

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 operating at higher frequencies and lamination steels operating at frequencies above 400 Hz. 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.[1-9] 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.[10] A systematic study was completed to detail the resulting impact on magnetic properties.

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. Dimensions of toroids 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 (refer to earlier work in reference 11). 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 2: 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 carbon, oxygen, and nitrogen 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)	Carbon (wt%)	Oxygen (wt%)	Nitrogen (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/cm^3 . 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.

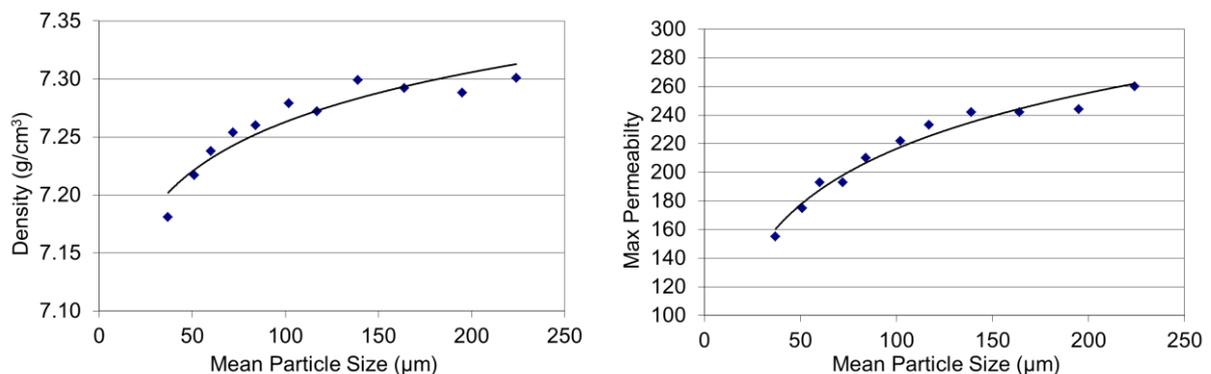


Fig 1: a.) Density as pressed at 660 MPa and b.) Maximum permeability as a function of mean particle size.

Initial permeability as opposed to maximum permeability, however, is not dependent significantly 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.

Core loss was measured at an induction of 0.001 T to get an idea as to how particle size influences the core loss. 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.

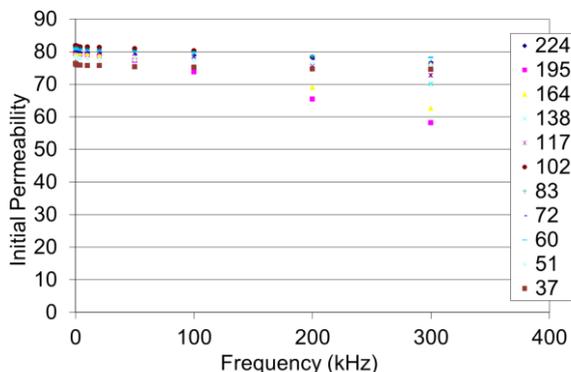


Fig 2: Initial Permeability versus frequency for various particle fractions.

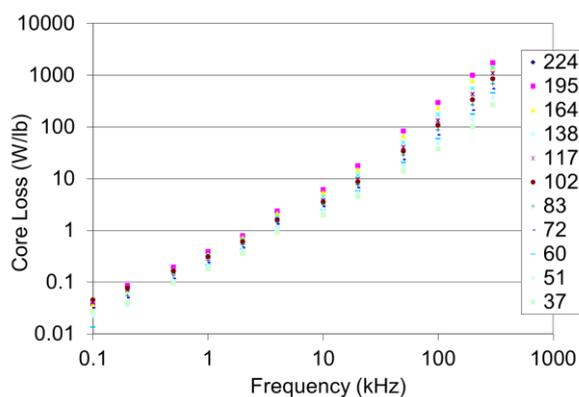


Fig 3: Core loss at an induction level of 0.001 T versus frequency for various particle fractions.

In a number of powder core applications for narrow bandwidth filters there is a need for filtering unwanted signals. The Q factor is the ratio of inductive reactance to resistance (winding resistance plus eddy current loss). The higher the Q factor the narrower the bandwidth where the powder core can be used. [11] Lower core loss helps to increase the Q factor. The effect of particle size on the Q factor is shown in Figure 4. It can be seen that the finer particle size fractions result in higher Q factor at higher frequencies.

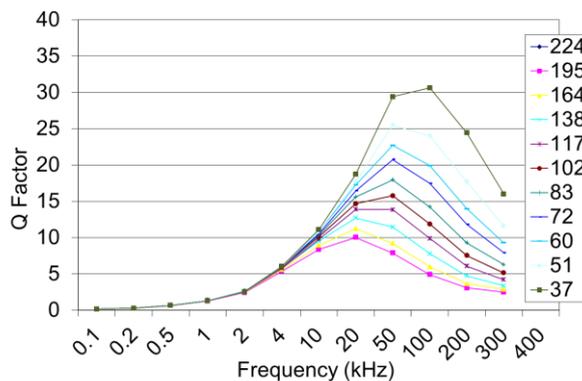


Fig 4: Effect of particle size on Q factor at various frequencies.

Effect of 2P2C Processing

The typical insulated composite production process involves compaction of the insulated iron particle and curing at a temperature that increases the mechanical strength without destroying the insulation. The desired microstructure is a distribution of pure iron particles that is divided by a very thin layer of insulation as shown in figure 5. The densification and

cured strength need to be balanced with the amount of damage that occurs to the insulating coating. Ideally every iron particle would maintain complete electrical isolation from its neighbors, however, the realities of powder metal compaction and needed curing make this impossible. Therefore, the material, compaction method, and curing conditions all need to be optimized to meet the application requirements.

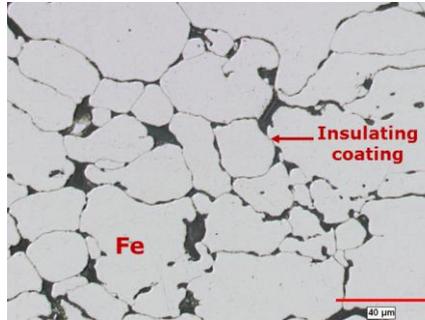


Fig 5: Typical microstructure of an insulated iron composite material

The standard one step insulated composite production route is outlined in figure 6a. 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. The standard compaction method is recommended for densities of <7.45-7.50 g/cm³. To allow for insulated composites at densities >7.50 g/cm³ an alternate two step compaction method, 2P2C, has been developed as outlined in figure 6b. In this case an extra curing step completed at 400 °C is done followed by a second compaction step and final curing at 450 °C.

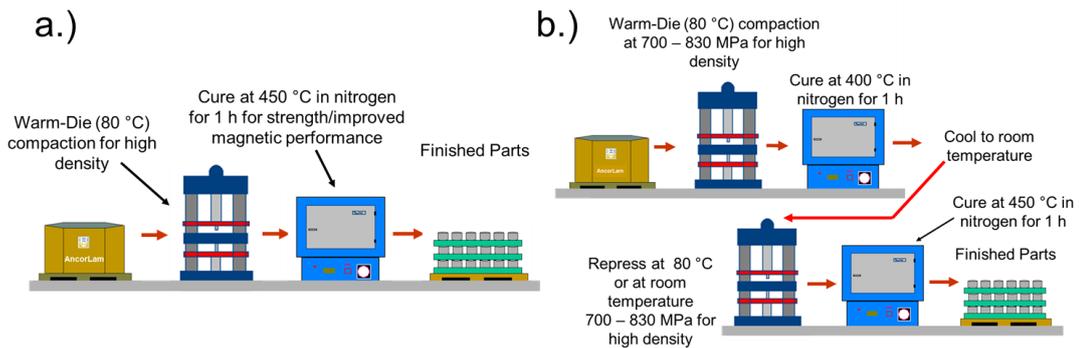


Fig 6: Overview of a.) the standard and b.) the 2P2C insulated iron composite production (Patent pending) methods.

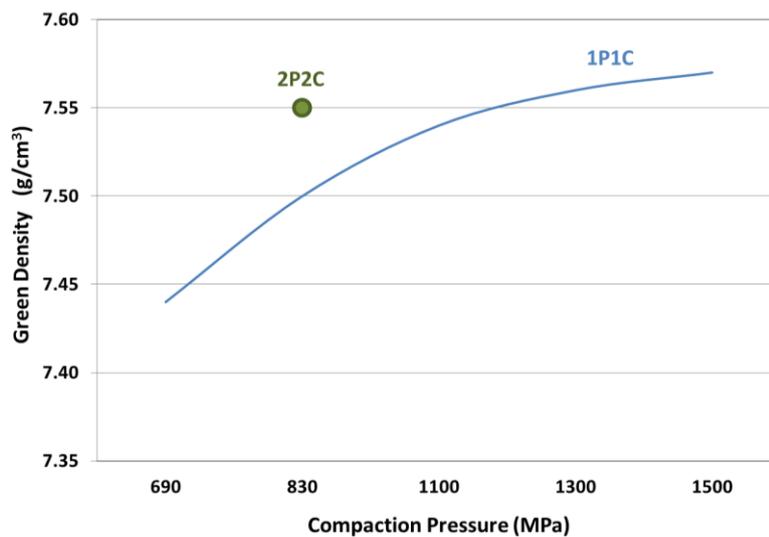


Figure 7: Density comparison of standard and 2P2C production methods

Figure 7 shows the relative difference in compaction pressures to achieve densities $>7.50 \text{ g/cm}^3$. The limits of the standard method 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 for both the first and second pressings. 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.

To better quantify the effects of 2P2C processing a study was carried out on different insulated iron types by single compaction and double compaction as outlined in Tables 3 and 4. The 2P2C 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 $0.07\text{-}0.09 \text{ g/cm}^3$ in the standard, 2, and 2F grades. A density increase of $0.15\text{-}0.20 \text{ g/cm}^3$ 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.

Table 3: Compaction and curing conditions for the first step of the 2P2C method

P1	P1 Density (g/cm^3)	C1 ($^{\circ}\text{C}$)	C1 Density (g/cm^3)	C1 Strength (MPa)	1P1C Resistivity ($\mu\Omega\text{-m}$)
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 4: Compaction and curing conditions for the 2P2C method

P2	P2 Density (g/cm^3)	C2 ($^{\circ}\text{C}$)	C2 Density (g/cm^3)	C2 Strength (MPa)	2P2C Resistivity ($\mu\Omega\text{-m}$)
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

A comparison of the core loss of various types of insulated composites utilizing coarser iron powder (2), finer iron powder (2F), normal distribution iron powder (Std), and the increased coating thickness (HR) is shown in the table 5. These data show that the particle size and coating can be optimized to meet an array of applications. The data outlined in table 6 shows the impact that varying the iron particle size along with using the 2P2C process has on magnetic properties. The data show that at show a clear improvement in permeability and induction levels. There is a slight increase in coercivity suggesting this 2P2C process could use higher curing temperature to reduce the hysteresis losses.

Table 5: Effect of processing route on the core loss of iron powder composites

Material System	Strength (MPa)	Core Loss at 1 T (W/kg)					Core Loss at 0.2T (W/kg)
		60 Hz	100 Hz	200 Hz	400 Hz	1 kHz	10 kHz
AncorLam - 1P1C	90	9	15	31	67	-	-
AncorLam HR - 1P1C	60	7.6	13	27	53	147	147
AncorLam 2 - 1P1C	40	9	15	31	67	245	172
AncorLam 2HR - 1P1C	60	6.7	12	25	54	163	-
AncorLam 2FHR - 1P1C	60	7.3	14	27	54	146	130
AncorLam 2HR – 2P2C	108	6.6	11	24	52	172	-

Table 6: Effect of processing route on the DC Magnetic properties of iron powder composites

Material System	Density (g/cm ³)	Maximum Permeability	B _{max} (T)	H _c (A/m)
AncorLam HR- 1P1C	7.45	299	1.52	276
AncorLam HR - 2P2C	7.55	433	1.63	283
AncorLam 2HR - 1P1C	7.45	347	1.54	252
AncorLam 2HR - 2P2C	7.58	479	1.65	256

Table 7 has been added for reference showing the typical properties of various insulated iron composite materials processed using the standard single step method.[12]

Table 7: Magnetic properties of various insulated iron powder composites as compacted at 830 MPA

	AncorLam	AncorLam 2	AncorLam HR	AncorLam 2FHR
Cured density	7.47	7.50	7.45	7.43
Strength (MPa)	90	40	60	60
B @ 10 kA/m (T)	1.47	1.6	1.52	1.5
Perm at 60 Hz	470	550	299	360
Resistivity, $\mu\text{-}\Omega\text{-m}$	>50	>50	>1300	>1300
Coercive field (A/m)	300	245	276	280
Core-loss - 1T 60Hz (W/kg)	9	9	7.6	7.3

Conclusions

- Examination of the effect of particle size on key soft magnetic properties showed that finer particles have lower core losses at higher frequencies and coarser particles have higher induction and permeability.
- Three optimized particle distributions were developed to economically cover a wider array of commercial applications.
- 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.

Acknowledgement

The authors would like to acknowledge the contributions that Christopher Schade, Wing Hong Chen, and William Tambussi for the extensive data collection that enabled the completion of this paper.

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