# EFFECTS OF PROCESSING AND MATERIALS ON SOFT MAGNETIC PERFORMANCE OF POWDER METALLURGY PARTS

**Francis G. Hanejko, Howard G. Rutz and Christopher G. Oliver**
**Hoeganaes Corporation**
**Riverton, NJ 08011**

**Presented at the 1992 Powder Metallurgy World Congress**
**San Francisco, CA, June 21-26,1992**

## ABSTRACT

Soft magnetic properties of P/M parts are influenced by materials and processing. This paper will review the magnetic properties of several iron-based materials along with how various processing steps influence magnetic properties. In particular, density, sintering temperature, sintering time and sintering atmosphere effects will be examined. Special attention will be paid to the influence that sintering conditions have on chemistry and the resulting effects on magnetic properties. Materials investigated in the study include pure iron and combinations of iron, phosphorus, silicon and nickel.

## INTRODUCTION

Powder metallurgy (P/M) parts have been used in magnetic applications for many years. Magnetic applications utilizing P/M offer both economical benefits and design flexibility. A wide range of magnetic performance requirements can be met via P/M through the proper choice of materials and the appropriate processing of those materials. Much has been written over the past several years pertaining to the use of P/M parts in soft magnetic applications. Topics that have been covered include the effects of density and structure on the magnetic properties,(1) the properties of several P/M alloy systems,(2) and soft magnetic applications for metal powders (3). This paper will attempt to combine much of this information into a usable design reference guide. Initially, basic magnetic concepts are reviewed and a description of the test procedure that was utilized in this investigation is given. Next, a review of several of the materials that are widely used for P/M soft magnetic applications is included and a discussion of why these materials are the materials of choice for their particular applications. Finally, this paper will review the effects that several important processing parameters have on the magnetic performance of the materials.

## OVERVIEW OF MAGNETIC PARAMETERS AND TESTING PROCEDURES

### Magnetic Parameters

Much has been written describing the magnetic properties of a material (4,5). A magnetic material can be characterized by its hysteresis loop, an example of which is illustrated in Figure 1.

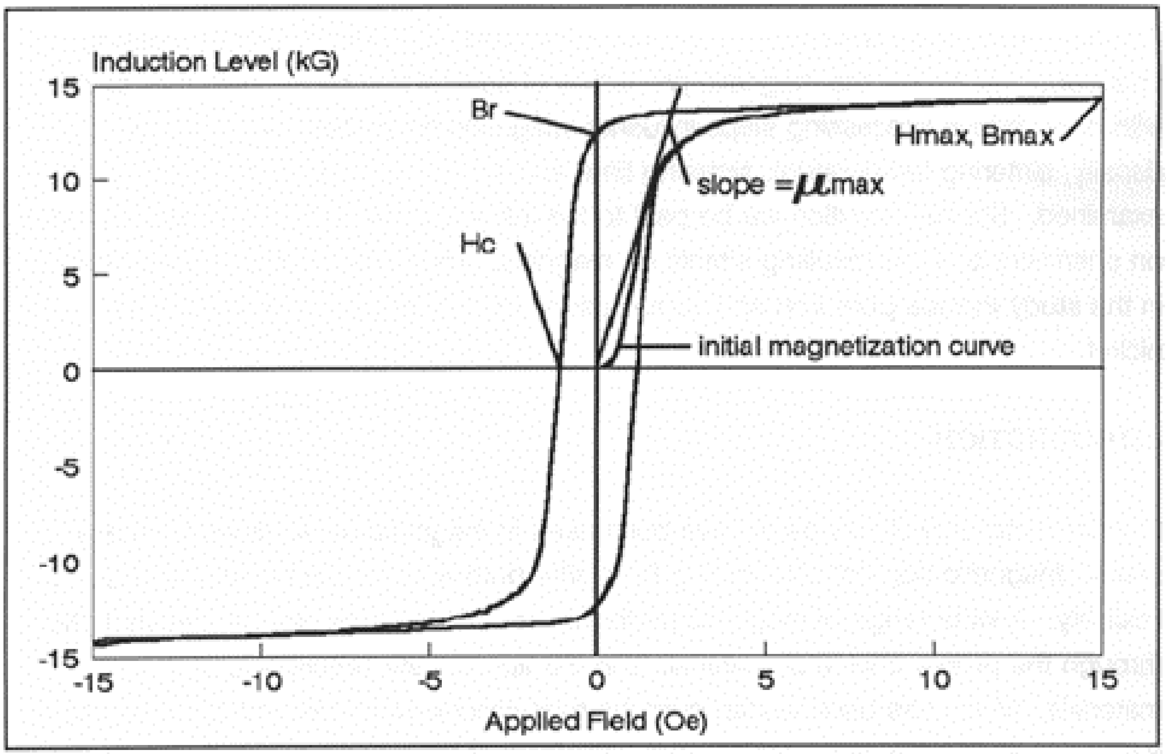

**Figure 1: Typical Hysteresis Loop**

A hysteresis loop relates the response of the magnetic induction (B) or flux density of a magnetic material to an applied magnetic field (H). Applied magnetic field is expressed in oersteds (Oe) and magnetic induction is measured in gauss (G). Saturation induction is that induction level where further increases in applied field result in no further increase in induction. The coercive force ($H_C$) of a material is the reverse magnetic field needed to bring the magnetic induction of a material to zero after the material has been exposed to a forward magnetic field. The residual induction ($B_r$) is the induction that remains in a material after the applied field has been removed (H =0). When the material has been exposed to a magnetic field sufficient to magnetize the material to saturation, the coercive force and the residual induction are referred to as the coercivity and the retentivity, respectively. The permeability (μ) is a measure of how easily a material may be magnetized and is defined as the ratio of the flux density to the applied field (B/H). The highest ratio of B/H along the initial magnetization curve is referred to as the maximum permeability ($\mu_{max}$). Permeability is expressed relative to the permeability of free space ($\mu_o$ =1) and is unitless although occasionally permeability is reported in units of G/Oe.

A soft magnetic material is characterized by a low coercivity while a hard magnetic material or permanent magnet possesses a very high coercivity. In general, properties that are characteristic of a good soft magnetic material are high permeability, high saturation induction, and low coercivity. Permeability and coercivity are strongly affected by changes in the processing of the material as well as different alloying schemes. Saturation induction is less sensitive to processing variables and is primarily influenced by the amount and type of alloy and the density of the finished part.

High electrical resistivity is important in materials for soft magnetic applications that are exposed to alternating electric fields. A varying magnetic field induces a voltage difference within the material which in turn yields a current. This current, commonly referred to as the eddy current, flows in the surface of the material in a direction that sets up a magnetic field in the direction opposing the original field, lowering the effective permeability of the material. Additionally, this current tends to generate heat within the material, reducing the operating efficiency of the device. The current can be reduced by the use of a higher resistance material. Alloying of the material has the primary influence on resistivity.

## Sample Preparation and Testing

Magnetic results that will be discussed in this paper were obtained from testing conducted on toroids measuring 3.60 cm OD, 2.23 cm ID and compacted to a height of 0.62 cm. After sintering, the toroids were then wound with 30 primary and 30 secondary turns of #28 AWG wire.

DC hysteresis loops were generated on an LDJ Model 3500 hysteresigraph; a microprocessor controlled unit capable of obtaining a complete hysteresis loop including the initial magnetization curve. Examples of the information that can be obtained from these hysteresis loops include coercive force, residual induction, maximum permeability, maximum induction and hysteresis loop area. The toroids were tested at a peak drive field of 15 oersteds. A long ramp time of 10 seconds was chosen to minimize any variation in results due to the formation of eddy currents in the varying magnetic field. Three toroids were prepared for each of the test conditions and each toroid was tested three times.

Typically, induction levels measured at an applied field of only 15 Oe are not representative of the saturation induction of a material. For a given material, the induction level measured at 15 Oe is dependent upon the permeability as well as the saturation induction of that material. It follows that the coercive force and the residual induction measured at a peak drive field of only 15 Oe are not the coercivity and the retentivity as previously defined. Limitations in the test equipment prevented reaching the saturation induction of the materials tested without the application of a high number of primary turns to the toroid. Actual reported values for saturation induction were measured on an LDJ SM-8100 Saturation Induction Measuring System.

## MATERIALS SELECTION

Designers of electromagnetic devices utilizing wrought materials are faced with a wide variety of magnetic materials from which to choose. Similarly, designers of P/M soft magnetic components are faced with a multiplicity of ferro-magnetic materials and processing paths to meet performance and cost requirements. This diversity of materials with seemingly over-lapping magnetic properties can lead to considerable confusion over what material is the best for a particular application. Several key questions to ask when specifying materials for a magnetic device are:

1. What are the critical magnetic property requirements for the device?
Depending on application, high permeability, low coercive force, high resistivity, high saturation induction or other specific magnetic requirements may be the key consideration.

2. What are the cost constraints for the final component? Included in this economic consideration are raw material costs, fabrication costs, secondary operation costs and finished part assembly costs.

3. What environmental situations will the device be required to withstand? This may include increased corrosion resistance or structural requirements.

Available P/M materials for magnetic applications include pure iron, iron phosphorus alloys, iron-silicon alloys, prealloys of nickel and iron and ferritic stainless steels. Table I summarizes these five materials according to relative raw material cost, typical part densities, and the resulting magnetic performance.

**TABLE I**
**Typical Properties of P/M Magnetic Materials**

| Alloy System | Typical Density (g/$cm^3$) | Approx. Relative Cost | $\mu_{max}$ | $H_c$ (Oe) | $B_{max}$ @15 Oe (kG) | Resist -ivity (μ - |
|---|---|---|---|---|---|---|

| | | | | | | cm) |
|---|---|---|---|---|---|---|
| Fe | 6.8/7.2 | 1 | 1800/3500 | 1.5/2.5 | 10/13 | 10 |
| Fe-P | 6.7/7.4 | 1.2 | 2500/6000 | 1.2/2.0 | 10/14 | 30 |
| Fe-Si | 6.8 | 1.4 | 2000/5000 | 0.8/1.2 | 8/11 | 60 |
| 400SS | 5.9/6.5 | 3.5 | 500/1000 | 2.0/4.0 | 6/8 | 50 |
| 50Ni/50Fe | 7.2/7.6 | 10 | 5000/15000 | 0.2/0.5 | 9/14 | 45 |

The following sections will describe the five P/M magnetic material types and their typical part applications.

## PURE IRON

Water atomized pure iron powders are the most frequently specified for sintered DC magnetic materials. These materials can be single pressed and sintered to densities up to 7.3 g/cm$^3$ with minimal dimensional changes following sintering (6). In general, the magnetic properties for pure iron can be improved as the overall level of impurities is reduced.

Table II lists typical magnetic properties for several pure iron materials compacted at 30, 40 and 50 tsi and sintered at 1120°C and 1260°C (2050°F and 2300°F) for 30 minutes in dissociated ammonia. This table indicates that increasing purity levels results in improved powder compressibility and enhanced magnetic performance.

Even though magnetic properties are generally improved by increased density (see below), Figures 2 and 3 illustrate that increases in the purity of the base iron result in improved magnetic properties at a given density level. These improvements in magnetic performance allow flexibility in specifying materials and processing parameters.

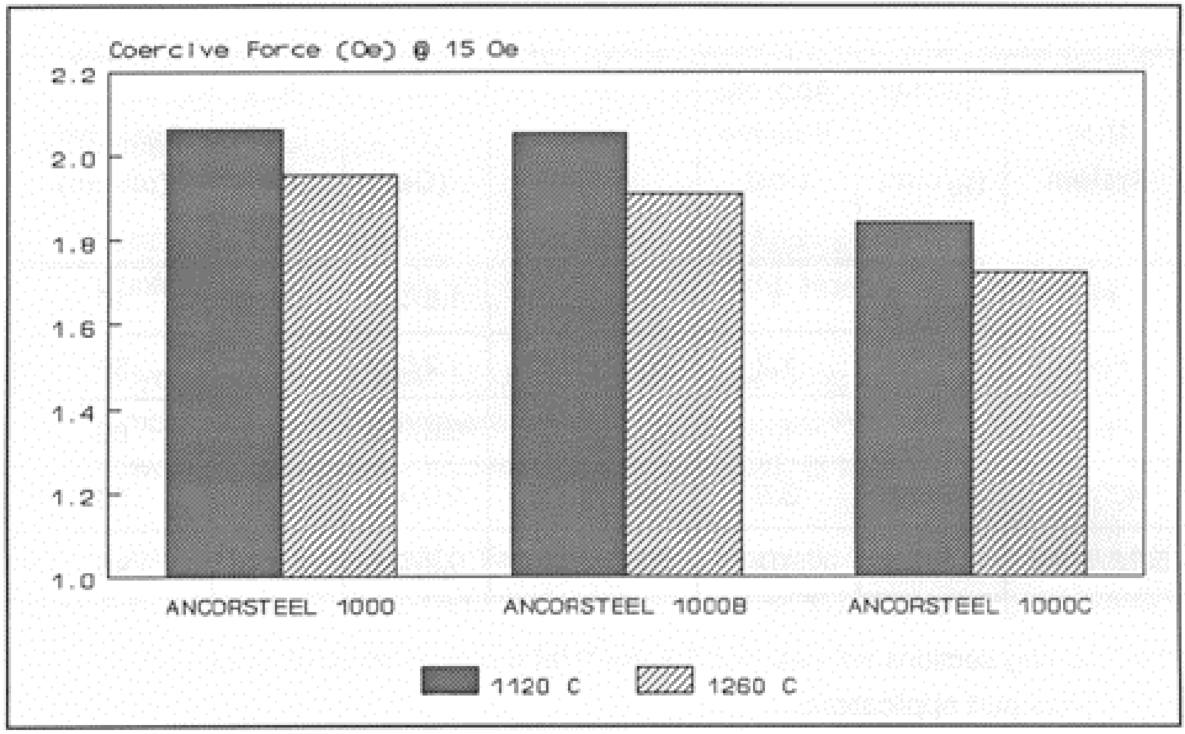

Figure 2: coercive Force of Several Pure Irons

## TABLE II
## Typical Magnetic Properties (15 Oe) of Ancorsteel[1] 1000, Ancorsteel 1000B and Ancorsteel 1000C

| Material | Sintering Temperature (°C) | Compaction Pressure (tsi) | Sintered Density ($g/cm^3$) | $H_C$ (Oe) | $B_R$ (kG) | $B_{max}$ (kG) | $\mu_{max}$ |
|---|---|---|---|---|---|---|---|
| Ancorsteel 1000 | 1120 | 30 | 6.70 | 2.03 | 8.3 | 9.8 | 1990 |
| | | 40 | 7.02 | 2.08 | 9.7 | 11.4 | 2320 |
| | | 50 | 7.21 | 2.09 | 10.6 | 12.4 | 2650 |
| | 1260 | 30 | 6.71 | 2.00 | 8.0 | 10.2 | 1920 |
| | | 40 | 7.03 | 1.93 | 10.0 | 11.9 | 2490 |
| | | 50 | 7.25 | 1.95 | 10.5 | 12.7 | 2790 |
| Ancorsteel 1000B | 1120 | 30 | 6.79 | 2.07 | 9.1 | 10.4 | 2150 |
| | | 40 | 7.09 | 2.06 | 10.7 | 11.9 | 2710 |
| | | 50 | 7.26 | 2.03 | 11.4 | 12.7 | 3020 |
| | 1260 | 30 | 6.80 | 1.95 | 9.5 | 10.9 | 2460 |
| | | 40 | 7.12 | 1.90 | 10.8 | 12.2 | 2890 |
| | | 50 | 7.28 | 1.90 | 11.8 | 13.2 | 3190 |
| Ancorsteel 1000C | 1120 | 30 | 6.82 | 1.84 | 9.2 | 10.6 | 2530 |
| | | 40 | 7.14 | 1.83 | 10.8 | 12.1 | 3070 |
| | | 50 | 7.30 | 1.83 | 11.6 | 12.9 | 3340 |
| | 1260 | 30 | 6.86 | 1.76 | 9.5 | 11.0 | 2730 |
| | | 40 | 7.14 | 1.72 | 10.9 | 12.4 | 3190 |
| | | 50 | 7.32 | 1.68 | 11.7 | 13.2 | 3570 |

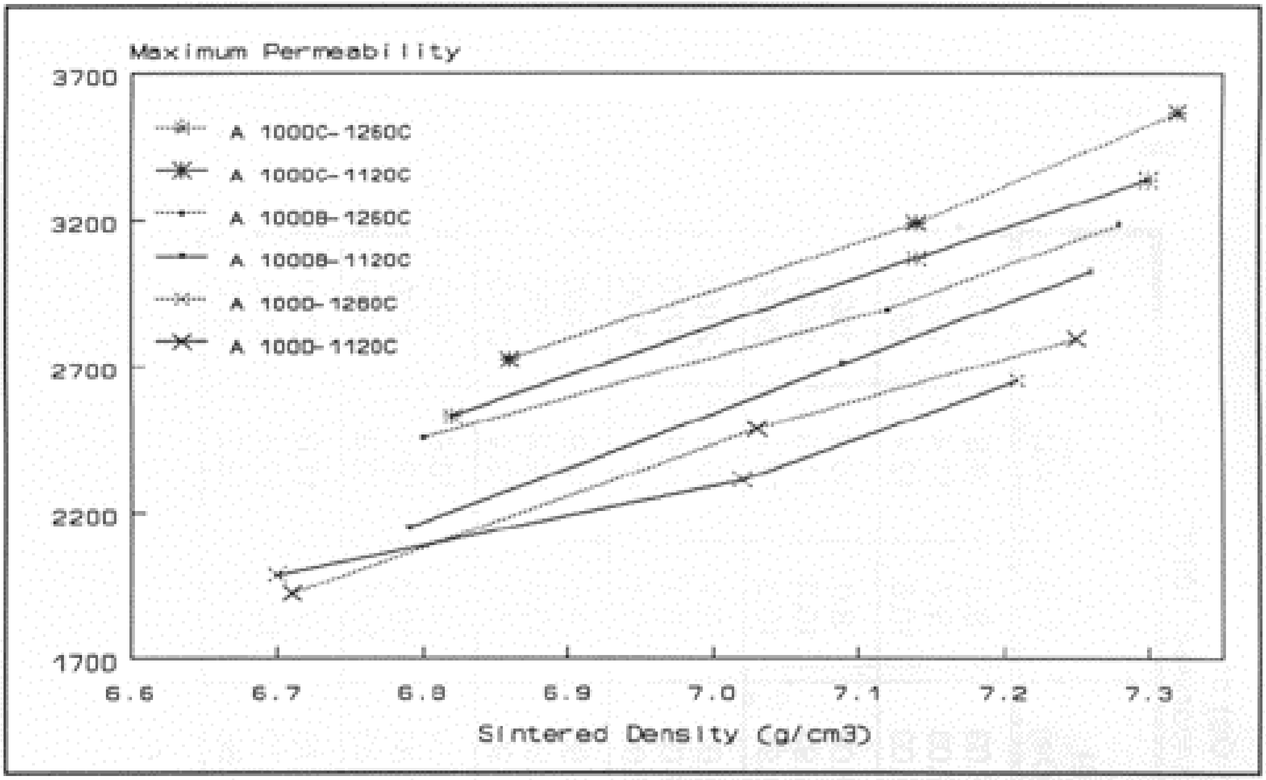

**Figure 3: Maximum Permeability of Pure Irons**

Typical applications for pure iron materials are flux return paths for DC motors (7,8). In these applications, the dominant magnetic property is saturation induction. Saturation induction is achieved via component density; the higher the density, the higher the saturation level (see Figure 10). Pure iron represents the lowest cost, most easily processed material to satisfy this requirement.

Pure iron powders are susceptible to nitrogen aging(9,10). Nitrogen aging is characterized by an increase in the coercive force after the magnetic device has been exposed to elevated temperatures for prolonged periods (Figure 4).

As indicated in Figure 4, nitrogen aging does not manifest itself immediately after sintering. As a result, the end user can find the magnetic performance of the part deteriorating with time. The key to preventing nitrogen aging is sintering in atmospheres with low percentages of nitrogen, thus, minimizing nitrogen pickup in the sintered part. Alternately, an iron-phosphorus material can be specified as these materials show reduced susceptibility to nitrogen aging.(11) Nitrogen content in the material below 25 ppm help reduce the aging effect.

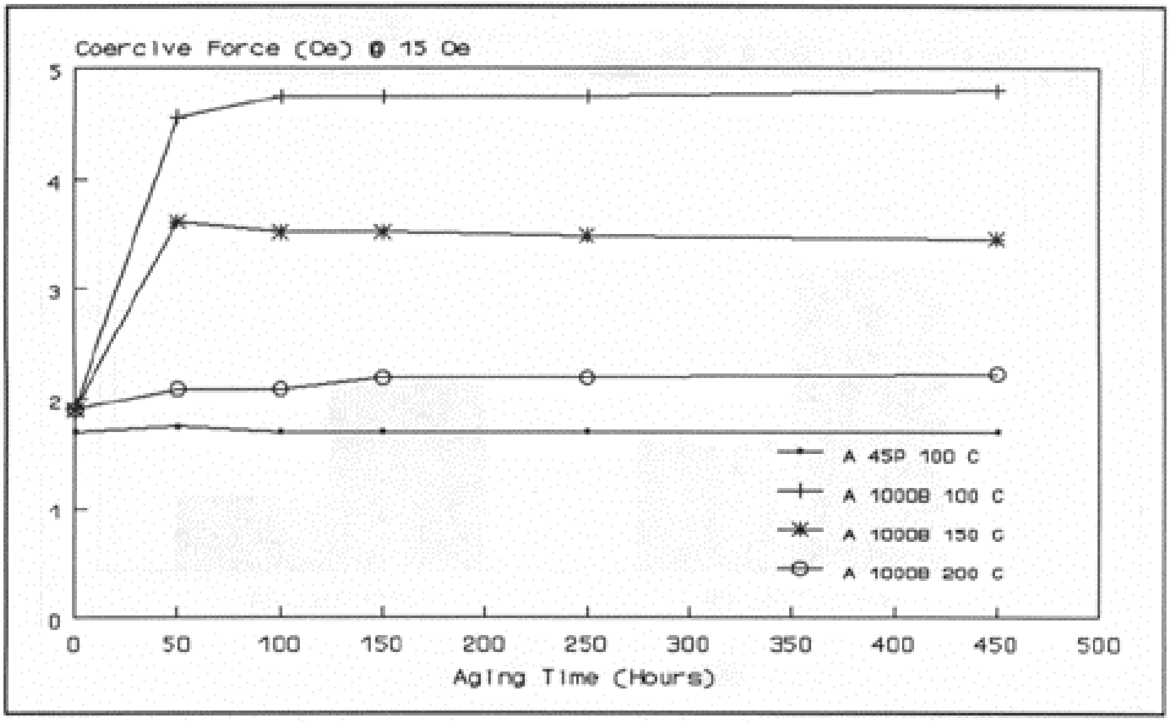

**Figure 4: The Effect of Nitrogen Aging on Coercive Force**

## IRON PHOSPHORUS ALLOYS

Iron-phosphorus alloys are the second most specified P/M soft magnetic material after pure iron. The 0.45% P/Fe alloy represents the dominant material in this family.

Iron phosphorus alloys are patented products of Höganäs AB and Hoeganaes Corporation that are produced by premixing pure iron with an iron-phosphorus intermetallic. (12) During sintering, the iron phosphorus intermetallic melts and diffuses into the iron, increasing the density of the sintered component while enhancing the resistivity and improving the magnetic properties of the P/M component. Table III lists typical magnetic properties of 0.45% P/Fe and 0.80% P/Fe alloys compacted at 30, 40 and 50 tsi and sintered at 1120°C and 1260°C for 30 minutes in dissociated ammonia. Figures 5 and 6 illustrate the improved magnetic performance of these alloys.

Typical applications for iron phosphorus alloys are speed sensors and magnetic solenoids and plungers. (13, 14) In these applications, high permeability improves the response time of the magnetic device and allows more efficient operation. Other applications utilize the alloys' liquid phase sintering capability to increase density and thus provide a higher saturation induction level.

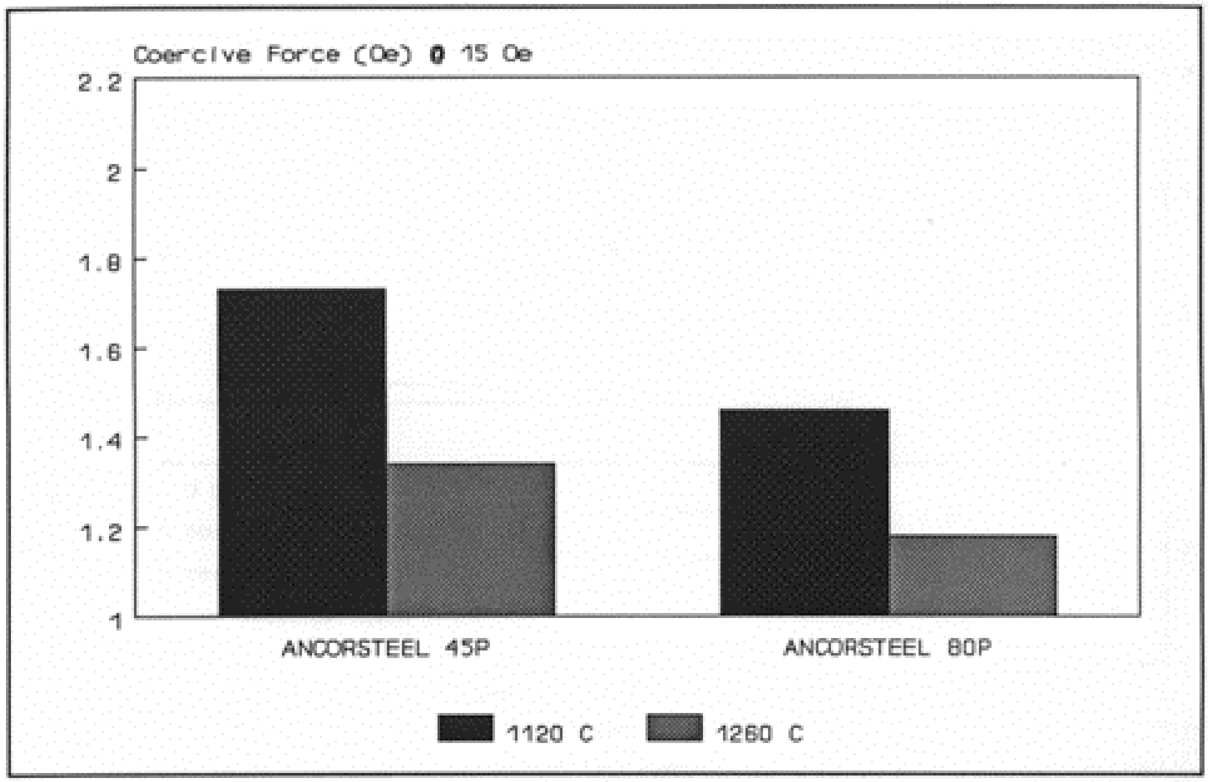

Figure 5: Coercive Force of Iron-Phosphorus Alloys

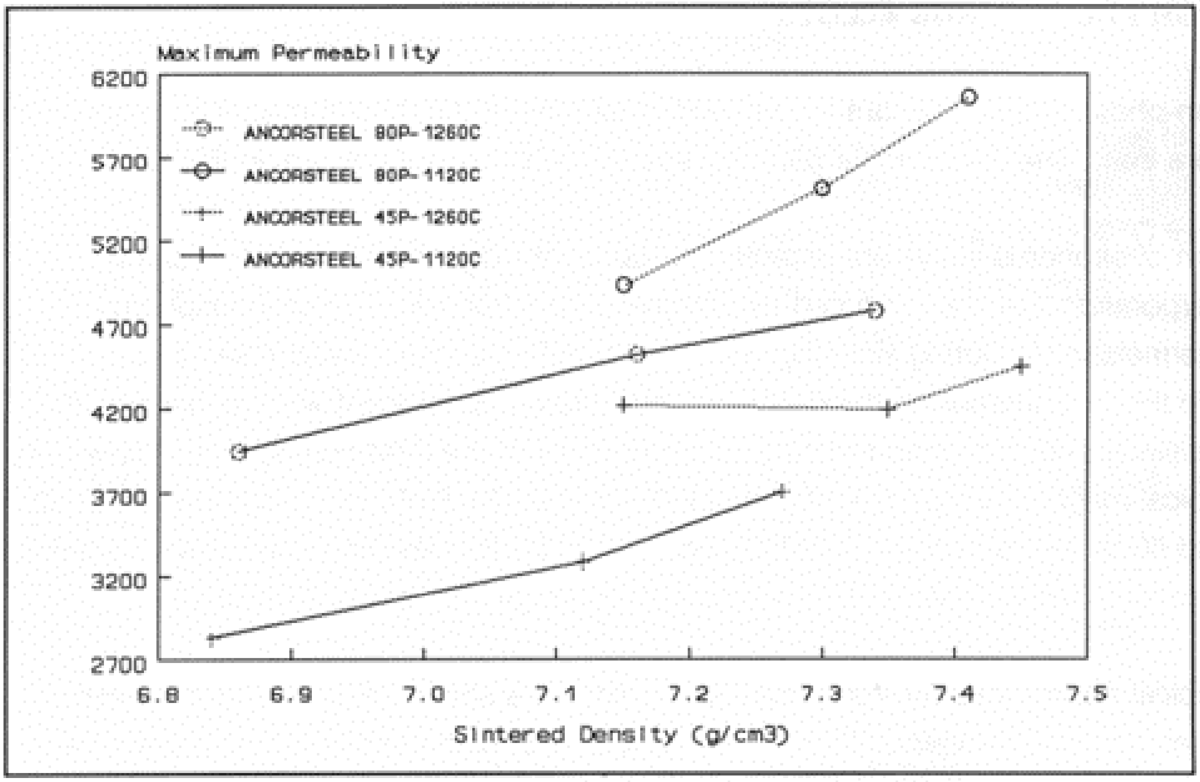

**Figure 6: Maximum Permeability of Iron-Phosphorus Alloys**

### TABLE III:
### Typical Magnetic Properties (15 Oe) of Ancorsteel 45P and Ancorsteel 80P

| Material | Sintering Temperature (°C) | Compaction Pressure (tsi) | Sintered Density (g/cm$^3$) | $H_C$ (Oe) | $B_R$ (kG) | $B_{max}$ (kG) | $\mu_{max}$ |
|---|---|---|---|---|---|---|---|
| Ancorsteel 45P | 1120 | 30 | 6.84 | 1.75 | 9.7 | 11.1 | 2830 |
| | | 40 | 7.12 | 1.73 | 11.0 | 12.4 | 3290 |
| | | 50 | 7.27 | 1.71 | 11.8 | 13.2 | 3700 |
| | 1260 | 30 | 7.15 | 1.38 | 11.0 | 12.7 | 4220 |
| | | 40 | 7.35 | 1.33 | 11.0 | 13.5 | 4190 |
| | | 50 | 7.45 | 1.29 | 11.8 | 13.9 | 4450 |
| Ancorsteel 80P | 1120 | 30 | 6.86 | 1.50 | 11.8 | 11.9 | 3940 |
| | | 40 | 7.16 | 1.45 | 10.6 | 13.1 | 4520 |
| | | 50 | 7.34 | 1.43 | 11.8 | 12.9 | 4780 |
| | 1260 | 30 | 7.15 | 1.24 | 11.2 | 12.9 | 4930 |
| | | 40 | 7.30 | 1.16 | 12.0 | 13.7 | 5510 |
| | | 50 | 7.41 | 1.14 | 12.4 | 14.1 | 6060 |

As mentioned above, additions of phosphorus decrease the P/M components' susceptibility to nitrogen aging. The presence of phosphorus lowers the solubility of nitrogen in iron alloys, thus less nitrogen is absorbed during sintering.(11) When utilizing phosphorus, a transient liquid phase is present during sintering resulting in larger shrinkage as the phosphorus content is increased. Higher sintering temperatures also result in significant increases in shrinkage and higher density (Table III). This higher density results in large improvements in magnetic performance but these improvements must be considered against the larger dimensional change experienced.

Phosphorus additions can have a beneficial effect on the mechanical properties of the P/M part. (15) Figure 7 shows the tensile strength and ductility of iron and iron phosphorus alloys. It is also worth noting that the particle size distribution of the iron-phosphorus intermetallic is critical. The size distribution affects both the dimensional change characteristics and the mechanical properties of the sintered P/M component.

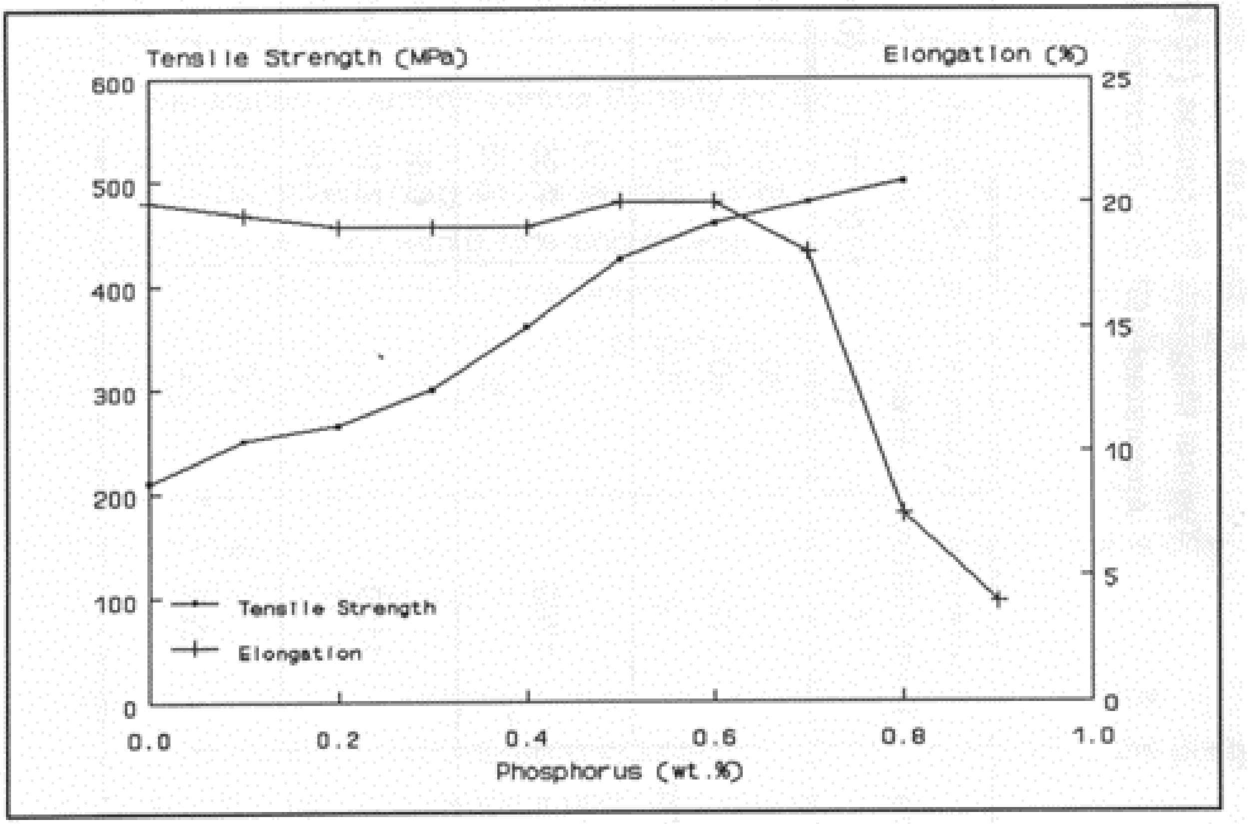

**Figure 7: Effect of Phosphorus Content on Tensile Properties at 7.1 g/cm$^3$ Density Sintered at 112O°C in DA.**

This enhanced strength and ductility can be utilized in part designs which are subject to mechanical stresses. Phosphorus additions in excess of 0.60% can result in a reduction in the strength and ductility of a part.

## IRON SILICON ALLOYS

Alloys of iron and silicon are made by premixing pure iron with a silicon-iron intermetallic. This approach allows the flexibility to incorporate as much silicon in the iron as is dictated by the part design. Increased silicon contents result in higher resistivity levels.

To realize the full benefit of the ferro-silicon addition, the sintering cycle must result in a homogeneous iron-silicon alloy(16,17). Unlike iron-phosphorus alloys which will homogenize at 1120°C, alloys of iron and silicon require sintering temperatures of at least 1260°C to achieve complete homogenization. This high sintering temperature requires specialized furnaces with high purity atmosphere requirements.

The usage of iron-silicon alloys is low. Unless the resistivities obtainable are necessary in the part design, pure iron or iron phosphorus materials offer more readily processed materials with equivalent magnetic properties.

## PREALLOYED IRON NICKEL POWDERS

Wrought alloys of 50Ni/50Fe and 36Ni/64Fe are characterized by extremely high permeability (up to 50,000) and very low coercivity (as low as 0.05 Oe). In wrought form, these materials are specified for magnetic applications requiring improved response time such as audio coils, pulse transformers and high speed relays.(18) A drawback to these materials is their relatively low saturation induction levels of 15 kG compared to steel having a saturation of 21.5 kG.

Table IV lists typical magnetic properties of a water atomized prealloyed 50Ni/50Fe powder compacted at 30 and 50 tsi and sintered for 30 minutes at 1120°C and 1260°C in dissociated ammonia. Despite good compressibility, the majority of commercial 50Ni/50Fe P/M components are double pressed/double sintered to densities in excess of 7.4 g/ $cm^3$. Double press/double sintered processing may appear costly, however, it is minor when compared to the high raw material cost (approximately ten times pure iron).

Alloys of 50Ni/50Fe often require magnetic annealing after the P/M processing to achieve maximum properties. Typical annealing parameters for this material are 1000°C/1070°C for two hours followed by a slow cooling (not to exceed 3C° per minute). The annealing cycle is often substituted for the second sintering cycle in a double press/double sinter process, thus reducing the total processing costs.

**TABLE IV**
**Sintered Density and Magnetic Properties of Ancor[2] 50Fe/50Ni Material Compacted at 30 tsi and 50 tsi and Sintered at 1120°C and 1260°C**

| Sintering Temperature (°C) | Compaction Pressure (tsi) | Sintered Density ($g/cm^3$) | $H_C$ (Oe) | $B_R$ (kG) | $B_{max}$ (kG) | $\mu_{max}$ |
|---|---|---|---|---|---|---|
| 1120 | 30 | 6.90 | 0.57 | 4.6 | 8.6 | 4730 |
| | 50 | 7.40 | 0.58 | 5.3 | 10.9 | 5430 |
| 1260 | 30 | 7.01 | 0.47 | 5.5 | 9.8 | 7140 |
| | 50 | 7.50 | 0.46 | 6.7 | 11.8 | 8910 |

There are many other alloys based on the Ni-Fe system, utilized in wrought metallurgy for soft magnetic applications. These alloys typically contain additions of molybdenum, vanadium, silicon and other elements. Although these alloys can be easily manufactured into powder, the additions result in significantly reduced compressibility. These alloys do not typically lend themselves in making effective P/M components.

## FERRITIC STAINLESS STEELS

P/M ferritic stainless steels are utilized for magnetic components because of their enhanced corrosion properties. Magnetic properties of ferritic stainless steels are generally inferior to pure irons because the ferritic stainless steels contain a minimum of 12% chromium. Magnetic properties of 430L and 434L stainless steels are listed in Table V.

These results should not imply that these materials are unusable but rather that some magnetic properties are compromised to obtain superior corrosion resistance. The 1990 MPIF P/M Stainless Steel Award of Distinction (a 430L ABS wheel sensor ring) was an excellent example of the optimization of magnetic performance and corrosion resistance. (19)

**TABLE V**
**Typical Magnetic Properties (15 Oe) of Ancor 430L and Ancor 434L**
**(1% Lithium Stearate, 2050°F, 30 Minutes, $H_2$)**

| Material | Compaction Pressure (tsi) | Sintered Density (g/cm$^3$) | $H_C$ (Oe) | $B_R$ (kG) | $B_{max}$ (kG) | $\mu_{max}$ |
|---|---|---|---|---|---|---|
| 430L | 40 | 6.45 | 2.29 | 4.7 | 7.3 | 1000 |
| | 50 | 6.67 | 2.32 | 5.1 | 7.9 | 1040 |
| 434L | 40 | 6.43 | 2.01 | 4.6 | 7.3 | 1090 |
| | 50 | 6.65 | 1.90 | 4.8 | 7.9 | 1170 |

During the processing of stainless steel magnetic parts, the parts fabricator must be cognizant of stainless steel's affinity for carbon and nitrogen. Not only will the corrosion and mechanical properties degrade but a significant reduction in magnetic response will occur as carbon and nitrogen are absorbed as impurities (see below).

### Impurity Levels from Processing

As mentioned above, impurity content in the base material can greatly influence magnetic performance. A second and perhaps greater impurity source in the finished component derives from sintering conditions. Two elements that have a potent effect on magnetic properties are nitrogen and carbon. Minimizing the carbon and nitrogen to the lowest possible levels will result in improved magnetic performance. Two potential sources of carbon contamination in the finished component are an inadequate lubricant burn-off and an improper sintering atmosphere.

To evaluate the effect of carbon and nitrogen, magnetic test toroids were compacted at 30 tsi from a 0.45% P/Fe material with 0.75% zinc stearate and sintered in a variety of atmospheres at 1120° C and 1260° C for 30 minutes at temperature. These samples were then tested for magnetic properties and analyzed for chemical composition. The results of the chemical analysis are presented in Table VI and are illustrated in Figures 8 and 9.

**TABLE VI**
**Carbon and Nitrogen Analysis of Ancorsteel 45P Samples Sintered In Several Atmospheres**

| Sintering Temperature | Atmosphere | C (Wt.%) | N (Wt.%) |
|---|---|---|---|
| 1120°C | Endo | 0.150 | 0.0133 |
| | 90% $N_2$/10% $H_2$ | 0.004 | 0.0095 |
| | D.A. | 0.005 | 0.0016 |
| | 100% $H_2$ | 0.019 | 0.0006 |
| 1260°C | 90% $N_2$/10% $H_2$ | 0.006 | 0.0077 |
| | D.A. | 0.006 | 0.0043 |
| | 100% $H_2$ | 0.010 | 0.0002 |

As is apparent from this data, sintering in an endothermic atmosphere resulted in the highest carbon and nitrogen levels. Switching to a 90% $N_2$/10% $H_2$ atmosphere resulted in much reduced carbon contents, however, the nitrogen content remained at a high level.

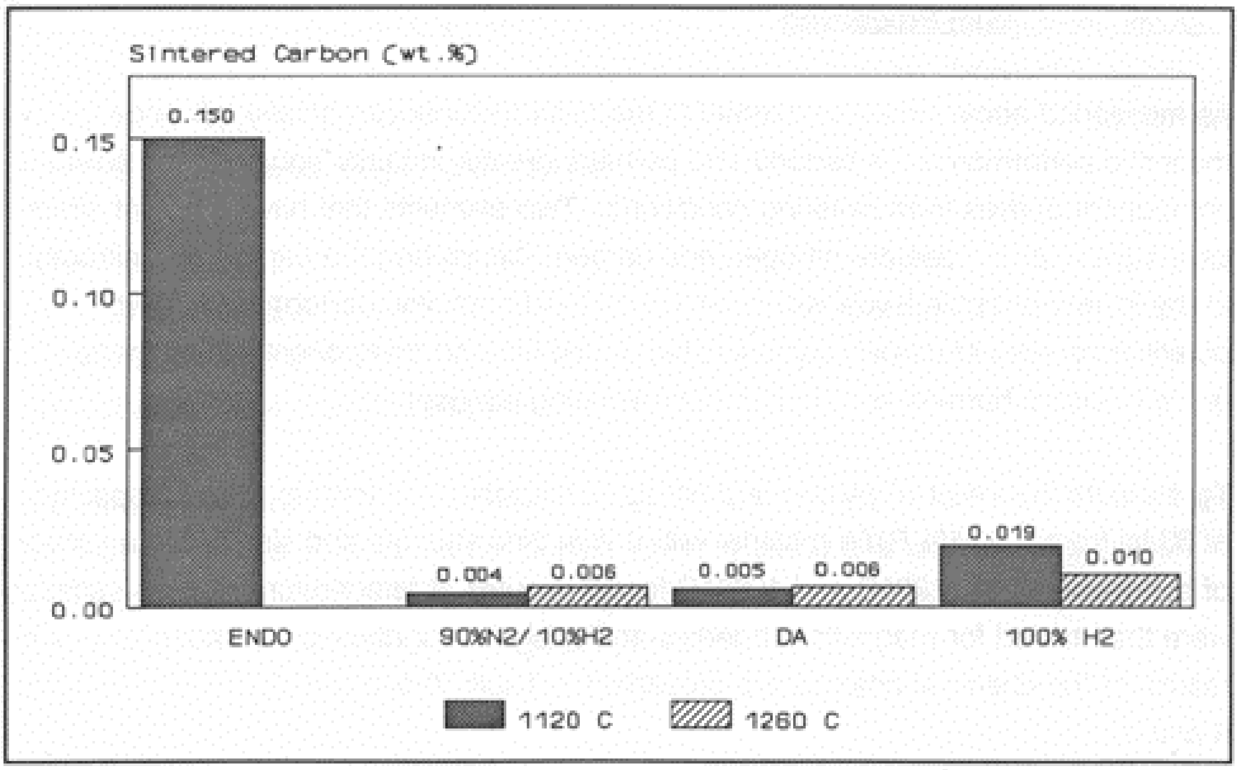

Figure 8: Effect of Sintering Atmosphere on Sintered Carbon Content

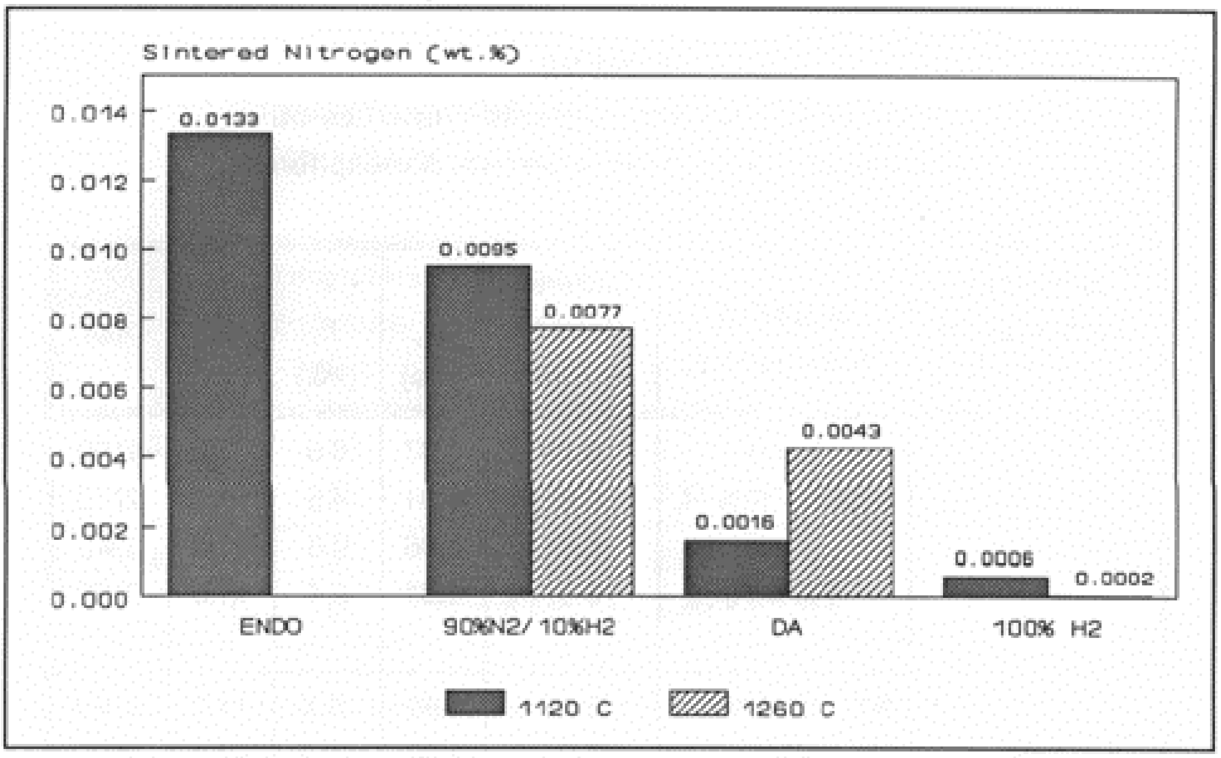

**Figure 9: Effect of Sintering Atmosphere on Sintered Nitrogen Content**

When toroids were sintered in a dissociated ammonia atmosphere, the carbon content remained at a low level while the nitrogen level reduced significantly. Toroids sintered in pure $H_2$ gas indicated the lowest level of retained nitrogen, however, the carbon content was higher than expected. No special burn-off step was used during these laboratory studies. It is theorized that the use of very dry hydrogen in the sintering furnace resulted in a very low oxygen availability to aid in pyrolysis of the lubricant. As a result, carbon levels in the finished part were high. This illustrates the need for a proper burn-off cycle prior to sintering soft magnetic parts in a dry hydrogen atmosphere. Similar trends were seen when sintering was performed at 1260°C utilizing hydrogen/nitrogen atmospheres. Density values and magnetic properties obtained from these samples are listed in Table VII.

The toroids sintered in endothermic gas clearly show the deleterious effect of high carbon and nitrogen levels on the finished magnetic properties. Coercive force is very high while permeability is greatly reduced. Changes in maximum induction are related more to changes in density and permeability at the relatively small drive field (15 Oe). In comparing the materials sintered in the 90/10 atmosphere with the dissociated ammonia atmosphere, the effect of nitrogen is apparent. The increased nitrogen content has raised the coercive force value, while lowering the permeability.

**Table VII**
**Sintered Density and Magnetic Properties of Ancorsteel 45P Sintered In Several Atmospheres**

| Sintering Temperature (°C) | Sintering Atmosphere | Sintered Density ($g/cm^3$) | $H_C$ (Oe) | $B_R$ (kG) | $B_{max}$ (kG) | $\mu_{max}$ |
|---|---|---|---|---|---|---|
| 1120 | Endo | 6.79 | 2.67 | 6.6 | 9.2 | 1190 |
| | 90% $N_2$/10% $H_2$ | 6.82 | 1.81 | 9.5 | 10.9 | 2770 |
| | D.A. | 6.84 | 1.66 | 9.6 | 11.2 | 2940 |
| | 100% $H_2$ | 6.87 | 1.91 | 8.4 | 11.0 | 2190 |
| 1260 | 90% $N_2$/10% $H_2$ | 6.96 | 1.62 | 9.5 | 11.3 | 3120 |
| | D.A. | 7.05 | 1.37 | 10.2 | 12.4 | 3820 |
| | 100% $H_2$ | 7.02 | 1.42 | 9.9 | 12.3 | 3380 |

Magnetic properties of the $H_2$ sintered material with higher sintered carbon compare unfavorably to the lower carbon containing DA sintered materials despite the significantly lower nitrogen content. These results clearly show that nitrogen and carbon are sources of decreased magnetic properties.

Even more dramatic is the effect of nitrogen on magnetic properties of stainless steels. Samples of 430L and 434L stainless steels with 1% lithium stearate were compacted at 40 tsi and sintered at 1120°C for 30 minutes in dissociated ammonia and 100% $H_2$ atmospheres. The results are listed in Table VIII.

The samples sintered in dissociated ammonia picked up significant nitrogen from the atmosphere and as a result did not densify upon sintering and were essentially non-magnetic. The samples sintered in hydrogen attained much higher density and resulted in a reasonable level of magnetic performance.

### TABLE VIII
### Sintered Density, Nitrogen and Magnetic Properties of Ancor 430L Sintered in Hydrogen and Dissociated Ammonia Atmospheres

| Material | Sintering Atmosphere | Sintered Density ($g/cm^3$) | N (Wt.%) | $H_C$ (Oe) | $B_R$ (kG) | $B_{max}$ (kG) | $\mu_{max}$ |
|---|---|---|---|---|---|---|---|
| 430 | 100% $H_2$ | 6.45 | 0.004 | 2.29 | 4.7 | 7.3 | 1000 |
| 430 | D.A. | 6.15 | 0.423 | -- | -- | 0.0 | 10 |
| 434 | 100% $H_2$ | 6.43 | 0.004 | 2.01 | 4.6 | 7.3 | 1090 |
| 434 | D.A. | 6.14 | 0.400 | 6.00 | 0.0 | 0.1 | 20 |

### TABLE IX
### Sintered Density and Chemical Analysis of Ancorsteel 45P Material Compacted Utilizing Several Lubricants

| | | 35 tsi | | | 45 tsi | | |
|---|---|---|---|---|---|---|---|
| Lubricant | Lubricant Amount (%) | Sintered Density ($g/cm^3$) | C (Wt.%) | O (Wt.%) | Sintered Density ($g/cm^3$) | C (Wt.%) | O (Wt.%) |
| Zinc Stearate | 0.75 | 7.01 | <0.01 | 0.038 | 7.21 | <0.01 | 0.037 |
| Lithium Stearate | 0.75 | 7.00 | <0.01 | 0.066 | 7.21 | <0.01 | 0.060 |
| Acrawax C | 0.50 | 6.95 | <0.01 | 0.043 | 7.19 | <0.01 | 0.043 |
| Acrawax C | 0.75 | 6.96 | <0.01 | 0.038 | 7.19 | <0.01 | 0.037 |
| Acrawax C | 1.00 | 6.95 | <0.01 | 0.039 | 7.15 | <0.01 | 0.038 |

These two experiments demonstrate that carbon and nitrogen can have a large negative effect on iron-based soft magnetic materials. In order to counter these negative effects, the lubricant must be burned off cleanly and the part must be sintered under conditions that will limit nitrogen and carbon pickup.

## LUBRICANT EFFECTS

To determine if the use of any of the common powder metallurgy lubricants resulted in a change in magnetic performance, samples of 0.45% P/Fe were blended with zinc stearate at 0.75 wt.%, lithium stearate at 0.75 wt.% and Acrawax C at 0.5, 0.75 and 1.0 wt.%. Toroids were compacted from each blend at 35 and 45 tsi, sintered at 1120° C in a 75% $H_2$/25% $N_2$ for 30 minutes, and tested for magnetic properties. No special lubricant burnout step preceded sintering. Table IX lists the sintered density, carbon and oxygen levels of the resulting specimens. These results indicate that all lubricants were burned out completely. The higher oxygen content in the lithium stearate sample is most likely the result of retained lithium oxide.

Magnetic properties for these tests are listed in Table X. The data suggest no significant variation in magnetic properties with various lubricant types or with increasing levels of Acrawax C. Good magnetic properties will be obtained with these lubricants providing adequate burnout of the lubricants is achieved. Incomplete burnout and the possible rise in sintered carbon content may, as mentioned above, result in poor magnetic properties.

## DENSITY EFFECTS

One of the most potent modifiers of structural P/M part performance is density. Magnetic performance of P/M parts is also strongly influenced by density. For a given alloy system, saturation induction is directly related to density. Saturation induction is important in permanent magnet flux return paths where sufficient field is available to saturate most materials. Pore-free pure iron has a saturation flux density of 21.5 kG. Decreasing density simply decreases the saturation flux density as indicated in Figure 10.

The higher the density of the part, the higher the saturation flux density and thus the smaller a part can be made in order to contain the flux produced by a permanent magnet.

**TABLE X**
**Magnetic Properties of Ancorsteel 45P Materials Compacted Utilizing Several Lubricants**

| | | 35 tsi | | | |
|---|---|---|---|---|---|
| **Lubricant** | **Lubricant Amount (Wt.%)** | **$H_C$ (Oe)** | **$B_R$ (kG)** | **$B_{max}$ (kG)** | **$\mu_{max}$** |
| Zinc Stearate | 0.75 | 1.74 | 10.4 | 12.0 | 3040 |
| Lithiun Stearate | 0.75 | 1.73 | 10.3 | 11.9 | 3060 |
| Acrawax C | 0.50 | 1.74 | 9.9 | 11.6 | 2860 |
| Acrawax C | 0.75 | 1.74 | 10.0 | 11.7 | 2940 |

| | | | | | |
|---|---|---|---|---|---|
| Acrawax C | 1.00 | 1.71 | 10.2 | 11.8 | 2970 |
| | | **45 tsi** | | | |
| Zinc Stearate | 0.75 | 1.77 | 11.2 | 12.8 | 3410 |
| Lithiun Stearate | 0.75 | 1.75 | 11.4 | 12.9 | 3530 |
| Acrawax C | 0.50 | 1.75 | 11.2 | 12.7 | 3420 |
| Acrawax C | 0.75 | 1.74 | 11.2 | 12.8 | 3340 |
| Acrawax C | 1.00 | 1.74 | 11.1 | 12.7 | 3330 |

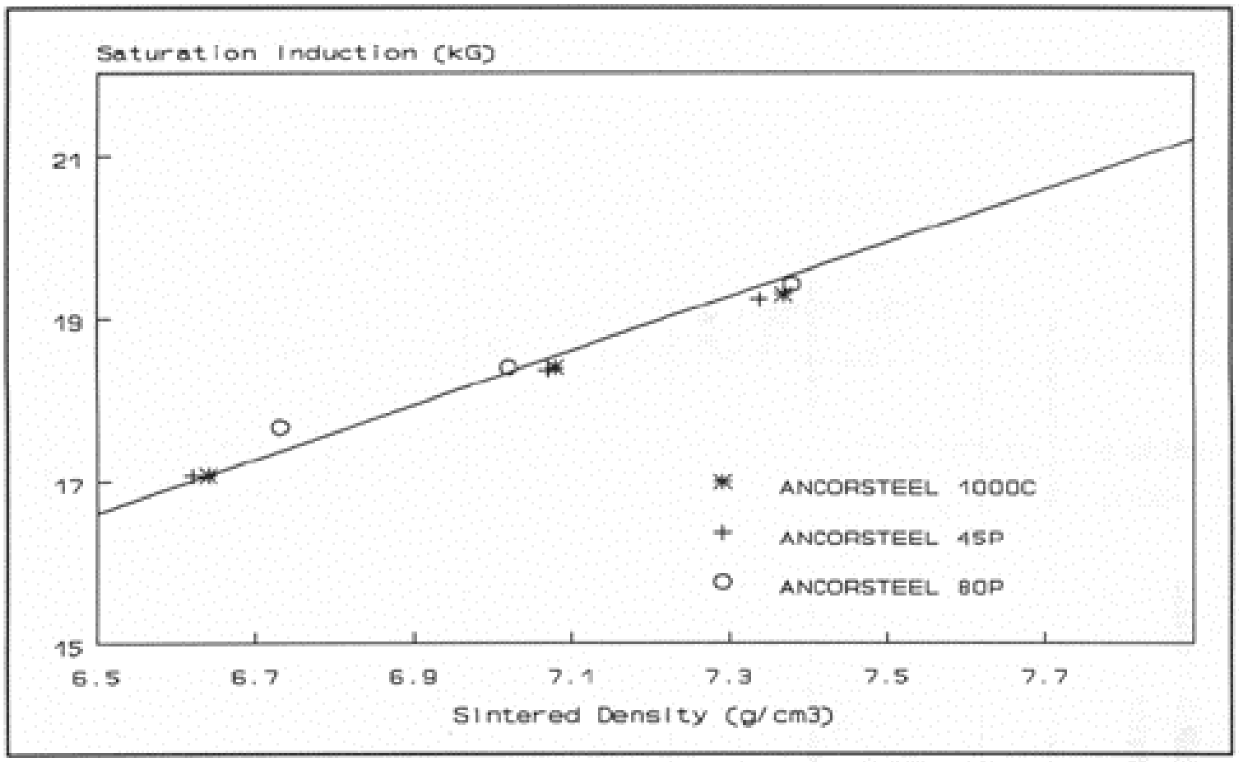

**Figure 10: Saturation Induction versus Density for Several Alloys**

Density also affects general magnetic properties. Samples of a pure iron and a 0.45% P/Fe material were blended with 0.75% zinc stearate and compacted into toroids at 30, 40 and 50 tsi. These samples were sintered at 1120 C for 30 minutes in dissociated ammonia and then tested for magnetic properties. (See results listed in Table II for Ancorsteel 1000B and Table III for Ancorsteel 45P).

Figures 11,12 and 13 indicate that increased density has a dramatic effect on the magnetic properties of permeability and maximum induction. Coercive force is only moderately affected by changes in density (Figure 13).

Essentially, as the density is increased, more iron is available to carry flux, thus improving the permeability and saturation induction. Coercivity is related to the purity within a material and is less dependent upon changes in density.

## SINTERING TEMPERATURE

Increasing sintering temperatures generally results in higher sintered density. This increase in density, by itself, will result in improved magnetic properties as previously discussed (see above). However, the use of higher sintering temperatures has a more

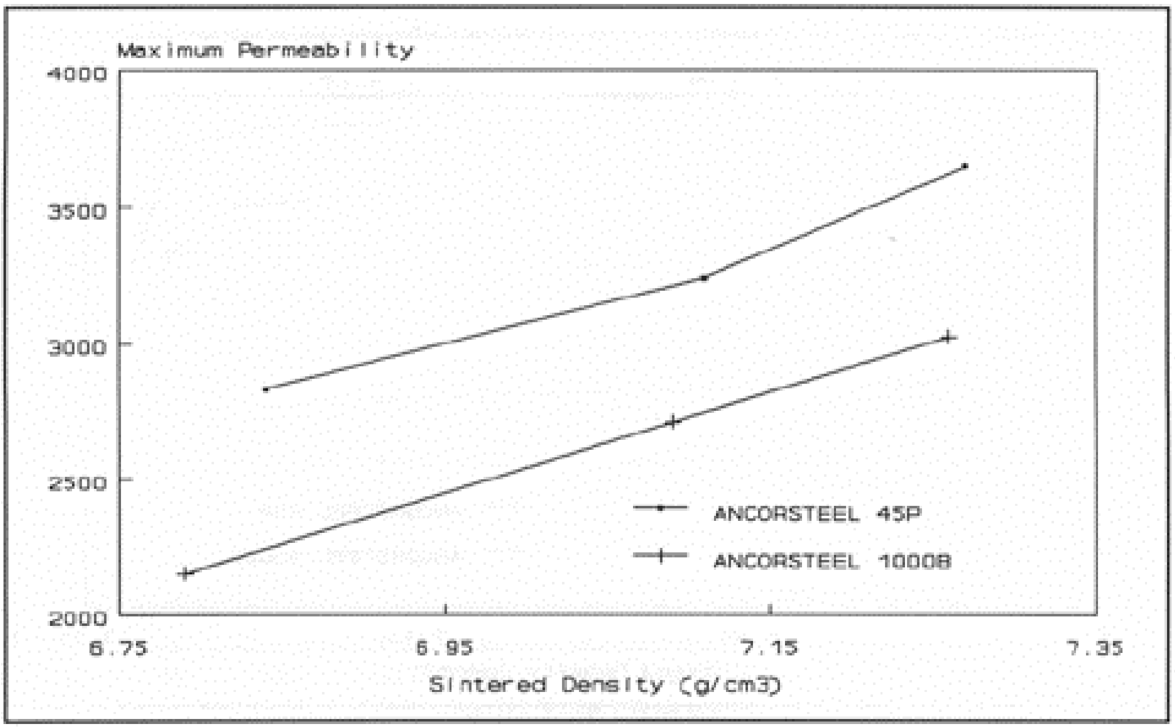

**Figure 11: Maximum Permeability of Several Materials at Varying Sintered Densities**

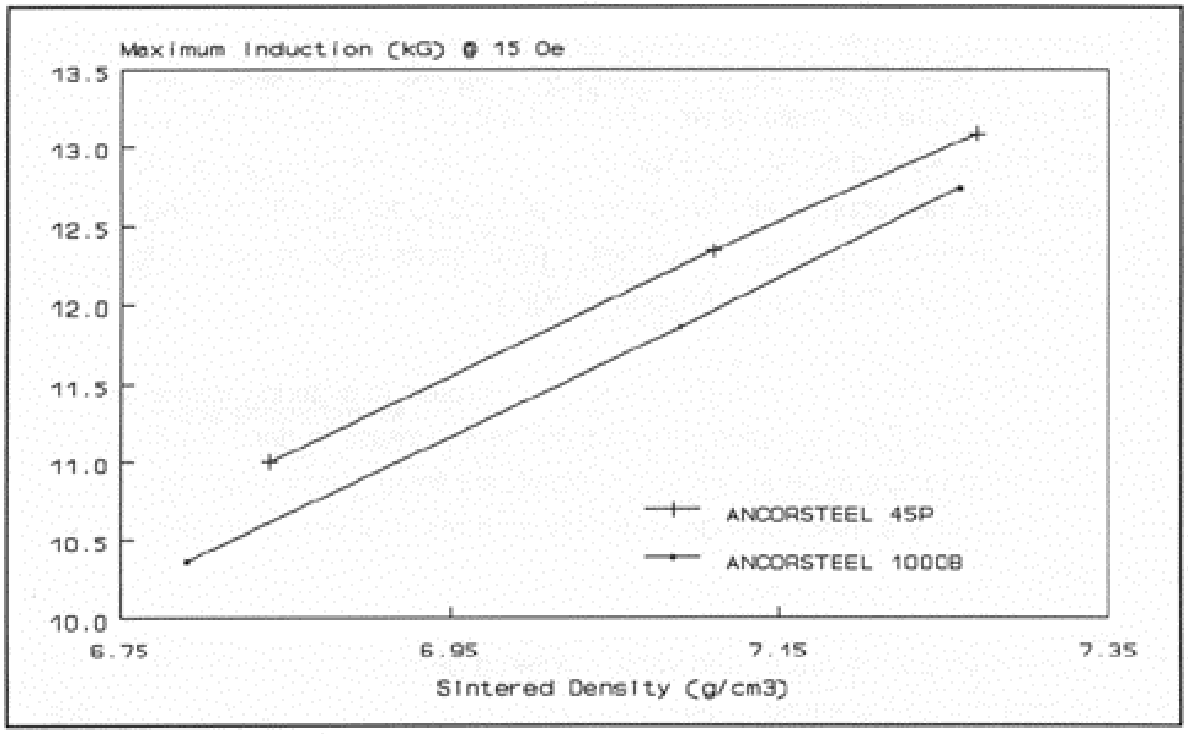

**Figure 12: Maximum Induction of Several Materials at Varying Sintered Densities**

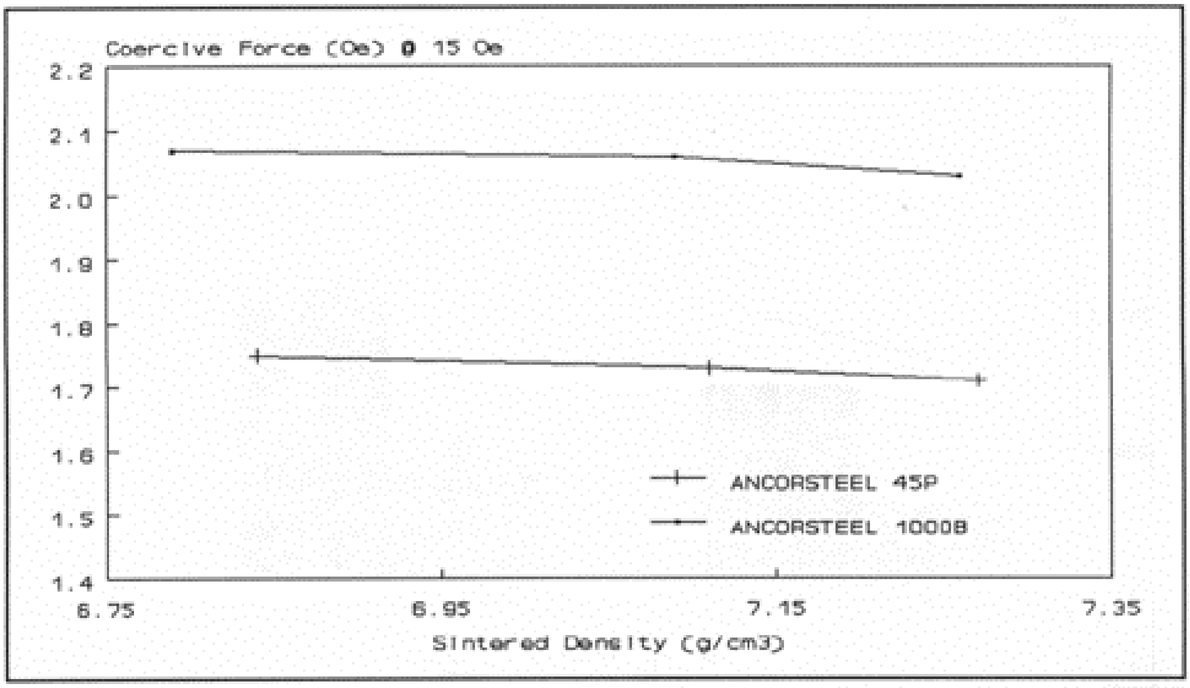

**Figure 13: Coercive Force of Several Materials at Varying Sintered Densities**

significant effect on magnetic properties than simple densification. The use of higher sintering temperatures results in larger grain sizes and more refined pore morphology and as a result, greatly enhanced magnetic performance.

To illustrate the effect of sintering temperature on magnetic performance, samples of a 0.80% P/Fe and pure iron material were blended with 0.75% zinc stearate and compacted at 30, 40 and 50 tsi. One half of the samples were sintered at 1120°C for 30 minutes while the second half were sintered at 1260°C for 30 minutes and all samples were tested for magnetic properties. (See results listed in Table II for Ancorsteel 1000C and Table III for Ancorsteel 80P.)

Figure 14 indicates the increase in density for the increase in sintering temperature. In particular, the 0.80% P/Fe samples show a significant increase in density with increased sintering temperature as a result of significant liquid phase sintering. The pure iron shows only a minor change in density as a result of increased sintering temperature.

If the magnetic properties are plotted versus sintered density (Figures 15, 16 and 17), improvements due to increased sintering temperature beyond increased density, are readily apparent.

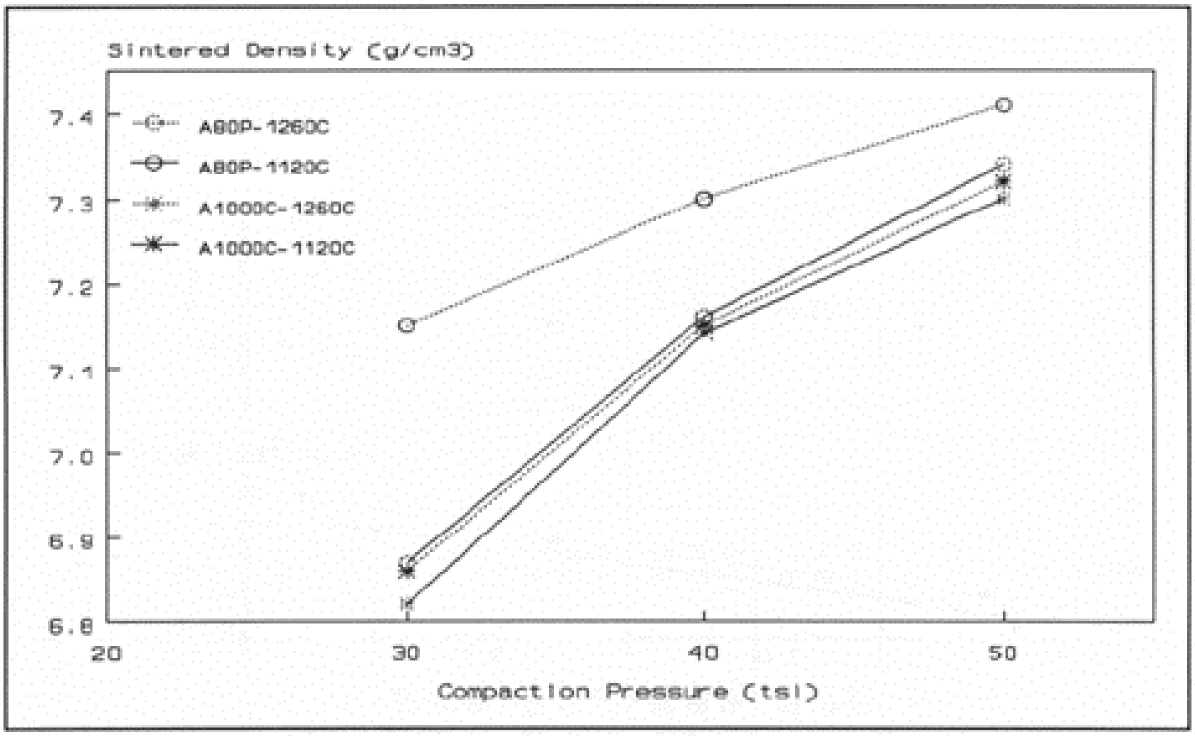

**Figure 14: Sintered Density versus Compaction Pressure for Materials Sintered at Several Temperatures**

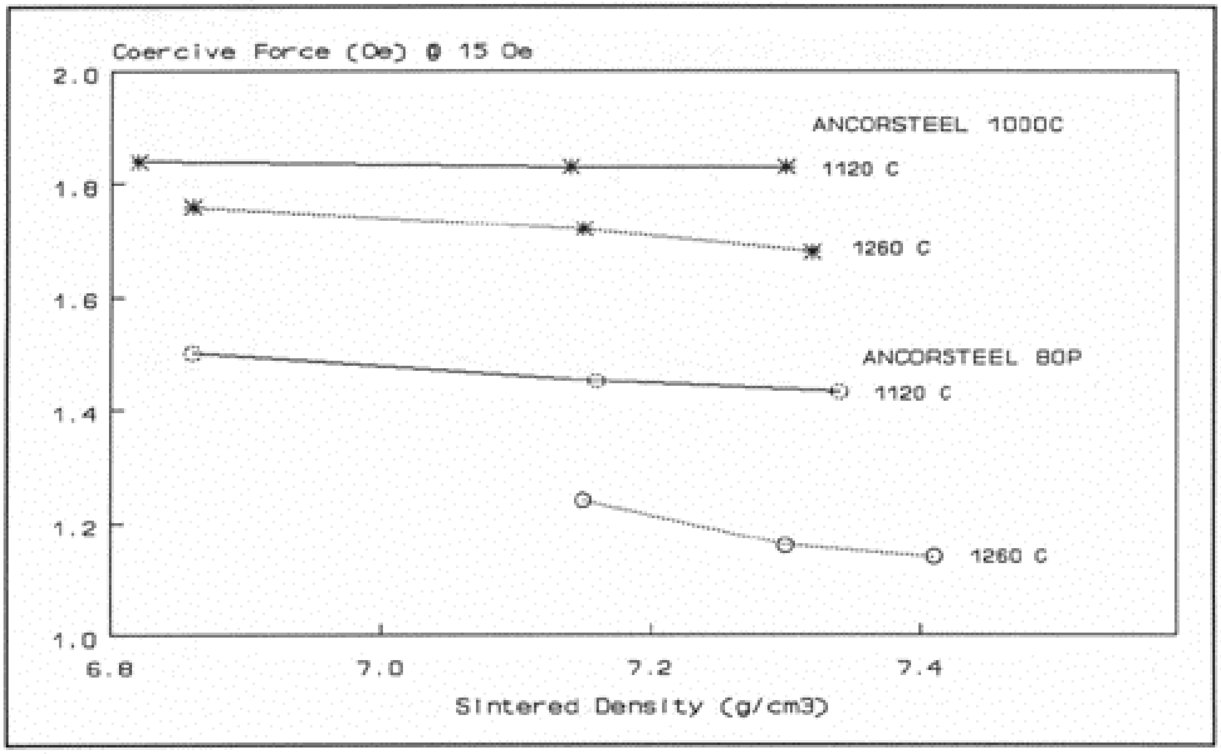

Figure 15: Effect of Sintering Temperature on Coercive Force

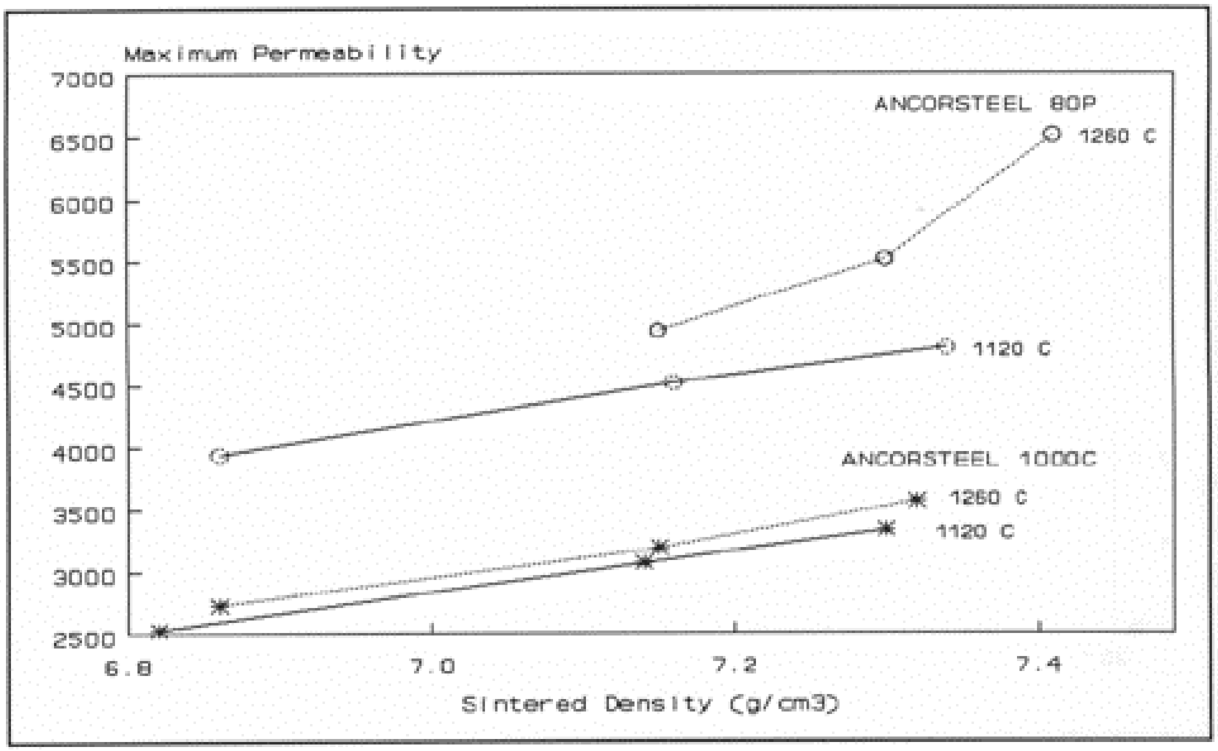

Figure 16: Effect of Sintering Temperature on Maximum Permeability

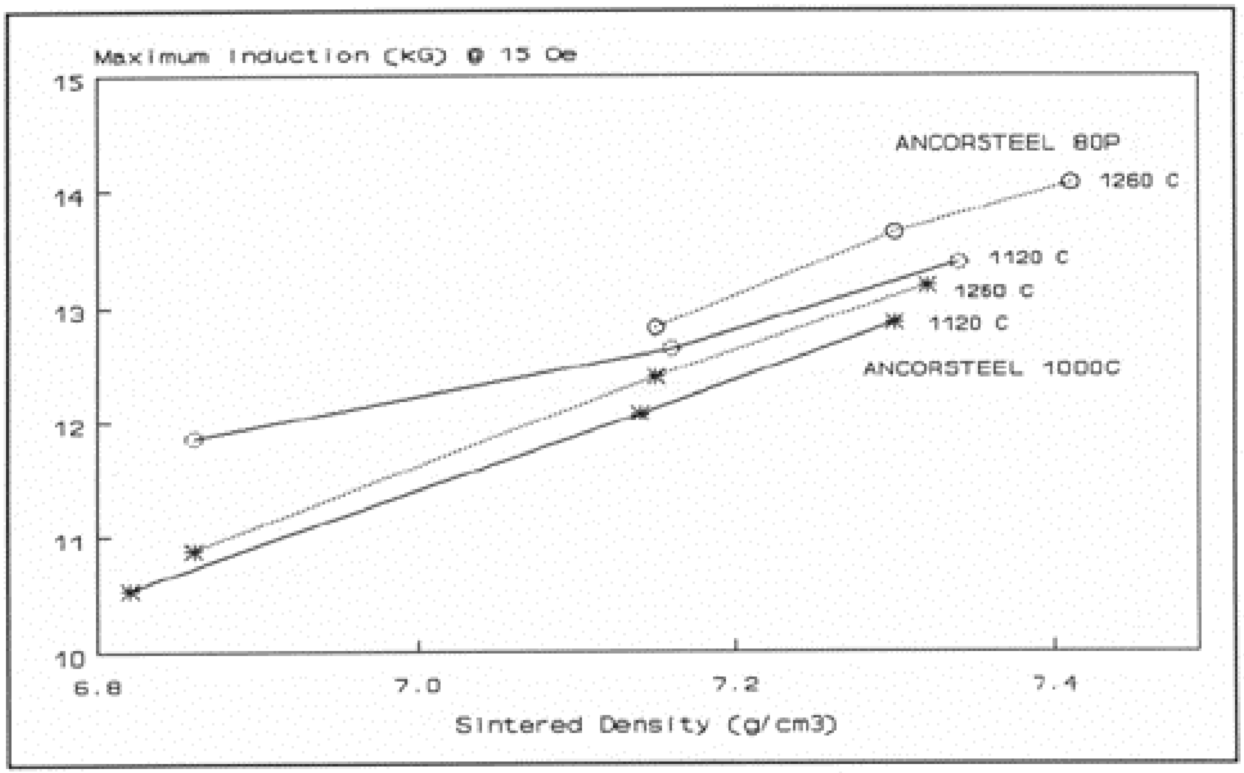

**Figure 17: Effect on Sintering Temperature on Maximum Induction**

For a given sintered density level, coercive force is reduced, while permeability, maximum induction and residual induction are increased with elevated sintering temperatures. High temperature sintering results in a more refined ferrite structure and improved soft magnetic properties.

The effect of higher sintering temperature is also evident in 50Fe/50Ni alloys. Table IV lists results from 50Fe/50Ni powders compacted at 30 and 50 tsi and sintered at 1120°C and 1260°C for 30 minutes in dissociated ammonia. As well as increasing density, increased sintering temperature resulted in improved magnetic performance. In particular, coercive force and maximum permeability were significantly improved.

## SUMMARY

The powder metallurgy route for manufacturing parts for soft magnetic applications offers a flexible, cost effective and proven technology. The preceding paper has discussed many of the options and suggested methods to optimize performance. The following offers a brief summary of those discussions.

1. Many different materials are available for P/M soft magnetic applications. Each material has strengths as well as limitations.

Not only magnetic requirements must be considered but concerns about physical requirements must be addressed.

2. Various processing routes allow significant cost optimization to occur. By utilizing higher densities or higher sintering temperatures, magnetic performance may improve enough to allow the use of a less expensive material. Similarly, the use of a more expensive raw material may allow utilizing less expensive processing steps.

3. Limiting the amount of carbon and nitrogen in the finished part is crucial to provide the best magnetic performance. Sufficient burn-off of lubricants and use of proper sintering atmospheres will provide optimal performance.

## REFERENCES

1. Kordecki, A., Weglinski, B., and Kaczmar, J., “Properties and Applications of Soft Magnetic Powder Composites”, Powder Metallurgy, 1982, Vol.25, No.4, pp 201.

2. James, B. A., Williams, G., “Review of the Magnetic Properties of Sintered Iron”, Powder Metallurgy, 1979, No.2, pp 75-84, Institute of Metals

3. Engström, U., Jansson, P., “Metal Powders for the Production of Soft Magnetic Parts”, The Institute of Metals 1985 Powder Metallurgy Group Meeting

4. Heck, C., “Magnetic Materials and Their Applications”, 1974, Butterworth & Co., Ltd.

5. Bozorth, R., “Ferromagnetism”, 1959, D. Van Nostrand Co., Inc.

6. Hoeganaes Corporation, Brochure on Ancorsteel® 1000/1000B/1000C, Form MCA-188, Hoeganaes Corporation, Riverton, NJ

7. Ashton, C. R., “P/M in the Automotive Industry, Present and Future”, Progress in Powder Metallurgy, 1977, Vol.33, pp 259-263, Metal Powder Industries Federation, Princeton, NJ.

8. Sanderow, H. I., “Soft Magnetic Materials - P/M Applications”, P/M Technical Conference, Philadelphia, PA, October 24-26, 1978, Hoeganaes Corporation.

9. Moyer, K. H., McDermott, M. J., “The Effect of Sintering in Hydrogen/Nitrogen Atmospheres and Subsequent Aging on the

Magnetic Properties of Iron”, Powder Metallurgy International, Vol.15 , (3), 1983, p 134.

10. Bolze, G. C., Capus, J. M., “Factors Affecting Magnetic Properties of Sintered Irons”, Modern Developments in Powder Metallurgy, Vol. 11, 1977, pp 355-370, Metal Powder Industries Federation, Princeton, NJ.

11. Jansson, P., Höganäs AB, Sweden, Private Communication, to be published.

12. Tengzelius et al., U.S. Patent #4,090,868 (May 23,1978) and Svensson et al., U.S. Patent #4,093,449 (June 6,1978).

13. Hanada, M., Takeda, Y. et al, “Development of a Powder Metallurgy Sensor Ring for Use in an Anti-Lock Brake System”, Sumitomo Electric Technical Review, No 28, January 1989, pp 234-240.

14. Ormerod, H., Taylor, T., Roozee, J., “Improvements and Applications of Permanent Magnet Materials in Automotive Sensors”, SAE Technical Paper No. 920171.

15. Engdahl, P., “Mechanical Properties and Microstructure of Phosphorus Alloyed Sintered Steels”, Modern Developments in Powder Metallurgy, Vol. 20, 1988, pp 655-665, Metal Powder Industries Federation, Princeton, NJ.

16. Kaczmar, J. and Weglinski, B., “Effect of Production Engineering Parameters on the Magnetic Properties and Structure of Iron-Silicon P/M Materials”, The International Journal of Powder Metallurgy and Powder Technology, Vol. 18, No. 1, 1982, pp 25-35.

17. Sabar, T. et al, “Magnetic Properties of Fe-Si Alloys by Powder Metallurgy”, MAG-13, No.5, September 1977, pp 1445-1447.

18. Chen, C. W., “Magnetism and Metallurgy of Soft Magnetic Materials”, 1977, North Holland Publishing Company.

19. Johnson, P., “New P/M Applications”, The International Journal of Powder Metallurgy, Vol.26, No.3,1991, pp 274.

**Notes:**

[1] Ancorsteel is a registered trademark of Hoeganaes Corporation

[2] Ancor is a registered trademark of Hoeganaes Corporation.