is presented. A discussion of the fabrication of power inductors using both core materials is followed by details of the experimental test fixture and evaluation procedure. Finally, results and analysis are discussed.

## 2. NANOCRYSTALLINE CORE MATERIALS

Alloys of FINEMET® FT-3M and HTX-002 core materials, compared in this study, are melt spin cast into tape form in the amorphous state. FT-3M is cast to a thickness of 18 μm, compared to an HTX-002 tape thickness of 25 μm. Toroidal cores are wound from each tape and impregnated with a binder for strength prior to annealing. Finally, the cores are cut to allow gapping for a specific inductor design.

### 2.1 FINEMET® FT-3M

FINEMET® FT-3M, developed by Hitachi Metals, is a nanocrystalline magnetic material formed by annealing amorphous ribbon consisting of Fe, Si, B, Cu, and Nb. The ribbon is made by spin casting the molten alloy on a cooling wheel to achieve rapid quenching, preventing crystallization and preserving workability of the material. After forming a tape wound core from the amorphous ribbon, the material is crystallized in an annealing profile at a temperature at-or-above 500 °C for on-the-order-of one hour. The resulting core material has a grain size of approximately 10 nm and a saturation flux density of 1.23 T for a maximum operating temperature of 125 °C. At 20 kHz, initial relative permeability is approximately $3.1 \times 10^4$ (Hitachi, 2007). Loss data for impregnated, annealed, uncut core material was determined empirically by MK Magnetics, Inc.; the core manufacturer (MK Magnetics,

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2008). From this data, the coefficients $k$, $\alpha$, and $\beta$ of the Steinmetz equation (1) were calculated to be 3.1, 1.2, and 2.0, respectively. Units for power loss, frequency, and maximum flux density are watts per kilogram (W/kg), kilohertz (kHz), and Tesla (T), respectively. An inductor core was fabricated from the FT-3M material, having an outer diameter of 10.8 cm, an inner diameter of 3.38 cm, and a height (ribbon width) of 4.50 cm; thus it occupied a volume space of 372 $cm^3$.

$$P_{loss} = k\ f^{\alpha}\ B^{\beta} \qquad (1)$$

### 2.2 HTX-002

Magnetics Inc. in conjunction with Carnegie Mellon University (CMU) has developed a series of high-temperature experimental alloys and processes for fabricating nanocrystalline magnetic cores. The U.S. Army Research Laboratory provided funding and collaborative research efforts in support of this work. The need for high power density magnetic components was motivation for the development of high saturation flux density and low-loss materials.

From several compositions, an alloy designated as HTX-002 exhibited a favorable combination of properties. The alloy containing Fe, Co, Nb, B, Si, and Cu was processed as described in (Long et al., 2008). After annealing, the resulting average grain size was determined to be 12 nm. The material has a saturation flux density of 1.47 T at a maximum operating temperature of 300 °C. At a 20 kHz operating frequency, initial relative permeability is 1.5 x $10^3$. Magnetics, Inc. reports Steinmetz equation coefficients of 4.3, 1.7, and 1.9 for $k$, $\alpha$, and $\beta$, respectively. Table 1 summarizes material properties for both cores.

Table 1. Nanocrystalline Material Properties

| | FT-3M | HTX-002 |
|---|---|---|
| $B_{SAT}$ (T) | 1.23 | 1.47 |
| Max Temp. (˚C) | 125 | 300 |
| Initial Relative Perm. | 3.1 x $10^4$ | 1.5 x $10^3$ |
| Loss (0.2T,20 kHz) (W/kg) | 4.77 | 32.9 |
| Mass (kg) | 2.3 | 1.4 |

Based on MK Magnetics Inc. and Magnetics Inc. material data.

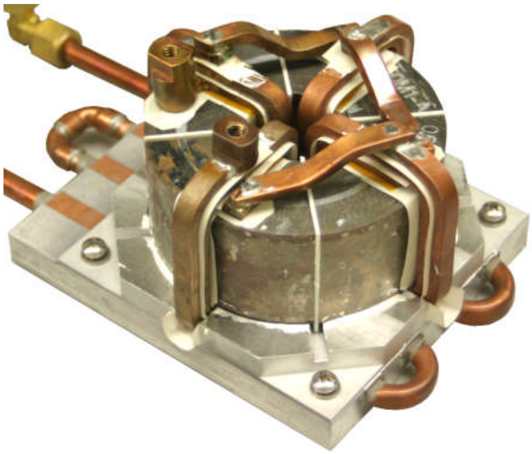
Using the HTX-002 material, an inductor core was fabricated having an outer diameter of 10.8 cm, an inner diameter of 3.51 cm, and a height (ribbon width) of 2.79 cm. Ribbon width was limited by processing equipment and resulted in a smaller core cross sectional area and a proportionally higher flux density compared to the FT-3M core, for a given test condition. The HTX-002 core occupied 229 $cm^3$; a 38% reduction in both volume and mass compared to the FT-3M core. However, experimentation was necessary to determine if the combination of material properties and the inductor design would support the use of HTX-002 material.

## 3. INDUCTOR FABRICATION

The design of a nanocrystalline core based inductor for the bi-directional HEV converter application was obtained from Premag, Inc. The selected approach offers small size and low weight from a thermal management system perspective at the converter level. Inductors were built from both the FT-3M and HTX-002 cores. Torodial tape wound cores were cut into four equivalent sections to provide adjustable gap length to achieve the desired inductance value. Each core section had a 0.86 cm wide and 0.48 cm thick copper two-turn winding, insulated with Nomex®. Each of the four gaps of the FT-3M inductor was set to 0.16 cm, yielding a total core gap of 0.64 cm and a measured inductance of 24.2 μH at 10 kHz. The gaps of the HTX-002 inductor were fixed at 0.10 cm for a total core gap of 0.40 cm and a measured inductance of 23.5 μH at 10 kHz. Each core section was attached to a custom aluminum base plate using a thermally conductive electrically isolating epoxy. Winding sections were connected above the core by a segment of winding material and terminals were attached using solder. The base plate assembly was mounted to a D6 Industries HYDROBLOK-Al-4P-06 liquid-cooled heat sink. Figure 1 shows the completed inductors.

Inductors have loss components that are empirically difficult to isolate and quantify. Resistive winding losses and non-linear winding current distribution due to skin effect can be identified. However, proximity effect and stray flux effects on winding current distribution are not easily calculated. Although core material losses can be determined using the Steinmetz equation, losses associated with discrete core gaps not only influence core loss, but also setup eddy currents in local conductive bodies. Core materials having high permeability require larger air gaps that increase stray flux. In packaged converter applications, these losses typically increase with gap length. In such cases, gap losses can be the dominant inductor loss component.

Both inductors had the same form factor except the core cross-section of the HTX-002 inductor was smaller than that of the FT-3M inductor. Although this resulted in a shorter winding length, an insignificant difference in total inductor loss was expected from differences in winding losses. Based on the Steinmetz coefficients for each material, the core loss was expected to be nearly 16 times greater for the HTX-002 inductor at the 20 kW converter operating point. However, the loss associated with the smaller HTX-002 core gaps, resulting from lower core permeability, was expected to be less than the corresponding loss for the FT-3M inductor.



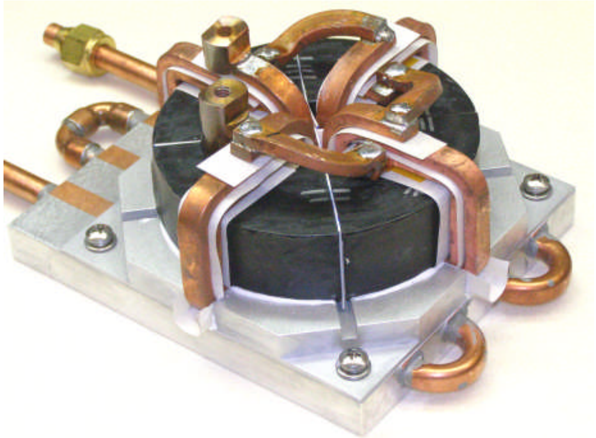


Fig. 1. FINEMET® FT-3M inductor (top), HTX-002 inductor (bottom).

## 4. EXPERIMENTAL EVALUATION

The inductors were operated using a single-phase 30 kW DC-DC boost power-stage test fixture. The power-stage was run in open-loop mode with the duty cycle adjusted in the range of 40% to 50% to achieve the desired output power level and to ensure that the inductor current was always in the discontinuous conduction mode. The input and output voltages used in the test fixture were also adjusted to facilitate the desired power level while maintaining a voltage conversion ratio of two.

Power dissipation data and thermal mapping for each inductor was captured using a thermo-anemometer chamber and an infrared camera. Testing was conducted in a controlled environment with an ambient temperature maintained between 23 °C and 24 °C. The barometric pressure was nearly constant but the relative humidity varied by as much as 10%. Ambient temperature, barometric pressure, and humidity as well as output air temperature and air velocity of the anemometer chamber were recorded. Tests were run to thermal equilibrium, each of which required approximately one hour. Inductor power dissipation, at a peak current of 251 A and a converter output power of 20 kW was determined by the process discussed in (Salem et al., 2007). Results of these tests showed that the FT-3M inductor had a power loss of 220 W compared to a loss of 475 W for the HTX-002 inductor. As previously stated, HTX-002 core material losses combined with a smaller core cross section led to a projected core loss of nearly 16 times that of the FT-3M inductor. However, the HTX-002 inductor loss was just over twice the FT-3M inductor loss. This result can be attributed to the shorter gap length of the HTX-002 inductor resulting from the significantly lower permeability of the core material.

In another set of tests, the lid of the thermo-anemometer chamber was removed to allow thermal imaging of each inductor using a FLIR infrared camera. For these tests, inductor cooling was provided by a 50% by volume aqueous solution of propylene glycol at 23 °C circulated through the inductor heat sink at a flow rate of 1.1 gpm. Voltage and duty cycle values were adjusted to step the output power level through the range of 5 kW to 25 kW, in 5 kW increments. Each inductor was coated with boron nitride to provide a uniform surface emissivity for accurate thermal imaging (Salem et al., 2005). Infrared images of the inductor were captured at thermal equilibrium showing the top core and winding area, from which average core and winding temperatures were obtained. Figure 2 shows images of each inductor at thermal equilibrium for 25 kW operation and peak currents of 275 A and 280 A for the FT-3M and HTX-002 inductors respectively. Figure 3 shows plots of the average core and winding temperatures of both inductors over the tested range. As expected, the average HTX-002 core temperature is consistently greater than that of the FT-3M core, while the average HTX-002 winding temperature is less than the average FT-3M winding temperature at higher power levels.

## CONCLUSIONS

An inductor based on a new nanocrystalline magnetic core material, HTX-002, having lower permeability, higher operating temperature capability and higher saturation flux density than FINEMET® FT-3M was built. The HTX-002 inductor was tested against a similar FT-3M inductor in a boost converter operated at up to 25 kW with a switching frequency of 15 kHz. Inductor power loss was measured using a thermo-anemometer at the 20 kW converter output power level. Due to material processing limitations resulting in a shorter tape width, the HTX-002 core had 38% less cross sectional area than the FT-3M core. Despite also having inherently higher material loss, the HTX-002 inductor was shown to have a loss of only just over twice that of the FT-3M inductor.

This result is attributed to the smaller gap losses of the HTX-002 core enabled by its significantly lower relative permeability. Thermal imaging of the inductors provided inductor temperature data and illustrated loss distributions. HTX-002 nanocrystalline core material offers advantages for inductors requiring high power density and high-temperature operation. ARL is continuing to work with Magnetics Inc. and CMU to develop and evaluate new high-temperature, low loss, and low permeability core materials to reduce the size and weight of future military HEV systems.

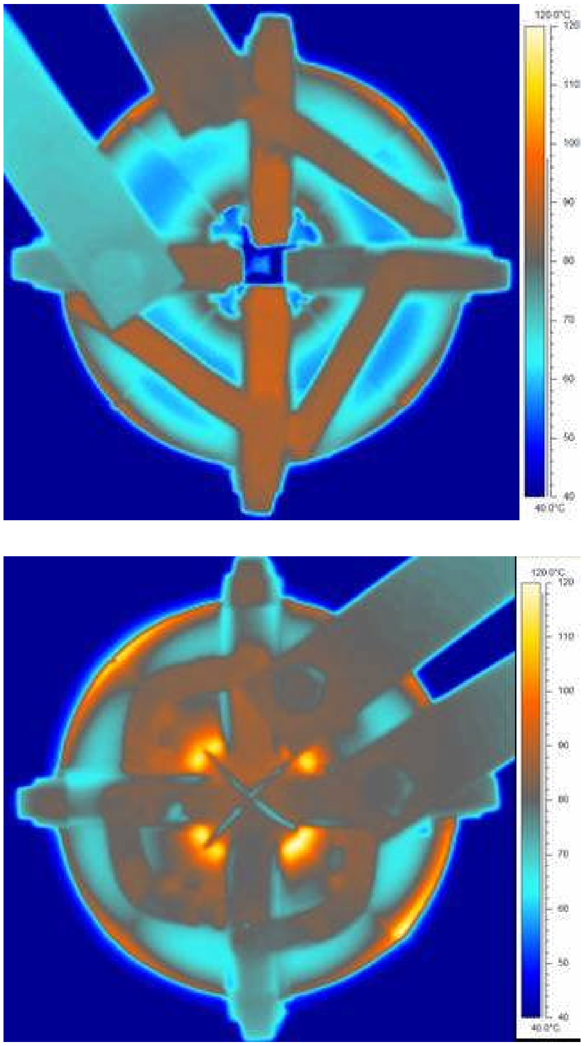


Fig. 2. Thermal images at 25 kW test at equilibrium: FINEMET® FT-3M inductor (top), new nanocrystalline HTX-002 inductor (bottom).

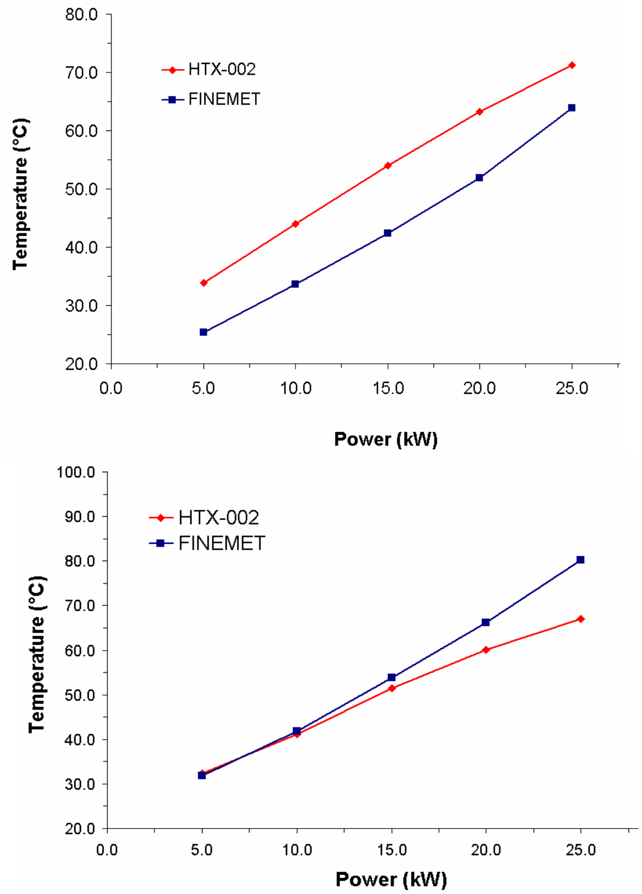


Fig. 3. Average core (top) and winding (bottom) temperatures over operating power range.

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