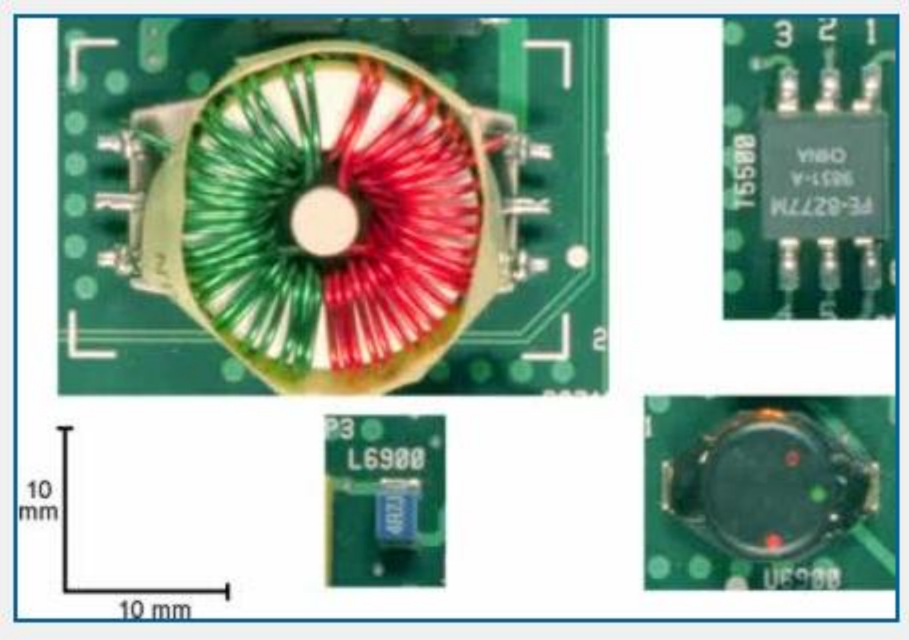
Electronic materials and components-Inductive components

Inductive components make use of the voltage that is generated when a field changes either on the same piece of wire (self-induction) or in a nearby piece of wire (mutual induction) The level of voltage generated is greatly increased if the wire is wound into a coil, and as much as possible of the magnetic field produced by the conductor is guided through that coil. Whilst low value inductors may have only an air core, typically the magnetic field from the coil is concentrated using a magnetic core to guide the field.



Some different formats of inductor

In order to understand the basis of the ferrite and other magnetic materials used in making inductors, we need to stand back and refresh what we know about magnetism. As with static electricity, the behaviour of the material is not perhaps what we might expect from our previous acquaintance with electronics. Much of this is to do with the fact that both phenomena are associated with fields.

Some magnetic basics

An electrical current loop generates a region of physical attraction or magnetic field, represented by a set of magnetic flux lines. The magnitude and direction of the field at any given point near the loop is the ‘magnetic field strength’, represented by H. This is a vector quantity, that it, it is associated with direction as well as magnitude, but this is not an aspect we need to dwell upon. Some materials are inherently magnetic; that is, they can generate a magnetic field without any obvious electrical current. A bar magnet is a familiar example of something which has an identifiable dipole (North-South) orientation.

For the free space around a source of a magnetic field we define a magnetic induction, B whose magnitude is the flux density. This is related to the magnetic field strength H by

$$B = \mu_0 H$$

where µ0 is the permeability of vacuum. If we replace the vacuum by solid material, the magnitude of the flux density will change, but can still be expressed in the form

$$B = \mu H$$

where µ is the ‘permeability’ of the solid. By analogy with Ohm’s Law, the magnetic induction B is analogous to current density, the magnetic field strength H to a voltage gradient (electric field strength), and permeability corresponds to conductivity. The presence of the material instead of the vacuum has changed the induction.

The magnetic behaviour of materials is generally expressed in terms of relative permeability µr, which is the ratio of the permeability of the material to the permeability of vacuum. This is a dimensionless quality of the same type as relative dielectric constant.

A few materials, such as copper and gold, have a value of relative permeability which is very slightly less than 1. Such ‘diamagnetic’ materials have structures which respond to an applied field by setting up a slight opposing field. A larger number of solids have values of relative permeability which are slightly greater than 1 (between 1.00 and 1.01). Materials which exhibit this ‘paramagnetism’ have electronic structures that set up a reinforcing field parallel to the applied field.

For both paramagnetic and diamagnetic materials, the contribution of the additional field is miniscule. However, there are materials with relative permeability which is substantially greater, as much as one million times in some cases. This phenomenon is referred to as ‘ferromagnetism’, one of the earliest materials used for this being annealed ‘soft’ iron. However, this term is slightly misleading, because a number of ferromagnetic materials contain no iron at all.

Both diamagnetic and paramagnetic materials behave linearly with the applied field. However, for materials whose induction increases dramatically with field strength, the connection between B and H is far from linear, as shown in Figure 3.

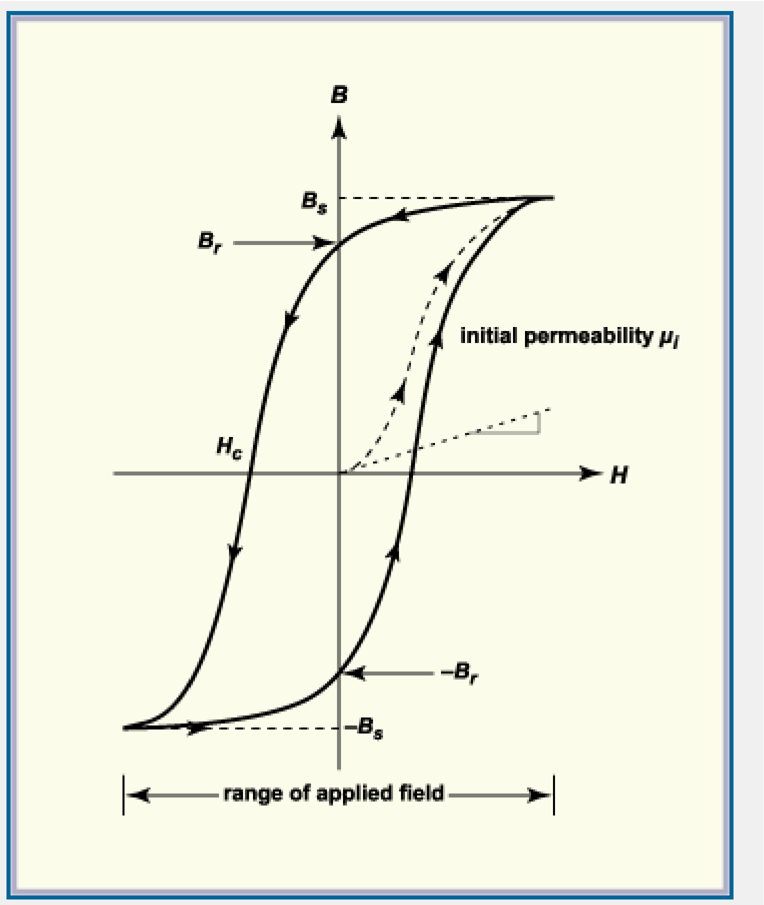


Figure 3: B-H plot for a ferromagnetic material

Starting with a de-magnetised sample, with no induction in the absence of a field, the initial application of a field generates a slight increase in induction, but after this there is a sharp rise, until the flux density reaches a maximum at ‘saturation induction’.

When the field is removed, the induction drops, but not to zero, and in order to remove this ‘remanent induction’ the field must be reversed. Induction is reduced to zero only when a ‘coercive field’ of Hc has been applied. By continuing the field reversal, the material can again be saturated, at the same level of induction, but in the opposite direction. Again there is a remanent induction as the field is reduced to zero. The B-H curve is a completely reversible path that will continue to be traced out as long as the field is cycled backwards and forwards between the saturation limits. This solid line is known as a ‘hysteresis loop’.

In order to understand where this loop comes from we need to look at the material, both at the atomic level and with a slightly wider view. We saw in Atoms and bonding the concept of electrons in orbit around a central nucleus, but we did not carry out the analogy further to consider each electron as spinning, in the same way that a planet rotates around its own axis whilst it travels along its orbit. This spinning electron creates a magnetic dipole which can be positive or negative, depending on the direction of spin. In a filled atomic shell, the electrons are all paired, each pair having two electrons of opposite spin, so there is no net magnetic moment. However, within certain materials, such as the transition metals with atomic numbers 23 to 28 (vanadium to nickel) there are unpaired electrons. Iron in particular has four unpaired electrons, and overall a comparatively high magnetic moment.

Not only do we need individual atoms to have a magnetic nature, we need to have adjacent atoms aligned, so that the overall crystal has a substantial magnetic moment. Adjacent atoms tend to align their electron spins and magnetic moments as part of the electron sharing that forms the metallic bonds.

Whilst it is clear that aligned atoms can produce a high value of induction, it is more difficult to explain how an apparently unmagnetised material can come about. The explanation is that the microstructure of an iron crystal is composed of ‘domains’, all of which have a common orientation from the crystallographic point of view, but differ in the orientation of their magnetic moments. A material that has equal volumes of material magnetically orientated in opposite directions has a net zero induction. However, during initial magnetisation a dramatic rise in induction takes place, caused by the domains orientated in line with the field growing at the expense of those not favourably aligned (Figure 4).

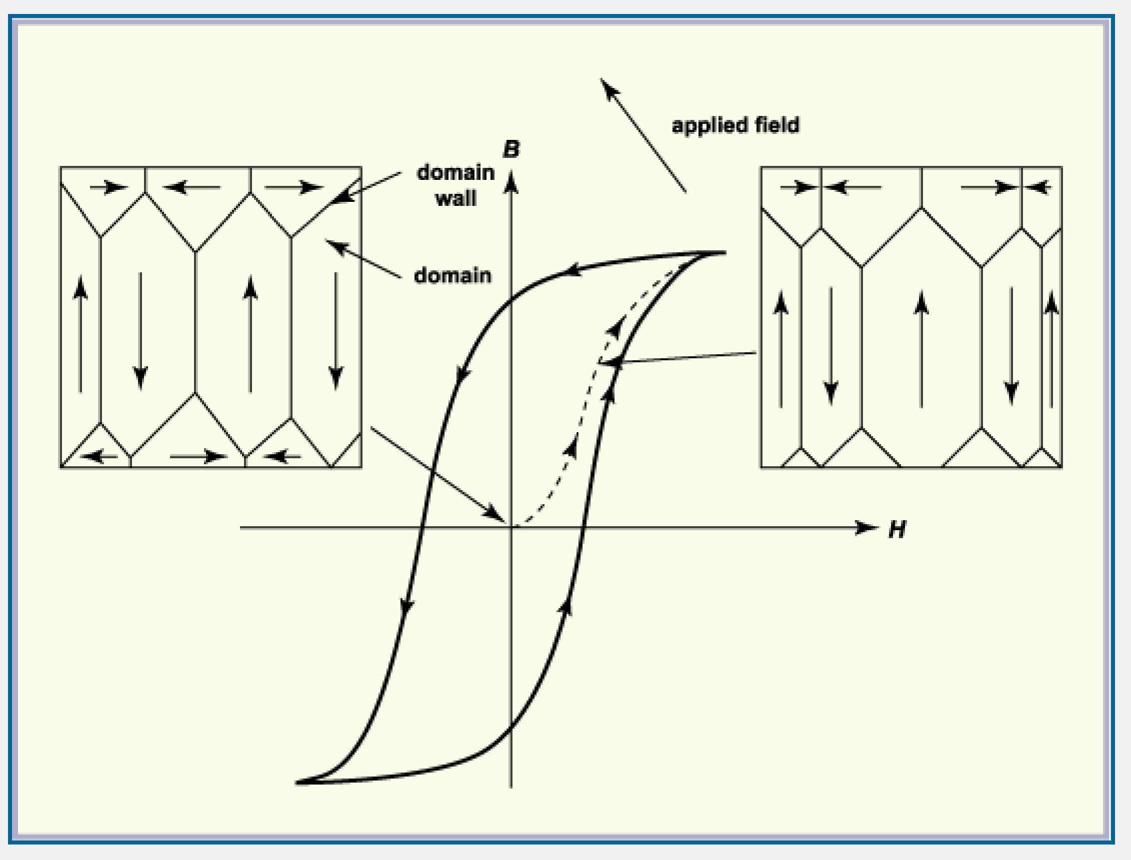


Figure 4: Domain growth during initial magnetisation

Don’t confuse the magnetic domain with the grain structure of the material. The domain wall is just a narrow region across which the orientations change through 180°: growth of a domain involves expanding the wall, but this is merely a shift in the region of re-orientation, and no atomic migration is required.

‘Soft’ and ‘hard’ magnets

Ferromagnetism is a basis of most of the useful metallic magnetic materials, such as are used in power transformers. Ferromagnetic materials fall into two classes: those whose domain walls are easily moved, the so called ‘soft magnets’; those with less mobile domain walls, termed ‘hard magnets’. These have markedly different hysteresis loops, as shown in Figure 5.

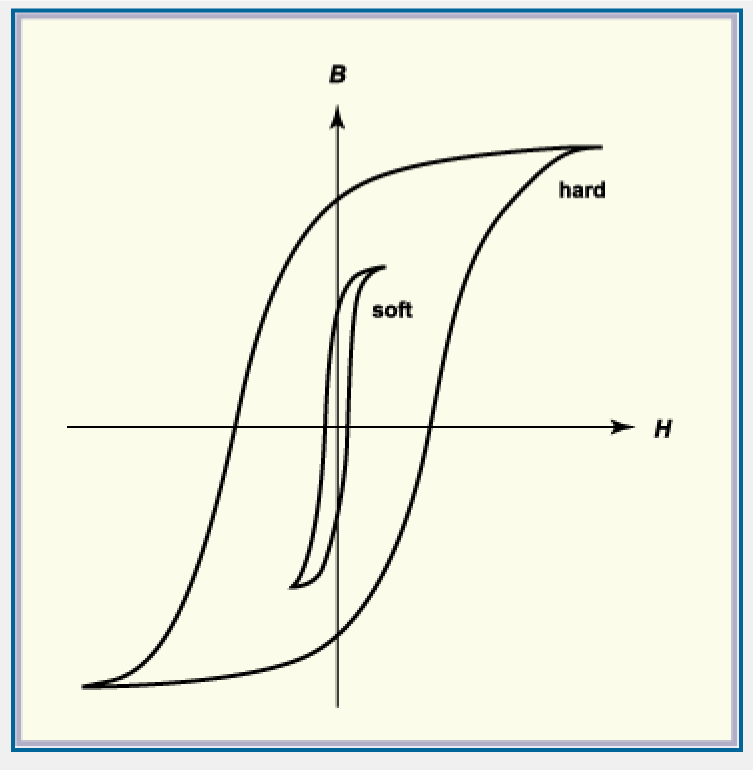


Figure 5: Typical hysteresis loops for soft and hard magnetic materials

Transformer applications use soft magnetic materials, because the area within the hysteresis loop represents the energy consumed as the loop is traversed at typical AC frequency of 50-60Hz. Although a small energy loss is desirable, a high saturation induction is also helpful, as it minimises the size of the transformer core.

A second source of energy loss is the heating effect of the eddy currents induced by the fluctuating magnetic field. As the power dissipated is inversely proportional to the resistance (Ohm's Law!), the loss can be reduced by increasing the resistivity of the material, and iron-silicon alloys have replaced plain carbon steels in low frequency power applications. Putting silicon in the iron also has the effect of increasing permeability, a double achievement for which Augustus Charpy, the inventor of the Charpy impact test was responsible. Further improvement in the magnetic properties is produced by cold-rolling sheets of the steel which tend to orientate the polycrystalline structure of the material, giving it a preferred orientation.

Fortunately you will generally not get involved with the specification of power transformers, but you should be aware of the material used and the general construction. Typically a transformer core is built from laminated silicon steel sheets with thicknesses in the range 150–650µm. These are annealed after stamping to give high permeability, and separated by very thin coatings of insulation, typically a varnish or phosphate passivation.

A number of different configurations is possible, of which one is shown in Figure 6. There is also a slight break in the magnetic loop in order to stop total short circuiting, which would otherwise reduce the efficiency very considerably.

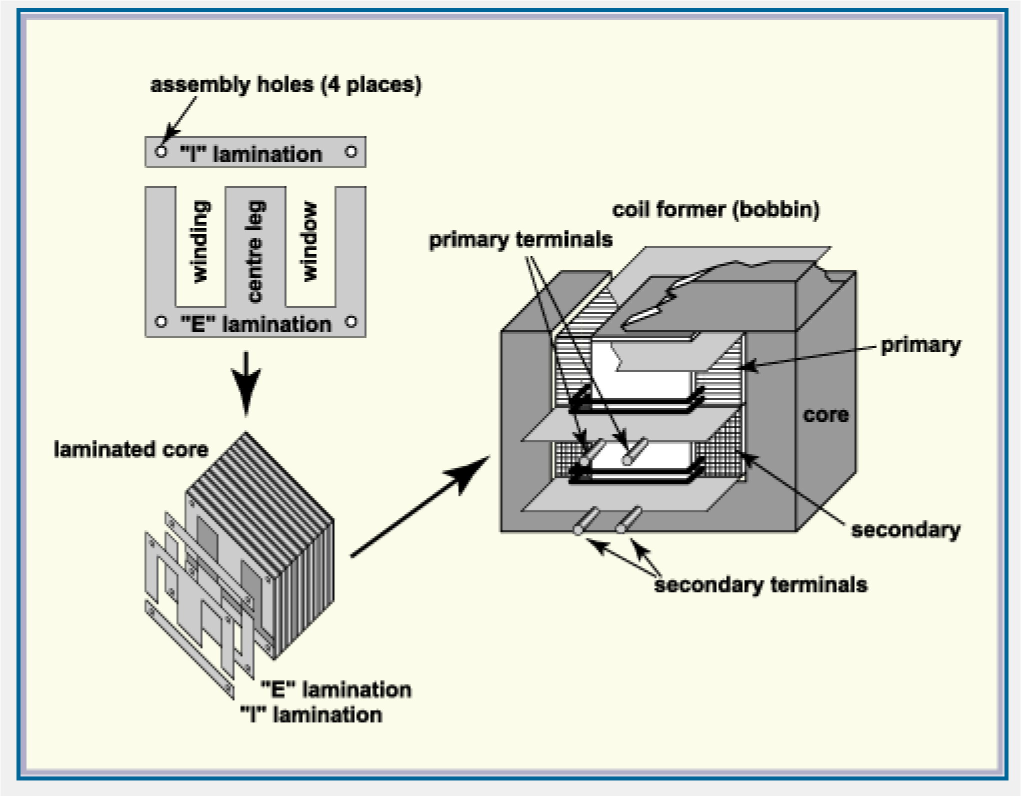


Figure 6: An E-core transformer assembly

Be aware that all transformers are mechanical assemblies as well as magnetic circuits, and that materials used may deteriorate or creep with time. It is not unusual for power transformers to loosen and become noisy and the insulation in the core deteriorates. Detailed discussion is beyond the scope of this course[1].

[1] http://sound.westhost.com/xfmr.htm and http://sound.westhost.com/xfmr2.htm form a two-part article on transformers by Rod Elliott. He has a bias towards hi-fi applications, but shares much insight into how transformers work.

Magnetic ceramics

The steel alloys used for transformer cores have high resistivity in order to prevent substantial eddy current losses. However, as the frequency increases, so does the potential for loss, and at even moderate audio frequencies these losses become unacceptable. Fortunately magnetic ceramics have inherently high resistivity, so are commonly chosen for high frequency transformers.

There is a wide range of magnetic ceramic materials, of which true ferrites are only one group of structures exhibiting ferromagnetic behaviour. Despite this, the term ‘ferrite’ is generally used for the whole range of such materials.

Ceramic magnets, and the ferrites used in making inductors, are magnetic because of a different mechanism, which is distinguished by the slightly different spelling of ‘ferrimagnetism’. However, whilst the mechanism at an atomic level is different, the hysteresis behaviour, and the presence and movement of domains, is exactly the same as with ferromagnetic materials.

The most commercially important ceramic magnets are associated with the spinel (MgAl2O4) crystal structure, an extremely complex crystal containing 56 ions. Whilst spinel itself isn’t magnetic, some compounds containing transition metal ions crystallise in this structure or the closely-related inverse spinel structure.

From the user point of view ferrites are hard ceramic materials, which are generally pressed, because they are too hard to form in other ways. They are also extremely brittle, and this must be borne in mind during assembly operations.

Practical inductors

Inductors come in many formats and sizes, the size depending on the inductance value and the current carrying capability required. Nearly always they have a wound coil, which may or may not be visible. Although large transformers have silicon-iron cores, and the very smallest inductors may be air-cored, or even just tracks on the PCB, most will have some kind of ferrite core. Figure 7 shows some of the standard types, but doesn’t really indicate the fact that these range very widely in size. Small coils can be self-supporting on their wires, or potted, but the larger cores normally need some kind of mechanical anchorage. Some styles of inductor also have shrouds and screens which require earth connection, although most ferrite-cored parts do not, as the ferrite contains the magnetic field.

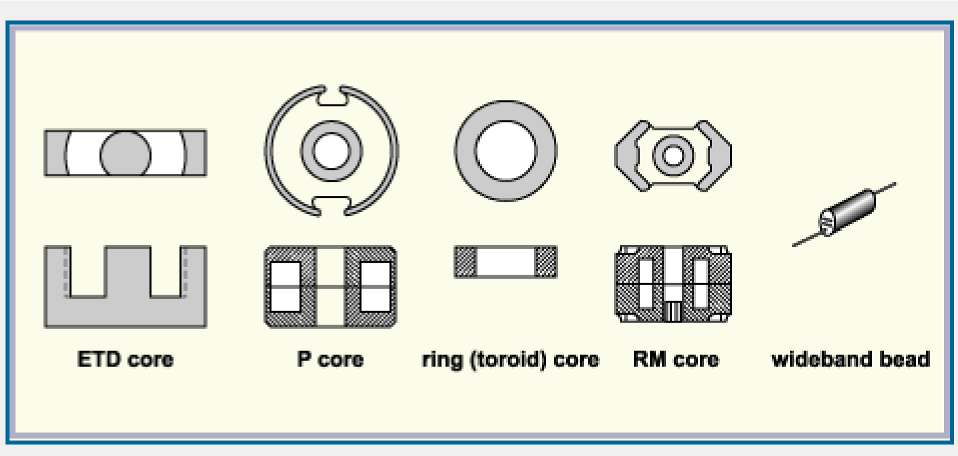
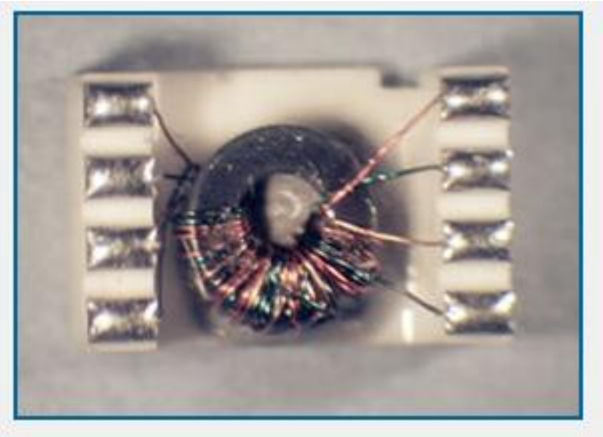


Figure 7: Some standard types of ferrite core

An inductor within a P core

It will be evident from the shapes of these inductors that they are not particularly easy to fit into a surface mount package.



A surface mount transformer, wound on a toroidal ferrite core (bare format shows construction)

Converting a wound ferrite core to a cuboid shape is something that requires the addition of terminals and enclosure, which is usually an epoxy resin potting. One such device is shown schematically in Figure 8. Typically, chip inductors are some 3 mm cube and available in the range 1–500 mH, the size depending on the current-carrying capability required.

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Some surface mounting styles of inductor

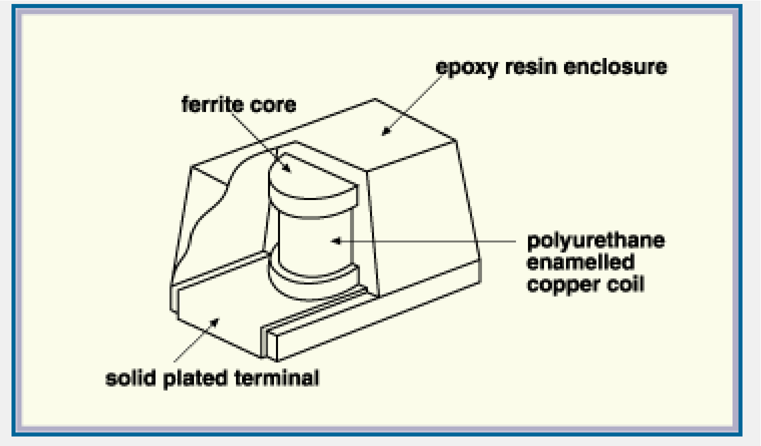

Figure 8: SM inductor construction

Did you notice the comment ‘nearly always they have a wound coil’? There are in fact ways in which printing techniques can be used to create inductors without any wire. If you want to find out how, you will have to do some research yourself!

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Source: http://www.ami.ac.uk/courses/topics/0238_ind/index.html