A Comparison of Molybdenum Permalloy Powder and Sendust Cores for Energy Storage Inductors

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Molybdenum permalloy powder and sendust cores are described and compared. Characteristics important for energy storage in electronic power conversion are used to contrast performance. General application recommendations are given and the significance of permeability with respect to energy storage density is reviewed.

Description and Historical Perspective

Powder cores made with iron that is in pure forms or alloyed with other metals continue to be invaluable for energy storage inductor cores in power conversion applications. Energy storage and release takes place in the gaps between magnetic metal powder particles. An insulation material that is applied to the powder before compaction maintains these gaps. Particle-to-particle insulation also reduces eddy currents in the core.

The magnetizing force (magnetic field of the winding) works with the easily magnetized metal to achieve high magnetic flux density (induction) in free space within the core. The free space is divided into the many gaps that are uniformly distributed along the entire length of the magnetic path. This distributed gap is one of the most important aspects of powder cores. Fringing fields and associated winding eddy current losses caused by one or two discrete gaps in the core path length are avoided.

Two alloys that provide exceptionally low loss and excellent stability of incremental permeability with DC magnetizing force were identified in the first half of the twentieth century. Molybdenum permalloy powder (MPP) consists of 81% nickel, 17% iron and 2% molybdenum and was introduced by Legg and Given of AT&T Laboratories in 1940. Molybdenum permalloy powder cores were originally used in inductors that compensated for the capacitance of long-distance telephone cables.

Masumoto at Tohoku Imperial University in Sendai, Japan developed sendust around 1936. (The word sendust is a contraction of Sendai and dust.) Sendust is approximately 85% iron, 9% silicon and 6% aluminum. It was developed as an alternative to permalloy, the nickel-iron alloy that was later improved with the addition of a small amount of molybdenum. Again, telephony was the major area of application.

These cores are still extensively used for inductors in telecommunication systems except that they are mostly in power conversion instead of signal transmission circuits. The low loss and stable inductance with DC magnetizing force that made them ideal for telephone cable loading coils also make these powder cores very useful in DC output power inductors.

Performance Comparisons

A remarkable characteristic shared by the two alloys is zero magnetostriction. Their compositions are two of the specific combinations of the alloyed elements that result in zero strain (relative elongation) from magnetization. This is consistent with the low loss of molybdenum permalloy and sendust alloys.

Precise core loss as a function of the magnitude and frequency of alternating magnetic flux density depends on the permeability. In general, the hysteresis loss is larger and the eddy current loss is smaller for a lower permeability. Originally, the lower permeabilities (14, 26 and 60) of molybdenum permalloy powder cores were developed for use in higher frequency inductors. Lower permeability increases the frequency of maximum quality factor (Q) for a given value of inductance.[1]

The majority of sendust and molybdenum permalloy powder cores used in power conversion have permeabilities of 60 or 125. The preference for these permeabilities is a natural result of the relationship between copper conductivity, maximum temperature rise or required efficiency and the allowable permeability change and loss of the core material. The lowest permeabilities, 14 and 26, though not specified as often, have great importance for applications requiring near constant inductance with DC and the ability to retain more inductance with high intermittent or surge currents.

General Application Recommendations

Continuous operation of 14 and 26 permeability powder cores at energy storage densities significantly greater than possible with a permeability of 60 is usually not practical. The large continuous current required for the magnetizing force results in excessive winding loss. Low permeability storage density capability can be effectively utilized for high magnetizing forces that are of short duration or that are duty cycled so that the winding has time to cool. (The relationship of permeability to energy storage density is illustrated in the last section of this article.)

For many DC switching power supply output inductors, it is advantageous for the value of inductance to gradually increase with decreasing load current. This is because the minimum inductance is generally selected to keep the ripple current less than a specified percentage of the maximum load current, typically about 20%. Lower continuous inductor current is possible with more inductance so an increase in inductance is beneficial at light load. (Continuous conduction helps with power supply stability.) Conversely, a physically smaller inductor is required since the minimum inductance at full load can be less than with a light load. Permeabilities of 60 to 125 usually provide a relatively small inductor and a useful variation of inductance with DC bias.

An important exception is the design that requires very fast response to a sudden demand for current. An example is a DC power supply for disk drive motors. The motors repeatedly start and stop so the current demand changes suddenly from full load to light load and back again. In this case, the inductance should be constant and as low as required so that the supply responds quickly to changes in current demand. Here, the lower permeability materials might provide the best solution to the inductor design problem. Higher frequency operation also improves transient response. With lower permeability for a given core size, the flux density, and consequently, core loss, at higher frequency is reduced. However, there is the penalty of increased winding loss.

Another specific example of an application that can utilize low permeability powder cores is the boost inductor used for power factor correction. Constant inductance is desirable for the full range of line frequency input current that passes through the inductor. Also, the ability to maintain most of the inductance at high magnetizing force helps to limit peak surge currents.

In summary, there are at least four types of energy storage requirements that indicate the possible use of 14 and 26 permeability powder cores.

1. Duty cycled current that allows time for a high magnetizing force winding to cool.
2. Constant inductance from low to high current for fast transient response or linear operation.
3. Inductance at high peak surge currents.
4. High frequency currents where the losses of a powder core need to be limited. Here, the low permeability is used for low flux density and eddy current loss.

With regard to the better type of powder core for a given application, molybdenum permalloy powder remains the premium product. This means that cores made with molybdenum permalloy powder usually have

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[1] See The Arnold Engineering powder core catalog *Magnetic Powder Cores*, 1998, pp. 9 and 10.

better overall performance but a higher cost per unit volume. The inductance with DC bias for any given permeability is higher than for a sendust core and the losses are significantly lower at frequencies up to 200 kHz.

It is important to recognize that the original development of molybdenum permalloy powder was for cost reduction. From the beginning, it had a higher price per unit volume than the material it replaced. The cost reduction came from savings in the package size of the application assembly. Molybdenum permalloy powder can also reduce costs by saving energy that would otherwise be lost in the winding and core.

For applications that do not result in a favorable balance between the higher cost of molybdenum permalloy and the savings in size or energy loss, sendust is an attractive alternative. This is especially applicable for cores of about one inch outside diameter and larger where the saving in material cost becomes more significant. Also, the lower eddy current loss in sendust competes with the hysteresis loss advantage of molybdenum permalloy as frequency increases. For the 60 and 125 permeability materials, the differences in losses at 300 kHz are relatively small.

A noteworthy advantage of sendust is lighter weight. For the 60-permeability type, a sendust core has only about 75% of the weight of a molybdenum permalloy powder core.

Core loss curves for sample 60 permeability sendust (Arnold Engineering Super-MSS™) and molybdenum permalloy powder cores are plotted together in Figure 1 for easy comparison. Graphs for percent incremental permeability with DC bias are shown in Figure 2.

Permeability and Energy Storage Density

Permeability is the ratio of magnetic flux density (induction field) to magnetizing force (magnetic field). Figure 3 shows graphs of flux density versus magnetizing force for three permeability values of an ideal core material and for free space. Ideal refers to

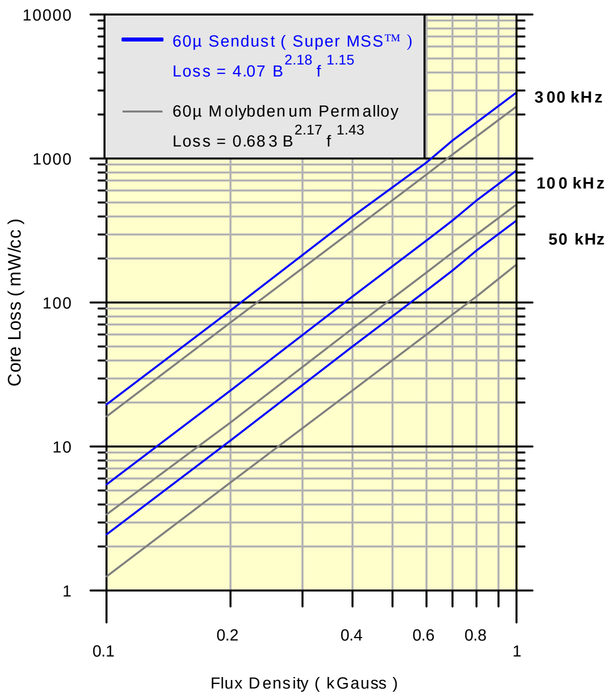

Figure 1. Core Loss Density

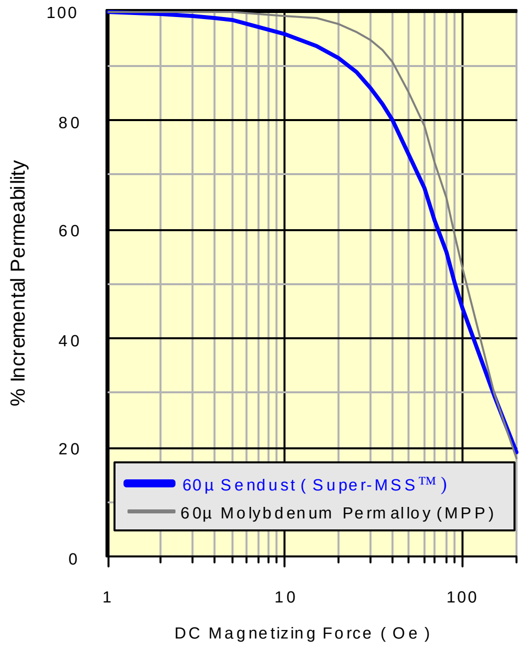

Figure 2. Percent Incremental Permeability versus DC Bias

the constant permeability (slope) and zero loss indicated by the straight-line graphs that begin at the origin. The situation is a little more complicated for a real core material in a power conversion application. However, the essential relationship of permeability to energy storage density can be explained using Figure 3.

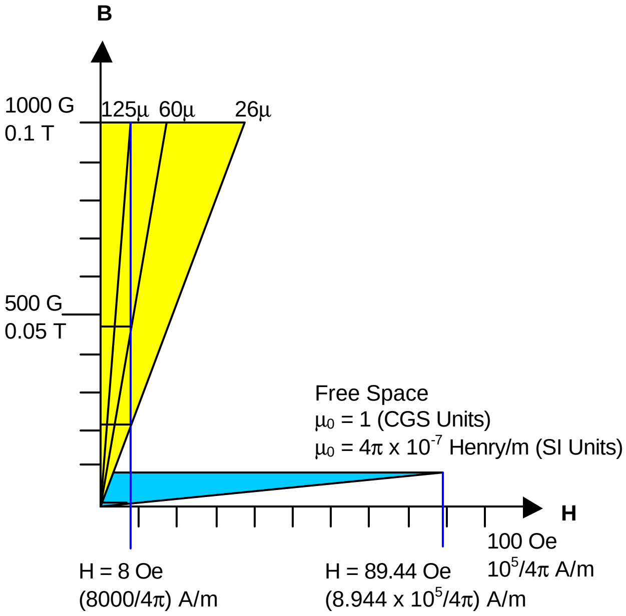

Figure 3. Graphical Representation of Energy Storage Density for Various Values of Permeability.

It can be shown that the area between each plot and the magnetic flux density (B) axis is the energy stored per unit volume of core material, or free space in the case of a non-magnetic core. Analysis of dimensions in terms of the natural laws identified by Faraday and Ampere suggests that this area is the energy per unit volume.

Refer to Figure 4 to help picture the relationships between voltage, current, magnetic flux density, magnetizing force and core dimensions. Faraday's law gives the dimensions of magnetic flux density, volt-second (applied across the winding leads) per turn (one passing of wire through the inside diameter of the core) per square meter of core cross-section (area inside a turn of wire). Ampere's law defines magnetizing force dimensions, ampere (current in the winding) -turn per meter of magnetic path length (an averaged circumference of the core). Therefore, the product of flux density and magnetizing force has dimensions of volt-ampere-second per cubic meter or joule per cubic meter of core.

Returning to Figure 3, it is apparent that for a given magnetizing force, the energy storage density is directly proportional to the permeability. Compared to the energy in free space, the core permeability can be considered the energy storage density multiplier. A 125 permeability material stores 125 times more energy than the same size core that is non-magnetic; a core made of nylon, for example.

The vertical line at eight oersteds marks triangular areas (1/2 B x H) that can be used to compare energy storage densities for four values of permeability. Clearly, the 125-permeability core will provide the most energy storage for an eight-oersted magnetizing force. A "free-space" core will require just over 89 oersteds of magnetizing force to store the same amount of energy.

It is also apparent that the lowest value of permeability provides the greatest amount of storage for a given magnetic flux density. Given that the loss and linearity of the material permit an operating flux density of 1000 gauss and if losses in the winding at about 38 oersteds can be tolerated, then a permeability value of 26 will give the highest energy storage density.

So the permeability is chosen in accordance with the maximum operating magnetic flux density of the material and the highest

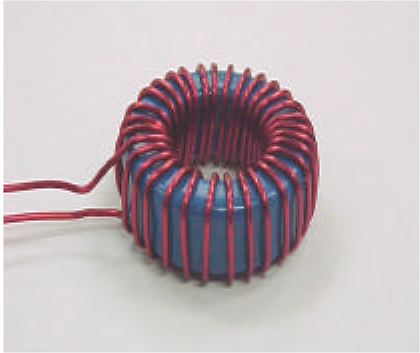

Figure 4. Typical Core and Winding.

practical magnetizing force. The maximum flux density is determined by material saturation or by its loss from high frequency flux density excursions. Winding loss limits the magnetizing force.

As a general rule, larger cores can be operated at higher magnetizing forces because of the increase in winding area relative to the magnetic path length. Consider the ring or toroidal type of core in Figure 4 and a wire carrying a fixed current. As the core inside diameter increases, it is possible to fit more wires per unit of path length (more ampere-turns per meter) without increasing the power loss density of the winding. As a result, the permeability can be lowered and the stored energy density increased without an increase in magnetic flux density.

Concluding Remarks

There continues to be a strong interest in both molybdenum permalloy powder and sendust cores for energy storage applications. This is due to the ongoing challenge of providing greater amounts of electronic power with smaller, lighter and more efficient power conversion devices.

Low permeability (26µ) sendust is a new material that is being utilized in high current and high frequency applications. The use of sendust overall grows as its value becomes recognized. Molybdenum permalloy powder cores remain the benchmark for performance.

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