

## Advancements in Insulated Powder Composites for Soft Magnetic Applications

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### Abstract:

Insulated powder composite materials offer an opportunity to replace lamination steels in soft magnetic applications such as DC motors, actuators, and other power electronics applications. This paper reviews recent advancements in powder and processing technologies that enables the fabrication of insulated composite components to densities in excess of  $7.40 \text{ g/cm}^3$  that exhibit high permeability with low losses. This paper shows magnetic properties of the AncorLam® insulated powder family processed via the 2P2C method reduce the need for high compaction pressures. In addition applications for these types of materials are discussed.

### Introduction:

Insulated powder 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. This technology has been in commercial use since introduced in the early 1990's, but has only enjoyed limited applications.(1-4) Recent improvements in the material systems and forming processes have enabled making this technology more attractive choice for some electronic and electric motor applications.

Figure 1 shows a typical microstructure of an insulated composite material (note the insulating coating has been exaggerated to show the coatings by optical microscopy for illustration purposes). The insulating coating between the iron particles serves several purposes. First it prevents electrical contact between the iron particles keeping the eddy current losses localized to particle and reducing total core losses low. Secondly, the coating helps generate mechanical strength of the compacts after curing. Although an attractive material, insulated composites have not displaced mainstream lamination steels in electric induction motors. This is because of insulating coating creates a distributed air gap in the material. This has the effect of lowering the saturation induction and permeability of the material.

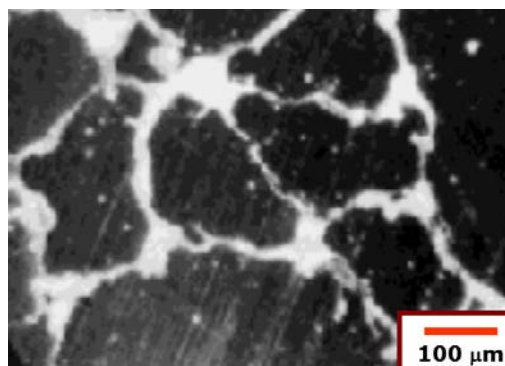


Figure 1: Microstructure of an insulated soft magnetic material.

However, this class of materials is suitable for a certain niche electromagnetic applications. Typically, these materials are suitable for higher frequency AC applications. The 3D flux capability allows this material to be used in lower frequency applications such as axial flux motors. In general, the higher the frequency the lower the core loss of insulated iron composites compared to lamination steels (see Figure 2). This figure shows the core losses as a function of frequency for AncorLam and typical lamination steel. At lower frequencies the lamination steel has lower losses than the insulated composite. As the frequency increases the losses increase at a greater rate for the lamination steel. At lower frequencies the core loss is dominated by hysteresis losses which are higher for insulated

composites. At higher frequencies, the eddy current losses are lower for insulated composites because the eddy currents are localized to the particle surface compared to lamination steels where the eddy currents are generated at the larger surface of the steel. Data from past studies show that AncorLam type materials compete well in DC applications operating at frequencies >400 Hz with lamination steel thicknesses >0.35 mm.(5)

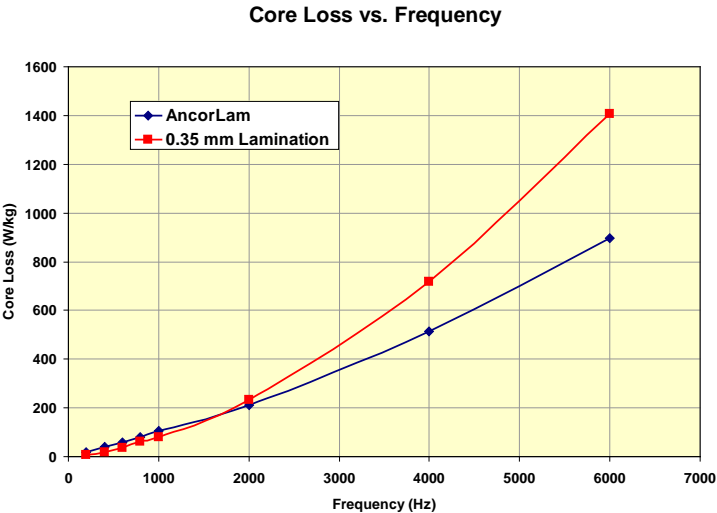


Figure 2: Core loss of Insulated composite and lamination steel as a function of frequency.

Within these limitations there is room for material and process optimization for specific applications and a family of insulated composite material is available. Typically, the particles size and coating type is modified to meet specific application types. Applications that need higher permeability have coarser particles and less insulation (designation 2). 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 I. The specific magnetic performance of each grade is available elsewhere.(6)

Table I: 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 composite and curing at a temperature that increases the mechanical strength without destroying the insulation. This is outlined in Table II. An insulated composite powder is compacted into the desired shape. The green part is then cured in N<sub>2</sub> 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 II: Typical 1P1C 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 <sub>2</sub>
3.	Finished Parts	

Insulated composites typically need to be compacted at very high compaction pressures to achieve density  $>7.40 \text{ g/cm}^3$  to attain reasonable permeability and induction levels. The current technology used globally to achieve density values  $>7.50 \text{ g/cm}^3$  requires very high compaction pressures at least  $>1000 \text{ MPa}$ . 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  $800 \text{ MPa}$ .(7) The 2P2C process is outlined in Figure 3.

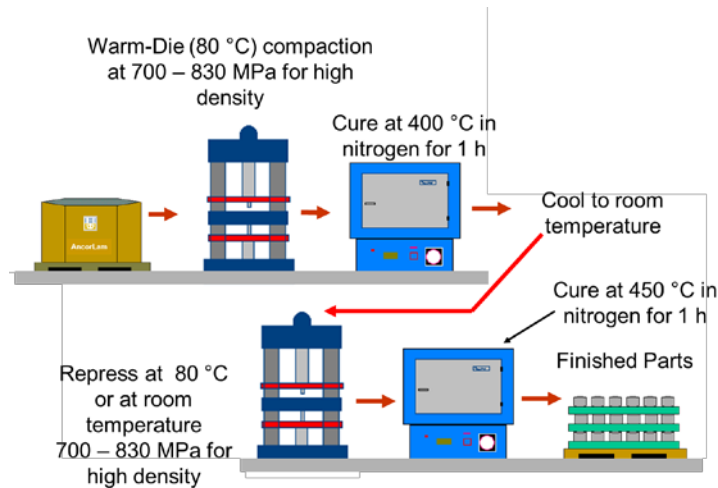


Figure 3: 2P2C production route

Figure 4 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  $7.55 \text{ g/cm}^3$  whereas the two step 2P2C achieves this density at  $830 \text{ MPa}$ . 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.

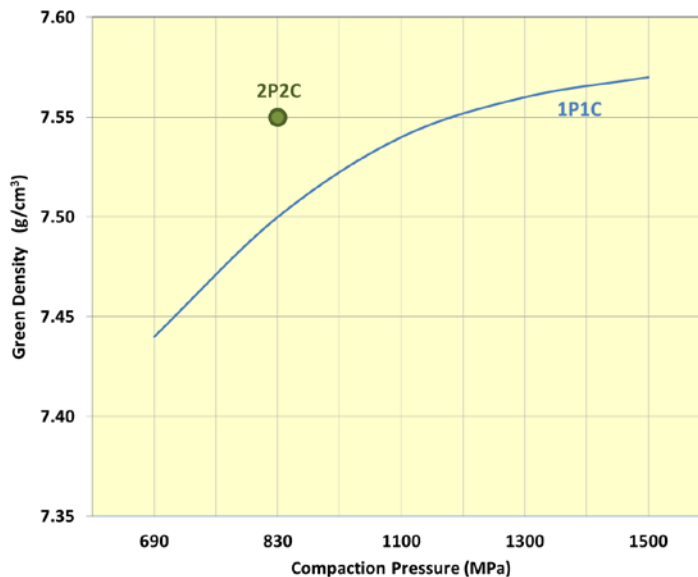


Figure 4: Density comparison of 2P2C vs. 1P1C

To better quantify the effects of 2P2C processing a study was done as outlined in Table III. AncorLam HR and 2HR were used for this evaluation. Toroids were compacted and magnetic properties were completed according to ASTM A773.

Table III: Compaction and curing conditions

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

Results:

In addition, a separate study was carried out on different insulated iron types by single compaction and double compaction as outlined in Tables IV and V. Table IV shows the single step compaction process data and Table V show the double step compaction process data.

Table IV: 1P1C properties of insulated composite materials

P1	P1 Density (g/cm <sup>3</sup> )	C1 (°C)	C1 Density (g/cm <sup>3</sup> )	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
830MPa, 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
830 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
830 MPa, 92°C	7.49	400	7.45	56	134

Table V: 2P2C properties of insulated composite materials

P2	P2 Density (g/cm <sup>3</sup> )	C2 (°C)	C2 Density (g/cm <sup>3</sup> )	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
830 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
830 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
830 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/cm<sup>3</sup> in the standard, 2, and 2F grades. A density increase of 0.15-0.20 g/cm<sup>3</sup> can be achieved on the HR and 2HR grades. All of 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.

**DC Results:**

The final density and DC results are outlined in Table VI. The data shows that at 830 MPa the 2P2C process yields a 0.10-0.13 g/cm<sup>3</sup> increase in finished density. The compaction pressure would need to reach about 1200 MPa to reach this density in a single step. The DC data also show 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. Figure 5 shows the corresponding hysteresis curves.

Table VI: DC Magnetic Properties

Condition	Density (g/cm <sup>3</sup> )	Max Perm	B <sub>max</sub> (T)	H <sub>c</sub> (A/m)
HR-1P1C	7.45	299	1.52	276
HR-2P2C	7.55	433	1.63	283
2HR-1P1C	7.45	347	1.54	252
2HR-2P2C	7.58	479	1.65	256

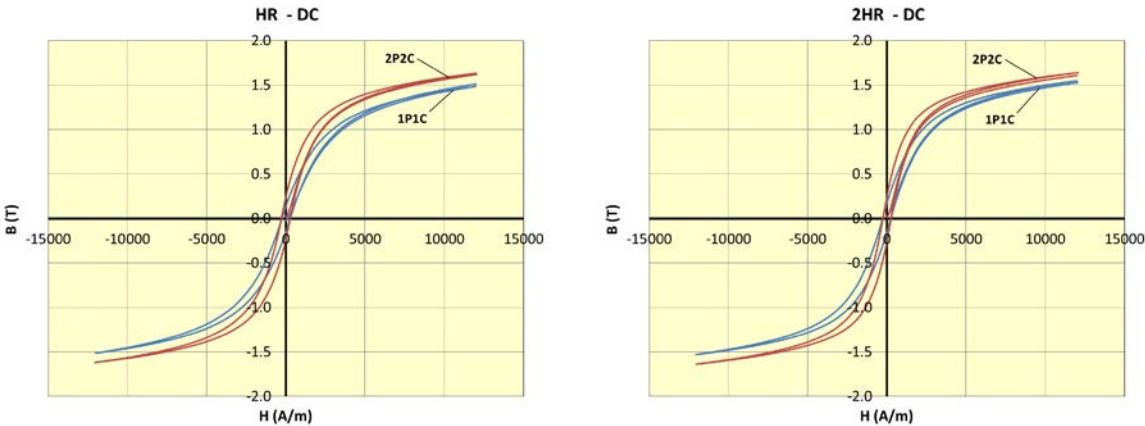


Figure 5: DC hysteresis curves for AncorLam HR and 2HR – 1P1C and 2P2C.

**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. Figure 6 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.

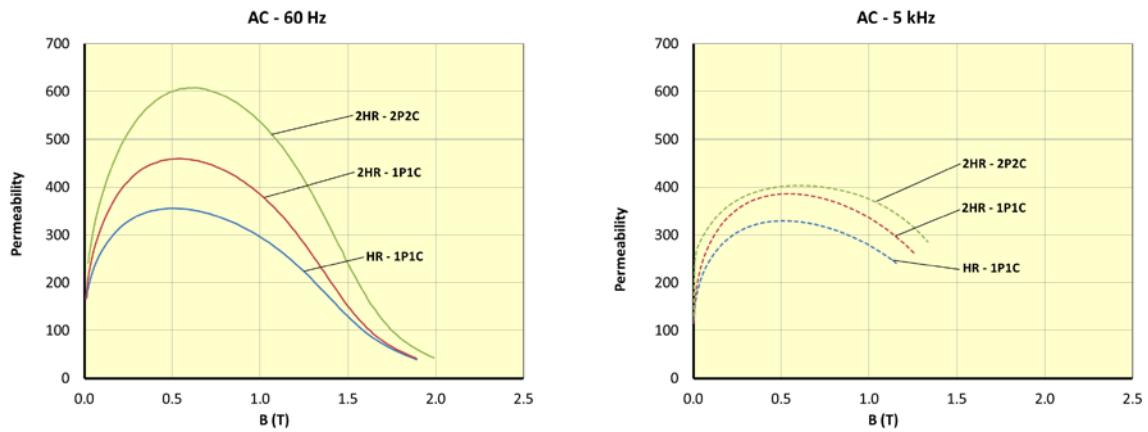


Figure 6: Permeability as a function of induction.

Core losses are very sensitive to operating frequency and tend to rise rapidly as frequency increases. Figure 7 shows log/log plots of core loss as a function of induction. At a given frequency the compaction method (1P1C vs. 2P2C) has little influence on the measured core losses. However, the high frequency data show a several order of magnitude increase in core loss. These data suggest that at higher frequencies these materials can replace ferrites.

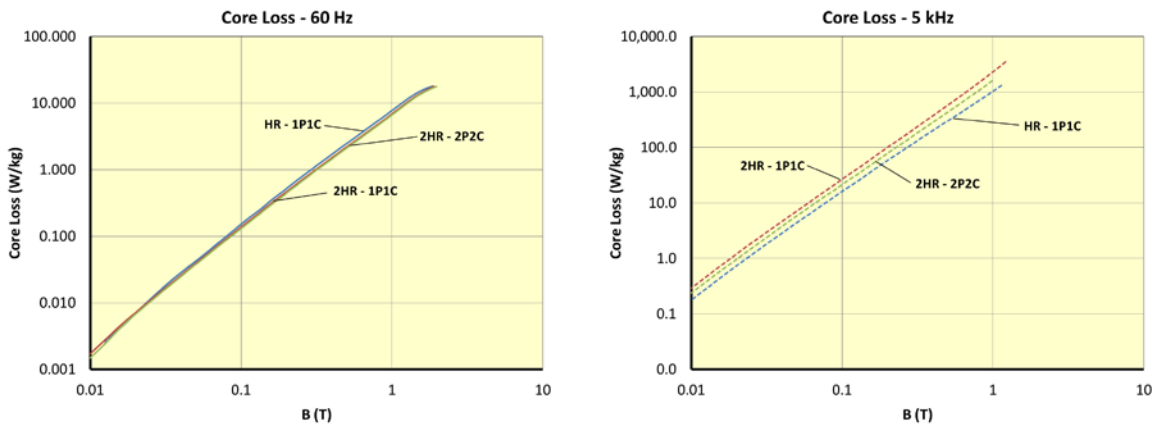


Figure 7: Core loss as a function of induction (Log/Log).

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 below. These data show that the particle size and coating can be optimized to meet an array of applications.

Table VII: Comparison of core loss values as a function of frequency

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	
Std - 1P1C	90	9	15	31	67	-	-	
HR - 1P1C	60	7.6	13	27	53	147	147	
2 - 1P1C	40	9	15	31	67	245	172	
2HR - 1P1C	60	6.7	12	25	54	163	-	
2FHR - 1P1C	60	7.3	14	27	54	146	130	
2HR - 2P2C	108	6.6	11	24	52	172	-	

## Conclusions

- A comparison of lamination steels and insulated composites show that the insulated composites are competitive at higher operating frequencies.

- 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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