TECHNICAL BULLETIN

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Ferrimagnetic[1] materials for HF welding impeders.

There is now a wide variety of ferrite types available from several manufacturers around the world. Only a small number will provide optimum performance in HF welding applications. This article highlights the important specifications & explains how to interpret them.

History

The very first impeders used a bundle of fine iron wires inside an insulating tube with coolant pumped through the tube to keep the wires from burning. This method of construction yielded extremely poor results, and was soon replaced by ferrite impeders, which are used to this day in virtually all HF welding applications.

A natural mineral form of ferrite called magnetite has existed since the Earth's early beginnings, and was the "lodestone" used by ancient navigators in primitive compasses. Commercially used ferrites are all manufactured products, and were developed independently by scientists in Japan and Holland during the 1940's.

Composition

Modern ferrites are ceramic crystal structures formed from ions of iron, manganese, nickel, chromium, zinc and oxygen. They are not alloys or mixtures of metals. Physically they are hard, dense and brittle, and can only be machined using diamond or cubic boron nitride saws and grinders.

Ferrites have similar but superior magnetic properties to the iron or steel laminations used in low frequency transformers, with the additional advantage that they have much higher electrical resistivity than metals, so eddy current heating is reduced. They can also be easily formed in a variety of intricate shapes.

There are two main types of ferrite, which are referred to as "hard" and "soft" ferrites. These terms do not refer to physical hardness, but rather to their abilities to retain magnetism. Soft ferrites retain very little permanent magnetism, and are the type used in impeders.

Manufacturing Process

Ferrites are relatively expensive because of the complex and critical manufacturing processes involved. A simplified overview of the manufacturing process is as follows:

High purity oxide powders of iron, zinc, manganese, cobalt and nickel are mixed and blended.

The mixture is then calcined - heated in a kiln at 900° C to 1100 °C - to start the process of forming the ferrite crystal lattice. The calcined material is ground to a fine powder in a ball mill, then dried, mixed with a binder and formed into shapes either by extrusion or pressing.

1 Metals such as iron, nickel & chromium are considered to be FERROMAGNETIC. Ferrite behaves differently and the term FERRIMAGNETIC is more frequently used to describe its properties.

The shaped pieces are dried, then sintered in a controlled atmosphere furnace at 1200° to 1400° to form the spinel crystal structure. During this phase, the material may lose as much as 40% of its volume. This shrinkage is predictable, but is not entirely even, resulting in some change of shape and variation in finished dimensions.

Final grinding and polishing may be applied if necessary to meet critical dimensional requirements, however this is an expensive process that is not normally applied to ferrite used in impeders. Impeder ferrite has fairly wide tolerances on length, diameter & straightness & these should be accommodated in the design of the impeder.

Permeability

Materials that are “magnetic” have the property of being able to “conduct” magnetic lines of flux in a manner similar that in which electrical currents are conducted in metals. Their ability to do this is expressed by their permeability.

Permeability is usually symbolized by the Greek letter μ, and is defined as the ratio of flux density (B) over magnetizing force (H).

$$\mu = B/H$$

If the flux path is through air, the permeability (μ) is unity, however if the flux path is entirely within a ferrimagnetic material, μ may as high as 10,000. Most non-ferrous metals have a permeability that is less than unity.

The actual permeability of ferrimagnetic materials depends on the magnetic properties of the material itself, as well as frequency, flux density, temperature, and even the magnetic path length and shape. Different ferrite manufacturers measure permeability under different conditions, so exact comparisons are almost impossible. The parameter most often given is “initial permeability”, which is by definition measured at very weak (<10mT) magnetizing forces. Because impeders operate at very high flux densities, often at or just below saturation, initial permeability is not particularly useful in selecting ferrite for this application.

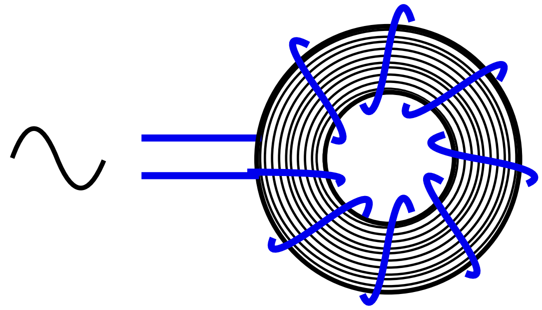


Fig 1.

Many of the important properties of ferrites are established by tests carried out using a toroidal winding, so that virtually all the magnetic flux is confined to the core. An alternating current is passed through the toroidal winding of sufficient magnitude to drive the core into saturation. (Fig 1) The magnetizing force (current through the coil) is plotted against flux density in the core, and the resulting plot is called a hysteresis loop or B/H curve. (Fig, 2)

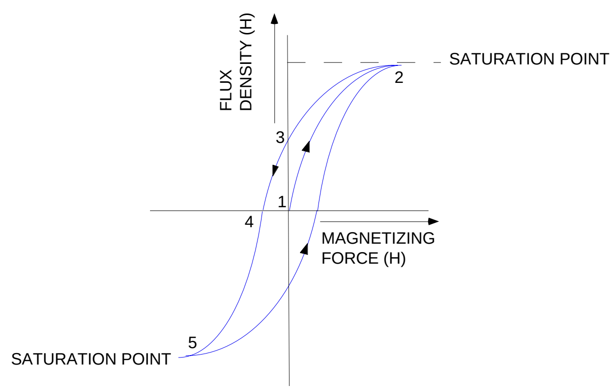


Fig. 2.

If we assume that the core was initially in a completely demagnetized state, the curve starts at point #1, and the flux density begins to increase non-linearly as the magnetizing force increases. At some point, an increase in magnetizing force no longer produces any increase in flux density, and at this point (#2), the core is considered to be saturated. As the magnetizing force is reduced, the flux density is reduced as well, but not at the same rate that it increased. At point #3 on the curve, the magnetizing force is zero, however the core still retains some residual magnetic field, or remanence. To reduce this field to zero, the magnetizing force must be reversed (point #5).

Because permeability can be defined as the ratio of flux density to magnetizing force, it can be expressed by the slope of the hysteresis loop at whichever point it is measured. It has its highest value at the very start of magnetization and becomes unity at saturation. As frequency and temperature change, so does the shape of the loop, so the whole process becomes fairly complex.

When an air gap is present, as is always the case with impeder cores, the hysteresis loop becomes greatly extended on the H axis. A large change in H field is needed to cause a fairly small increase in flux density, so the permeability is low. This also causes a very gradual approach to saturation instead of the sharp “knee” associated with some published B/H curves.

Ferrite Losses

The magnetic cores of motors & transformers are made from high quality iron or steel which is laminated from thin sheets to minimise heating due to losses in the magnetic core. These losses increase with frequency, making laminated cores useless at the frequencies used for most induction welding. The losses in ferrite are many times lower than those of laminated cores, however they are still a limiting factor in high power applications like tube welding.

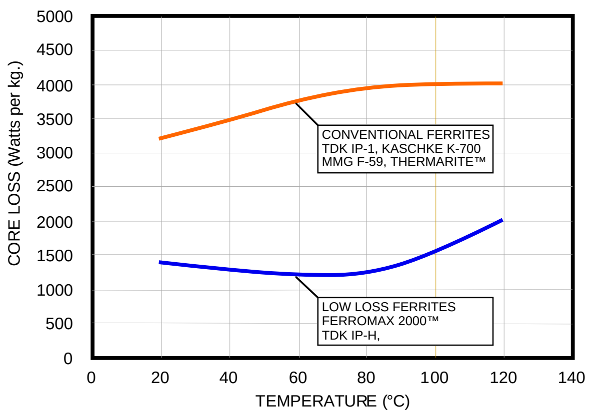


Fig 3.

A theorectically perfect ferrite material would not require any cooling, however this does not yet exist. Great improvements have been made in the design of high power ferrites over the last 10 years or so, however most impeders still require liquid cooling. Modern low loss ferrites require substantially lower volumes of coolant than the type of ferrite originally used for impeders. They operate at lower temperatures, resulting in higher saturation flux densities and greatly reduced thermal shock. These materials may last up to three times longer than first generation impeder ferrites.

Losses in ferrite occur as a result of two main factors:

Coercive (Hysteresis) Losses

Coercive or hysteresis losses occur because of the magnetic behavior of ferrite. Matter is made of atoms which are popularly represented as a positively charged nucleus surrounded by orbiting electrons carrying a negative charge. Because the electrons have charge & spin, a weak magnetic magnetic field is associated with them.

In most materials, the electrons are paired or the atoms align in such a manner that the magnetic fields sum to zero, however a few materials form groups of atoms in which the spin axes are aligned. These groups are known as Weiss Domains & they may contain as many as 10^{14} atoms. Although relatively large, the domains are still considerably smaller than the spinel crystals in ferrites, which are in the order of 10 - 20 µm in diameter.

In “soft” ferrites, the Weiss domains are randomly aligned within the crystals in the absence of an external magnetic field. As an external field is increased in magnitude, those domains which have mobility within the crystal lattice progressively align themselves with the field, increasing the flux density within the ferrite. When all the domains which are capable of realignment have done so, a condition known as saturation occurs. Increasing the H field beyond this point results in the flux density increasing at the same rate as free space.

When the magnetizing force is reduced to zero, most of the domains revert to their random polarization, however a few do not, causing a condition known as remanence. A reversal of the applied field is required to realign these remanent domains. Obviously energy must be expended to reverse the alignment of these domains, and this energy is converted into heat in the ferrite. The amount of heat loss is proportional to the coercive force required to reverse the remanent domains, and to the frequency of the applied field.

During the magnetization cycle, energy barriers must be overcome, so the flux in the ferrite will always lag the applied field, resulting in the familiar shape of the hysteresis curve. If the resistance to magnetization (coercivity) is small, a large induced flux will result at a given H field, and the permeability will be high. When the ferrite is saturated, the flux will increase at the same rate as in free space, and the permeability becomes unity. The shape of the hysteresis curve is also an indication of the coercive losses. A "fat" curve indicates high coercive losses.

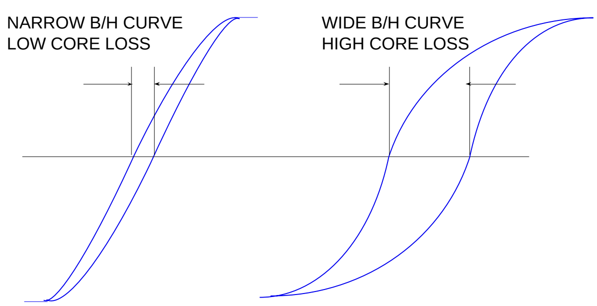


Fig. 4

Permanent magnets have a large value of coercivity & remanence, resulting in a fat hysteresis loop. "Soft" magnetic materials, such as the ferrites used in impeders, should have low remanence and a narrow loop.

Electrical Resistance Losses

A theoretically perfect ferrimagnetic material would be an insulator & would not conduct electricity at all. Iron & other ferromagnetic materials are all electrical conductors, so induced eddy currents flow within them when they are within a fluctuating magnetic field. The current establishes a magnetic flux that opposes the applied flux, reducing the permeability of the material. In addition, heat is generated by the current flowing through the resistance of the core.

Eddy currents are controlled in low frequency transformers & motors by making the core out of thin laminations which are insulated from each other by varnish or an oxide layer. As the frequency is increased, the laminations have to be made thinner and eventually a limit is reached on how thin they can be made. The increasing number of insulating layers also reduces the permeability of the core.

Ferrite is a semiconductor, so it falls somewhere between an insulator & a conductor. Manufactured ferrites are made by mixing oxides of iron & other divalent transition metals, then calcining the mixture at ±1000°C. This process forms the spinel crystal structure. The calcined mix is then wet milled to a fine powder, dried, mixed with an organic binder to form a stiff paste, similar to clay. Following this, it is pressed or extruded to its desired shape and sintered at 1200-1250°C to achieve the desired magnetic & electrical properties. Sintering is carried out in an oxygen rich atmosphere, which results in the individual crystals to being surrounded with a boundary layer of fused organic binder & oxygen atoms.

The resistivity of the crystallates is in the order of 10^{-3} Ωm for manganese/zinc ferrites, however the bulk resistivity is much higher due to the presence of the boundary layer of oxygen atoms. As the applied voltage is increased, charge carriers attain sufficient energy to cross the boundary layer, resulting a pronounced non linearity in the voltage/current relationship. This mechanism is made use of in metal oxide varistors (MOV's), which are used as voltage variable resistors. Ferrites used for impeders typically have a bulk resistivity of 1 to 3 Ωm.

Temperature also affects the action of the boundary layer, and since any eddy current heating will result in an increase in core temperature, and an additional non linear element is introduced.

Ferrite manufacturers quote a value for resistivity for their products, but do not usually specify the measuring voltage, so this parameter is of little use in determining eddy current losses. In addition, all resistivity measurements are carried out using DC. With AC & at higher frequencies, the situation changes dramatically. As the frequency is increased, the resistances of the crystal boundaries are more or less short circuited by their capacitance, so what we now have is a complex network of leaky capacitors!

The situation is further complicated by the fact that ferrite manufacturers base most of their published data on tests carried out on toroidal samples. Toroids are pressed, and therefore exhibit a higher density than extruded shapes such as the rods used in impeders. This too has a large effect on resistivity, since it affects the thickness of the boundary layer between the crystals.

It is usually assumed that eddy current losses increase with the square of frequency. This is based upon the premise that for any given magnitude of the H field, the induced voltage is proportional to the rate of change of the flux. Since power is given by E2/R, a square law relationship would appear to exist with respect to frequency, at least for sinusoidal waveforms. This does not apply in the case of ferrite because the resistance varies non linearly with voltage, temperature & frequency.

Coercive (hysteresis) losses predominate at low frequencies & eddy current losses predominate at high frequencies, however the relationship depends upon the composition, temperature & density of the ferrite.

Permeability is defined as B/H (flux density/ magnetizing force), but this ratio varies with frequency in a complex manner because there is a phase difference between the two variables. This is usually solved by using complex number expressions, which results in permeability having a “real” part,(μ’), which contributes to the inductive reactance, and an “imaginary” part, (μ”), which represents the core losses. As in A.C. circuit theory, these components exist at right angles to each other. Figure 5 shows the loss triangle formed by the two components.

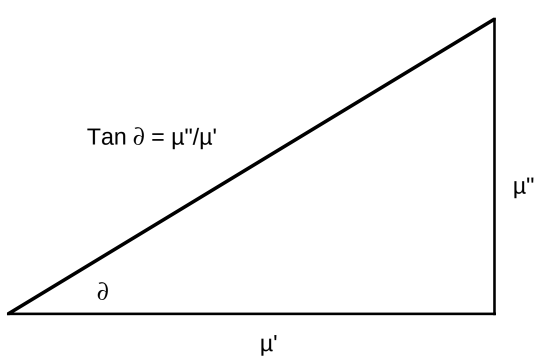


Fig 5.

The angle formed is ∂, the loss angle. The tangent of that angle, tan ∂, is the ratio of the imaginary part to the real part. As frequency increases, the real (inductive) part remains relatively flat then falls sharply. The imaginary (loss) part remains low, then rises sharply. Ferrite manufacturers define the ratio of loss tangent to initial permeability as the Loss Factor. A typical graph of loss factor and initial permeability is shown below. This material would be suitable for use in impeders at frequencies up to 1MHz. At higher frequencies, hysteresis losses would become excessive, and permeability would decline.

A simple test has been developed for comparing the total losses ferrite samples at high flux levels & frequencies, although in its present form, this procedure does not provide calibrated data. Two samples are tested at a time. The reference sample is usually TDK type IP-H ferrite. This was chosen as a reference because we have the greatest experience with it, and because it has proven to be extremely consistent over time.

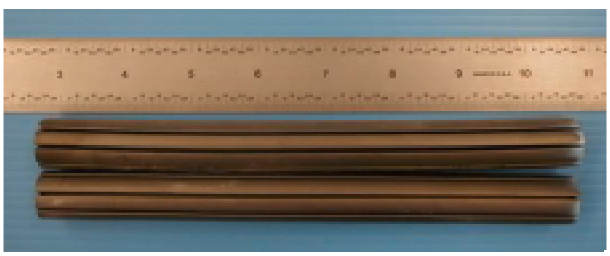
Each sample is placed in a simple calorimeter, with a measured amount of water sufficient to cover the samples. Each calorimeter is then placed within two identical inductors which are connected electrically in series to the output of a 400 kHz. induction heating generator. The series connection ensures that the same current flows in both coils, resulting in identical H fields.

Water temperature is measured in each calorimeter & noted. Power is applied for 60 seconds. The calorimeters are then agitated gently for 60 seconds to stabilize the water & ferrite temperature and the water temperatures are again noted. The temperature rise in each sample is an accurate indication of the total losses in the samples.

This test that does not provide quantitative data, however it closely simulates the conditions which occur in an impeder, and the results are consistent with those obtained on working tube mills, using return flow impeders.

Mechanical Considerations

Because of the high shrinkage that occurs when ferrite is dried and sintered, it is very difficult to accurately control the final dimensions. The finished diameter of a ferrite rod may vary by ±15% from batch to batch, and by as much as 10% within a given batch. There are also fairly wide variations in roundness, straightness & in case of hollow ferrites, in concentricity.



The photograph above shows ferrite that has excessive bow. This is a common problem that requires additional clearance be allowed between the ferrite & the inside of the impeder tube. The bow reduces the mass of ferrite that can be used in a given size impeder, & thus degrades performance.

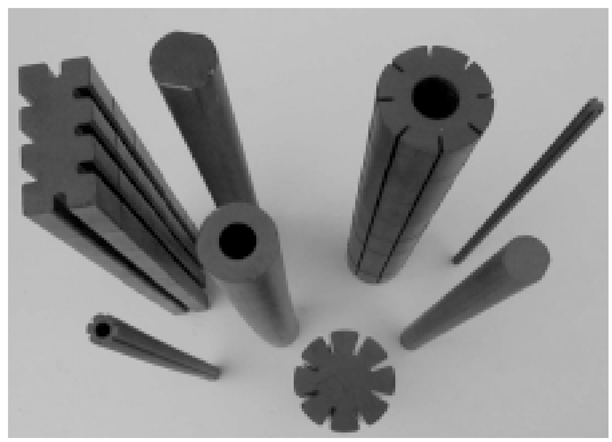
The cost of grinding ferrite to an exact finished size is usually much too high to justify for impeder use, so impeders have to be designed to accept the wide tolerances that exist in extruded ferrite. Some manufacturers do a better job than others in maintaining dimensions & straightness, and this can become a major factor in selecting a particular ferrite type.

If the ferrite is relatively straight & has a consistent diameter, less clearance is required between the ferrite & the inside of the impeder case. This may allow a larger ferrite mass to be accomodated, resulting in more efficient welder operation.

Contrary to popular belief, ferrite does not deteriorate during use. Impeders eventually fail because the outer casing burns or wears away, releasing the ferrite, or because the ferrite becomes broken due to mechanical or thermal shock. When a ferrite rod breaks, air gaps are introduced which reduce the permeability & therefore the amount of flux that is supported by the impeder.

Some brands & grades of ferrite resist breakage better than others. Variations in the sintering conditions affect the strength of the ferrite & the higher the flexural strength, the better.

Ferrite from some manufacturers has transverse cracks and internal voids, caused by uneven shrinkage during drying, or by variations in the extrusion process. These cause stress concentration points, which can lead to premature mechanical failure. Mechanical integrity is therefore an important factor in ferrite selection.



Summary

The selection of a particular grade of ferrite for use in an impeder is a complex matter that requires care and experience. Because there is no “perfect” material available, some compromises must invariably be made. As more ferrite materials become available, the selection process becomes even more difficult. Alternative materials such as silicon steels and amorphous (“glassy”) metals have potential use in certain specialized impeders, however their cost is many times that of ferrite, and their losses are higher, placing an even greater demand on the cooling system design.

Electronic Heating Equipment, Inc.
P.O. Box 7139 - Bonney Lake - WA - 98390 - USA
Phone: 1-360-829-0168   Fax: 1-360-829-0170
email: impeder@sprynet.com   Web: www.impeder.com