Process Experience With High Permeability Soft Magnetic Composites

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Abstract

Soft magnetic composites (SMC) materials provide a significant opportunity for the powder metallurgy (PM) industry in electric motor applications. Newer grades with higher permeability have been introduced to the market and proper processing is critical to maximize performance. A batch furnace capable of different thermal profiles and atmospheres has been used to explore different parameter sets to shed light on critical curing variables. Examples of proper and problematic curing will be shared along with magnetic property impacts.

1. Introduction

The application and future expansion of soft magnetic composite (SMC) materials and components in electric motor assemblies can be a major opportunity for powder metallurgy (PM) parts in the electrification era. These materials have the ability to not only compete with typical lamination stacks when pushed to higher frequency and drive levels in more traditional motor designs, but also allow for freedom of design for motor concepts. Like with sintered soft magnetic materials (Soft-Magnetic Alloys in MPIF 35-SP [1]), where processing conditions are specifically noted in order to attain or maximize certain properties, SMC materials need to be properly and carefully processed in order to balance the required properties and ensure proper performance.

A constant conflict in magnetic components, when used in AC applications, is the balance between losses in the system and the permeability of the part. This is true for both lamination steels and for SMC products, and is the common problem of power vs efficiency.

Efficiency in AC motors comes from the motor design but also by limiting losses; namely copper, hysteresis, and eddy current losses. SMC powders, like lamination steels, limit these eddy current losses by constricting their movement between particles or layers. In both instances, this limiting of eddy currents is accomplished through the use of a specialized coating specifically applied to the iron substrate. These coatings act as an electrically resistive film and increase the electrical resistivity between layers, which helps isolate the generated eddy currents’ size, thus, reducing heat generation.

Where these materials differ is how these distributed layers effect other properties, especially when utilized in a standard radial flux motor design. In traditional radial flux motors made with lamination stacks, the copper windings are in such an orientation that the magnetic flux is generated perpendicular to the axis of motor rotation. Further, the lamination stack is oriented in such a direction such that magnetic flux can flow unimpeded, but generated eddy currents are limited in size. Thus, the insulative layer is unobtrusive to permeability of the stack, but limits losses in the system. Alternatively, if a lamination stack is designed with an airgap in the system or if the lamination stack is oriented in a tangential manner, the effective permeability is lowered as the magnetic flux flow is impeded, which lowers overall permeability (Figure 1).

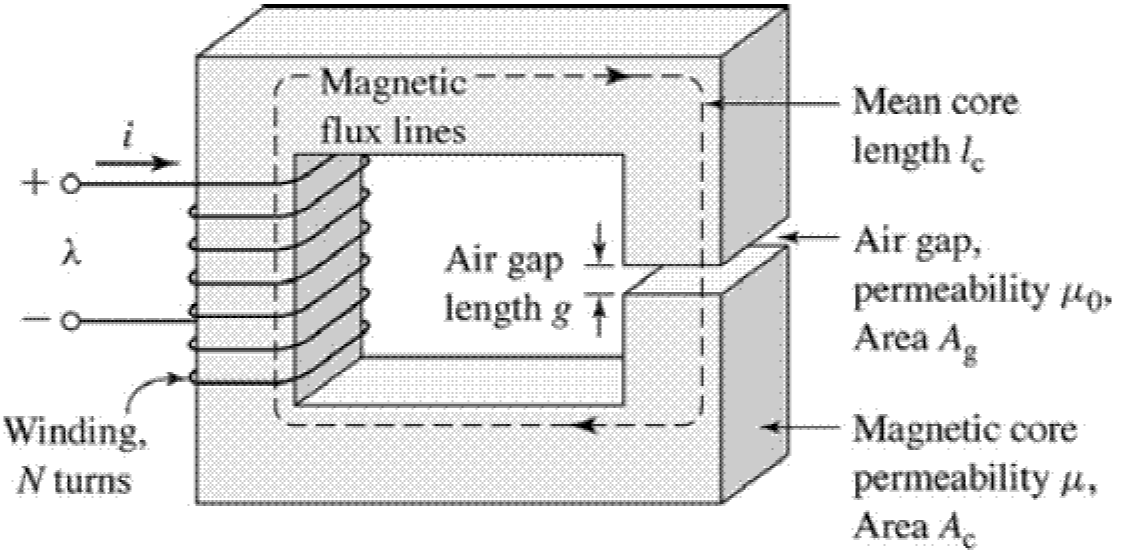

Figure 1: Series Magnetic Circuit with an Air Gap [2]

In SMC powders, the 3D nature of the powder is a positive, as it can allow for new and alternative motor designs (transverse flux motors and axial flux motors) and simplify manufacturability. But can also act as a negative, as the powder is 3D in nature, so to, is the insulation when it is applied. This insulation thus both acts in the same axis as a lamination stack (between layers limiting eddy current movement), but also splitting or breaking the magnetic flux that is generated. As such, one can think of a SMC component as having a distributed air gap throughout the entire body of the part (Figure 2). This, then, acts in a manner similar to a more traditional airgap in lamination motor designs.

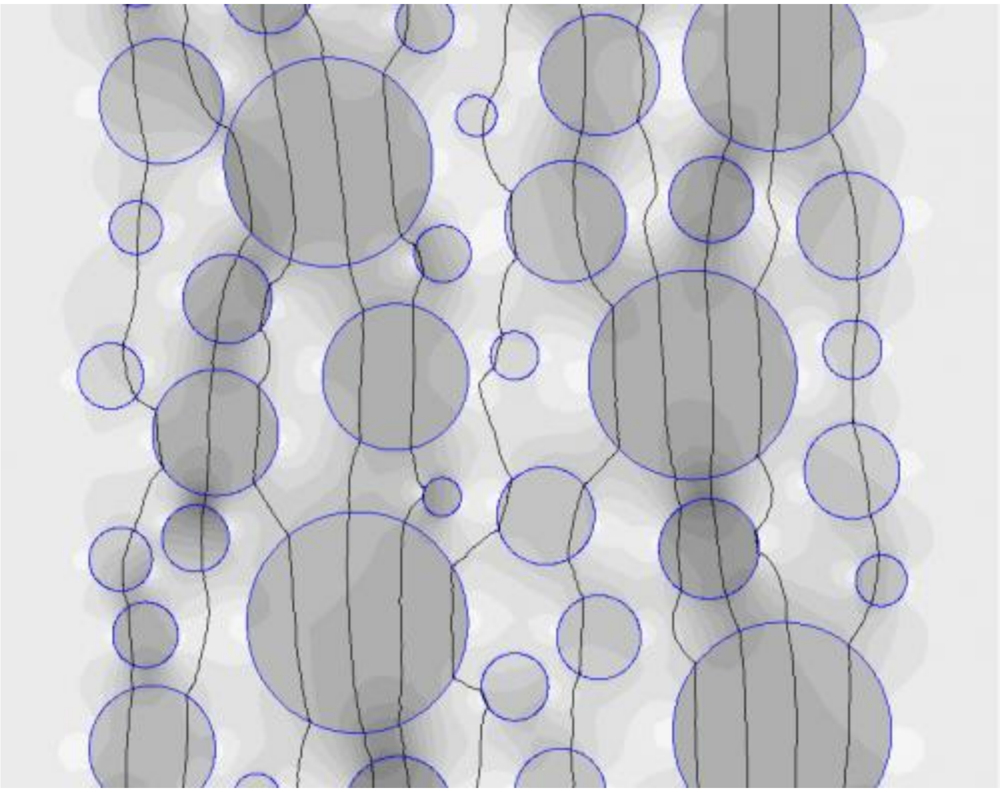

Figure 2: Distributed airgap representation for composite materials where black lines illustrate distribution of magnetic flux [3].

As such, the insulative coating that SMC powders rely on are the reason for the often opposing nature of core loss and permeability in SMC components. In order to maintain the balance between these properties and to attain target magnetic performance, the variables surrounding the processing of these materials must be well controlled.

2. Materials and Experimental Procedure:

The impact that processing parameters have on SMC material properties was analyzed using two different SMC products during comparative testing. One commercially available (AncorLam®) powder and one new developmental high permeability SMC powder (Dev. High Perm) were used as the base materials to explore the key parameters around SMC processing.

All samples were compacted using laboratory-scaled equipment to attain the targeted compaction conditions and desired density to mimic production settings. The production of green strength (rectangular bars with approximate dimensions of 31.8 x 12.7 x 12.7 mm LxWxH) and toroidal rings (55 mm OD, 45mm ID) were utilized to characterize the density, strength, residual carbon content, resistivity and magnetic properties of the materials.

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Thermal treatment of all samples was completed using a Gasbarre batch steam treating pit furnace with full control of thermal profile and atmosphere settings.

Cured toroidal specimens were then prepared in a series of insulating tape and copper wire in order to test the magnetic behaviour in both DC and AC conditions utilizing a SMT700 hysteresisgraph.

3. Results and Discussion

In order to analyze and identify a proper processing profile for SMC materials, a holistic approach must be taken with regards to key material properties. These properties may differ depending on the final use case of the part, but by understanding their relationship, a robust, repeatable processing route can be developed.

With SMC materials, like with any PM part, the process begins with material selection. Second to material grade selection, which includes a choice of lubricant, comes compaction, followed by the thermal treatment. While these are all important steps in any PM product, when dealing with SMC components, they each have an outsized impact on the final part properties.

Previous work has explored how different lubricant types can be removed from SMC compacts effectively up to a nominal curing temperature of 450°C (842°F) [4], while secondary work has shown the impact that the presence of lubricants and coatings in general have on select magnetic properties [5]. By utilizing the learnings in both cases, one can start to isolate important factors needed to reach maximum magnetic performance.

The compaction process is the first internally controllable process which can have a large impact on the final properties of a SMC part. Beyond the shape factor and the final density of the part, which inherently will have a direct impact on the parts performance, ($\mathbf{B_{sat}=(SMC\ Density/Density\ Iron)*2.15T}$), there is an impact of the conditions utilized in the shaping of the part itself. Lindsley et al's paper showed how compaction temperature not only had an impact on the yield stress of the particles, but how this temperature impacted different combinations of coatings and lubricant. In broad terms, it was observed that with increasing temperature of compaction, the resultant parts showed higher permeability and higher core loss. It is within this area that the first comparison will focus.

Samples of SMC material were compacted at three different temperatures and subsequently processed under a nominal curing cycle. These were used to imitate compaction below the desired temperature, at the desired temperature and above the desired temperature (further denoted as Low T Compaction, Nominal T Compaction, High T Compaction). While, previously, both core loss and permeability were shown to increase with compaction temperature, this relationship is more nuanced. With the Ancorlam sample, you can see (Figure 3) that when the sample is compacted at the Low T Compaction setting, the permeability of the component is compromised, but the sample retains its insulative properties. Alternatively, when the compaction was completed under High T Compaction settings, the permeability of the sample is further increased but this associated gain comes with the negative aspect of increased core loss. Finally, however, when the sample is compacted under the Nominal T Compaction settings, a smaller gain in permeability is observed but the sample is largely unaffected in terms of its insulative properties. It is here in this state that the material is able to balance both core loss and permeability without the direct increase of one at the expense of the other.

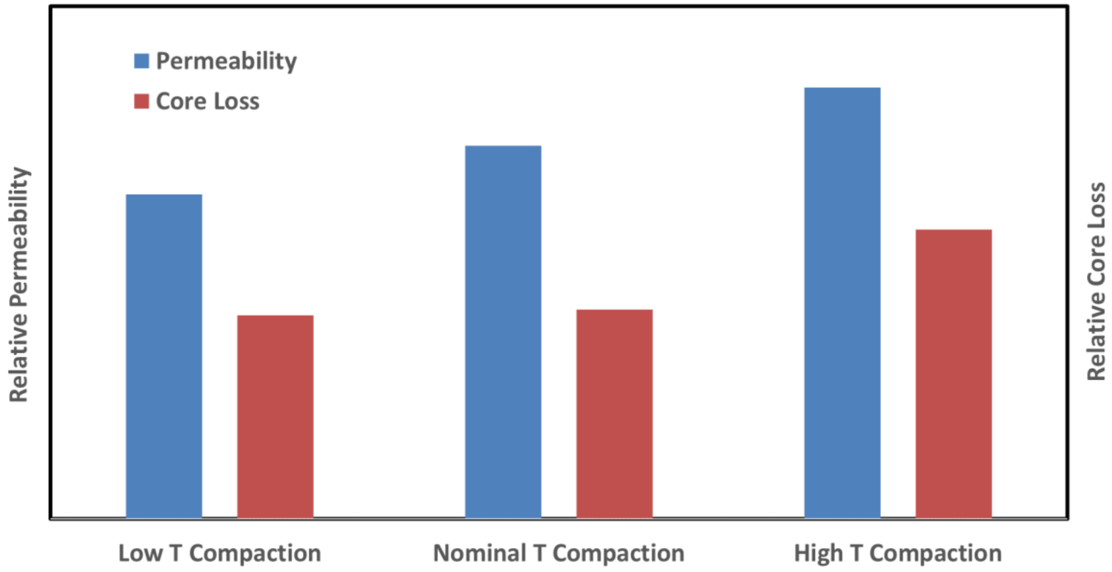

Figure 3: Impact of compaction settings on measured magnetic properties.

In order to assess the impact of thermal treatment on SMC properties and show the relationships that the properties hold, an experiment similar to the compaction study was conducted. Here, samples compacted under Nominal T Compaction conditions were subjected to one of four different thermal treatments. Namely, no thermal treatment (Green), a low temperature thermal treatment (Low Cure), a high temperature thermal treatment (High Cure) and a nominal temperature thermal treatment (Nominal Cure). In order to evaluate the changes curing temperature have on part performance, carbon, transverse rupture strength, resistivity, core loss and permeability were used for comparison.

Carbon is an important check for SMC materials and its control is crucial in the design of the front end of the thermal cycle. Residual carbon retained within the SMC compact can negatively impact overall performance and be utilized as a simple Go/No-Go gage. SMC delubrication cycles are often more difficult than a standard PM material due to the low maximum temperature targeted in the processing of these materials. Furthermore, the high density of components used in SMC applications also increases the delubrication step complexity [6]. Based on Table I, and in combination with the work by KJS et al, it can be observed that the Low Cure condition was insufficient in removing lubricant from the samples. Alternatively, once a thermal profile is found to be sufficient in the removal of the lubricant, it will not matter what the upper temperature limit is of the profile, and no further gain in terms of delubrication will be attained (Nominal to High Cure).

Table I: Impact of thermal treatment on carbon content of magnetic materials.

Thermal Treatment	Green	Low Cure	Nominal Cure	High Cure
Carbon Content (%)	0.30	0.07	0.02	0.02

When looking at break strength, a general linear increase can be seen in transverse rupture strength with increasing thermal treatment with most of the gains coming from a movement from no thermal treatment (Green) to Nominal. A similar but opposite trend can be seen when looking at resistivity, which gradually lowers with increasing thermal treatment temperature. Since both of these trends, as shown in Figure 4, show no large plateau or "sweet spot" area, they should not independently be utilized in the selection criteria for thermal treatment max temperature.

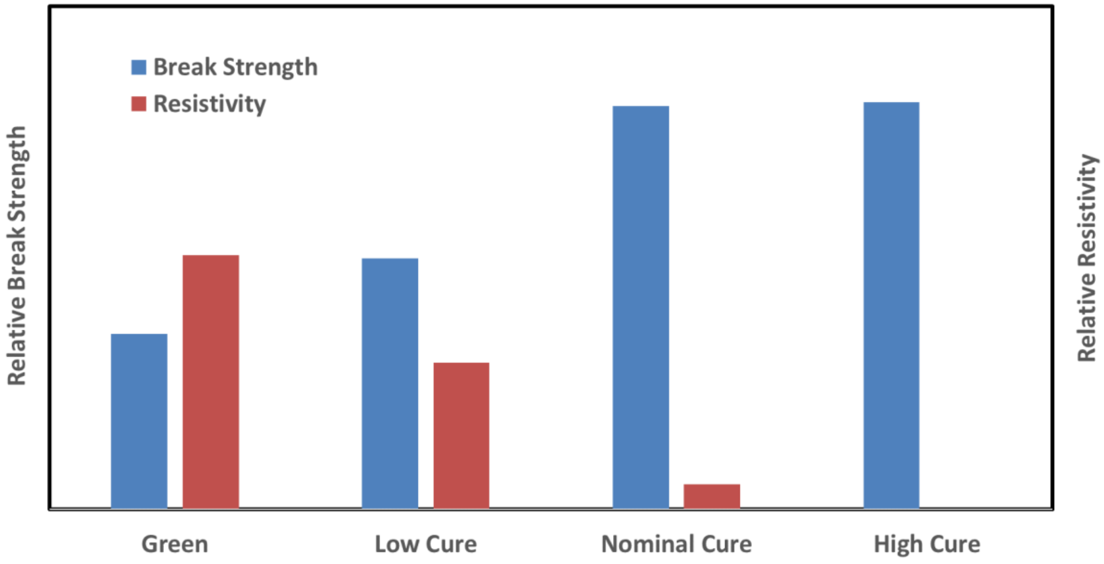

Figure 4: Impact of thermal cycle on the strength and resistivity of SMC components.

Finally, core loss and permeability were again compared. Here, when looking at the impact of thermal treatment on the samples (Figure 5), a similar but exaggerated trend to that in compaction conditions was observed. Again, with increasing thermal temperature, a gradual increase in permeability is obtained. When focused on core loss in the system, the thermal cycles could easily be sorted into two opposing factions. Green, Low and Nominal cure conditions showed little-to-no change in core loss with increasing thermal treatment, while the High Cure setting showed a multiple-fold increase in the measured core loss. This change in behaviour, along with the previously shown resistivity data showing the resistivity approaching zero at the highest thermal treatment condition, indicate that the coating is no longer acting as intended. As noted, the coating applied to the SMC materials, like in lamination steels, is needed to isolate the generated eddy current in the component. With loss of functionality of this coating, the generated eddy currents are not isolated in size and become the major constituent of system losses. Under Nominal Cure conditions, specifically, a balance of low core loss and increased permeability is found.

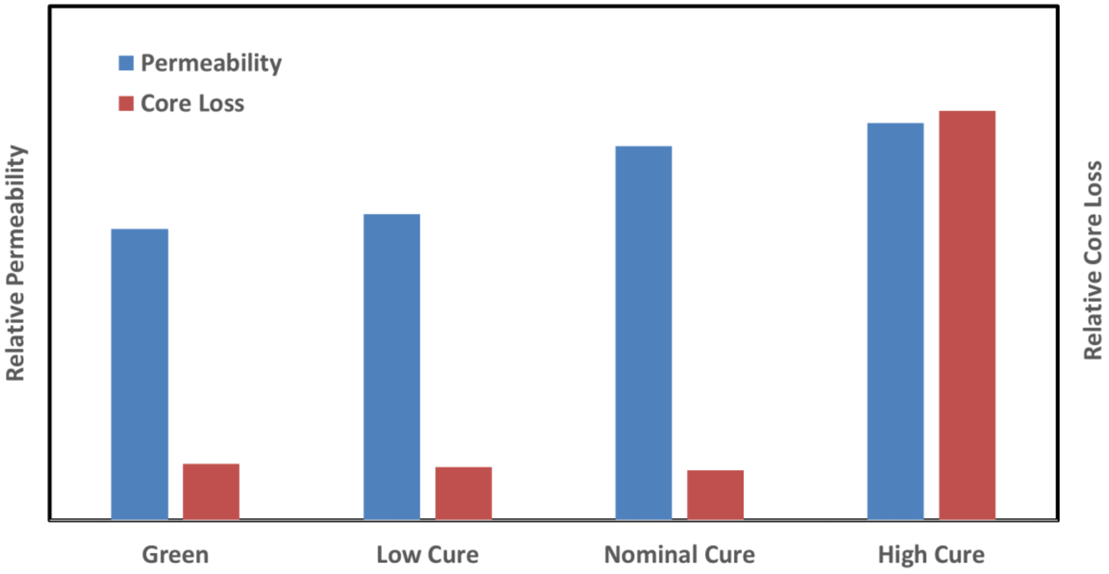

Figure 5: Impact of thermal cycle on measured magnetic properties.

Only once nominal production settings are found for different materials can the true differences in product properties be fully attained. Samples of the standard SMC product and Dev. High perm material were each produced under their respective nominal settings with results shown in Table II. Both materials were compacted to a green density of 7.40 g/cm^3 as to allow for a head-to-head comparison. Even with a change in material, the balance of properties remains between both core loss and permeability. As previously shown with the trends of the standard SMC material, if a higher permeability was targeted through processing parameters alone, this gain comes at the expense of core loss. Since eddy current losses are exacerbated with operational frequency, any damage or breakdown introduced into the coating will first appear at higher frequency levels and, thus, can be used as an indicative measurement point regardless of true operational frequency needed for the component.

Table II: Comparison of SMC material properties.

Magnetic Response								
Material	DC @ 1T		50 Hz @ 1T		400 Hz @ 1T		1000 Hz @ 1T	
	B_m (T)	μ_{max}	H_c (A/m)	Core Loss (W/kg)	H_c (A/m)	Core Loss (W/kg)	H_c (A/m)	Core Loss (W/kg)
AncorLam	1.0	401	269	6.2	325	54.8	351	155
Dev. High Perm	1.0	540	235	5.3	264	47.3	305	137

4. Conclusions:

With SMC materials, the utilized production route has an outsized impact on the end performance of the parts. From initial compaction settings to delubrication and thermal treatment, all aspects of production must properly be controlled. From this study, the following conclusions can be made:

- Changes in the temperature of compaction have a lasting and permanent effect on the end magnetic properties of the components.
- Excessive compaction temperature of SMC materials causes both an increase in permeability and in core loss.
- Cured carbon results can be used as a Go / No-Go gauge for design of the front end of the thermal cycle.
- Increases of the thermal curing cycle for SMC materials generally increases break strength of components and decreases resistivity.
- Increases in the thermal curing cycle for SMC materials increases permeability.
- Excess temperature in the curing cycle will cause a resultant breakdown of the coating, resulting in excess core loss.
- The selection of alternative products (Dev. High Perm) allows for a balance of increased permeability without the degradation of other properties.

5. References:

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