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A Comparative Study: Dynamic and Thermal Behavior of Nanocrystalline and Powder Magnetic Materials in a Power Converter Application

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In the design stage of power electronics applications, such as power converters, lack of components precise characterization and losses diagnosis has unacceptable effects on system's efficiency, reliability and power consumption. Passive components, especially magnetic ones, play a key role in power converters. Therefore, accurate characterization and modeling of magnetic materials is mandatory in order to predict their realistic behavior under variable operating conditions. Temperature is one of the conditions that induce major changes in a component's behavior by modifying the material's magnetic properties. This paper investigates the nanocrystalline and powder materials magnetic and thermal behavior in a DC-DC converter application. Core loss measurements under variable conditions are performed on toroid shape sample. Measured results are analyzed for different frequencies, flux densities, and temperatures.

Keywords: *Magnetic behavior, Thermal behavior, Magnetic losses, Materials characterization, Nanocrystalline and Powder Materials, DC-DC power converter*

I. Introduction

The increasing demand of low power consumption and high efficiency devices force designers to precisely analyze losses in each component constituting an electronic system [1]. Magnetic components constitute a major part of electronics devices, especially power converters [2], thus behavior and loss analysis of these components is essential [3]–[5]. In fact nonlinear characteristics of magnetic materials and both dynamic and thermal effects have a non-negligible influence on device performance [6]. Mainly, three kinds of magnetic materials are used in power converters: ferrite, iron powder and nanocrystalline materials. Powder and nanocrystalline materials have higher saturation flux density, lower hysteresis losses, and lower DC bias effects than ferrites but ferrites have lower cost and lower losses at very high frequencies due to their high resistivity. Concerning thermal behavior, ferrites have lower operating and Curie temperatures. However, ferrites have been extensively studied unlike nanocrystalline and powder materials.

Based on this context, this paper investigates the magnetic and thermal behavior of both nanocrystalline and iron powder materials for power conversion applications. A comparison between these materials based on the application is provided. Static and dynamic characterizations of both materials are presented. A buck converter circuit with variable voltage, frequency and load is realized. Then core losses measurements under variable conditions are performed. Temperature effects on the performance of both magnetic cores are discussed as well.

II. Nanocrystalline and Powder Magnetic Materials

A powder core consists of small particles of pure iron and/or metal alloys, coated with a thin insulating layer and pressed to a bulk material at high pressure. The insulating coating reduces eddy currents by increasing the resistivity of bulk material and decreases the permeability by acting as small air gaps inside the core material. During compaction, internal stresses are generated in the material. A heat treatment process is applied to relieve these stresses and increases the strength of the powder core [7].

Magnetic nanocrystalline materials are formed by an assembly of regions of coherent crystalline structure (grains), having an average grain diameter from 1 to 50 nm, exhibiting magnetic order and embedded in a magnetic or nonmagnetic matrix. Ribbons of nanocrystalline alloys are made by rapid solidification, deposition techniques and solid state reactions where the initial material may be in the amorphous state and subsequently crystallized. The alloy composition, crystal structure, microstructure and morphology determine the material's magnetic properties [8].

Two toroid cores are chosen to be studied in a power converter application: A low permeability nanocrystalline core K44B200 (Fe-Si-B-Nb-Cu) provided by MECAGIS (Known as Aperam Amilly Alloys) [9] and a low permeability powder

core HKBH Sendust (Fe-Si-Al) provided by TOHO ZINK [10]. These cores are chosen for their small size (to maintain a small size converter) and low permeability (to avoid magnetic core saturation). The low permeability (down to $\mu_r=200$) nanocrystalline is a recent material resulting from mechanical stress annealing of amorphous material [11] [12]. This material possesses high saturation induction, low losses and very good linearity. The Sendust (Fe-Si-Al) powder materials invented in Japan have relatively low cost and are used in commercial converters [13]. They are known for their low losses and stable performance with temperature.

A. Materials Characterization

To characterize the presented magnetic materials, a B-H measurement test bench, controlled by a LabVIEW program is available. The test bench allows amplitude, phase-shift, form-factor and DC bias corrections. B-H measurements are performed on test transformers consisting of primary and secondary coils wound on the magnetic cores. Characteristics of these test transformers are shown in table 1. A sinusoidal current is applied to the primary winding, to create a magnetic field H according to Ampere's law (equation 1). The flux density B is derived from the measured secondary voltage according to Faraday's law (equation 2). Where, N_1 and N_2 are the primary and secondary number of turns respectively and A is the cross section of the magnetic material. This is a well-known and widely used measurement technique [14]. Static and dynamic measurement results for the powder core are shown in Figure 1 and Figure 2 respectively, while those for the nanocrystalline core are shown in Figure 3 and Figure 4.

$$\oint H(t) dl = N_1 i_1(t) \quad (1)$$

$$v_2(t) = N_2 \cdot A \cdot \frac{dB(t)}{dt} \quad (2)$$

Figure 1 shows a major static loop, and Figure 2 shows three dynamic minor hysteresis loops at 30 kHz for different applied flux densities of the powder material. Similarly, Figure 3 and Figure 4 represent static and dynamic hysteresis loops of the nanocrystalline material. Both materials have a thin static loop with a reversible behavior and a relatively low coercive field. This static behavior signifies low hysteresis losses and a good DC bias performance due to the good linearity of both materials. These materials properties, besides their low permeability allowing high DC current, make them good candidates for inductors used in power converters (like a buck inductor).

The dynamic behavior for these materials is shown by the increase of dynamic B-H loops area with frequency and flux density. This signifies higher iron losses (equivalent to B-H loop area) with higher frequencies and flux densities, which is common for all magnetic materials. Given the form of dynamic hysteresis loops the iron losses are expected to be low for frequencies up to 100 kHz. More details on iron losses are discussed in the next sections

B. Temperature Effects

Temperature influences the material's magnetic behavior by modifying its magnetic properties [15]. A nonlinear evolution of magnetic parameters (saturation magnetization, relative permeability, coercive field) as function of temperature exists [16] – [18]. Since different magnetic materials do not possess the same behavior for the same thermal conditions, performance of the system containing magnetic components depends greatly on operating temperature range. Thus, thermal effects must be taken into account before introducing materials in the application.

To study temperature influence on magnetic behavior, materials are characterized at different operating temperatures. One core from each material is used for all temperature testing. The materials under test are placed in a programmable thermal chamber (laboratory furnace) equipped with thermocouples placed in direct contact with the material. The thermal chamber provides a stable isolated test environment (air). Gradual temperature elevation is controlled with a time step of 15 minutes between each test temperature which is maintained for a dwell time of about one hour. After that, measurements are carried out for a short duration to avoid additional self-heating effects.

The relative permeability is measured at static conditions (1 Hz) under an applied flux density of 1T. Change of relative permeability with temperature for both iron powder and nanocrystalline materials are traced and shown in Figure 5. One of the temperature effects on the powder core magnetic behavior is the permeability decrease of 8% at 200 °C. Contrarily, temperature affects the nanocrystalline core by increasing its permeability to reach about 420 at 230 °C. This value is greater than double the initial value at 25 °C, indicating the sensitivity of this material to temperature.

These materials have an inverse variation of permeability as a function of temperature. The permeability of the studied iron powder material decreases and that of the nanocrystalline material increases with temperature. These results are not generalized to all iron and nanocrystalline materials. Since, for example, temperature effects on “high permeability” nanocrystalline materials are different, as their permeability decreases with temperature [19].

In addition to permeability, coercive field vary as well with temperature. Under the same static conditions, change of coercive field with temperature for both materials is measured and traced in Figure 6. Again, temperature affects inversely the studied magnetic materials. The coercivity of the powder core increases about 120% at 250 °C, while the coercivity of the

nanocrystalline core remains constant with temperature. From this point of view, the powder core seems to be more sensitive to temperature than the nanocrystalline core.

The change of both permeability and coercivity with temperature is reflected on magnetic losses. To clarify this point, static magnetic losses as function of temperature in both materials are measured and shown in Figure 7. This Figure shows the increase of static losses in the powder core by about 40% at 250 °C and the decrease of static losses in the nanocrystalline core by about 55% at 250 °C.

From Figures 5, 6 and 7, we can notice that the permeability increase is the dominant contributor to the decrease of static losses in the nanocrystalline material (permeability increased by a factor of 2 and static losses decreased by a factor of 2). However, for the powder core, the coercivity increase is clearly the dominant contributor to the increase of static losses. As a result, powder and nanocrystalline cores show inverse static behavior with increasing temperature. In fact, temperature affects the powder core by increasing its coercivity and increasing its static magnetic losses with a slight permeability variation. Contrarily, it affects the nanocrystalline core by increasing its permeability and decreasing its static losses with no coercivity variation.

It is believed that the magnetic anisotropy and the resulting low permeability of the stress-annealed nanocrystalline materials are due to the remaining stress after this annealing treatment [20]. This stress could be relaxed when exposed to high temperatures. In our case the stress is not relaxed after a short time exposure to 250 °C and both permeability and coercive field remained constant ($\mu_r = 207$ and $H_c = 10$ A/m). The Same observations apply to the powder core which keeps the same characteristics before and after temperature exposure.

The dynamic behavior of studied materials is critical. This behavior may vary differently according to the operating temperature and the corresponding application. In the next section, dynamic behavior of both iron powder and nanocrystalline materials is studied in a buck converter application.

III. DC-DC Converter Application

In DC-DC power converters, magnetic materials are excited with non-sinusoidal waveforms and are subjected to DC bias. Both non-sinusoidal waveforms and DC bias have non-negligible effects on magnetic losses [21] [22]. Indeed in buck converter, a pulse modulated voltage is applied on the inductor and a DC bias depending on the load exists. This creates non-centered minor hysteresis loops, consequently core losses prediction becomes complex.

A. Converter circuit

In order to investigate magnetic component behavior in buck converter application (Figure 8), a 40 W buck circuit shown in Figure 9 is realized (with $L=46 \mu\text{H}$ or $L=79\mu\text{H}$ and $C=4.7 \mu\text{F}$). The design allows different voltage levels and frequencies. Nanocrystalline core inductor with 30 turns copper wire is used in the circuit and can be easily replaced by another inductor. To precisely measure magnetic losses, a small shunt ($R_s=200 \text{ m}\Omega$) is added in series with the inductor and secondary turns are wound to the same core. The shunt allows precise current measurements, while open secondary side allows voltage measurement excluding copper losses.

B. Magnetic Losses

The total energy W absorbed per unit volume by the magnetic core is related to the area of the corresponding hysteresis loop as shown by equation (3). Thus the power lost during a period T is expressed by equation (4):

$$W = \oint H \cdot dB \quad (3)$$

$$P = \frac{1}{T} \int_0^T H(t) \cdot \frac{dB}{dt} \cdot dt \quad (4)$$

By substituting equations (1) and (2) in equation (4), we can express the magnetic losses per unit volume as function of primary current and secondary voltage of the inductor having N_1 primary turns and N_2 secondary turns, where V is the magnetic core volume.

$$P = \frac{1}{V \cdot T} \int_0^T \frac{N_1}{N_2} v_2(t) \cdot i_1(t) \cdot dt \quad (5)$$

Therefore using equation (5), Core losses are calculated from both primary current and secondary voltage measurements. These measurements are performed by a 1.5 – 6 GHz bandwidth, 40 GS/s LECROY oscilloscope. Core losses of both powder and nanocrystalline materials are measured under variable operating condition of the buck converter. Figure 10 represents the core losses in the buck as function of flux density and frequency (powder material) while Figure 11 represents the core losses in the buck as function of frequency and temperature (nanocrystalline material).

From Figures 10 and 11 we can notice the variation of losses with frequency, applied flux density and temperature. In general losses increase with frequency and applied flux density, which is the case for both studied materials. However these materials have different losses and behave differently under temperature effects. The behaviors of both materials in the buck application are compared below.

C. Materials Comparison in Application

Core losses per unit volume for both powder core HKBH and nanocrystalline core K44B200 materials are compared under a constant flux density (100 mT). Results are shown in Figure 12 for frequencies up to 80 kHz. We can notice that even the losses in powder material are relatively low, but they are about double the losses in nanocrystalline material.

Considering both materials as inductor cores in the buck converter operating at a constant frequency-to-voltage ratio (4 V-40 kHz or similar), the inductors will sustain the same frequency and voltage. But since both converters have the same load, they have the same DC current as well, and the same output power. So keeping the same frequency-to-voltage ratio when comparing both converters guarantees the same voltage, power and frequency on the one hand and a constant flux density on the other hand (useful to compare losses as frequency varies). In this case the loss difference between the two cores is much lower. In fact, as shown in Figure 13, the losses in mW at 40 kHz are 11 and 14 for nanocrystalline and powder respectively. Considering the same number of turns for both inductors, this is due to the smaller size of the powder core. When it comes to application, the core size is of great importance. Even though nanocrystalline cores have lower losses, they are limited to a minimum size of 10×7×5 mm due to fabrication process and fragility [9]. On the other hand powder cores can reach a size of 5×2×3 mm easily and even less [23].

In all cases, regarding the core power losses for these two materials, both are considered very good candidates for the buck converter application. In the given intermediate frequency range, they overcome ferrite materials and are used in commercial converters with efficiency higher than 92% [13].

Furthermore temperature effects on dynamic magnetic losses in application are studied for both materials. These losses in the buck converter application are traced for temperatures up to 150 °C. Results are shown in Figure 14 for both iron powder and nanocrystalline materials. We can notice that core losses in the powder core increase with temperature while those in the nanocrystalline core decrease with temperature. This gives the advantage of higher efficiency to nanocrystalline materials for high temperature applications.

The change of dynamic losses (Figure 14) is higher compared to the change of static losses (Figure 7). Thus, elevated temperature has a more significant effect on the dynamic behavior of both materials, but with different magnitudes. This temperature influence on dynamic losses is related to eddy currents and wall motion effects. And since the materials have different structures and compositions, they have different resistivities which may vary differently with temperature.

In summary, temperature effects on the static and dynamic behavior of studied materials are opposite. Temperature effects are more important at dynamic operating conditions. At medium temperatures like 100 °C, which can be attained

during materials self-heating, losses and permeability can vary up to $\pm 40\%$. This means an error up to 40% compared to datasheet values.

Finally, it's not easy to conclude which is a better core for the buck converter application. There is a compromise between point of operation, size, frequency, and temperature. The powder core has a lower cost and better permeability stability with temperature whereas the nanocrystalline core has lower core losses and better coercivity stability with temperature. Both materials have a very good performance in the intermediate frequency range.

V. Conclusion

In this paper the behavior of low permeability iron powder and nanocrystalline magnetic components in a buck converter application is studied. These materials are characterized under variable frequencies, flux density levels and temperatures. Static and dynamic hysteresis loops are traced as well as the variation of permeability with temperature. Dynamic and thermal behaviors of chosen materials are compared in a DC-DC converter. Realization of a buck test circuit allowing different voltage levels and frequencies is presented. Core losses and temperature effects on these losses for both core inductors are discussed. Measurements show that coercive field and permeability can vary up to 120% with temperature while core losses can vary up to 60%. Results show the better performance of nanocrystalline materials having lower losses yielding to a higher efficiency converter. However powder cores are cheaper than nanocrystalline cores creating a compromise between performance and cost.

Tables and Figures captions:

Table 1: Characteristics of test transformers having powder (HKBH) and nanocrystalline (K44B200) core materials.

Figure 1: Static characterization of the powder magnetic material (HKBH).

Figure 2: Dynamic characterization of the powder magnetic material (HKBH).

Figure 3: Static characterization of the Nanocrystalline magnetic material (K44B200).

Figure 4: Dynamic characterization of the Nanocrystalline magnetic material (K44B200).

Figure 5: Change of relative permeability as function of temperature for both iron powder and nanocrystalline materials.

Figure 6: Change of coercivity as function of temperature for both iron powder and nanocrystalline materials.

Figure 7: Change of static losses as function of temperature for both iron powder and nanocrystalline materials.

Figure 8: Buck converter circuit.

Figure 9: Developed buck converter used for measurements.

Figure 10: Powder core losses in the buck application as function of flux density swing (ΔB) and frequency.

Figure 11: Nanocrystalline core losses in the buck application as function of frequency and temperature ($f/V=10000$).

Figure 12: Core losses per unit volume of both powder and nanocrystalline core materials at constant flux density (100mT).

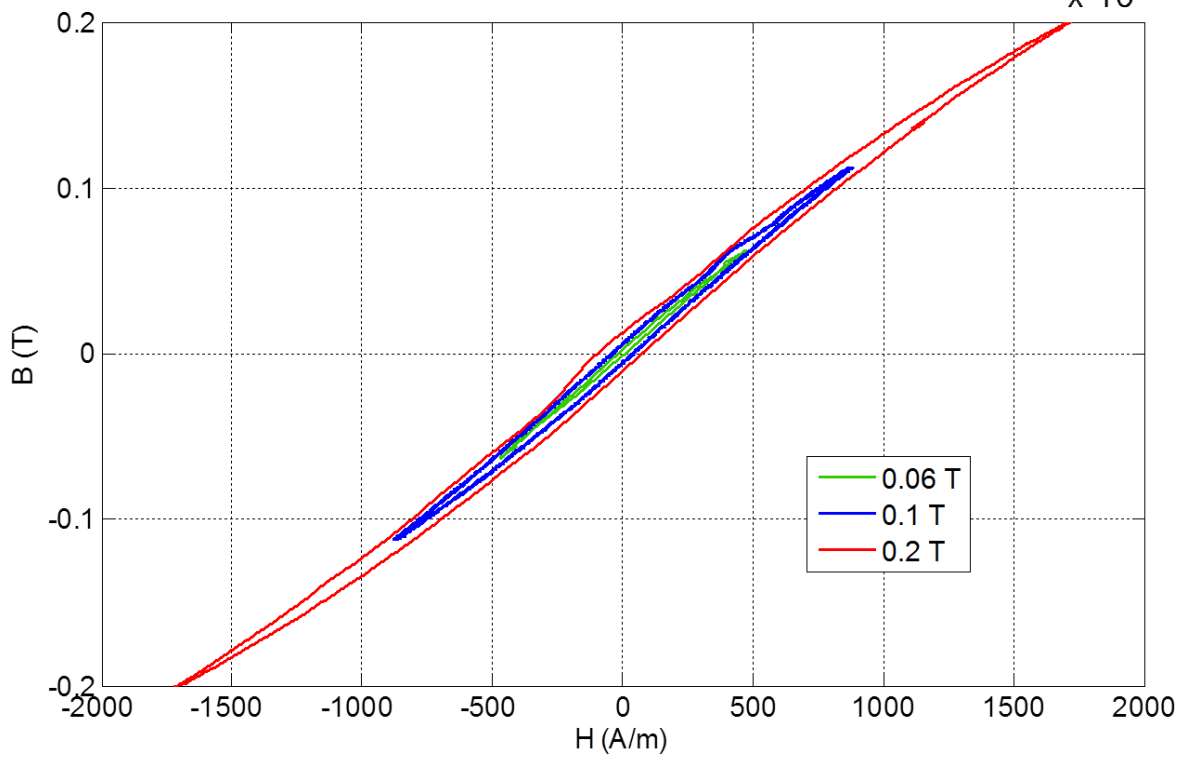
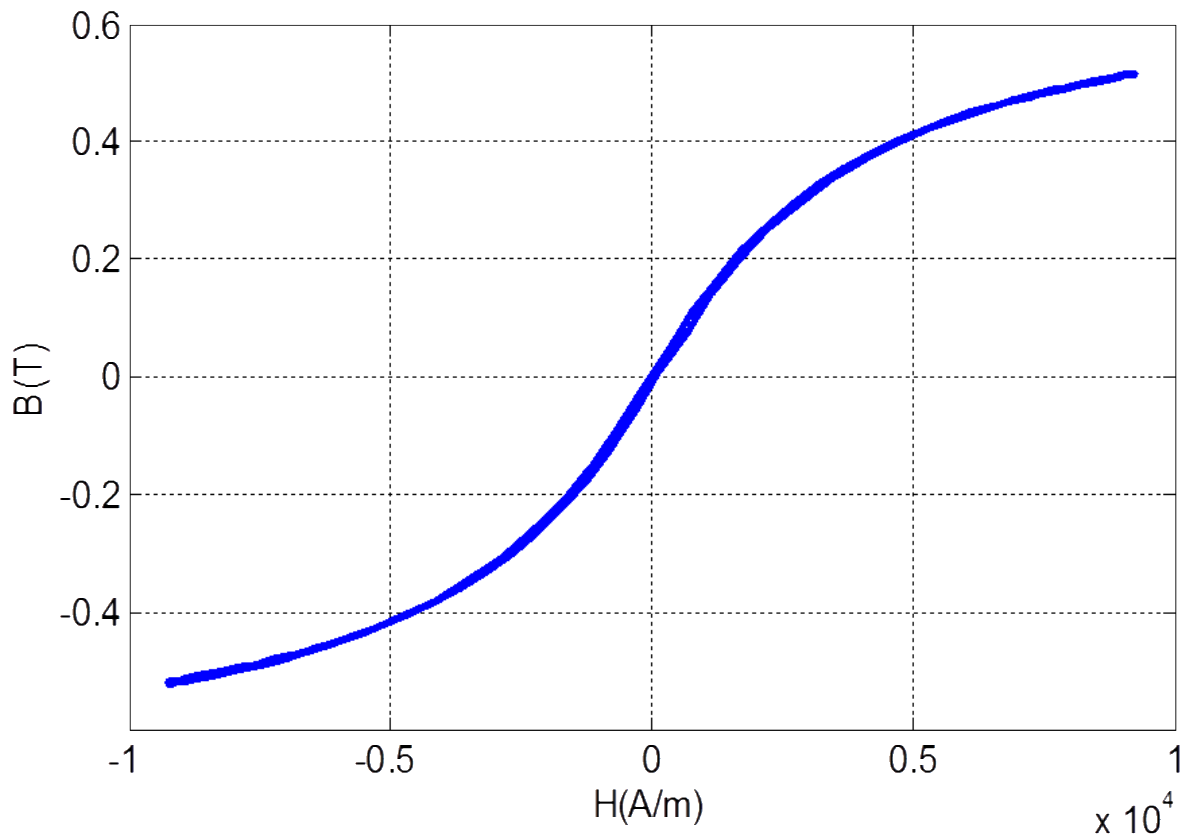
Figure 13: Core losses powder and nanocrystalline core materials in the buck converter for (f/V =constant) operating points.

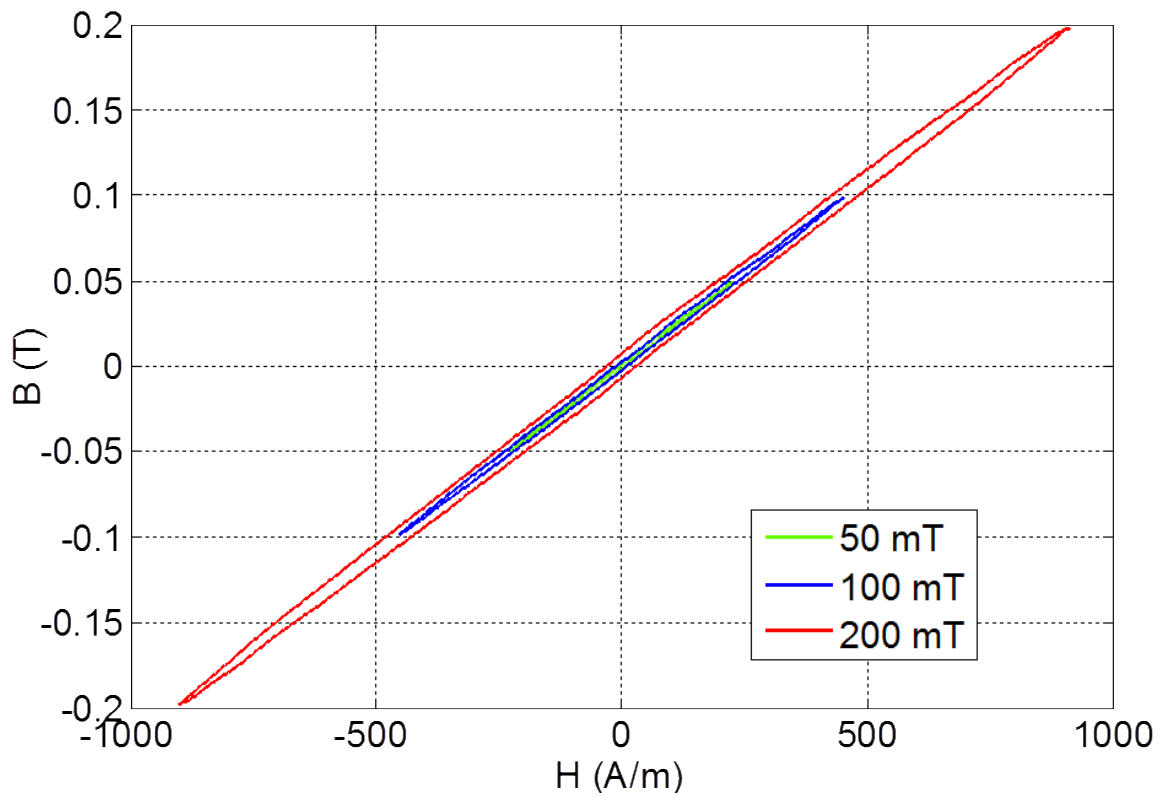
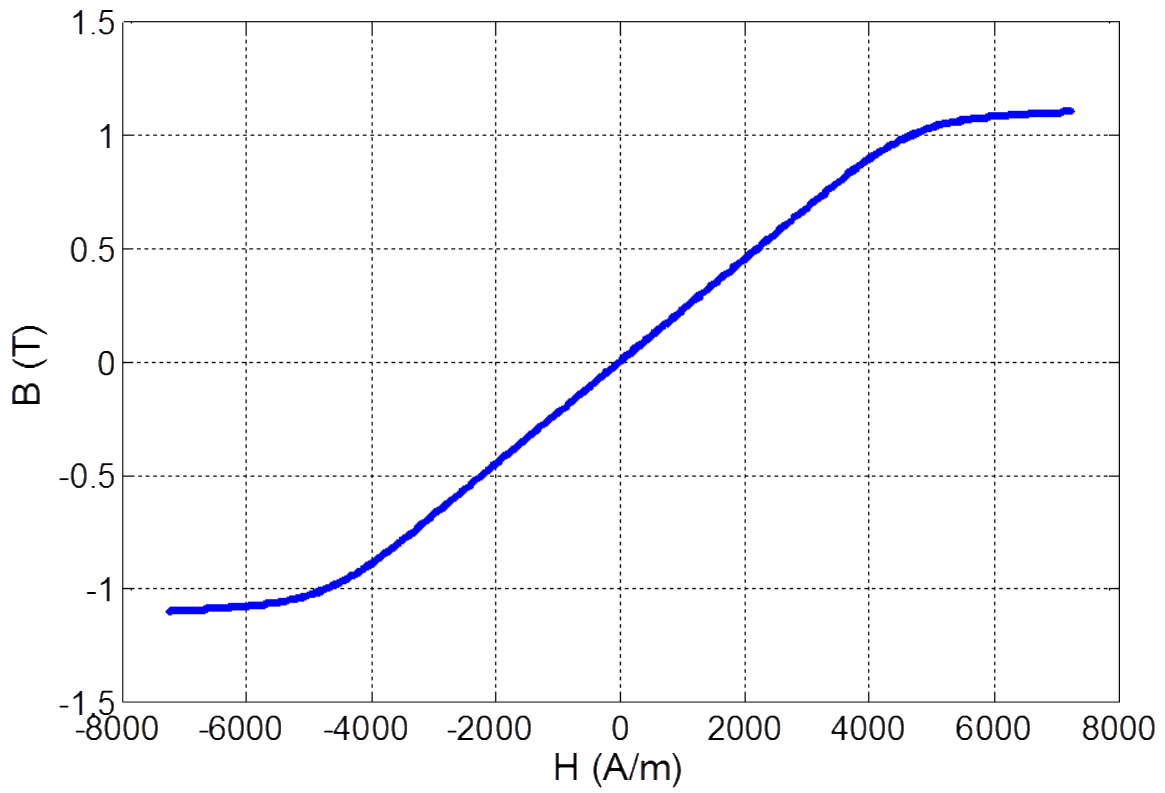
Figure 14: Change of core losses as function of temperature both iron powder and nanocrystalline materials at 50 kHz-100 mT.

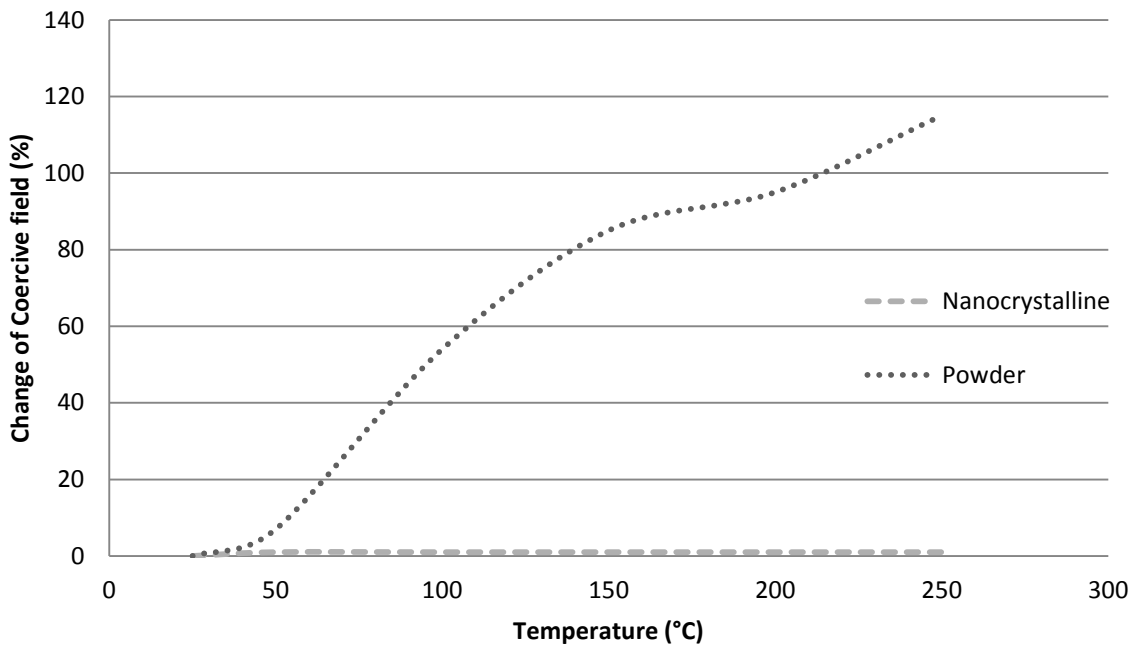
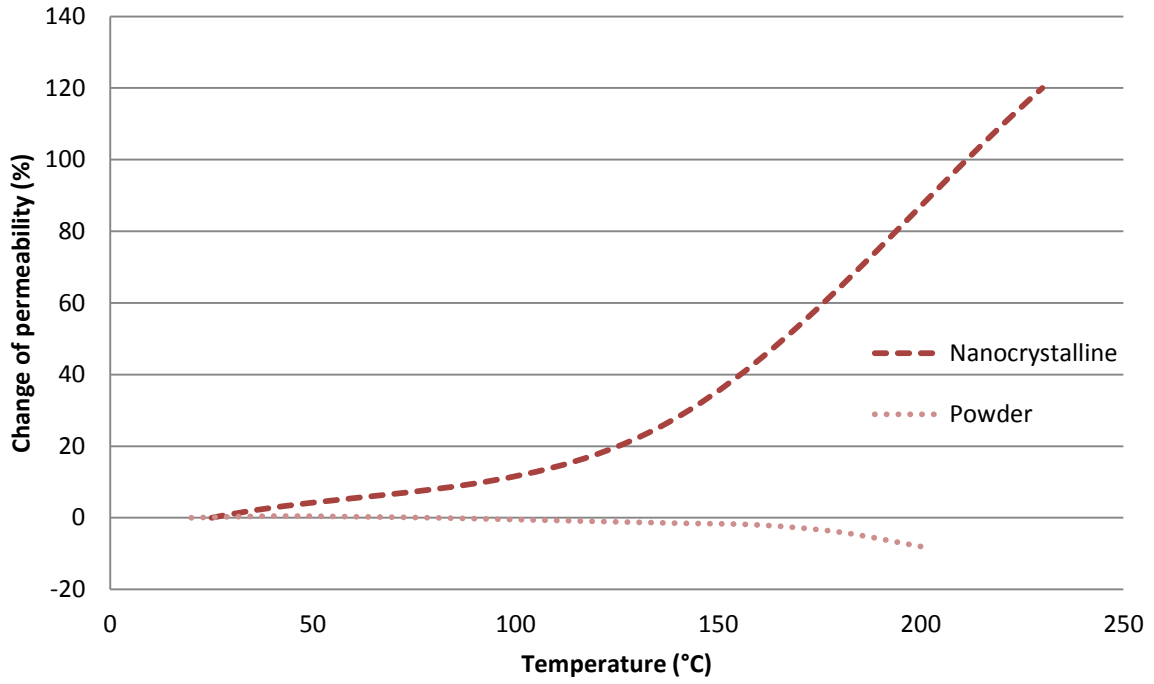
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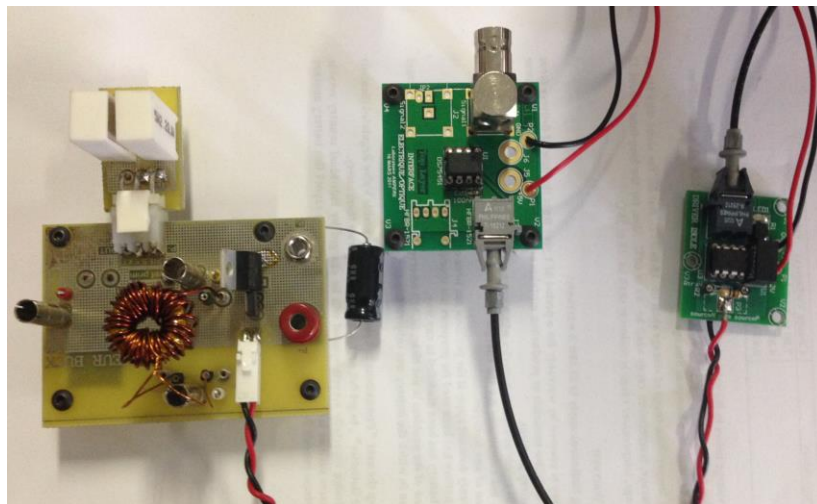
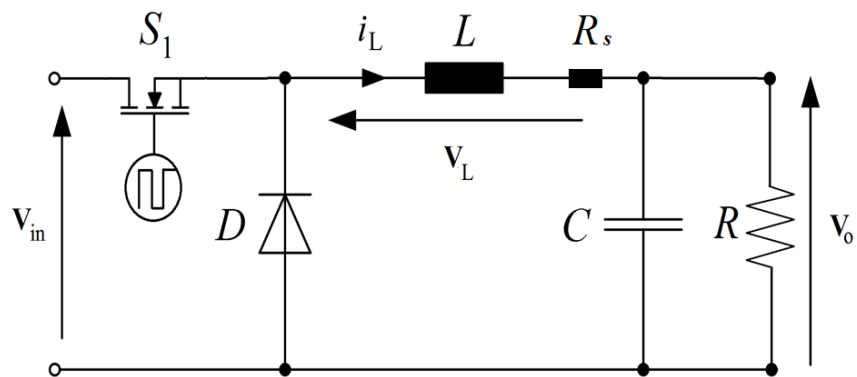
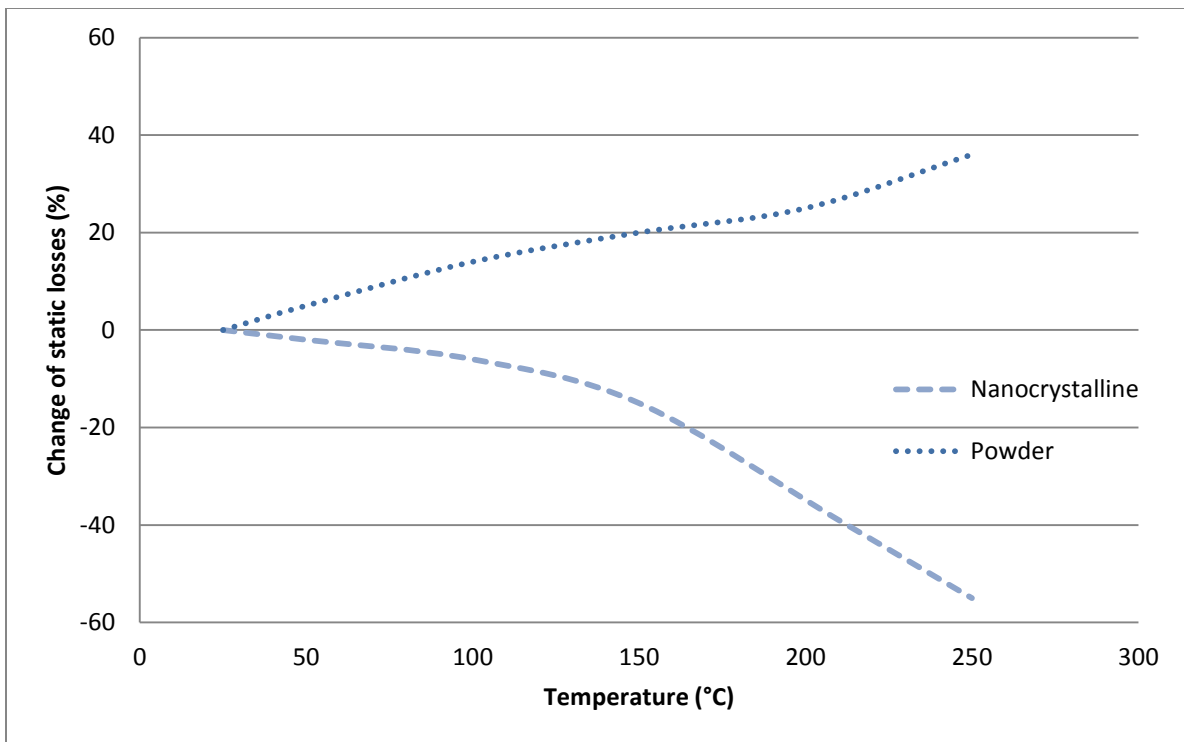
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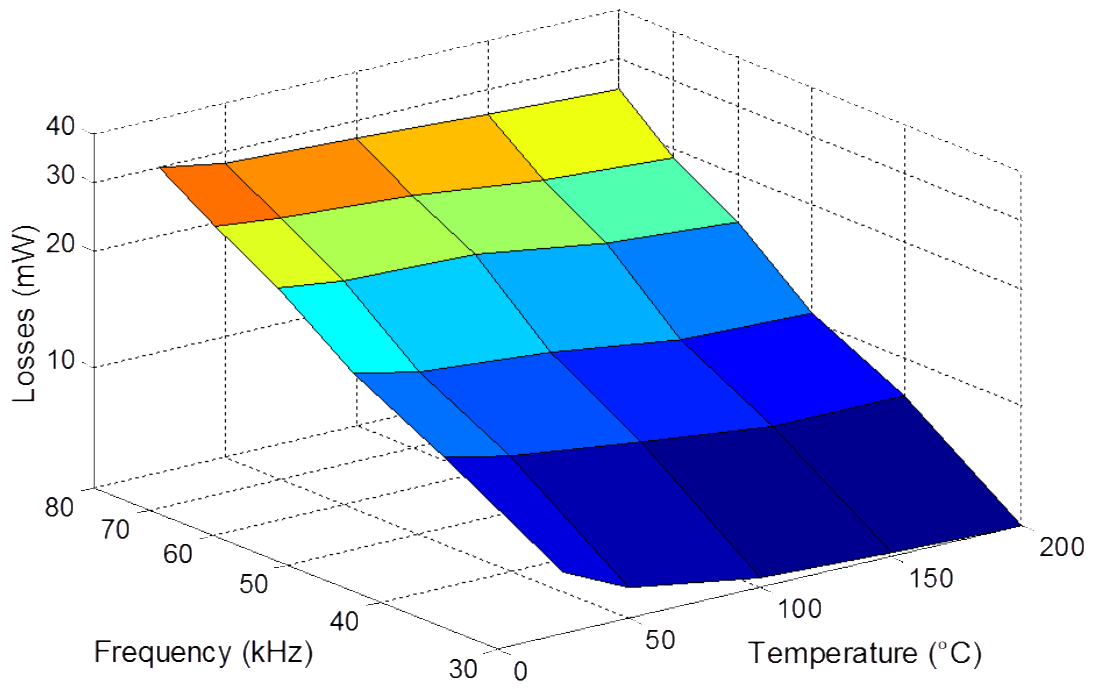
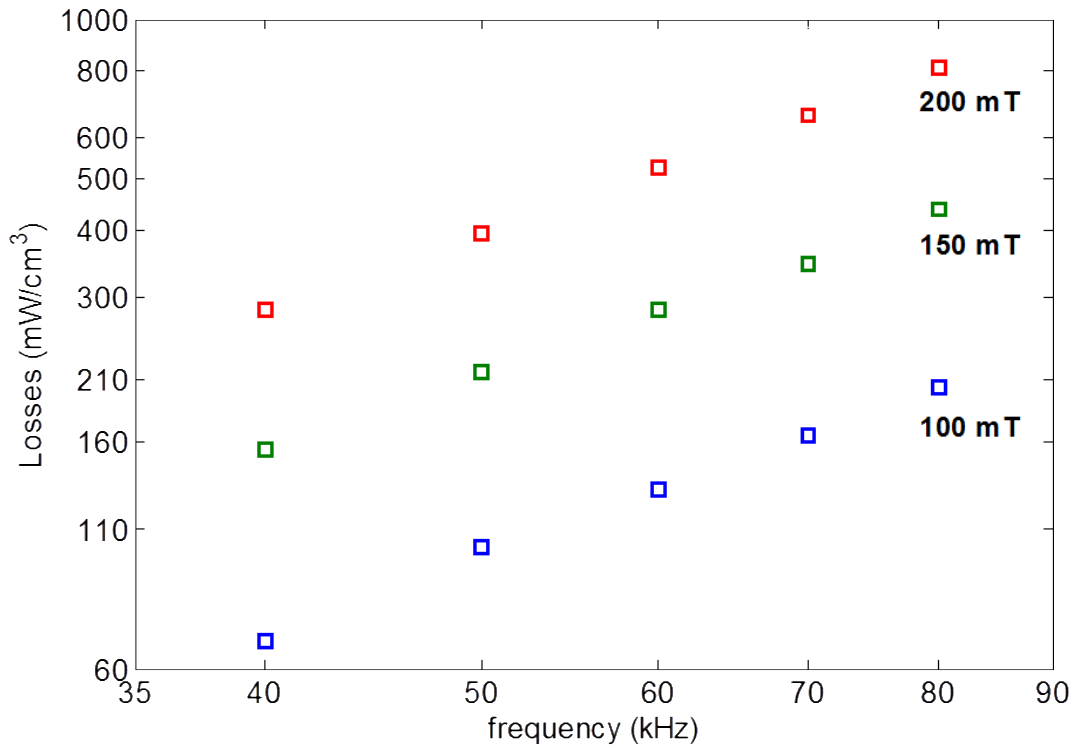
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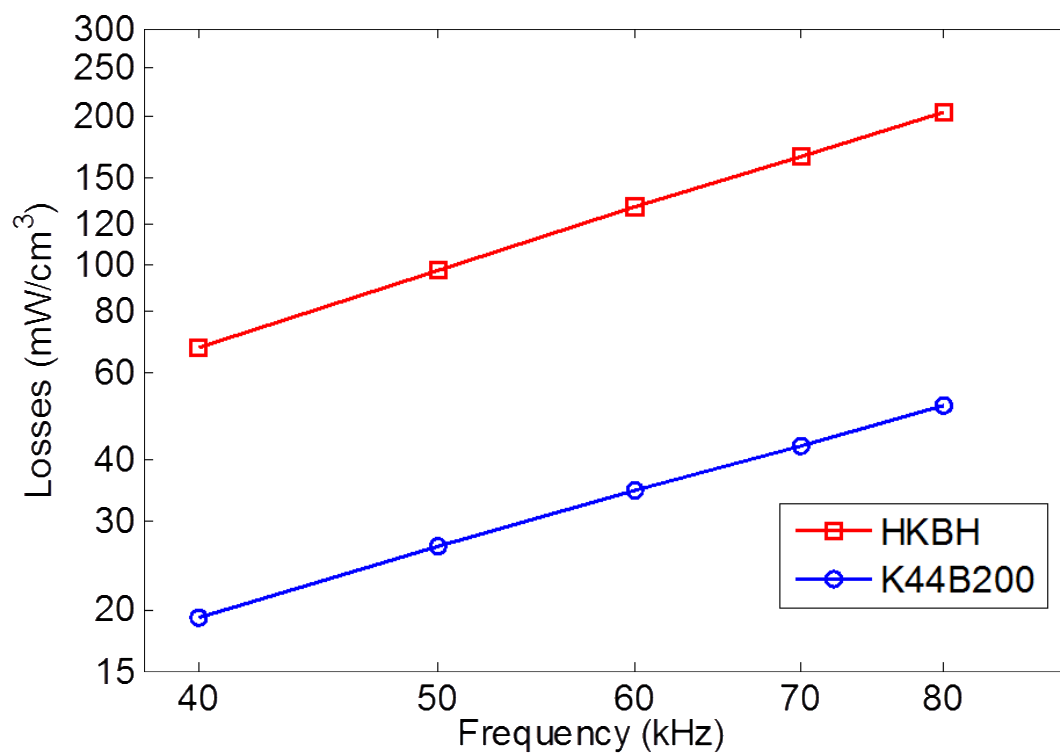
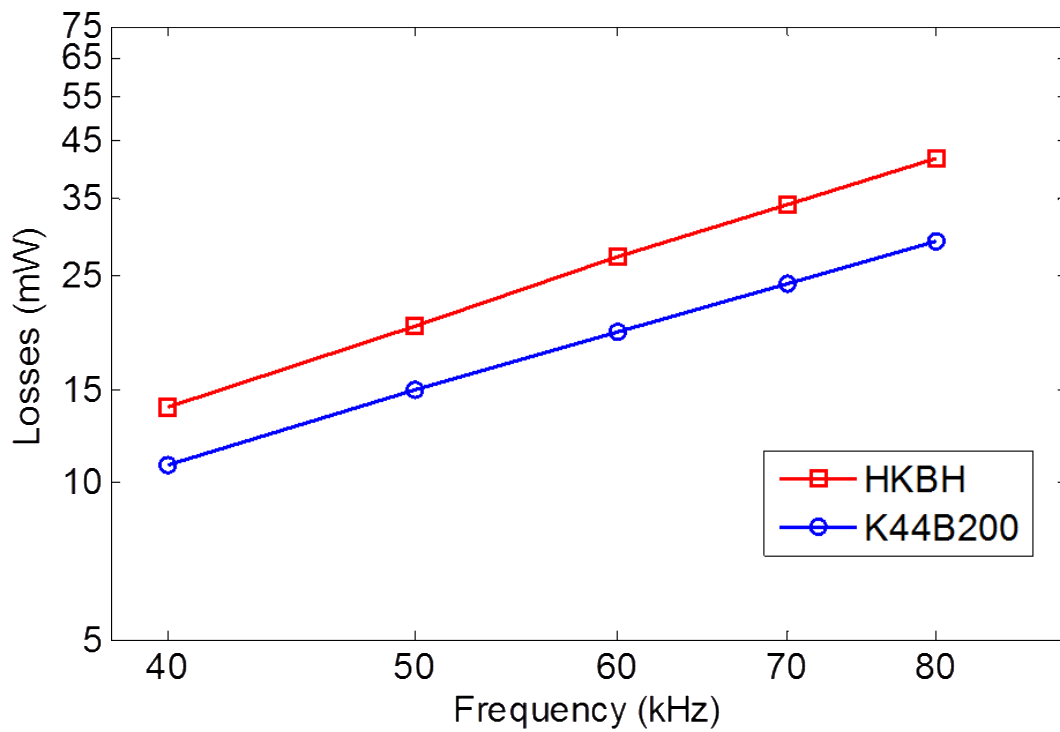


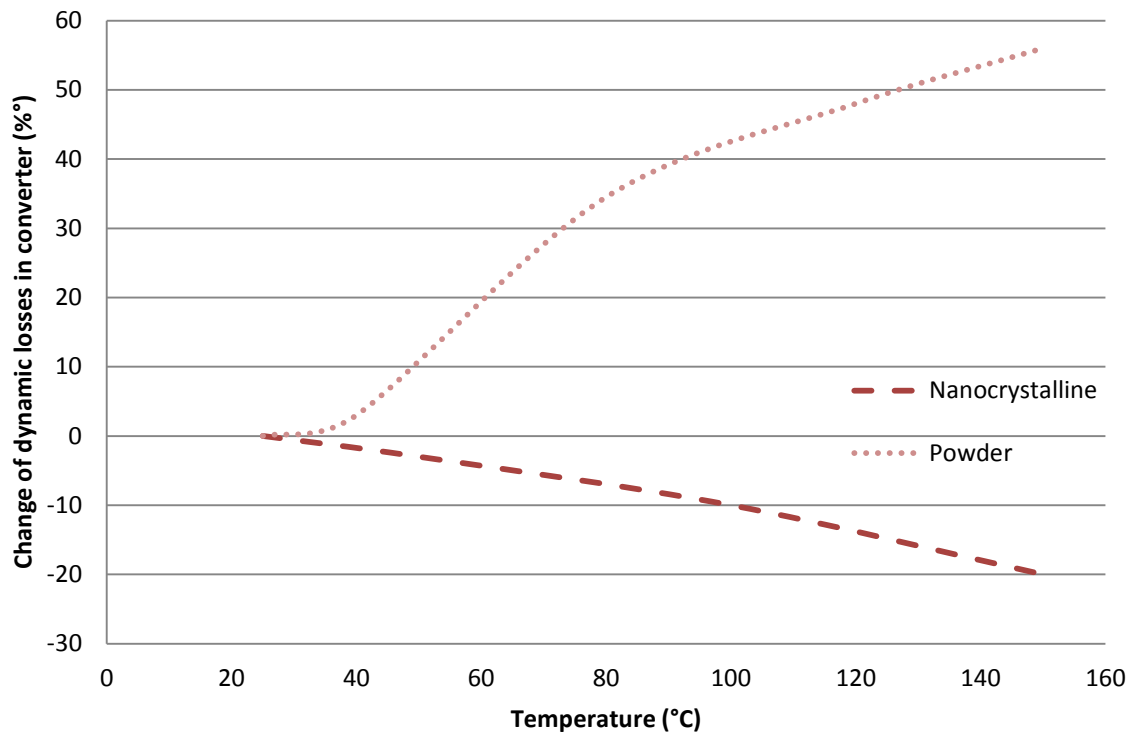












Properties of Chosen Materials		
	<i>HKBH</i>	<i>K44B200</i>
D_{ext} (mm)	10	16
D_{int} (mm)	4,6	10
S (mm ²)	9,45 (8,73 effective)	18 (14 effective)
l_m (mm)	23	40
N1	30	30
N2	3	3
μ_r	100	200
B_s (T)	0,6	1,2

