

Effect of Particle Size and 2P2C Technology on the Soft Magnetic Properties of Composite Iron Compacts

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Abstract

Iron powder usage in electromagnetic applications has gained wider acceptance to replace ferrites at lower frequencies and lamination steels at higher frequencies. In this paper the effect of particle size distribution of screened pure iron powder on induction, permeability, coreless and Q factor is described. For applications of soft magnetic materials replacing lamination steels in motors and actuators the typical median particle size used is 140 microns that can be processed to produce components that have acceptable levels of induction and permeability. This paper also outlines a process route called 2P2C that allows for compaction of composite iron compacts to densities greater than 7.45 g/cm³ increasing the composites' strength and magnetic performance. .

Keywords: Soft Magnetic Composites; Magnetic Materials.

Introduction

Insulated iron composites are a niche unique to powder metallurgy. This method uses pure iron powder with a highly insulating coating to provide a soft magnetic ferrous material that is suitable for a variety of electromagnetic applications. These coated powders offer 3D flux carrying capability compared to traditional lamination steels where flux is maximized in the rolling direction. Iron powders have been in usage for over hundred years for soft magnetic applications. The advancements in producing high quality highly compressible powder over the past 40 years opened up significant opportunities for iron powder in replacing ferrites and other competing materials in electronic circuits.[1-5] The performance of an insulated iron composite varies greatly depending on the starting particle size of the iron particles. To quantify the range of properties possible a systematic investigation was completed on the effect of particle size on induction, core loss and permeability. Based on these results two standardized particle size distributions were chosen to further advance the technology of insulated iron composites for moderate and higher frequency applications such as transformers, actuators and reactor cores.

Insulated iron composites typically need to be compacted at very high compaction pressures above 1000 MPa to achieve final densities >7.50 g/cm³ to attain desired permeability and induction levels. The practical upper compaction limit is 600-830 MPa for current production and pressing at levels beyond limits the size and complexity of the final component. Recently a new two-step compaction process, called 2P2C, has been developed to achieve the needed higher density levels without the need to exceed 830 MPa.

Experimental

High purity water atomized iron powder (Ancorsteel 1000C from Hoeganaes Corporation) was used in all these experiments. This powder was screened to various sieve fractions. Powders from each sieve fraction were measured using a laser particle size analyzer and tested for chemical purity. These results are shown in Table 1. Each sieve fraction was coated with a proprietary coating to magnetically insulate individual particles. The coated powder was mixed with 0.75% Zinc stearate and compacted into toroids at room temp with a compacting pressure of 660 MPa. The compacted toroids were cured at 450 °C in nitrogen for one hour. Magnetic measurements were conducted by wrapping 35 primary and 35 secondary copper windings using #28AWG wire. DC hysteresis loops were generated at 800, 1600, 2100 and 3200 A/m and AC hysteresis loops were generated at

500 Hz and peak induction levels of 0.1, 0.2, 0.3, 0.4, and 0.5 T. Testing of initial permeability and core loss at an induction level of 0.001 T was performed. For the 2P2C data, magnetic properties of AncorLam products were measured on toroids at a specified density. Toroidal dimensions were 36.1 mm OD x 22.3 mm ID x 5.76 mm H at room temperature (25 °C) using the ASTM A773/A773M-01 procedure with 400 primary turns and 40 secondary turns.

Results and Discussion

Effect of Particle Size

The narrow particles sizes fractions shown in the following section can be targeted for special applications; however, these narrow particle size ranges can only be produced by screening and are very expensive. To cover more common applications, three powder distributions were developed that could be produced economically in mass volume for applications such as inductors, actuators and motor cores. The particle size ranges for the standard material are shown in Table 1. The data in the following section shows how particles size impacts magnetic properties and can be used as a guide when selecting powders for specific applications. Typically the particle size and coating type is modified to meet specific application types . In general, applications that need higher permeability have coarser particles and less insulation. Applications that operate at higher frequencies use finer particles and or increased insulation. A summary of achievable magnetic properties for select standard insulated iron composite materials is provided later.

Table 1: Particle size range of standard insulated iron composites

Material Type	Particle Size Range (µm)
AncorLam 2F	37-140
AncorLam	37-224
AncorLam2	140-224

Table 2 shows the average particle size of various screened fractions of Ancorsteel 1000C powder and their chemical analyses. The mean particle sizes listed correspond to the measured data in the subsequent figures. The low level of C, O2, and N should be noted as iron purity is essential to ensuring the maximum ferro-magnetic performance.

Table 2: Particle size and chemical analysis of screened fractions

Mean Particle size (µm)	Screen Fraction (mesh)	C (wt%)	O2 (wt%)	N2 (wt%)
224	-60/+80	0.003	0.056	0.002
195	-80/+100	0.003	0.058	0.002
164	-100/+120	0.003	0.062	0.002
139	-120/+140	0.003	0.055	0.003
117	-140/+170	0.003	0.053	0.002
102	-170/+200	0.003	0.056	0.001
84	-200/+230	0.003	0.054	0.001
72	-230/+270	0.003	0.054	0.002
60	-270/+325	0.002	0.054	0.002
51	-325/+400	0.004	0.058	0.001
37	-400	0.004	0.065	0.001

Effect of particle size on density and maximum permeability are shown in figure 1. A distribution of coarser particle is more easily compressed because there is less internal friction to overcome within the compact and the

coarser particles have a larger grain size. Increasing the mean particle size increases the compacted density from 7.2 to 7.3 g/cm³. However, the increase in permeability is from 160 to 260. This increased permeability results from both the higher compacted density, thus reduced air gap, and the larger grain size intrinsic in coarser particles.

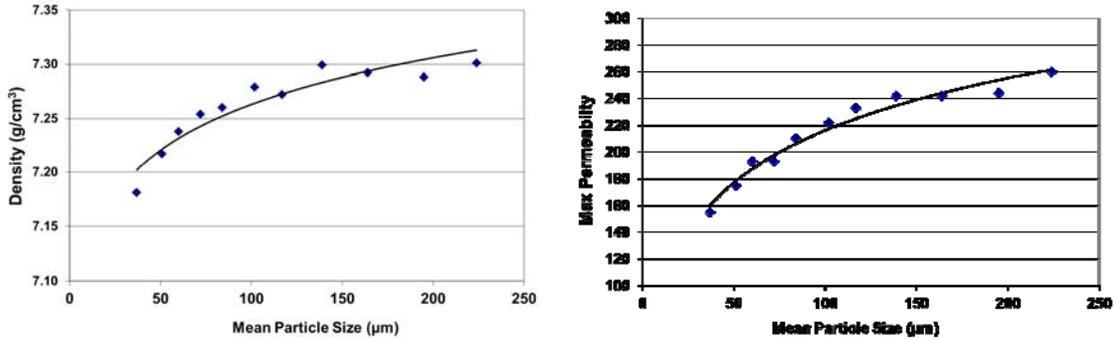


Fig 1: a.) Density as pressed at 660 MPa and b.) Maximum permeability as a function of mean particle size.

Initial permeability, however, is not dependent on density as initial magnetization process is more reflective of material purity. Figure 2 shows the effect of particle size on initial permeability. As expected, the compact density has very little influence on the initial permeability. An additional characteristic of insulated iron powder is that initial permeability is independent of frequency over a large frequency range.

Initial permeability Vs Frequency and Average Particle sizes

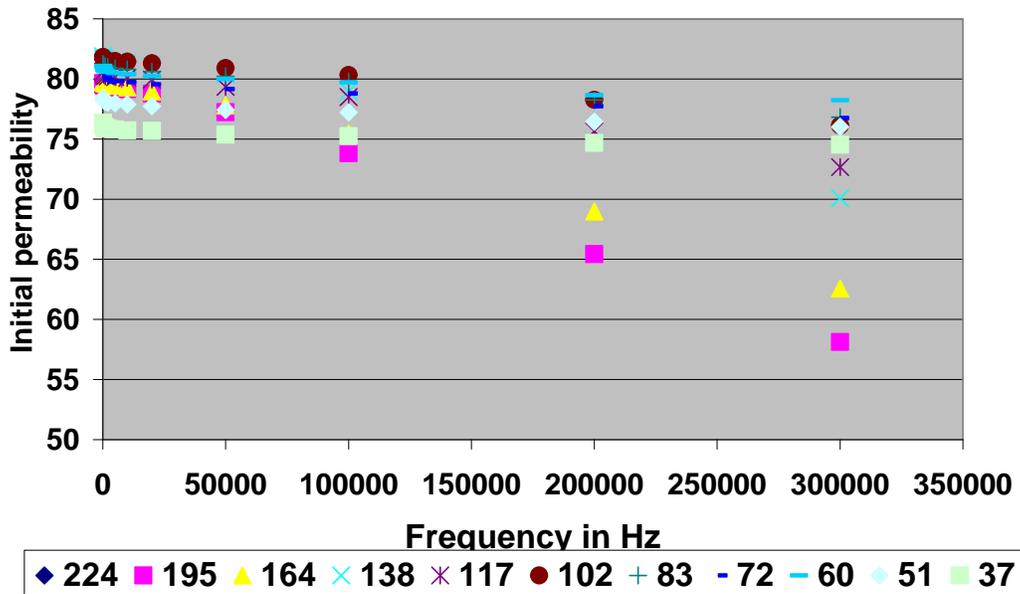


Fig 2: Initial Permeability versus frequency for various particle fractions.

Figure 3 shows the core loss as a function of frequency for various particle sizes. In general, the core loss increases with frequency; however, particle size also influences the losses in that the small particles tend to have lower core losses at higher frequencies than coarser particles because of the higher the composite resistivity resulting in lower the eddy current losses when small particle size fraction are used.

Coreloss at .0001 Tesla for Various average particle sizes at various frequencies

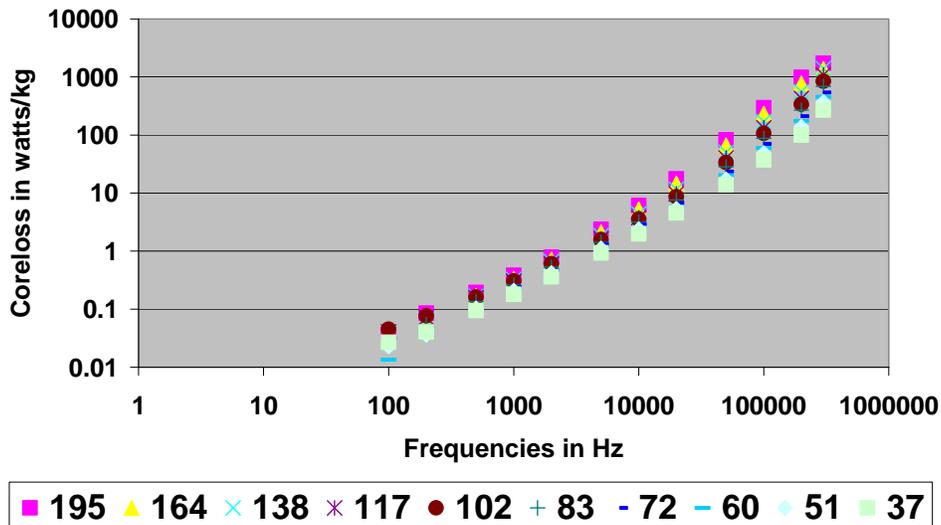


Fig 3: Core loss at an induction level of 0.001 T versus frequency for various particle fractions.

Typically the particles size and coating type is modified to meet specific application types. In general, applications that need higher permeability have coarser particles and less insulation. Applications that need to operate at higher frequencies use finer particles (designation F) and or increased insulation (designated as HR). A generic summary of materials and application types is presented in Table 3. The specific magnetic performance of each grade is available elsewhere⁶.

Table 3: Typical applications with suggested material type

AncorLam Type:	Std	2	HR	2HR	2F	2FHR
Motors requiring high induction/ permeability		•	•	•		
Actuators (<400 Hz)		•		•		
Small Transformers (>400 Hz)			•	•		
Permanent Magnet DC Motors		•	•	•		
Ignition Coils	•	•	•	•		
Fuel Injectors / Switching Actuators		•		•		
Ballasts		•				
High frequency applications for power electronics (10-30 kHz)					•	•

The typical production process involves compacting the insulated iron particle and curing at a temperature that increases the mechanical strength without destroying the insulation. This is outlined in Table 4. An insulated iron composite powder is compacted into the desired shape. The green part is then cured in N₂ at 450 °C resulting in the final cured component. The curing has the benefits of increasing mechanical strength of the compact and it also partially stress relieves the iron improving magnetic response, specifically the hysteresis losses.

Table 4: Typical IPIC production route for an insulated composite component.

Step	Process	Conditions
1.	Compact Powder	Die at 80 °C or Room temperature
2.	Cure	450 °C, 1 hr, 100% N ₂
3.	Finished Parts	

Insulated composites typically need to be compacted at very high compaction pressures to achieve density >7.40 g/cm³ to attain reasonable permeability and induction levels. The current technology used globally to achieve density values >7.50 g/cm³ requires very high compaction pressures at least >1000 MPa. Compaction at these very high pressures limits the size and complexity of the final component. Recently Hoeganaes Corporation, USA, developed a new technology called 2P2C to reduce the need for compaction at pressures greater than 800 MPa[7]. The 2P2C process is outlined in Figure 4.

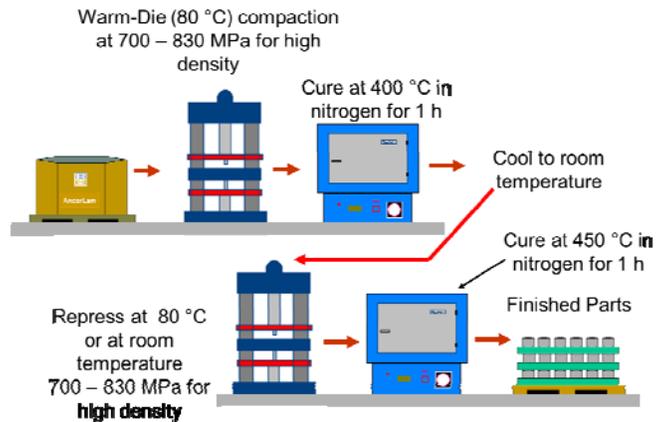


Fig 4: 2P2C production route [7]

Fig 5 shows the relative difference in compaction pressures to achieve densities $>7.50 \text{ g/cm}^3$. The limits of 1P1C are clear in that a compaction pressure $>1100 \text{ MPa}$ is needed to approach 7.55 g/cm^3 whereas the two step 2P2C achieves this density at 830 MPa . While the 2P2C involves more process steps, it does not require the use of sophisticated high pressure presses and tooling. Lower compaction pressures also allow for more complexity in the final part.

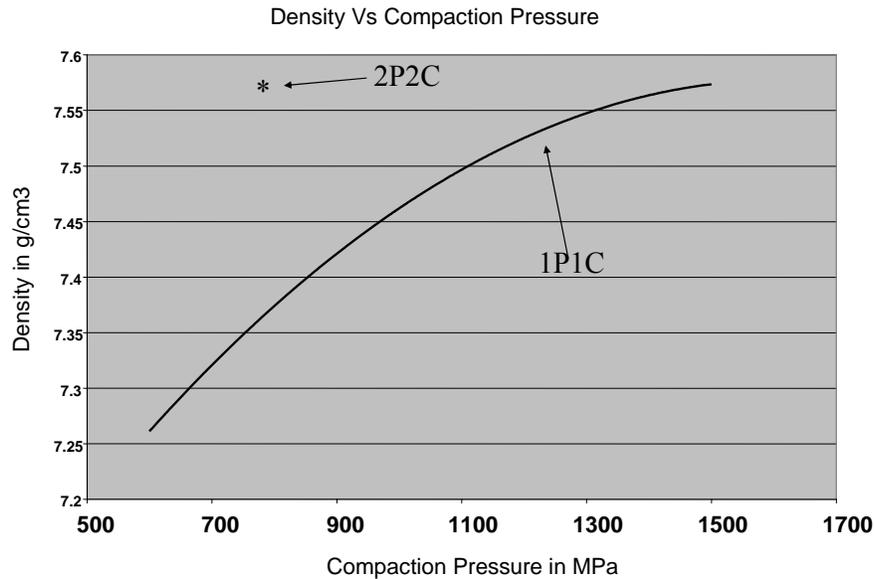


Fig 5: Density comparison of 2P2C vs. 1P1C

To better quantify the effects of 2P2C processing a study was done as outlined in Table 5. Toroids were compacted and magnetic properties were completed according to ASTM A773.

Table 5: Compaction and curing conditions

Condition	P1	C1	P2	C2
1P1C	830 MPa 93°C	450°C - 100% N2	-	-
2P2C	830 MPa 93°C	400°C - 100% N2	830 MPa 93°C	450°C - 100% N2

Results:

Table 6 shows the single step compaction process data and Table 7 show the double step compaction process data.

Table 6: 1P1C properties of insulated composite materials

P1	P1 Density (g/cm ³)	C1 (°C)	C1 Density (g/cm ³)	C1 Strength (MPa)	1P1C Resistivity (μΩ-m)
AncorLam					
690 MPa, RT	7.30	400	7.29	31	650
830 MPa, RT	7.40	400	7.39	34	816
690 MPa, 92°C	7.37	400	7.36	77	159
690 MPa, 92°C	7.49	400	7.48	87	129
AncorLam 2					
690 MPa, RT	7.32	400	7.32	30	993
830 MPa, RT	7.41	400	7.41	35	805
690 MPa, 92°C	7.41	400	7.40	49	79
690 MPa, 92°C	7.52	400	7.50	51	83
AncorLam 2F					
690 MPa, RT	7.30	400	7.28	46	1046
830 MPa, RT	7.42	400	7.41	47	1041
690 MPa, 92°C	7.36	400	7.35	50	136
690 MPa, 92°C	7.49	400	7.45	56	134

Table 7: 2P2C properties of insulated composite materials

P2	P2 Density (g/cm ³)	C2 (°C)	C2 Density (g/cm ³)	C2 Strength (MPa)	2P2C Resistivity (μΩ-m)
AncorLam					
690 MPa, RT	7.37	450	7.36	39	486
830 MPa, RT	7.48	450	7.48	45	618
690 MPa, 92°C	7.44	450	7.44	86	149
690 MPa, 92°C	7.55	450	7.55	97	150
AncorLam 2					
690 MPa, RT	7.41	450	7.40	43	1545
830 MPa, RT	7.51	450	7.50	48	890
690 MPa, 92°C	7.47	450	7.46	102	66
690 MPa, 92°C	7.56	450	7.56	116	66
AncorLam 2F					
690 MPa, RT	7.36	450	7.36	46	1245
830 MPa, RT	7.48	450	7.48	54	1131
690 MPa, 92°C	7.42	450	7.42	102	91
690 MPa, 92°C	7.54	450	7.54	121	102

The two compaction step process also allows for further customization of the insulated composite material system. Adjustments to the compaction and curing processes influence mechanical and magnetic properties.

Compaction at ambient temperature has the effect of lowering the achieved density slightly. The data show that higher strength and resistivity can be realized by modifying the compaction conditions. In general, the 2P2C approach increases density by 0.07-0.09 g/cm³ in the standard, 2, and 2F grades. A density increase of 0.15-0.20 g/cm³ can be achieved on the HR and 2HR grades. All these were pressed with sufficient lubricant for ejection; 0.3% for the regular grades and 0.5% the HR grades. Reducing the lubricant content will increase the density for all of the grades. It is instructive to note that strength of all of the 2P2C processed materials are significantly higher allowing for easier assembly in electromagnetic devices. The main benefit is that measured resistivity of the material increases by a very large amount. Higher resistivity values correspond to lower core loss values and indicate that the material would be more suitable for higher frequency applications.

AC Results:

AC magnetic property testing was conducted over a range of frequencies 60 Hz to 10 kHz. Data at 60 Hz and 5 kHz are shown here. Generally AC peak permeability is higher than DC permeability. The data shows the benefits of the 2P2C processing, especially at lower frequencies. Fig 7 shows the permeability as a function of induction. The peak permeability of 2HR rises from about 450 to just over 600 at 60 Hz. At higher frequencies the improvement less pronounced as the higher losses due to eddy currents reduces the overall permeability of the material.

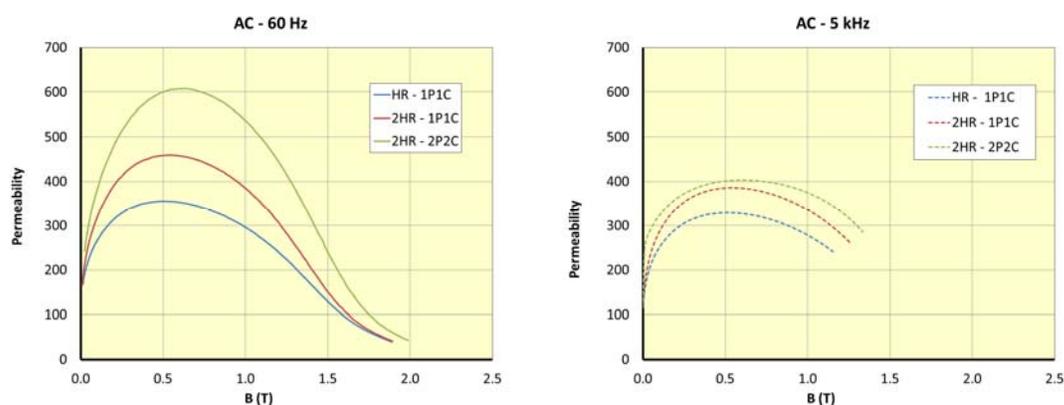


Fig 7: Permeability as a function of induction.

Conclusions

- The current generation of insulated composite materials is suitable for a variety of application types, but is not competitive with high volume induction motor applications. R&D is underway to improve the insulating materials for lower frequency applications.
- The two part, 2P2C, compaction method allows for compaction to high densities without the need for compaction pressures >1000 MPa. This technique maintains the integrity of the insulating coating and permeability and induction increases.
- The 2P2C process can be modified to meet specific application needs such as the highest possible induction or to lower core losses.

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