

## Development of a New High Density AC Magnetic Material Possessing Good AC Magnetic Performance with Enhanced Mechanical Strength

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### Abstract:

A key initiative of PM's non-sintered soft magnetic development is the attainment of high component density ( $>7.5 \text{ g/cm}^3$ ) while maintaining a high resistivity to minimize total core losses under AC operating conditions. This paper will present results obtained with a new insulation and lubricant system that enables single compacted densities greater than  $7.5 \text{ g/cm}^3$  using a compaction pressure of 830 MPa and a die temperature of  $107 \text{ }^\circ\text{C}$ . These conditions produce a DC permeability of  $\geq 500$  with a saturation induction at 12,000 A/m of  $>1.6$  Tesla. Despite the high density achieved; a bulk resistivity of  $\sim 7,000 \text{ } \mu\Omega\text{cm}$  was maintained, thus promoting low core losses at operating frequencies up to 1 kHz. Another key feature of this insulation and lubrication system is the development of high strengths in the post compaction cured condition; strengths up to 135 MPa were achieved. This higher level of strength permits broader application of these materials. The optimal curing condition for this material is in the range of  $425 \text{ }^\circ\text{C}$  to  $450 \text{ }^\circ\text{C}$ . Presented in this paper will be both the magnetic and mechanical property characteristics.

### Introduction:

Magnetic performance of soft magnetic composites is analogous to the PM structural press and sinter performance in that high component density is critical to the achievement of high performance. Attaining high density can be accomplished through the use of high purity, high compressibility iron powder coupled with proper lubricant and compaction conditions. Warm die compaction techniques enable as-compacted densities approaching 98% of the pore free density of the iron powder – lubricant theoretical density. [1] Thus, reducing the lubricant content to the lowest possible level while still permitting ejection from the die will produce a soft magnetic composite component giving optimal permeability and saturation induction levels. It is important to maintain relatively high resistivity at these high densities because high densities often result in particle to particle contact; thus, leading to increased eddy current losses.

The advanced powder lubrication system utilized in this study was initially developed for conventional press and sinter structural components. This lubricant is a proprietary development facilitating the use of 0.25 w/o lubricant and giving green densities greater than  $7.5 \text{ g/cm}^3$  when coupled with compaction pressures of 830 MPa and a part ejection temperature of  $107 \text{ }^\circ\text{C}$ . [1] Ejection characteristics of this lubricant system for an FLN2-4405 material are shown in Figure 1. The 4 ejection curves

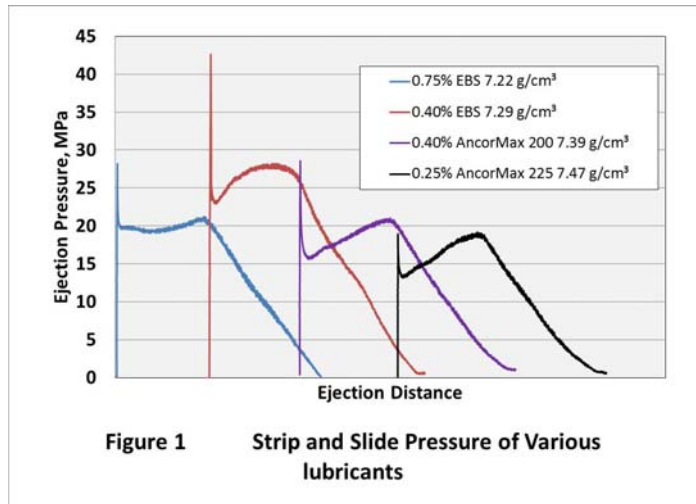


Figure 1 Strip and Slide Pressure of Various lubricants

represent cold die compaction using either 0.75% or 0.40% EBS lubricant and a proprietary lubricant designated AncorMax 200 which uses 0.40% total lube with a die temperature of 93 °C and lastly the advanced lubricant system (AncorMax 225) using 0.25% lubricant and a die temperature of 107 °C. The advanced lubricant has the same ejection strip and slide stresses as a 0.75% EBS lubricant addition; though providing a ~0.25 g/cm<sup>3</sup> higher green density (Figure 1). An additional benefit observed for the structural PM premixes was improved green strength. This is important in soft magnetic components because these materials are non-sintered and attainment of high ‘as-cured’ strength is often critical to part performance.

**Experimental Procedure:**

Table 1 lists the two AncorLam materials evaluated; in both premixes the total lubrication amount added was 0.25% by weight. Green strength bars (12.5 mm x 12.5 mm x 31.5 mm) and magnetic toroids (36 mm OD x 25 mm ID x 6 mm tall) were compacted utilizing a hydraulic press with the dies preheated to a temperature of 107 °C. The green strength bars were used to measure resistivity via the 4 wire method using a Keithley resistance bridge (ASTM Test method A712-75). Curing was done in a box furnace at 450 °C for 1 hour at temperature using a 100% nitrogen atmosphere. Green strength measurements were done at room temperature in accordance to MPIF Standard 15. [2] Magnetic toroids were initially wrapped with a layer of insulating tape then wrapped with 35 secondary windings of 28 gauge enamel coated copper wire. A second layer of insulating tape was wrapped atop the secondary windings and then the primary winding of 200 turns of 22 gauge enamel coated copper wire was wrapped onto the toroid. Testing was done at frequencies up to 10,000 Hz and applied fields up to 12,000 A/m. The magnetic toroids were tested using an automatic hysteresisgraph (Model SMT-700, Magnetic Instrumentation, Inc.).

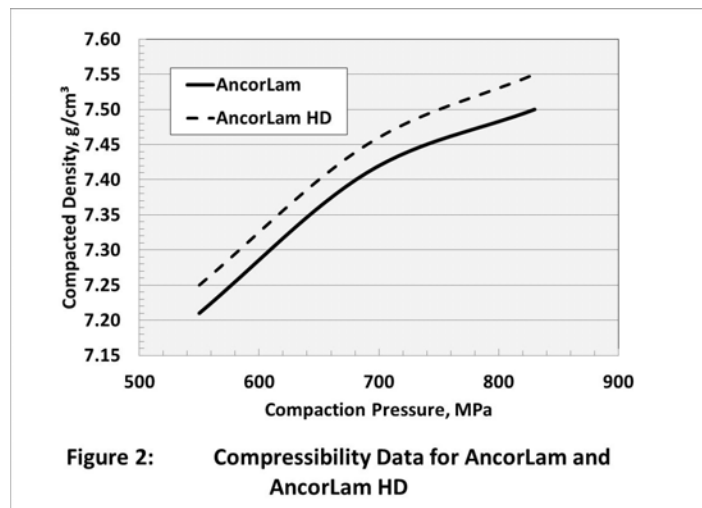
**Table 1: Materials Evaluated**

Material	Key Characteristics
AncorLam HD	High Density, High Perm, highest induction level
AncorLam HR – HD	Moderate density, high resistivity

**Results:**

**a. Physical properties**

Shown in Figure 2 is the compressibility comparison for the advanced lubricant in relation to existing lubricant systems. Reducing the lubricant level from 0.40% to 0.25% results in higher green density over the range of compacting pressures evaluated. At the 830 MPa compaction pressure, the HD material achieves approximately 98% of pore free density. Caution should be used in compacting to higher densities, because compaction to densities above 98% of pore free density (PFD) can result in the formation of micro-laminations within the compacted part.



**Figure 2: Compressibility Data for AncorLam and AncorLam HD**

**Table 2: Compacted and cured densities of AncorLam and AncorLam HD**

<b>Lube System</b>	<b>Compaction Pressure, MPa</b>	<b>Green density, g/cm<sup>3</sup></b>	<b>Cured density g/cm<sup>3</sup></b>	<b>Cured strength, MPa (psi)</b>	<b>Cured resistivity, uΩcm</b>
<b>Standard AncorLam</b>	550	7.21	7.20	86 (12500)	6,900
	690	7.41	7.39	103 (14950)	6,900
	830	7.51	7.47	107 (15600)	7,000
<b>AncorLam HD</b>	550	7.25	7.24	102 (14850)	8,400
	690	7.43	7.42	119 (17350)	7,400
	830	7.55	7.53	130 (18800)	7,400

Table 2 presents the cured densities of both materials utilizing compacting pressures from 550 to 830 MPa. Higher 'cured' densities are achieved with the lower lubricant of the AncorLam HD material. The higher densities result from reduced lubricant removal during the curing cycle and lesser green expansion from the die after compaction. Also shown in Table 2 is the resistivity and cured strength of the two materials. The AncorLam HD material has higher resistivity despite having higher cured density. This should result in reduced losses at operating frequencies. 'Cured' TRS strength is also increased to ~130 MPa which is approximately 20% higher than the existing material.

**a. Magnetic Properties**

The magnetic data for the AncorLam HD and AncorLam HR – HD is shown in Table 3. All the data shown was measured at 1 Tesla. Note the AncorLam HD maintains constant permeability up to approximately 1000 Hz. Above that frequency the permeability decreases as the eddy current losses increase. The high resistivity AncorLam HR – HD enables constant permeability up to 10 kHz. The AncorLam HR – HD has lower core losses relative to the AncorLam HD at frequencies above ~1 kHz; whereas, the standard material exhibits lower losses up to the 1 kHz frequency because of the reduced hysteresis losses. As noted earlier, the post compaction curing was done at 450 °C.

**Table 3: Magnetic Properties of AncorLam HD and AncorLam HR – HD Tested at 1 Tesla**

<b>Material &amp; Density</b>	<b>Frequency, Hz</b>	<b>Max Perm</b>	<b>Residual Magnetism, T</b>	<b>Coercive Field Hc (A/m)</b>	<b>Core loss, w/kg</b>
<b>AncorLam HD at 7.54 g/cm<sup>3</sup> cured density</b>	DC	515	0.27	264	-
	60	504	0.29	275	7.53
	400	504	0.32	320	58
	1000	500	0.36	396	178
	5000	450	0.59	870	1955
	10000*	375	0.45	920	2400
<b>AncorLam HR – HD at 7.33 g/cm<sup>3</sup> cured density</b>	DC	240	0.14	323	-
	60	235	0.14	330	8.6
	400	230	0.14	350	61
	1000	230	0.15	375	163
	5000	230	0.20	525	1134
	10000*	230	0.17	510	1250

**\* Tested at induction level of 0.6 Tesla**

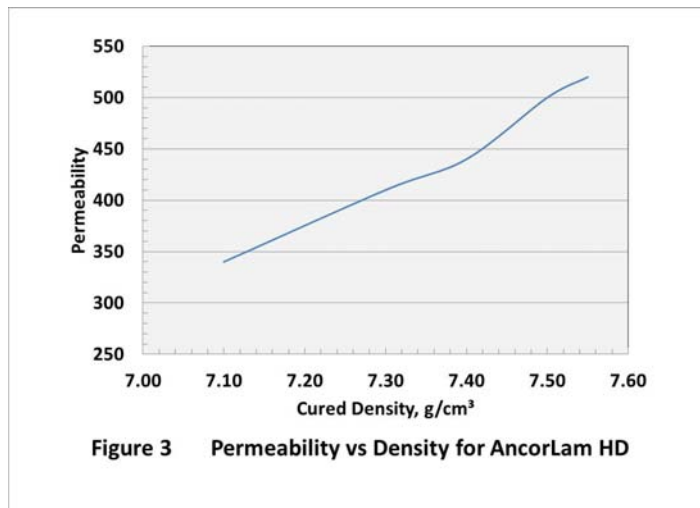
Table 4 gives the magnetic saturation at 12,000 A/m for the two materials. The higher density achieved with the AncorLam HD promotes higher induction and lower core losses at this near saturation value of induction at frequencies 1000 Hz and below. Above 1000 Hz, the higher resistivity of the AncorLam HR- HD provides lower core losses. In Table 4, note is made that the AncorLam HD has a higher induction relative to the AncorLam HR – HD; thus, the losses up to 1000 Hz appear higher for the AncorLam HD. This is a result of the higher induction leading to naturally higher losses

**Table 4: Magnetic saturation and core losses at saturation of AncorLam HD and AncorLam HR-HD**

Material	Frequency, Hz	Hmax, A/m	Max Induction, Tesla	Core Loss, w/kg at max. induction
<b>AncorLam HD at 7.54 g/cm<sup>3</sup> cured density</b>	DC	12000	1.65	-
	60	12000	1.62	17
	400	12000	1.62	138
	1000	12000	1.62	430
	5000	4300	1.23	3000
	10000	2200	0.62	2400
<b>AncorLam HR – HD at 7.33 g/cm<sup>3</sup> cured density</b>	DC	12000	1.42	-
	60	12000	1.40	15
	400	12000	1.40	107
	1000	12000	1.40	295
	5000	4300	0.96	1140
	10000	2200	.60	1250

**Discussion:**

Density, resistivity and ‘cured’ strength are three key considerations for the use of soft magnetic composites. Implicit in this discussion is the cost of the raw material and ease of producing the final magnetic component. In this study, a standard high purity iron powder was surface treated to provide a magnetically insulating coating. This study evaluated the use of a new lubricant that enabled using only 0.25% total lube. In so doing, the compacted density was increased to 98% of the PFD or approximately 7.55 g/cm<sup>3</sup>. Increasing the part density increased the magnetic saturation to >1.6T and gave a permeability of >500. Figure 3 shows the effect of density on the magnetic permeability of AncorLam materials. Although higher perms have been reported in the literature, this material offers this level of perm and induction using commercially available iron powder. In addition to the high density, the cured strength of this material is >130 MPa.



**Figure 3 Permeability vs Density for AncorLam HD**

**Conclusions:**

From the work performed in this study, the following conclusions are made:

1. AncorLam HD shows improved green density and cured density compared to existing material by about 0.05 g/cm<sup>3</sup>. Post curing at 450 °C, the AncorLam HD has a transverse rupture strength of ~130 MPa. A maximum induction of >1.6 Tesla was achieved with this material.
2. AncorLam HR-HD has higher resistivity and lower density but maintains constant permeability up to ~10 kHz.
3. Cured density has a strong influence on permeability. Higher densities promote higher permeability and higher induction.

**References:**

1. F. Hanejko, "High-Density Compaction Using Lubricant Levels of 0.25 w/o", Oral Presentation, Presented at PowderMet 2013, June 24 – 27, 2013, SIP 3 Technologies for PM Growth.
2. Standard Test Methods for Metal Powders and Powder Metallurgy Products, Metal Powders Industry Federation, 2012 Edition, Princeton NJ 08540, pp. 43-46.