DATATRONICS

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The Effect of Stress on Initial Permeability In Ferrite Cores

Introduction:

Many of today's modern electronic circuits are built around magnetic components. A principal player in the design of these magnetic components is the ferrite core. Ferrite cores come in many different shapes and sizes and are made from many different raw materials. The magnetic properties of ferrite materials depend on many things. Such characteristics as the size of the grains created, typically between 5 and 40 um, and the sintering (firing) processes strongly determine the properties of the final product.

Once a ferrite core is completed there are other outside conditions that can also determine the performance of the magnetic component in which it is used. The purpose of this paper is to discuss in particular the effects on Initial Permeability (μi), thus inductance, which are a result of the various construction techniques and environmental conditions encountered. Permeability is generally defined as the ratio between the induced magnetic flux in the material and the magnetic force which causes it. In many applications the change in initial permeability is not as critical as the resulting minimum value. A simple review is in order.

As can be seen below ferrite magnetic material consists of small crystals that have magnetic domains.[1] These domains determine many of the characteristics of the ferrite core, both electrically and mechanically. It will be shown that these physical construction traits are very important in the resultant changes in initial permeability due to stress.

Magnetism in ferrites

A sintered ferrite consists of small crystals, typically 10 to 20 μm in dimension. Domains exist within these crystals (Weiss domains) in which the molecular magnets are already aligned (ferrimagnetism). When a driving magnetic field (H) is applied to the material the domains progressively align with it, as shown in Fig.2.

During this magnetization process energy barriers have to be overcome. Therefore the magnetization will always lag behind the field. A so-called hysteresis loop (see Fig.1) is the result.

If the resistance against magnetization is small, a large induced flux will result at a given magnetic field. The value of the permeability is high. The shape of the hysteresis loop also has a marked influence on other properties, for example power losses.

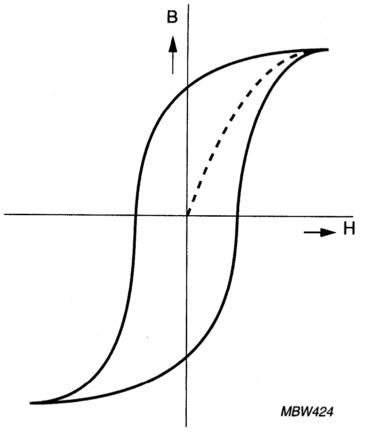


Fig.1 Hysteresis loop.

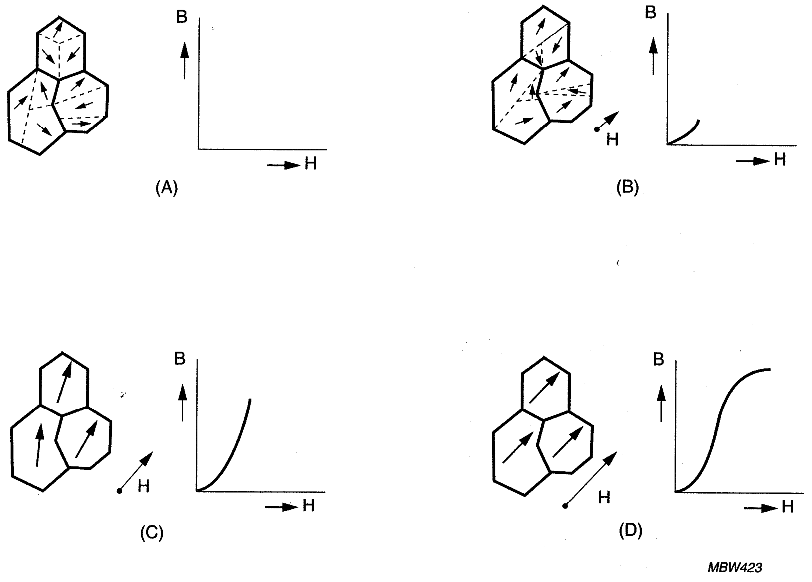


Fig.2 Alignment of domains.

The size of the grains helps determine the value of the initial permeability. In general, the larger the grain size the larger the initial permeability.

Another important factor of μi is the porosity of the grain structure. Pores and other imperfections tend to pin domain walls and limit their movement.[2,3,4,5] Less movement equates to lower μi. When large grains are produced some pores become internal to the grain. Internal pores are not as detrimental to initial permeability as ones on the domain walls. A linear relationship between μi and grain size has been found in both MnZn and NiZn ferrites provided the grains are essentially free of pores. This relationship also holds true for high permeability materials.

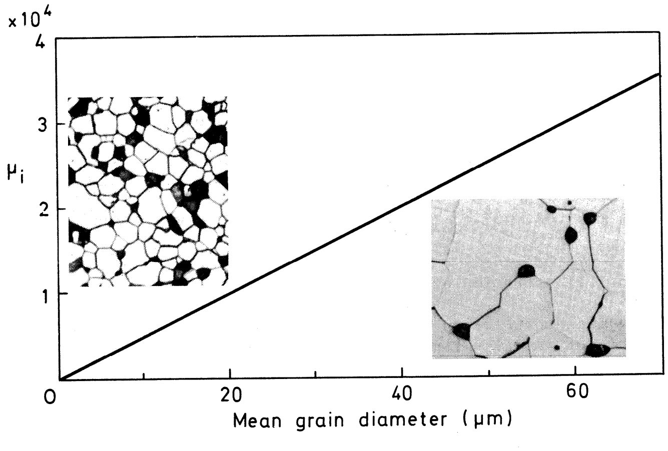
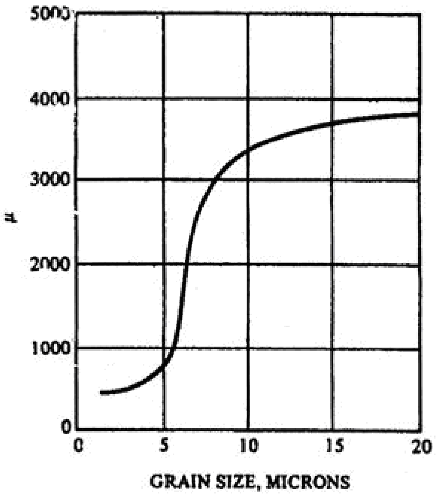
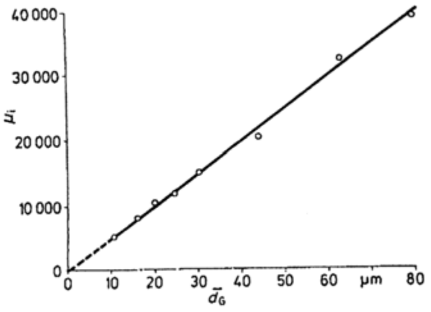


FIG. 3 Initial permeabiity as a function of grain size for a MnZn ferro-ferrite.

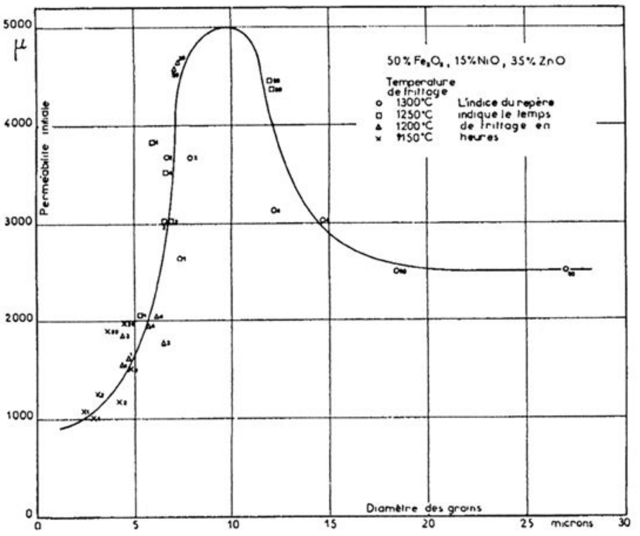
The effect of porosity can be seen in the graphs, especially the ones showing NiZn. The reduction in permeability for NiZn grain sizes above 10 microns is attributed to pores.



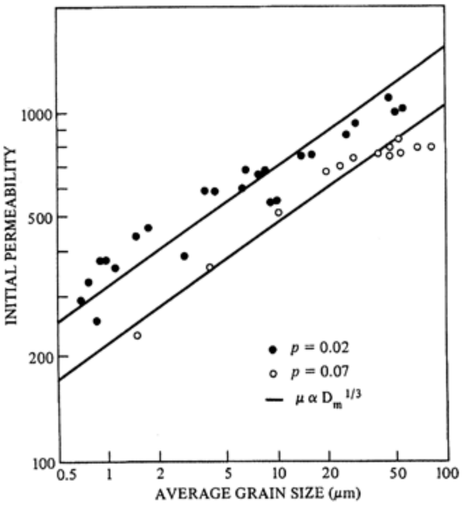
Permeability of a MnZn ferrite as a function of grain size in microns (Guillaud)



Permeability of High Permeability MnZn Ferrites as a function of Grain Size. (Roess 1966)



Permeability of a NiZn ferrite as a function of grain size (Guillaud 1960)

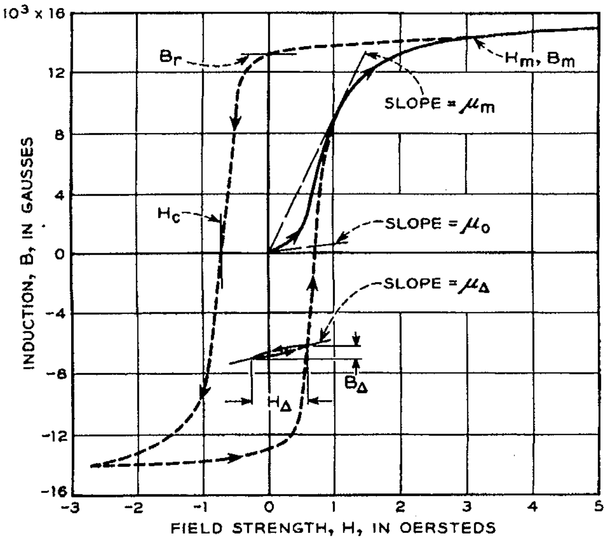


Permeability versus grain size for 2 different porosities in NiZn ferrites (Igarishi 1977)

Initial Permeability

Permeability is defined as the instantaneous ratio of B/H. A special case of a minor B-H loop is one in which the H level is extremely small. In this type of loop (~.1 mT) the material is not magnetized to saturation levels. Under these conditions of low and decreasing values of applied field the system is said to be in the Rayleigh region and the permeability linearly approaches the initial permeability value.[6,7]

μi = limit (B/H) as B → 0

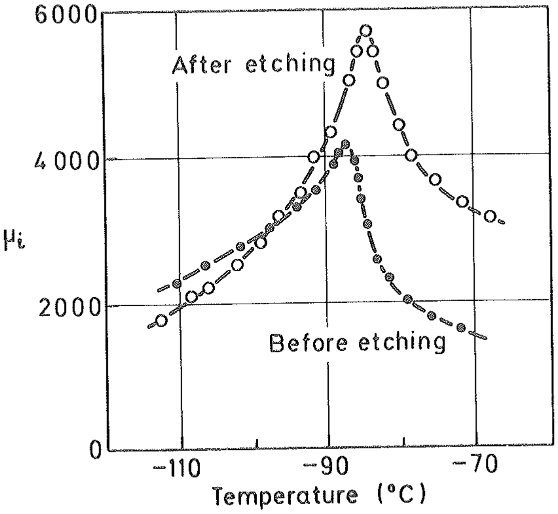


As can be seen in the chart above there are several values of permeability at different points on the B-H curve. Note: Some literature uses μo for indicating initial permeability. Because initial permeability is always given (and for consistency between materials and manufactures) it is a very useful parameter to compare as the effects of mechanical stresses on ferrite cores are investigated.

Stress Effects on Ferrite Materials

The characteristics of ferrite cores are very sensitive to stress. Stresses on the core affect not only the mechanical properties but also the magnetic properties. This is especially true for initial permeability. Stresses can be created during the manufacturing process of the core or the construction of the final product.

The graph to the right shows the effects of stress on the low temperature μi peak of a ferrite core. This core was created by machining bulk material. The outer stress-filled layers (from the machining process) were removed by etching.[8] Also, something as simple as a slight change in material composition can cause a reduction in μi. For example, during the sintering process of a ferrite material some zinc will be evaporated from the outer surfaces. This thin, minor variation in composition will cause stress to the material and reduce μi. Simply removing the thin outer layer of material will raise μi dramatically.



Other stresses can be created when the end product is assembled. One popular construction method is to encapsulate the part. The encapsulant places stress on the ferrite material when it cures. From the equation below it can be shown that the higher the stresses are on the core the lower the value of μi.[9]

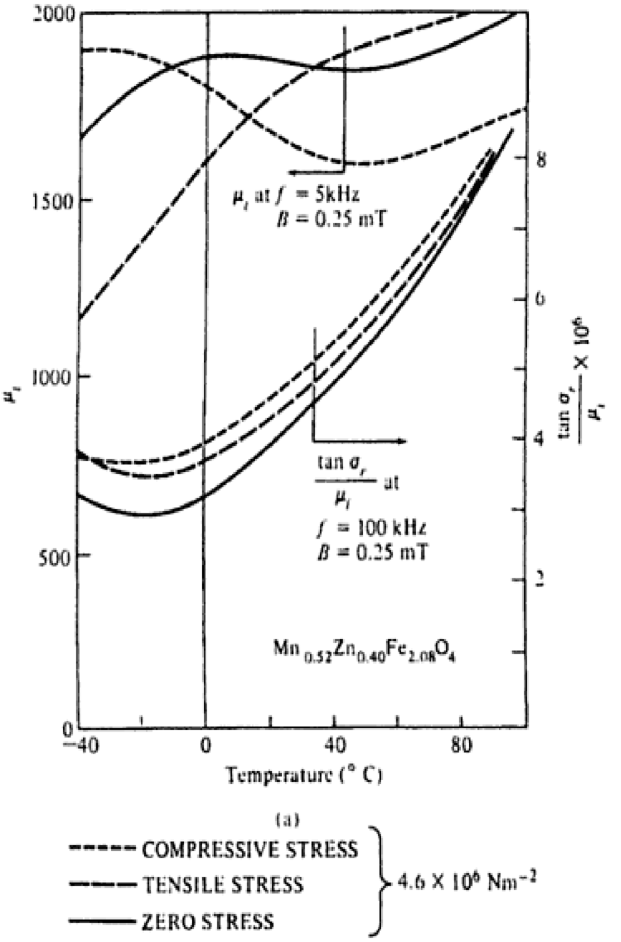
$$\mu_i \cong \frac{1}{\dfrac{1}{\mu_o} + k \cdot \sigma_T}; \qquad k \approx 30 \cdot 10^{-6} \cdot \frac{1}{\text{MPa}} \qquad \sigma_T = \text{Actual effective stress}$$

The actual effective stress is difficult to calculate. It is composed of many factors including the shrinkage of the potting material due to curing, the hardness of the encapsulant, and the mismatch of the coefficients of linear thermal expansion. As noted in the introduction section of this paper pores exist in ferrite materials. If pores become filled with encapsulant the initial permeability is also reduced.

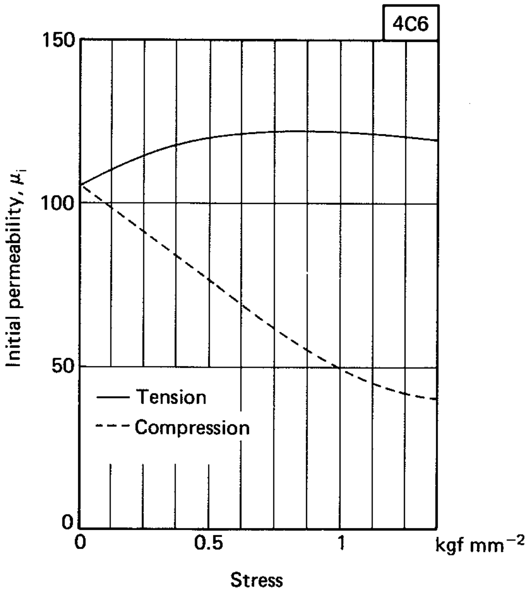
These stresses are aggravated due to the fact that the final product will see and operate over wide temperatures. The temperature changes of stress vary considerably around the point of operation. Looking at the chart to the left it can be seen that both the temperature of operation and direction of stress can affect µi. [10]

An important point to remember is that these kinds of changes in µi are not guaranteed or even specified by ferrite manufacturers. What are the characteristics of operating at 50kHz? Or at 100mT? Additional changes from batch-to-batch of cores will very likely occur, also. This can be very difficult to predict.

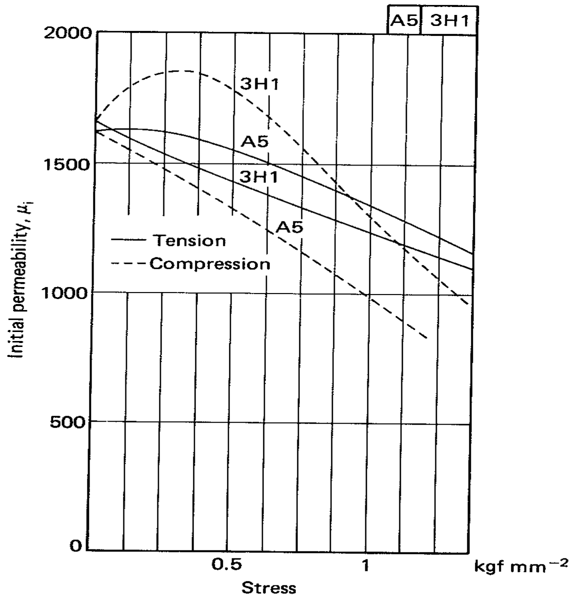
Adding to task of determining µi for design purposes are variations in the encapsulating process. Many factors contribute. How do the stresses change for different cure temperatures? How do the stresses change from one epoxy to the next? Is there filler used in the encapsulating process? Is a buffering compound used?



Stresses change the initial permeability of all materials, MnZn and NiZn, and all permeabilities, low and high. It is worthwhile to note that large changes in µi may be produced by moderate stresses. A review of the graphs shown below will yield valuable insight into the issues of stress vs initial permeability. [11] **A5 is a power material.**



	Code No.	Manufr	Class
NiZn ferrite:	4C6	4	VIII



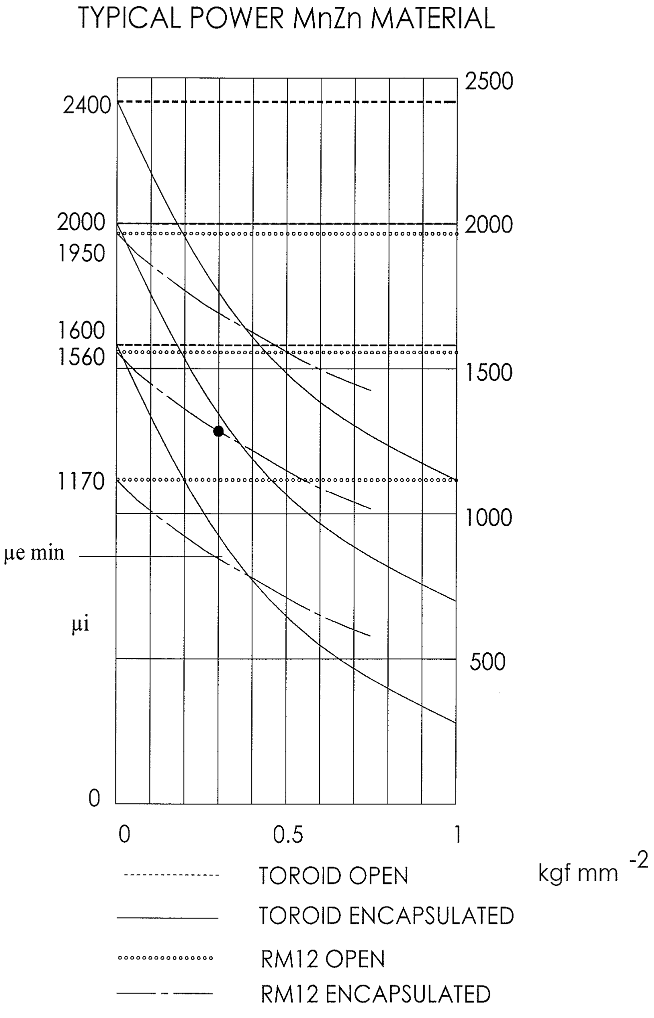
	Code No.	Manufr	Class
MnZn ferrite:	A5, 3H1	4	I

Design Considerations

Power materials such as MnZn are optimized for efficient operation while converting voltages and currents from one level to another. High Permeability NiZn materials are designed for Wideband operations. Both can suffer in performance due to applied stresses. One of the more critical issues faced by a designer is to be able to communicate design characteristics to the customer. In many instances a customer will come to rely on a designer for a solution to a given application. Of prime importance is the ability to test a product satisfactorily for all parties involved.

An example of an application would be a design using a MnZn power material. Depending on the application a power design could use a toroid geometry (low power) or core set (high power).

A refined example could be a power transformer based on a ferrite core set such as a RM12/I. See Appendix A. Many designs based on this core set are constructed using clamping clips and are un-potted. This particular geometry and material has proven to be a good choice in many applications. The designer can turn to the data sheet and see that the effective permeability (μe) is around 1560 and the inductance factor (AL) is 5050+/-25% nH/t^2. The designer incorporates the +/- 25% AL variation into his successful design and the customer is happy.

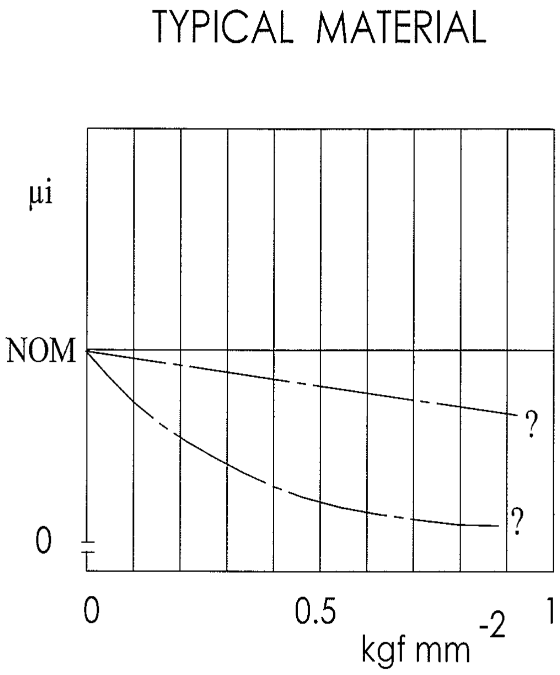


On a second design the customer has a very similar power application but now needs to worry about environmental conditions and therefore must have a potted unit. The designer knows that the same core set and material will work well in this application but now encounters lower inductances due to the stresses on the ferrite material attributed to the encapsulating of the unit.

As seen on earlier pages, stresses due to encapsulation cause the μe to be lower and this lowers the inductances. The saturation flux levels are the same as for an un-potted unit but the designer now has to allow for higher magnetizing currents and energy in his circuit design. But to what extent?

Looking at the typical graph to the right it can be seen that the μe of an encapsulated unit is not constant but falls-off due to stress levels. 1560 is the nominal starting point for both open and encapsulated units (RM12/I). This nominal value can change +/- 25%. However, the rate of fall-off is not specified buy the core manufacturer. What will happen from unit to unit, core batch to core batch, or potting variations is anyone's guess.

How can the designer get an agreement with the customer on what is a good transformer for this application? First it is known that an open unit would work fine and it would be easy to specify. Second it is known that for an encapsulated unit there will be a fall-off in inductance and, if designed for it, the circuit could be made to work. Therefore the key to a good design would be to be able to determine the absolute minimum value of μe. The same issue would surface for a low power design that was based on a toroid geometry. However, without an air gap the μi would fall-off even faster and be even more unpredictable. It would be very difficult to predict the total possible variation.



As stated earlier an additional challenge to predicting the stress levels to be seen in a typical design is the variations and differences in coefficients of thermal expansion of the materials used. Appendix B shows typical properties of ferrites and Appendix C shows properties of one of many epoxies used for encapsulation. Perhaps the most volatile is the difference in the coefficients of thermal expansion. Ferrites are around 10×10^{-6} and epoxies are around 150×10^{-6}. Another wrinkle to this issue is that epoxies have different coefficients of thermal expansion above and below their glass transition temperature. Generally speaking this coefficient is about one third of the value (50×10^{-6}) below the glass transition temperature. The different characteristics causing stress on the ferrite material are a moving target for the designer.

A Design Method

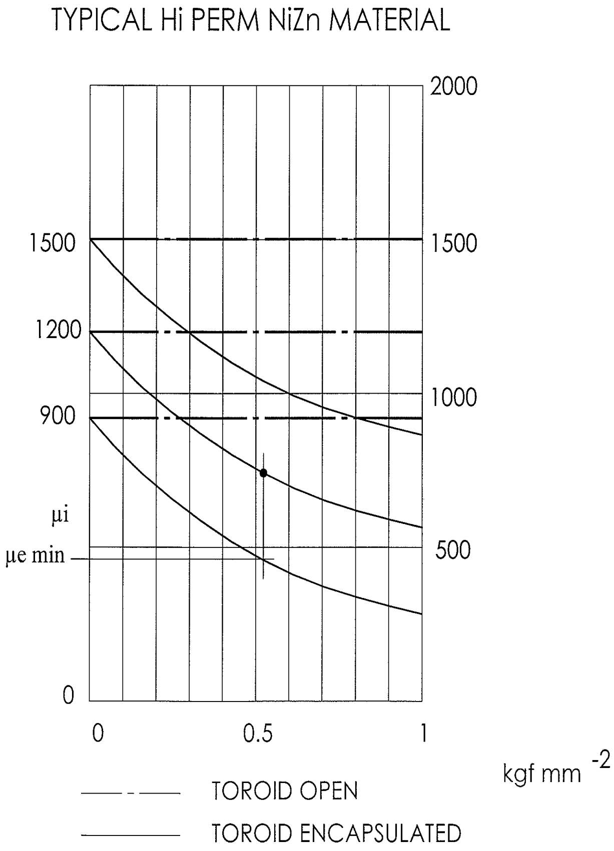
Using before and after test results of sample encapsulated units a designer can get good results for specifying their design. In this example, using an RM12/I core set of 3C96 material (see Appendix A), a sample group has been built and the un-potted inductances measured. These measurements can be compared to the specified AL value (5050+/-25% nH/t^2) and then correlated to μe (~1560). Using the un-potted μe measurements the graph shown above for typical power material can be used to show the starting point. Next the sample units are encapsulated and the inductances are measured again. A drop in inductance (and its corresponding μe) can be placed on the graph (see dot). From this point drop down to the curve that represents the minimum μe. Now going to the left a minimum μe can be read. This would represent the minimum inductance a design would have to work with. Of course, if this is too low the cores could be sorted before assembly for higher starting values. Again this example is typical and results can vary.

Below is some data for two such examples. One uses an RM12/I core set (MnZn) and the other uses a high-perm NiZn toroid (Appendix D). The un-potted μe values were very close to nominal. The μi* values have been empirically determined using this method. As stated earlier these parameters will not be specified by the ferrite manufacturers and can

vary from batch to batch of cores. For the RM12/I design the core sets were glued together.

Material		Shape	AL			μo			μi*			~Stress Level*
			-25%	Nom	+25%	-25%	Nom	+25%	-25%*	Nom*	+25%*	Kgf/mm^2
MnZn	3C96 Power	RM12 I	3787	5050	6313	1170	1560	1950	967	1291	1613	0.125
NiZn	4A15 HiPerm	TN13/7.5/5	457	610	763	900	1200	1500	572	754	931	0.55

* = Non-controlled or non-specified parameter



The actual materials (from Ferroxcube) are not as important as are the trends seen in the figures. In every case the initial permeability changes with stress. Some materials change in opposite directions depending whether the stress is in tension or in compression. It can be seen from the graphs that it is very difficult to know exactly where the resulting initial permeability will be due to stress. These changes in initial permeability due to stress are by no means guaranteed or even specified by the ferrite core manufacturers.

In conclusion, design engineers have known for a long time that it is very difficult to define the range of change in the inductance of a magnetic component due to stress. The undeniable changes in inductance are best specified as a minimum and this minimum is best empirically determined. However, a minimum of inductance can be determined for testing purposes.

In Summary:

1. **Ferrite cores are like pieces of ceramic.**
2. **The properties of ferrite cores are based on a small crystalline structure that contains magnetic domains.**
3. **The magnetic domains within a ferrite core are influenced by many things such as composition, size of crystals, and stress.**
4. **The initial permeability of a ferrite core is based on the characteristics of the magnetic domains.**

5. **The value of initial permeability of a ferrite core due to stress varies considerably. In most cases much more than 10%.**
6. **The resulting permeability is very difficult calculate and can best be found through empirical methods. Once found the minimum value can be determined.**
7. **In actual circuit applications a minimum value of initial permeability is all that is needed and any increase is usually beneficial. Any delta inductance variations are not as the minimum inductance.**

References:

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