THE MANUFACTURE OF ELECTROMAGNETIC COMPONENTS BY THE POWDER METALLURGY PROCESS

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ABSTRACT

The powder metallurgy process provides the ability to manufacture net shape parts from a variety of materials in a cost effective manner. A market segment that has exhibited the ability to take advantage of powder metallurgy's flexibility has been in electromagnetic applications. This area has shown significant growth in the past decade that should continue for the foreseeable future.

This paper will discuss materials and processes that have proven successful in several electromagnetic applications. Both sintered materials for DC type applications and insulated materials for AC applications will be reviewed along with appropriate processing techniques for each. Specific applications for both materials will be presented.

INTRODUCTION

Magnetic materials are essential elements in today's electronic world. From the motors and turbines that provide the power for industry to the high frequency transformers that power computers, magnetic materials are becoming increasing more important as the consumer demands: greater reliability, higher energy efficiency, and lower manufacturing costs. Powder metallurgy (P/M) processing offers the product designer a wide range of magnetic materials that covers both DC and AC applications. The recent collection of papers written on this subject is affirmation to the high interest in P/M magnetic applications.[1-4]

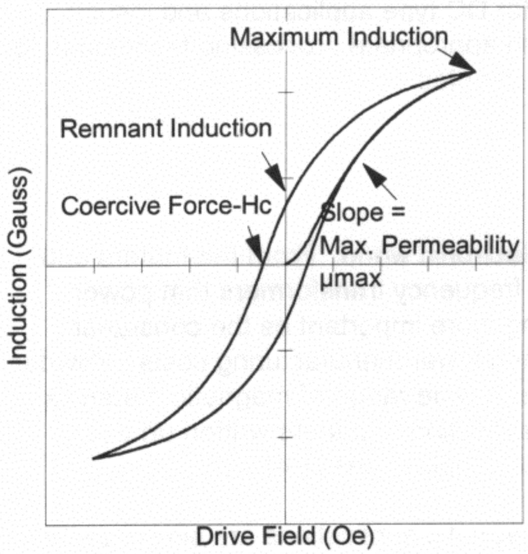
The advantages of the P/M parts making process in magnetic applications are similar to the advantages offered in structural applications. Specifically, these include: greater material usage, the ability to produce complex shapes to net shape, and the ability to tailor the magnetic properties to the specific application by controlling the material and the processing parameters.

The automotive industry has embraced P/M magnetic usage with applications such as the ABS wheel sensors, engine sensors, and solenoid components.[5] Recently, Delphi Energy and Engine Management Systems have utilized P/M processing to manufacture automotive ignition coils.[6] This part represents the first commercial use of a plastic coated iron powder expanding the usage of P/M into non-traditional AC applications. These various applications demonstrate the utility of P/M processing; more importantly, they offer the promise of greater applications in a much broader market base.

Throughout this paper, the discussion will focus on soft magnetic materials. Soft magnetic materials are characterized as those materials that can be both easily magnetized and easily demagnetized. Relating these effects to the B-H or Hysteresis curve shown as Figure 1, soft magnetic materials have higher permeability, higher saturation induction, and lower coercive force values relative to hard magnetic materials.

The uses for soft magnetic materials are typically classified as either DC or AC applications. DC or direct current applications are characterized by a constant applied field (from a battery type device). The most common DC applications are found in automobiles. Key magnetic characteristics for DC applications are permeability, coercive force, and saturation induction. AC or alternating current applications are characterized by a constantly changing applied field. Key magnetic parameters in AC applications are permeability, saturation, and total core losses resulting from the alternating magnetic field.[7]

Powder metallurgy processing can be applied to both DC and AC types of applications. DC applications typically utilize a press and sinter process as outlined in Figure 2. The choice of alloy system, density, and sintering practice can greatly affect the resultant magnetic properties. AC applications were typically once exclusively satisfied by steel laminations. However, the recent introduction of polymer coated iron powders has opened the door for P/M to be utilized in AC applications. These polymer coated powders are used in the as pressed condition; no sintering is required. The presence of the high performance polymer provides adequate strength to meet part requirements.[8]



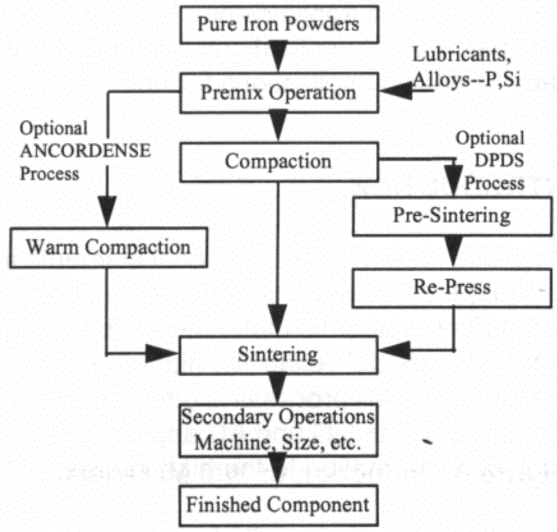


Figure 1: Hysteresis Loop with Initial Curve - (B-H) Curve

Figure 2: Various P/M Manufacturing Routes

This paper will review the processing parameters and resulting magnetic performance for both sintered and non-sintered P/M materials. Emphasis will be given to defining application specific requirements and selecting the optimal P/M material.

PROPERTIES AND PROCESSING OF SINTERED P/M MATERIALS

For DC applications, the P/M part designer has multiple choices for alloy systems and part processing techniques to meet the specific magnetic performance requirements. The magnetic properties of permeability, coercive force, and induction at an applied field are considered structure sensitive properties. That is, they are affected by the part processing and metallurgical factors such as alloying elements and residual interstitial elements.

To fully utilize P/M's cost advantage, material selection can be optimized depending upon the part application. For example, in applications where saturation induction is the key magnetic parameter, these applications are ideal candidates for the unalloyed iron materials.[9] It has been demonstrated that saturation induction of P/M materials is a linear function of part density regardless of the alloy content of the iron system. Thus selecting an unalloyed iron that satisfies the part density requirement will result in the lowest cost P/M part. Figure 3 shows the saturation induction and the induction at 15 Oersteds for both pure iron and iron phosphorus alloys, sintered at 2050°F (1120°C). This data clearly indicates that both the phosphorus and unalloyed irons have the identical saturation induction at a given density. However, the induction at lower levels of applied fields is affected by the alloying in the powder.

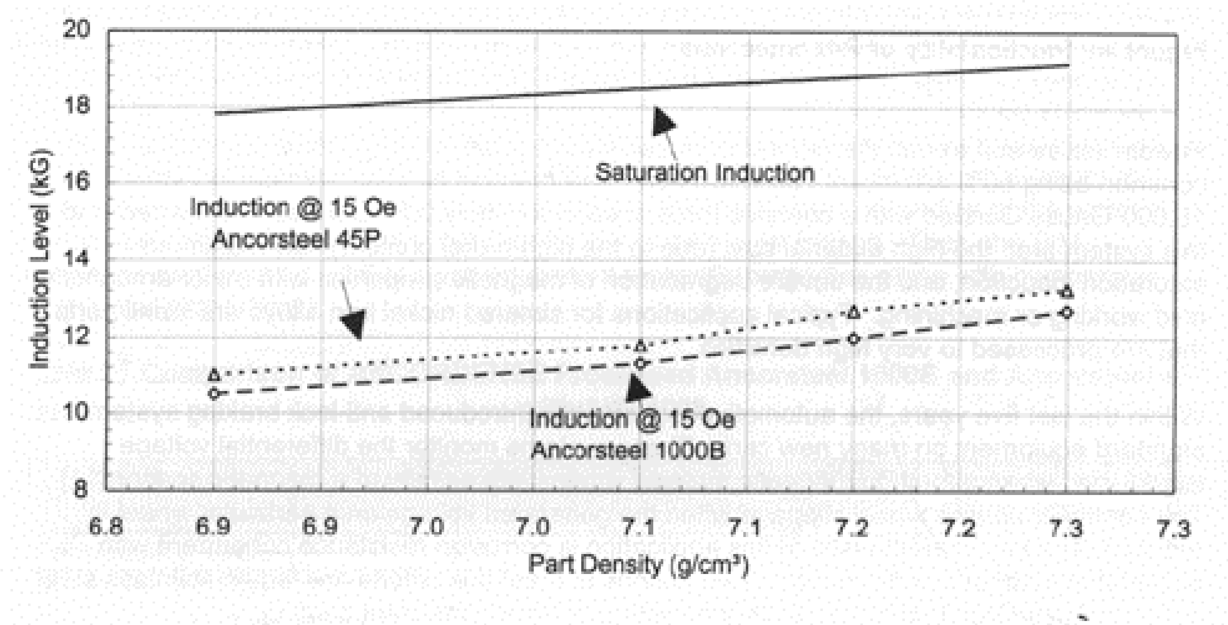


Figure 3: Induction of P/M Materials

Permeability is that property of a magnetic material that denotes how easily the material is magnetized. High permeability is desirable in those applications where a quick response to an applied current is important. Relays and printer actuator mechanisms are examples of applications requiring a fast response.[10] Additions of phosphorus and silicon can significantly improve the magnetic permeability relative to pure irons. Figure 4 shows the permeability as a function of density for pure iron, iron phosphorus alloys, and iron silicon alloys. The iron and iron phosphorus materials were sintered at 2050°F (1120°C). Whereas, the sintering of the iron silicon alloys was done at 1260°C (2300°F). This was necessary to homogenize the silicon that was added as a silicon iron master alloy.

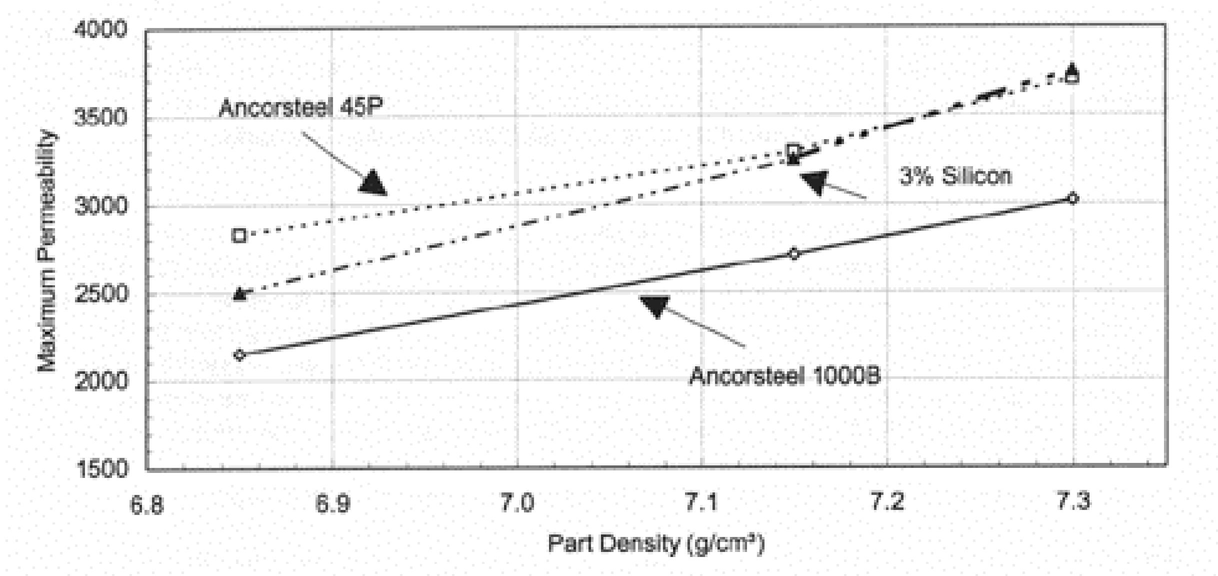


Figure 4: Permeability of P/M Materials

Powder alloys that exhibit the highest permeability are prealloys of iron and nickel, the most common being 50% w/o nickel / 50% w/o iron. This material exhibits permeability values up to 15,000 Gauss/Oersted with a coercive force of approximately 0.25 Oersteds. Drawbacks to this system are: the high material cost (due to the high nickel content), low maximum saturation induction, and the severe degradation of magnetic properties with minor amounts of cold working or machining. Typical applications for sintered nickel iron alloys are small parts that are processed to very high densities.

Within the last five years, the automotive industry has introduced anti-lock braking systems as standard equipment on many new cars. These systems monitor the differential voltage established when a toothed magnetic material rotates in proximity of a magnetic sensor.[11] The controller senses wheel slippage when the generated voltage on a particular wheel is reduced. The key characteristic of this application is corrosion resistance concurrent with acceptable magnetic performance. Two options to meet this criteria are ferritic stainless steel or an unalloyed iron that has been treated with a corrosion resistant coating.

Shown in Table I is a summary of the P/M alloy systems and the expected magnetic properties. It can be used as a guideline for selecting a P/M magnetic material. Greater detail about each of the alloy systems is available in the literature.

Table 1: Typical Properties of Sintered P/M Materials

Alloy System	Typical	Max. Perm.	Hc	Bmax	Resistivit

	Density Range (g/cm^3)	μmax	(Oe)	@ 15 Oe (kGauss)	y (μ cm)
Iron	6.8 to 7.2	1800 to 4000	1.5 to 2.5	10 to 13	10
Iron-Phos	6.7 to 7.4	2500 to 6000	1.2 to 2.0	10 to 14	30
Iron-Si	6.8 to 7.5	4000 to 10000	0.3 to 1.0	8 to 11	60
400 Series SS	5.9 to 7.2	500 to 2000	1.5 to 3.0	5 to 10	50
50Ni/50Fe	7.2 to 7.6	5000 to 15000	0.2 to 0.5	9 to 14	45

Processing Considerations

To this point in the paper, the discussion has concentrated on the materials and key magnetic parameters. P/M processing is unique in that the magnetic properties can be tailored via part density and sintering to meet the specific requirements. As mentioned earlier, density has a significant effect on the part performance. Higher density P/M parts exhibit increased permeability and saturation induction without any degradation of the coercive force. Techniques to increase the part density include double press/double sinter, warm compaction, or restriking a fully sintered part.

Increasing the density by either double press/double sinter or warm compaction processing results in sintered densities approaching 7.4 to 7.5 g/cm^3. At these density levels, the permeability and saturation induction approach the values achieved for fully dense wrought steels. Table 2 shows a comparison of a low carbon wrought steel with pure iron and phosphorus irons pressed to 7.3 to 7.35 g/cm^3. The wrought steel was evaluated in the as forged condition. Performance of the P/M materials is comparable in both permeability and saturation induction to the wrought AISI 1008 at 15 Oe. The P/M materials are superior in terms of lower coercive force values. Interestingly, the mechanical properties of the warm compacted Ancorsteel 45P are similar to the low carbon steel forging. Thus, the P/M alternative produces a part that gives equivalent magnetic properties along with comparable mechanical properties.

Table 2: Comparison of ANCORDENSE Processed Ancorsteel 1000B and Ancorsteel 45P with AISI 1008

Property	AISI 1008 [12]	Ancorsteel 1000B @ 7.30 g/cm^3	Ancorsteel 45P @ 7.35 g/cm^3
Permeability, G/Oe	1900	2700	2700
Induction @ 15 Oe	14,400	15,000	15,100
Coersive Force, Oe	3.00	2.1	1.9
Yield Strength,	285 (42,000)	145 (21,000)	285 (42,000)

Mpa (psi)			
Tensile Strength Mpa (psi)	386 (56,000)	225 (32,800)	405 (59,400)
Elongation, %	37	13.7	12

It is worth noting that repressing a P/M part has a significant negative effect on the magnetic properties. Table 3 shows the effect of repressing on the magnetic properties with and without an annealing step. The decrease in magnetic performance resulting from the restrike is eliminated when the part is given a subsequent annealing operation. An excellent review of the effects of secondary processing on the magnetic performance of P/M parts has been given by Frayman.[13]

Table 3: Effect of Repressing on the Magnetic Properties of Ancorsteel 45P at 6.8 g/cm^3

Condition	Max Perm	Coersive Force, Oe	Induction @ 15 Oe
As Sintered	2,260	1.98	11,000
Sintered-Sized	1,160	2.69	9,800
Sintered-Sized-Annealed	2,270	2.22	11,200

Structure sensitive properties of magnetic materials are the permeability, coercive force, and residual induction. With P/M magnetic parts, the permeability and residual induction are affected by the density of the component. However, it has been shown that the coercive force is not density sensitive.[9] Permeability is affected by both the density and microstructure of the final part. Several key parameters that influence the structure sensitive properties in magnetic materials are grain size, pore size and morphology, and material purity (in particular residual interstitial elements, such as carbon and nitrogen). Figure 5 shows the permeability of Ancorsteel 45P sintered at 1120°C (2050°F) and 1260°C (2300°F). Sintering at the higher temperature results in a larger grain size and greater pore rounding; consequently, higher permeability.

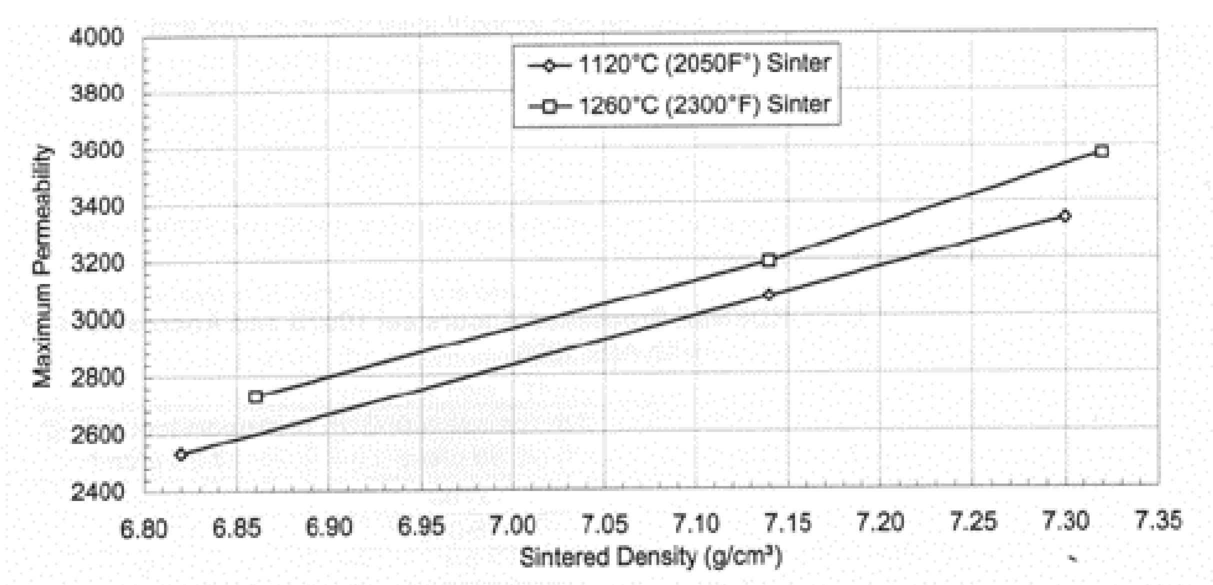


Figure 5: Effects of Density and Sintering Temperature on the Permeability of Ancorsteel 45P

Figure 6 illustrates the effect of both sintering temperature and elevated nitrogen levels on the coercive force and permeability. The data illustrates that sintering at an elevated temperature results in a significantly lower coercive force and higher permeability. The presence of increased nitrogen levels results in a degradation of the magnetic properties. Carbon has a similar effect to nitrogen on the magnetic performance; that is, the higher the carbon content the lower the magnetic response. High nitrogen and high carbon contents are the result of improper sintering and/or improper atmosphere selection. Care is necessary to ensure that proper lubricant burn out is effected and that a clean furnace is utilized to insure a low carbon content. Nitrogen content can be minimized by utilizing pure hydrogen in the sintering atmosphere.

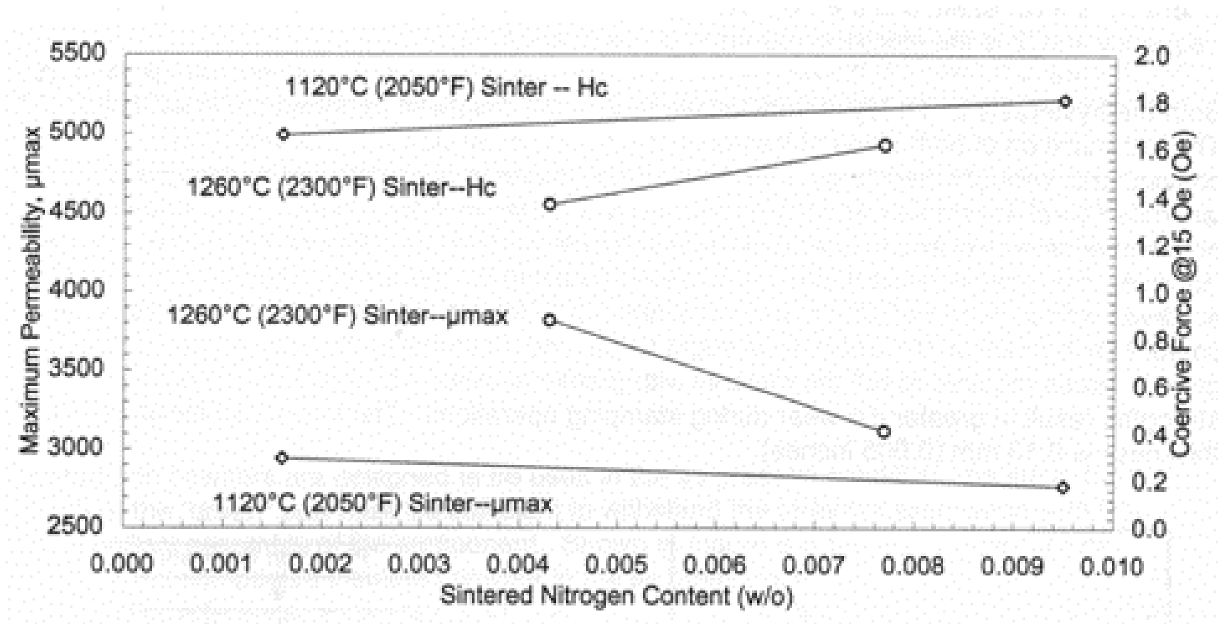


Figure 6: The Effect of Nitrogen Content and Sintering Temperature on Magnetic Properties of Ancorsteel 45P

PROPERTIES AND PROCESSING OF INSULATED MATERIALS

Sintered P/M materials are well suited for DC magnetic applications. However, their usefulness in AC applications is limited. AC applications are characterized by an alternating magnetic field. The consequence of this alternating applied magnetic field is the generation of heat within the magnetic material. This heat build up can be equated to the summation of hysteresis losses and eddy current losses.

Hysteresis loss is defined as the energy absorbed by the material as the alternating magnetic field sweeps around the hysteresis curve.[7] The hysteresis loss is a function of the loop area of the B-H curve and can be expressed as follows:

$$\textbf{Hysteresis losses} = K_H \bullet \textbf{Loop Area} \bullet f \qquad \textbf{Eq(1)}$$

where K_H is a constant, the loop area is the area contained in the hysteresis loop in G-Oe and f is the frequency in Hz. Hysteresis losses are affected by the coercive force of the material, illustrated in Figure 1. Specifically, higher values of coercive force result in higher hysteresis losses and lower values of coercive force result in lower hysteresis losses.

Eddy current losses are generated in the magnetic material in a direction opposing the applied alternating magnetic field. Eddy current losses are affected by the frequency, the induction level, the resistivity of the material, and the thickness of the material. A mathematical expression for eddy current loss is as follows:

$$\text{Eddy Current Loss} = K_E \cdot (d^2 \cdot B^2 \cdot f^2)/\psi \quad \text{Eq(2) [7]}$$

where K_E is a constant, d is the thickness of the material, B is the induction level, f is the frequency and ψ is the electrical resistivity of the material.

Both the hysteresis and eddy current losses reduce the magnetic performance in AC fields. The minimization of both types of losses is critical in high efficiency AC devices. In conventional wrought metallurgy, minimizing these losses is accomplished by the use of laminated steel assemblies and higher resistivity steel laminations. Referring to equation 2, both higher resistivity and thinner laminations reduce the total core loss of the device. However, the most significant effect is achieved by using thinner steels. Higher resistivity is achieved with additions of silicon and aluminum. Both thinner laminations and increased alloy content have practical limitations in wrought metallurgy. Increasing the alloy content leads to greater forces required to roll the material with greater likelihood of cracking. These higher strengths result in greater die wear during stamping operations. The lower limit for gage thickness is 0.13 mm (0.005 inches).

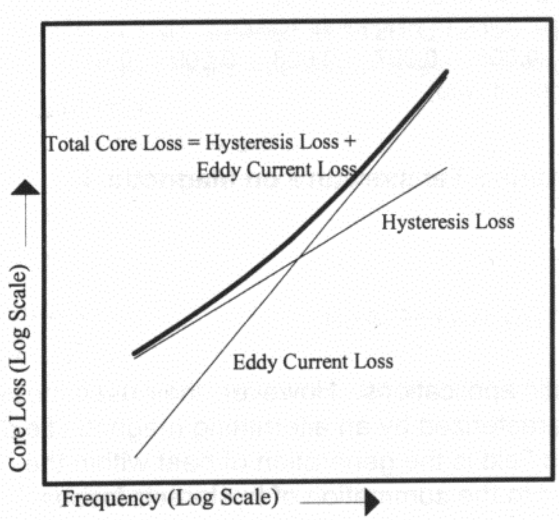


Figure 7: Components of Core Loss vs Frequency

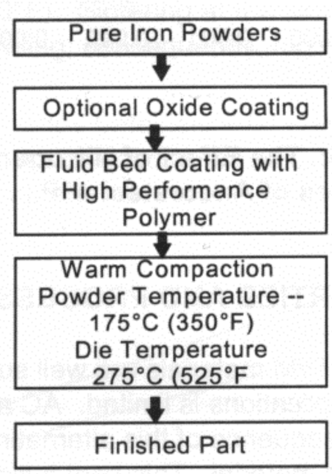


Figure 8: Processing Route for Ancorsteel Insulated Powders

Conventional steel laminations are used quite successfully in 60 Hz applications. As the frequency increases, eddy current losses begin to dominate and ultimately reach unacceptable levels. Figure 7 shows graphically the relationship between total core losses, eddy current losses and hysteresis losses. The intersection point of hysteresis loss and eddy current loss is that point at which the hysteresis losses dominate at lower frequencies and the eddy current losses dominate at higher frequencies. This transition point can be shifted by varying the thickness of the sheet as well as the resistivity of the material. As stated earlier, the most dominant variable in the total core loss is the thickness of the material; its contribution to total losses is a function of the thickness raised to the second power.

Because the thickness of the material is the dominant variable in total core losses, the use of powder metallurgy in AC applications has been proposed many times. The reasoning for this is the inherent small particle size of powders. However, the usage of powder metallurgy processing has been limited to SMPS (switched mode power supplies) and loading coils.[14] The fine particle size of the powder allowed these applications to operate in the kilohertz frequency range. The recent introduction of iron powder plastic composites was intended to extend the application base for P/M into lower frequency applications. A polymer was incorporated to both electrically insulate the powder particles and add mechanical strength to the as pressed component. The manufacturing route for this material is shown in Figure 8. An optional oxide coating is utilized for those applications requiring greater interparticle resistivity.

The polymer coating level used is typically less than 1 weight percentage. Compaction is performed utilizing heated powder and heated tooling at compaction pressures of 400 MPa to 675 MPa (30 to 50 tsi). The combination of heated powder and high compaction pressure results in flow of the polymer forming a continuous matrix around the iron powder particles. A die-wall spray lubricant is applied to facilitate part ejection. The strength of the compacted part can be enhanced by using the optional thermal treatment with no loss in magnetic properties.

Material Properties

Insulated iron powders are designed to be used in the as pressed condition. As such, the strength of the “green” part must be sufficient to withstand the stresses associated with the winding or final assembly of the component. Shown in Figure 9 is the transverse rupture strength of the compacted insulated powder in the as pressed and as pressed and cured condition. For reference, a standard P/M unalloyed iron is also included. It is noteworthy that the strength of the insulated iron is approximately 100 MPa (15,000 psi) in the as pressed condition. After the optional low temperature heat treatment the strength increases to nearly 240 MPa (35,000 psi). Comparable strength of the standard P/M material in the "green" or as compacted condition is approximately 20 MPa (3,000 psi).

Three distinct coated iron powders are currently available. Table 4 shows the composition and the DC magnetic properties of these three materials. Although three grades are presented, the manufacturing process for these powders is very flexible and thus powders can be custom tailored to meet specific application requirements.

The effect of frequency on the permeability of these three materials is shown in Figure 10. The Ancorsteel SC-120 material provides the highest permeability at the lower frequency levels while the TC-80 material indicates the best high frequency performance. The increase in eddy currents as the frequency is increased results in a decrease in effective permeability and a "roll-off" in permeability values with increasing frequency. The SC-120 material is designed to provide the highest performance at lower frequency levels by controlling the particle size and utilizing only the polymer coating. The TC-80 material uses a finer particle size distribution, the oxide coating and a higher level of polymer coating to provide maximum reduction of eddy currents. The performance of the SC-100 material lies between the other two grades.

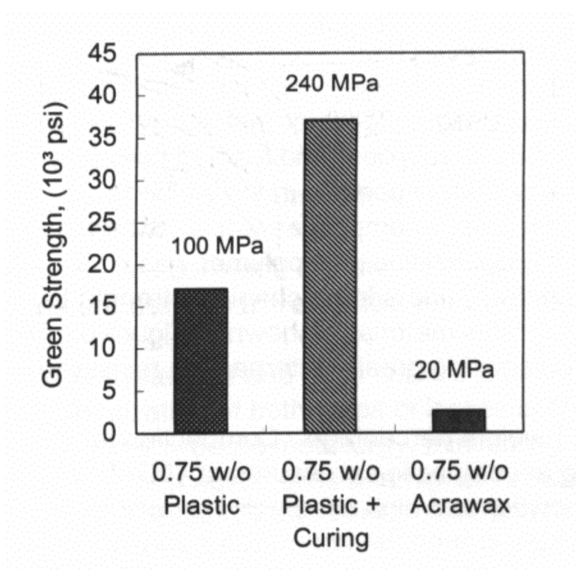


Figure 9: "Green Strength" of Powders Compactedat 690 MPa (50 tsi)

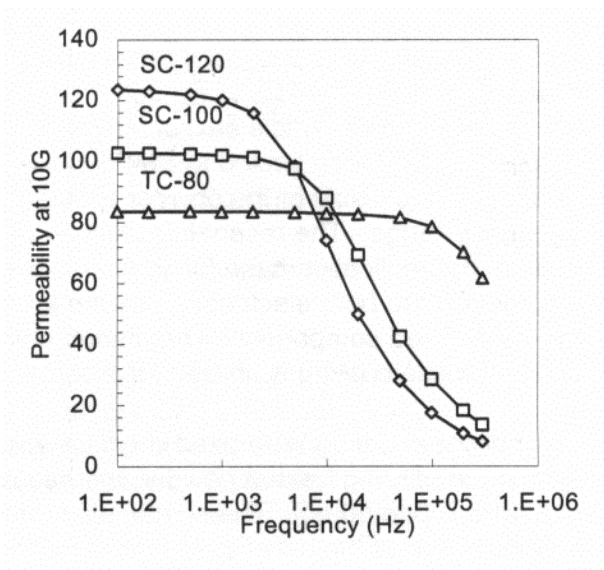


Figure 10: Initial Permeability vs Frequency

Figure 11 shows the effect of frequency on total core losses for the TC-80 material compared with a lamination steel. The lamination steel is a non-oriented 3 w/o silicon iron rolled to a thickness of 0.2 mm (0.007 inches). At low frequency levels, where the core losses are dominated by hysteresis losses, the laminated material shows lower losses than the coated powder material. This limits the low frequency performance of plastic coated iron compacts, as the hysteresis losses are high relative to laminated steels. However, the reduced eddy current loss inherent in the plastic coated iron results in lower losses and thus higher efficiency at the higher frequency range where the total core losses are dominated by the eddy current losses (Figure 7).

Table 4: Summary of DC Magnetic Performance of Coated Iron Powder

Ancorsteel Material	Polymer Coating (w/o)	Oxide Coating	Density at 690 Mpa (50tsi) g/cm^3	Initial Perm	Maximum Perm	Coercive Force (Oe)	Induction at 40 Oe (G)
SC120	0.60	NO	7.45	120	425	4.7	11,200
SC100	0.75	NO	7.40	100	400	4.8	10,900
TC80	0.75	YES	7.2	80	210	4.7	7,700

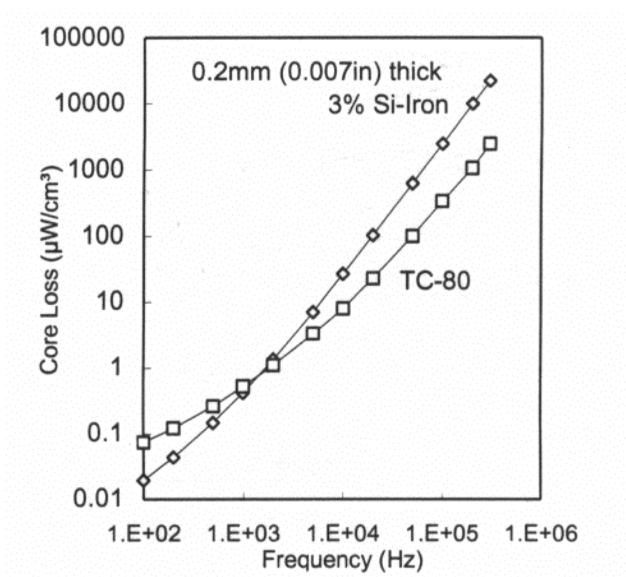


Figure 11: Core Loss oc Ancorsteel TC80 vs 3 w/o Silicon Lamination at 5000 G

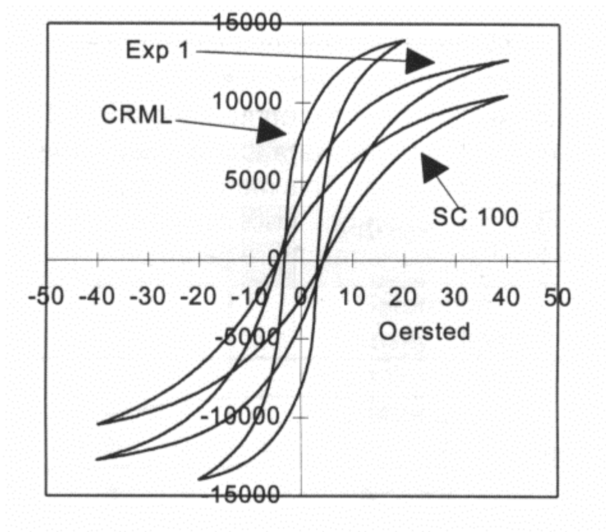


Figure 12: B-H Curves for Ancorsteel SC 100, Exp 1, and CRML

Future Directions

The future direction of the insulated iron powder development is aimed at those applications that have lower operating frequencies; in particular those applications at 60 Hz. Two approaches are being explored: one is the achievement of higher densities by optimizing the amount of polymer. The second approach is to combine the insulating material with a powder based lubricant to facilitate the compaction process. Table 5 is a comparison of the standard Ancorsteel SC100 with a modified material targeted for the low frequency applications. With optimization of the polymer content, a significant increase in green density is achieved along with a corresponding increase in the magnetic performance. The increase in density from 7.35 g/cm^3 to 7.50 g/cm^3 increases the initial permeability approximately 16%, with a corresponding increase in the maximum permeability from 450 to 680 G/Oe. The saturation induction at 40 Oe increase from approximately 10,600 Gauss to 12,660 Gauss. The corresponding B-H curve for the two materials is shown in Figure 12. For comparison a laminated stack of CRML (cold rolled motor lamination stack) is also included.

Table 5: Summary of Magnetic Data for Ancorsteel SC100 and Modified Insulated Powder Both Compacted at 69OMPa (50 tsi)

Material	Initial Perm, at 10 Gauss	Max Perm	Coercive Force (Oe)	Induction @ 40 Oe (Gauss)
SC 100	95	450	4.45	10,570
Exp 1	110	680	4.45	12,660

The second area of interest is the possible elimination of the need for warm compaction while maintaining the magnetic performance. Figure 13 shows the permeability versus frequency response for three experimental grades of insulated powders. Nearly identical magnetic performance to the warm compacted material is achieved without the need for heating the powder or tooling. This material does have limited strength and limited temperature capability. However, it is intended to supplement the existing insulated iron materials for those applications that have lower strength requirements.

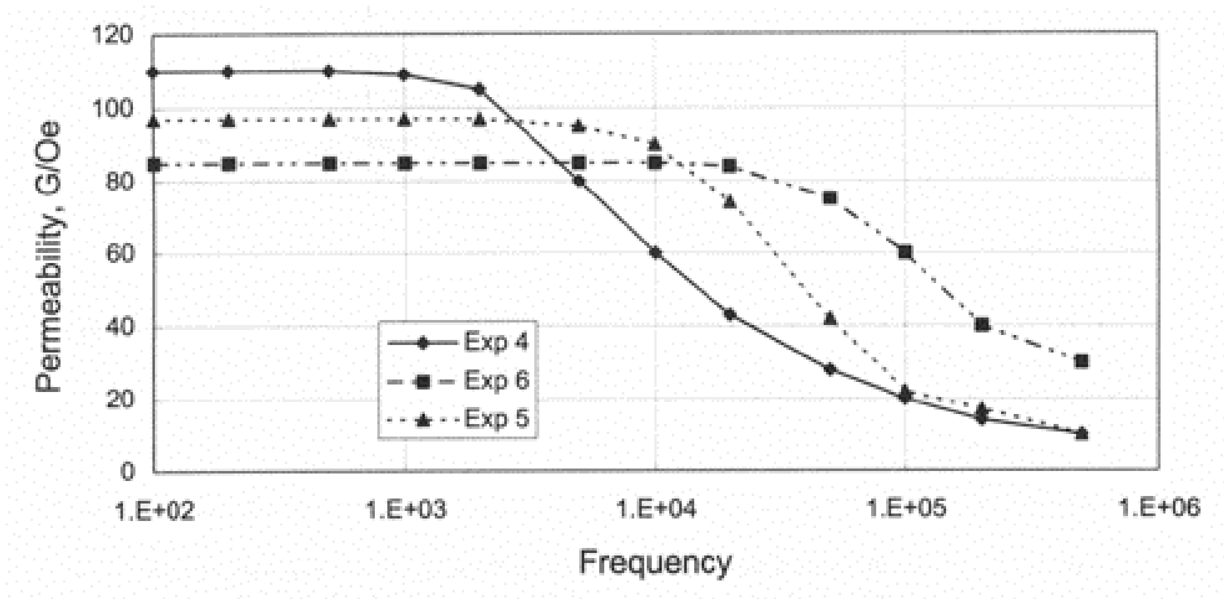


Figure 13: Permeability of Experimental Insulated Powders

SUMMARY

The use of sintered P/M materials has grown significantly during the past several years. The flexibility of design along with the efficiency of the P/M manufacturing process has provided significant opportunity for growth. Table 6 outlines several areas where P/M applications have proven successful along with the material type and performance concerns that dictate the material selection.

Insulated iron powders have found a significant automotive application in the area of ignition systems. The combination of low eddy current losses and the shape making characteristics of the P/M manufacturing process have provided a unique opportunity. In this application, the material is compacted into the core of the ignition coil that converts low voltage into the high voltage the fires the spark plug. The ability to fire the plug electronically provides significantly reduced assembly cost, no moving parts in this solid state ignition and improved control of the entire system. The core is compacted in three pieces, a center spool and two end caps. The spool is wound with the primary set of windings followed by a bobbin containing a large number of fine secondary windings. The end caps are attached to the spool to complete the assembly. The design requires that the flux travel in all three dimensions during the firing and that the coil operate at elevated frequencies. These requirements are well met by the insulated iron powder.

Table 6: Applications for Ferrous Sintered P/M Materials

Application Type	Typical Material	Performance Criteria
Motor Frames	Fe, Fe-P	Saturation, Density, Bmax
Pole Pieces	Fe, Fe-P, Fe-Si	Saturation, Density, Permeability
Relays and Actuators	Fe-P, Fe-Si, 50Ni/50Fe	Response Time, Permeability, Coercive Force
ABS Toner Rings	400 SS, Fe, Fe-P	Corrosion, Permeability
Other Sensors	400 SS, Fe, Fe-P	Corrosion, Permeability

Additional applications have proven viable for this material including Brushless DC and linear motor components. The further application of insulated iron can be enhanced by increasing the permeability and lowering the coercive force. Optimizing the polymer content with an understanding of the part requirements can lead to greater design flexibility with the use of insulated iron powders.

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