Powder Metallurgical Materials and Processes for Soft Magnetic Applications

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***Abstract*—For many designers of electrical machines, the term "soft magnetic materials" automatically means laminated electrical sheet. This is unfortunate, since for many applications, particularly at low frequencies, laminated sheet is rarely the best material choice. Soft magnetic powder materials are available to satisfy the needs of virtually any application imaginable, from plain iron, giving good induction for DC applications, to ultra-high permeability nickel irons. The use of these materials brings with it all the attendant advantages of powder metallurgical (PM) production: low cost, tight tolerances, complicated forms, and minimal material waste. For high frequency applications, a range of soft magnetic composite materials or SMCs are available which can provide magnetic performance comparable to or surpassing that of laminated sheets, while at the same time allowing much greater freedom to the designer due to their isotropic nature, which permits the implementation of complicated 3D flux paths. This paper presents a review of the available powder-based soft magnetic materials, together with typical applications and a consideration of some of the factors which must be taken into account when producing powder-based components for magnetic applications.**

Keywords—soft magnetic materials, powder metallurgy, sinter, SMC, dielectromagnetic

I. INTRODUCTION

Powder metallurgy or PM is well established as a technique for the production of soft magnetic components for electromagnetic applications. To avoid confusion it should be noted that the abbreviation PM is used throughout this paper to mean Powder Metallurgy, and not Permanent Magnet. The term *soft* in relation to magnetism refers to materials which are easily magnetised under the influence of an external magnetising field, and which give up their magnetisation when the external field is removed. These materials are principally the ferromagnetic elements iron, nickel and cobalt and their alloys. Unlike hard magnetic materials, or permanent magnets, which retain their magnetisation in the absence of an external field and are used as *sources* of magnetic flux, soft magnetic materials are used as *guides* and *amplifiers* of magnetic flux. They act as a conduit in magnetic circuits allowing electrical signal to be converted to movement, as in the case of motors or actuators, or movement to be converted to electrical signal, as in the case of sensors. The complicated geometries required to form magnetic circuits are well suited for PM production by pressing and sintering.

If the applied field is then reduced to zero, the induction will not reduce along the same path; the magnetisation curve shows *hysteresis*. In an unmagnetised sample of ferromagnetic material which has not been subjected to an external field, the magnetic moments of the atoms are subdivided into *magnetic domains* of opposing orientation which cancel each other out, leaving no overall net magnetisation. As the unmagnetised sample is subjected to an increasing applied field, these magnetic domains rearrange themselves, with domains which are approximately aligned with the external field growing at the expense of domains which are aligned against the applied field. This happens by the movement of the *domain walls* separating the differently aligned regions. Imperfections in the crystalline structure of the material such as vacancies, dislocations, inclusions, second-phase precipitates, or grain boundaries represent an obstacle to the free movement of these domain walls which requires additional energy to be overcome. It is this which leads to hysteresis when the external field is removed. When the external field is reduced to zero, a certain net magnetisation will remain, known as the *remanent induction* or B_r. Additional energy must be expended, in the form of an external field in the opposite direction to the original magnetising field, in order to reduce the magnetisation of the sample to zero. The magnitude of this field is given the nomenclature H_c, and is referred to as the *coercive force* or *coercivity* of the material. The higher the permeability of a material, the easier it is to magnetise. The lower the coercive force, the easier it is to demagnetise. The hysteresis loop is completed by increasing the applied negative field to once again reach saturation, and then reversing the cycle. The area under the loop gives the energy expended per cycle to change the magnetisation of the material. Multiplied by the frequency of magnetisation, this gives the *hysteresis losses*, measured in Wkg^{-1}.

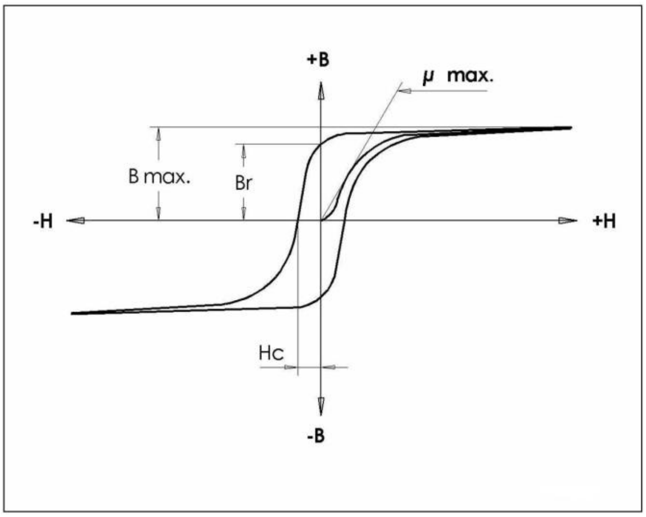

Figure 1: Hysteresis loop for a ferromagnetic material

The production of sintered soft magnetic parts is broadly similar to the production of sintered structural steel parts. High densities favour high induction. Except in the low field region of the B-H curve, induction varies linearly with density. Other factors being equal (type of iron powder, sintering conditions, process route), an increase in density of $0.1gcm^{-3}$ gives an increase in induction of 0.05T (figure 2).

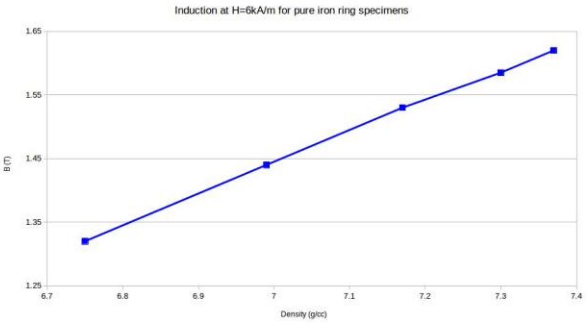

Figure 2: The variation of induction with density for pure iron samples sintered at 1120ºC

High permeability and low coercive force are favoured by high purity powders, a large grain size, and very low oxygen, nitrogen, and carbon levels. In the sintering of structural parts, fast cooling rates are advantageous to refine microstructure and increase strength. In the sintering of soft magnetic components on the other hand, slow cooling rates are favoured in order to promote grain growth. Optimum results are obtained by sintering at high temperature (>1250ºC) in a pure dry hydrogen atmosphere in order to avoid nitrogen pick-up, encourage grain growth, and produce smaller, more rounded pores to minimise the generation of internal demagnetising fields. Particular care must be exercised in the dewaxing phase in order to avoid carbon contamination.

If soft magnetic parts are submitted to finishing operations which leave residual stresses such as sizing, machining, or tumbling, then a stress-relieving anneal will be required to restore the permeability and coercive force to their as-sintered values. The coercive force is also an important parameter for the quality control of soft magnetic parts, since unlike the permeability it can be measured directly from a finished component.

II. CONVENTIONAL SOFT MAGNETIC MATERIALS

A. *Pure Fe*

In the world of PM parts production, where we are constantly looking for more sophisticated alloying systems to obtain higher strengths in structural components, plain iron might seem to be too simple a material to be of much interest. In fact, due to its very high level of induction, it is an extremely important material for soft magnetic applications. The excellent compressibility of pure iron makes it easy to reach high densities, its dimensional stability on sintering makes tight tolerances achievable, and it has the lowest cost of the PM soft magnetic materials.

Material	**Density gcm^{-3}**	**Coercive Force Am^{-1}**	**Saturation Induction B_S Teslas**	**μ_{MAX}**	**UTS MPa**	**Elongation %**	**Rockwell Hardness**
Pure Iron	7.2	150	1.8	3000	220	10	56F
	7.6	80	2.05	6000	250	30	50F

Table 1: Magnetic and mechanical properties of sintered pure iron.

Table 1 shows the properties typically obtainable from pure iron at different densities. The values shown at a density of $7.2gcm^{-3}$ were obtained after sintering at 1120ºC, while those shown at $7.6gcm^{-3}$ were obtained after sintering at 1250ºC.

Figure 3: Toothed sensor rings produced from sintered iron for antilock braking systems.

For many years the most typical examples of sintered pure iron parts were the toothed reluctor rings (also known as tone rings) used in automotive anti-lock braking systems. These ABS rings were produced in many sizes and designs (figure 3), but all operated on the same principle (figure 4). Attached to axles or driveshafts, they allow the rotation of the wheels to be monitored, with the movement of the teeth past an inductive sensor causing fluctuations in a magnetic field which generates an alternating voltage from the sensor coil. The frequency of the output signal is related to the wheel speed and the number of teeth on the sensor ring. If the alternating signal ceases, it indicates that the wheel is no longer rotating.

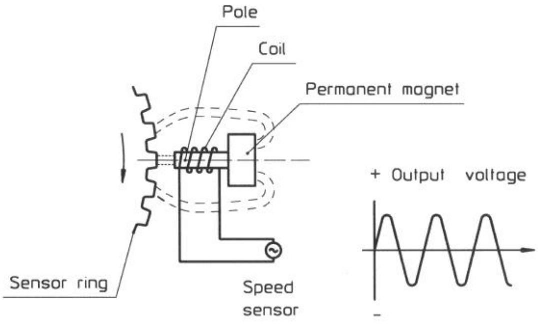

Figure 4: Operating principle of an ABS sensor ring

Although this is a robust system mounted in millions of vehicles, it has the disadvantage that not only the frequency but also the amplitude of the output signal decreases with the rotational speed of the sensor ring, and below vehicle speeds of a few km/h it is too low to be read. For this reason in recent years antilock braking systems have moved away from using passive sensors and toothed rings to active sensor arrangements which are more reliable at low speeds. However, the same principles are used in other kinds of toothed and slotted sensor disks. The use of an asymmetric profile allows not only speed of rotation but also position to be measured using inductive or Hall-effect sensors. This kind of part is used in camshaft position sensors such as those shown in figure 5.

The use of pure iron sintered parts is not restricted to automotive applications. Figure 6 shows pure iron components forming part of an electromagnetic disk brake used in home automation systems for the opening and closing of blinds and sun awnings.

B. Phosphorous Iron

Pure iron, for all its magnetic virtues, is a material with insufficient strength and hardness for many applications.

Carbon cannot be added to increase the strength of iron without adversely affecting its soft magnetic properties, increasing its coercivity to the point where it effectively becomes a permanent magnet. In fact the use of the terms *soft* and *hard* to classify to the magnetic behaviour of a material originally derive from the observation that hard carbon steel retained magnetisation to a much greater extent than soft malleable iron.

Figure 5: A variety of target wheels produced from sintered iron used in camshaft position sensors

Figure 6: Pure iron parts used in an electromagnetic disk brake in a home automation system

Fortunately phosphorous, which is the next most potent ferrite strengthening element after carbon, can be added to iron to increase strength and hardness without any loss of magnetic properties. In fact, phosphorus iron will generally show lower coercive force and higher permeability than pure iron at the same density. This is because the phosphorus is a ferrite-stabiliser, and allows partial alpha-phase sintering, leading to much larger ferrite grain size, an effect which is particularly noticeable in phosphorous iron sintered at high temperature as shown in figure 7. A large grain size favours the free movement of magnetic domain walls.

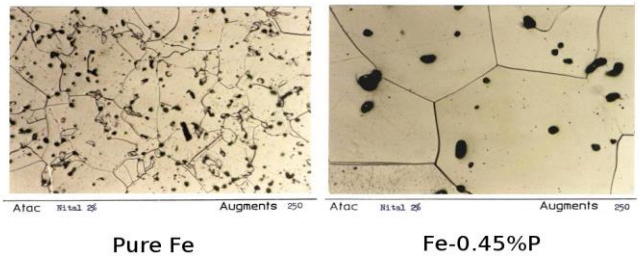

Figure 7: The ferrite grain size in pure iron and phosphorous iron after high temperature sintering

Table 2 lists sample properties for the most commonly used composition; iron alloyed with 0.45% phosphorous. This composition is a popular choice due to its dimensional stability when sintered at 1120ºC. The values at a density of 7.2gcm^{-3} were obtained from samples sintered at 1120ºC, while the samples at a density of 7.6gcm^{-3} were sintered at 1250ºC. The increase in permeability due to increased grain size after high temperature sintering is clear.

Material	**Density gcm^{-3}**	**Coercive Force Am^{-1}**	**Saturation Induction B_S Teslas**	**μ_{MAX}**	**UTS MPa**	**Elongation %**	**Rockwell Hardness**
Fe – 0.45% P	7.2	106	1.8	400	350	14	63B
	7.6	44	2	10900	500	20	68B

Table 2: Magnetic and mechanical properties of sintered phosphorous iron.

The combination of magnetic and mechanical properties of Fe-P has led it to be widely used in the production of components for linear actuators such as flux washers, pole plates, and housings which are often crimp-fitted. These linear actuators are used in fuel injectors or in solenoids which increasingly are replacing vacuum or mechanically activated devices.

Figure 8: Flux tube and pole piece from a solenoid, produced from sintered Fe-P

Figure 8 shows a flux tube and pole piece which form part of a solenoid for a module used to provide electrohydraulic control of automatic and dual-clutch transmissions. Several such solenoids are used in each module.

C. Silicon Iron

Iron alloyed with 3wt% of silicon has a higher hardness than phosphorous iron, and can be used for applications requiring increased resistance to wear or impact such as the plungers or armatures in linear actuators. However the main benefit of the alloying of iron with silicon is the resultant increase in resistivity, by a factor of four relative to pure iron, which allows magnetic properties to be maintained in applications where the frequency of magnetisation-demagnetisation is higher than a few hertz.

Sintered silicon iron parts are prepared from a pure iron base powder mixed with a ferro-silicon master alloy. As well as reducing the compressibility relative to pure iron or iron-phosphorous, this makes high temperature sintering (above 1250ºC) an absolute requirement, both in order to achieve homogenisation of the composition as well as to promote the large grain size required for optimum permeability and coercive force. Best results are obtained by sintering in a pure hydrogen atmosphere. Table 3 lists the properties achieveable in Fe-3%Si at two density levels.

Material	Density gcm^{-3}	Coercive Force Am^{-1}	Saturation Induction B_S Teslas	μ_{MAX}	Resistivity µΩcm	UTS MPa	Elongation %	Rockwell Hardness
Fe – 3% Si	7.3	64	1.8	8000	50	400	15	70B
	7.5	48	1.9	9500	48	410	17	79B

Table 3: Magnetic and mechanical properties of sintered silicon iron.

Figure 9 shows a variety of parts produced from sintered silicon iron. The parts labelled “1” and “2” are, respectively, an armature and stator ring used in electronically-controlled unit injectors for heavy-duty diesel engines of the sort used in lorries, buses, or marine applications. Both of these parts are produced at a density of 7.4 gcm^{-3}.

Figure 9: Parts for linear actuators produced from sintered silicon iron

At an even higher density of 7.5gcm^{-3}, 3% silicon iron is currently finding application as the material for the pole pieces in the metering pumps for AdBlue which are being used in selective catalytic reduction (SCR) systems being introduced in passenger vehicles to allow them to comply with Euro VI NOx emission levels.

D. Nickel Iron

The nickel-irons, often referred to as Permalloys, are the family of soft magnetic materials with the highest permeabilities and lowest coercive forces. An alloy with 80%Ni can give a permeability of around 75000, with a coercive force as low as 2Am^{-1}, though this comes at the expense of a very low saturation induction in comparison with pure Fe. Fe-50%Ni combines a relatively high maximum induction with very high permeability and low coercive force, and is the most widely-used of the sintered nickel irons. Table 4 lists the properties obtainable for 50% and 80% nickel-irons: in both cases these values are obtained sintering at temperatures above 1250ºC in a dry hydrogen atmosphere.

Material	Density gcm^{-3}	Coercive Force Am^{-1}	Saturation Induction B_S Teslas	μ_{MAX}	UTS MPa	Elongation %	Rockwell Hardness
Fe – 50% Ni	7.9 – 8.05	5 - 16	1.6	25000 - 30000	420	18	64
Fe – 80% Ni	8.5	2	0.8	74900	440	20	68

Table 4: Magnetic and mechanical properties of sintered nickel irons.

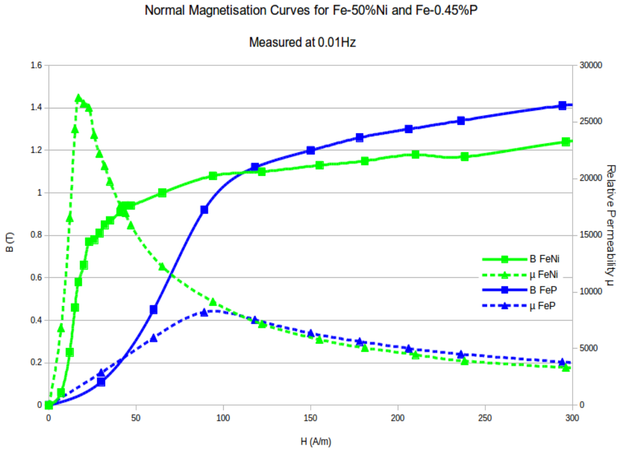

Figure 10: DC B-H Curves for sintered Fe-50%Ni and sintered Fe-0.45%P

Figure 10 shows a comparison of the B-H curves of Fe-50%Ni and Fe-0.45%P at low values of applied field. The nickel iron sample had a density of 7.9gcm^{-3}, while the Fe-0.45%P had a density of 7.6gcm^{-3} (similar proportions of their respective full densities).While the phosphorous iron has a much higher saturation induction, at applied fields of up to 100Am^{-1} it is the nickel iron which has the higher induction. To achieve an induction of 0.46T in the nickel iron requires only one quarter of the applied field required in the phosphorous iron. This makes nickel-iron an excellent choice for low current drain applications, such as battery-powered valves and switching systems.

Figure 11 shows a selection of parts produced from sintered nickel iron. The parts labelled 1 and 2 are the closure plate and core from a high-speed pneumatic valve. Banks of such valves are used in automated sorters for foodstuffs such as peas or rice. The product to be sorted falls in a continuous stream past artificial vision cameras, and when contaminants or out-of-specification items are detected, the valves are triggered to cause a jet of compressed air to remove the unwanted item from the product stream. Because of the very high throughput of such machines, the opening and closing times of the valve are of paramount importance. A few miliseconds' delay in opening the valve and the contaminant would not be rejected, while any lag in closing the valve would lead to rejection of good product. To achieve such rapid opening and closing, very high permeability and very low coercive force are needed, and the core and closure plate are therefore produced from Fe-50%Ni, with a density above 7.95 gcm^{-3}, sintered at high temperature in a dry hydrogen atmosphere. No other material could give the required performance.

Figure 11: A selection of parts produced from sintered nickel iron

Nickel iron is a high value material: Fe-50%Ni can cost between ten and fifteen times as much as pure iron. This makes the net-shape PM process a particularly attractive production route, even for fairly simple shapes, through the avoidance or minimisation of material waste.

It should be mentioned that the permeability and coercive force of the nickel irons are extremely sensitive to cold work, and even fairly small amounts of deformation can cause the coercive force to increase by one or even two orders of magnitude. Particular care must be taken in part handling and assembly, and if finish machining operations are required, they must be followed by high-temperature annealing.

E. Cobalt Iron

The value of cobalt-iron alloys lies not in their permeability, but rather in extraordinarily high values of saturation magnetisation, the highest of the soft magnetic materials. An alloy of iron with 35% Cobalt can give a saturation induction of more than 2.4T, but an alloy of Fe-50%Co, known as Permendur, is generally preferred due to offering improved permeability with only a slightly lower value of saturation magnetisation.

Material	**Density gcm^{-3}**	**Coercive Force Am^{-1}**	**Saturation Induction B_S Teslas**	**μ_{MAX}**	**UTS MPa**	**Elongation %**	**Rockwell Hardness**
Fe-50% Co	>7.95	150-180	2.35	3000 - 4000	200-400	<1 - 2	85B

Table 5: Magnetic and mechanical properties of sintered cobalt iron.

Table 5 shows properties typically obtained in sintered Fe-50%Co. The ranges of values depend on a final annealing treatment, which can be varied to favour magnetic or mechanical properties.

Figure 12 shows B-H curves for samples of Fe-50%Co and pure iron. The pure iron sample was pressed, high-temperature sintered, and sized to a density of 7.71gcm^{-3}, followed by full annealing. The cobalt iron sample was pressed and sintered to a density of 7.98gcm^{-3}. At an applied field of 5.9kAm^{-1}, the cobalt iron shows an induction of 2.22 T, nearly 0.4T higher than the pure iron. Magnetic force varies with the square of flux density, hence this difference in induction could give almost a 50% increase in force. It is for this reason that cobalt iron is the material of choice for applications such as pole pieces for electromagnets, beam guide systems for electron microscopes, and high-efficiency motors and generators, which require either the maximum possible force, or the minimum possible size of component to produce a given force.

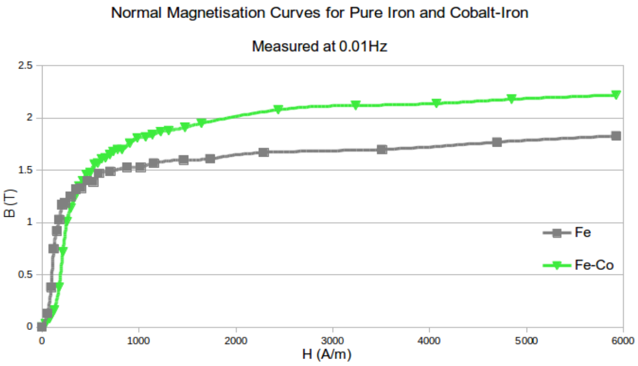

Figure 12: DC B-H curves for sintered pure iron and sintered cobalt iron

A further advantage of cobalt-iron is its high Curie point, the temperature at which thermal agitation overcomes ferromagnetism. A Fe-50%Co alloy has a Curie temperature of around 950ºC, compared with 770ºC for pure iron. This allows cobalt iron to maintain its magnetic properties will little degradation up to temperatures around 500ºC, making it the only choice of material for applications with high working temperatures such as the cores of ultra-compact motors where space constraints do not allow for adequate cooling.

PM might be considered to be an under-exploited production route for cobalt iron. Even more so than nickel iron, cobalt iron is a high value material, costing up to 50 times the price of pure iron. It is also notoriously difficult to machine, earning it the nickname “crackalloy” among machinists. This increases the value of a net-shape forming process, avoiding wasted material and avoiding or minimising slow and difficult machining operations.

III. SOFT MAGNETIC MATERIALS FOR HIGH FREQUENCY APPLICATIONS

The materials described thus far are suitable primarily for applications under conditions of static magnetisation, or when the magnetisation-demagnetisation cycle occurs at a frequency of no more than a few Hertz. When the frequency of the magnetisation/demagnetisation cycle is increased beyond this, the properties of conventional sintered soft magnetic materials show a rapid deterioration.

Figure 13 shows a sequence of B-H curves measured from a sample of sintered iron at frequencies from 0.1 to 1000Hz. Above 1Hz, the permeability and maximum induction show a significant fall-off.

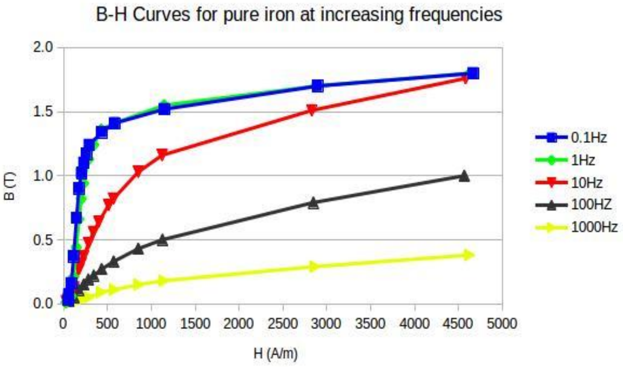

Figure 13: B-H curves for sintered pure iron at different magnetising frequencies

This fall off is due to the generation of *eddy* or *Foucault currents* in the iron sample.

According to Faraday's law, a variation in the intensity of a magnetic field generates a voltage or electromotive force which is proportional to the rate of change of the flux density. In an electrically conductive medium, such as a soft magnetic iron, this will cause loops of current to flow. The more rapid the change in the magnetic field, the greater the amount of energy which will be dissipated in the form of resistive heating of the iron part. The eddy currents will themselves induce a secondary magnetic field which opposes the change. The overall effect is observed as a severe decline in the permeability of the material as the frequency of magnetisation increases.

The losses due to eddy current formation are given by equation 1, where K is a constant, f is the frequency of the magnetising cycle, B is the maximum induction attained, d is the smallest dimension of the material perpendicular to the magnetic field, and ρ is the electrical resistivity of the material.

$$P_e = \frac{K\, d^2\, f^2\, B^2}{\rho} \qquad (1)$$

The increased electrical resistivity of iron alloyed with silicon mitigates the problem of eddy current formation to a certain extent, and Fe-3%Si can be used at frequencies up to a few tens of hertz. The resistivity could be increased still further by increasing the amount of silicon beyond 3wt%, but in practice the resultant loss of compressibility and increase in fragility makes this impractical, and since the eddy current losses increase with the square of the frequency of magnetisation, an increase in the resistivity alone is not sufficient.

The traditional method of restricting eddy current losses is to reduce the value of d in equation (1) by using a laminated stack of thin sheets of silicon steel separated by an electrically insulating varnish. In this way d may be reduced from tens of milimetres to 0.5mm or less. Since the eddy current losses are proportional to the square of this parameter, such a reduction in d has a significant limiting effect.

In the world of PM materials, the alternative to the laminated stack is the Soft Magnetic Composite or SMC. Here it is the iron powder grains which are separated from each other by an electrically insulating layer, either in the form of a phenolic or silicone resin, or in the form of an oxide or phosphate coating of the powder. In this way the parameter d is reduced still further, down to the size of the powder grain, typically from 20 – 120µm. In comparison with laminated stacks, SMC materials offer a greater resistance to eddy current formation, as well as presenting designers with the advantage of magnetic properties which are isotropic, rather than being confined to two dimensions as in the case of laminates. This opens up the possibility of producing *transverse* or *axial flux motors*, which would be impossible or prohibitively expensive to fabricate from conventional laminated sheet. The possibility of producing complicated 3D flux paths has been exploited to good effect in the production of high torque claw pole motors using SMC materials [1], amongst other noteworthy examples.

SMCs are a special class of PM material, as they are not sintered. Sintering at conventional temperatures would break down the insulating barrier between iron particles, and hence these materials are subjected to a curing treatment at a much lower temperature, typically up to 500ºC. As a consequence, these materials have much lower mechanical strength than conventional sintered materials, with a TRS of 140 MPa representing the upper limit of what is currently achievable. A further consequence of the low curing temperature is that there is no effective stress relief for the cold work done during the compacting process. This means that the coercive forces of these materials are relatively high, and their permeabilities are relatively low in comparison with conventional sintered irons. In practice, however, this is not a problem at the working frequencies for which these materials are designed. Figure 14 shows the maximum permeability of a sintered pure iron and a soft magnetic composite material (Somaloy 500 made by Höganäs AB) at different magnetising frequencies. Although the permeability of the SMC material is much lower than that of the sintered iron at low frequencies, it remains constant as the frequency is increased, while that of the sintered iron drops off sharply. At frequencies above 100Hz, the permeability of the SMC material is higher.

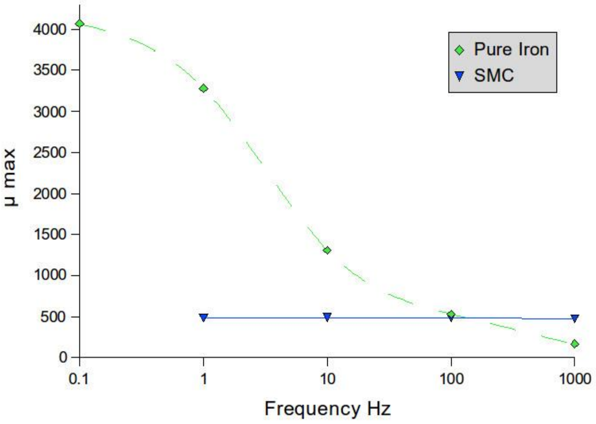

Figure 14: Variation of maximum permeability with frequency of magnetisation for sintered pure iron and an SMC material

In recent years the number of grades of SMC materials available has proliferated, with variations to the base powder grain size and the type and quantity of insulator allowing the properties of the material to be targeted to specific types of application. SMC grades are now available which permit curing at temperatures high enough to give effective stress relief, which allows maximum permeabilities of up to 1000 to be achieved. Raising the permeability much beyond this level is limited by the insulating layers within the material forming a distributed air gap. Improved pressing lubricants and the use of warm compaction allow high densities ($>7.5 gcm^{-3}$) to be achieved in order to maximise induction. Other grades have insulating systems which allow them to operate at frequencies of tens or hundreds of kHz. Table 7 shows the ranges of properties available from currently available SMC materials.

SMCs are increasingly being chosen for the production of high efficiency motors, ignition cores [2], transformers, chokes, sensors, or fuel injector cores. Figure 15 shows components from two types of PM soft magnetic material which form part of a variable stiffness engine mount. The part on the left is an orifice plate fabricated from Fe-0.45%P while the part on the right is a core plate produced from an SMC material. By varying the magnetic field in the core plate, the viscosity of a magnetorheological fluid is altered, and hence its resistance to passing through the slots in the orifice plate. This system is used in the Porsche 911 GT3 to improve handling dynamics by holding the motor rigidly during hard cornering, while maintaining driver comfort during more relaxed driving.

Property	Typical values
μ_{MAX}	300 - 1000
B_{max} at $10kAm^{-1}$ (T)	1.32 – 1.63
TRS (MPa)	30 - 140
Losses at 1T, 400Hz (W/kg)	32 - 63
Resistivity (μΩ.m)	70 - 22200

Table 7: Ranges of properties obtainable in different SMC materials

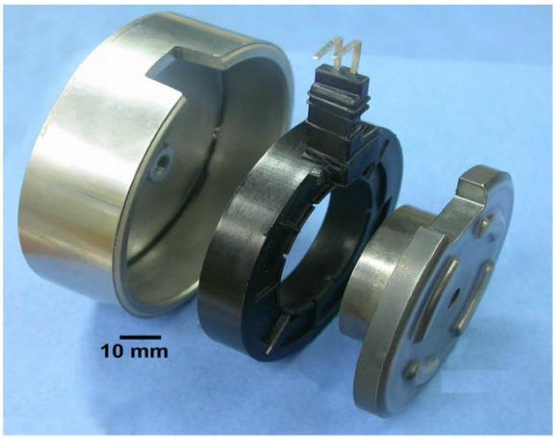

Figure 15: Orifice plate, winding, and core plate from a variable stiffness engine mount

IV. CONCLUSIONS

In the automotive sector the number of opportunities for electro-magnetic components in transmission, braking, steering and emission control systems is steadily increasing and, with the advantages of net-shape production and the great range of soft magnetic materials available in powder form, the PM sector is well-placed to take advantage of this.

V. ACKNOWLEDGEMENTS

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VII. BIOGRAPHY

Mark J. Dougan was born in Watford, England in 1968. He received his B.Sc. and Ph.D. in Metallurgy from the University of Manchester in 1991 and 1995 respectively. He worked as a Research Assistant in the Thermal Spray Centre in the University of Barcelona, and in the Department of Metallurgy in the University of Leeds before joining AMES, SA in Barcelona in 1999. He is currently Chief Metallurgist in the AMES PM Tech Centre, working on material and process development, failure analysis, and with special responsibility for soft magnetic materials.