Comparison of Soft Magnetic Composites (SMC) and Lamination Assemblies

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Abstract

Soft magnetic composite (SMC) use in electric motors offers a significant growth opportunity to the PM industry. Barriers exist, however, that have prevented wide-scale adoption. Beyond the need for motor redesign, users need to understand the difference in performance and stated properties of SMCs and the dominant stator core technology using lamination (electrical sheet) steels. Lamination steels used for stator cores have excellent magnetic properties within individual sheets. The comparison of these individual sheet properties, such as maximum saturation and permeability, with powder-based soft magnetic composite properties creates an unfavorable view of SMCs. The properties of lamination assemblies, however, is lower than individual sheets due to stacking factor and the presence of insulation layers. Further, it is commonly understood that these stacks tend to work best at lower frequency, whereas SMC is more suited to higher frequency. The number of direct comparisons of SMC and lamination steel stacks is limited in the literature, resulting in broad generalizations. In this study, test rings made with assemblies of 2 lamination steel grades and 2 grades of SMC have been evaluated under different test conditions. The effect of ring size and amount of lubricant are also discussed. The direct comparison between SMC and lamination steel will enable users of the technology to understand the benefits and limitations of each approach, leading to the best engineering solutions.

Introduction

Lamination steel stacks are the common cost-effective solution to limit eddy current loss in alternating current motor applications. An insulating layer is applied to the surface of an electrical steel sheet, and the layers are stacked up to form the motor stator or rotor. Electrical steels used for motor applications are typically iron, iron-silicon or iron-silicon-aluminum alloys that are relatively free of other alloying or trace elements and have been processed in a way to optimize grain size between 100-200 μm [1] and limit any deformation in the material. Most higher end electrical steels have between 2.5 and 3.5%Si+Al [2] where the addition of silicon reduces electrical conductivity and thereby reduces eddy current loss in motors. Higher Si contents would be desirable from a magnetic standpoint, but the ability to process the sheet material becomes difficult (reduced ductility) as Si content exceeds 4%. Densities of 7.6 to 7.75 g/cm^3 are often noted depending on the silicon content of the steel. Inorganic coatings applied to the sheet steel act as an insulator and prevent electrical current to flow between sheets when arranged in a lamination stack. The insulation is generally a phosphate base with inorganic fillers. This coating can be between 2 to 3 μm thick, or roughly 1% the thickness of the sheet. In a concept similar to pore-free density in PM components, the lamination steel stack density is lower than wrought steel due to the lower density components in the coating and any air gap between layers. This is known in the industry as stacking factor. As the metal sheet thickness decreases and the coating comprises more of the stack, the stacking factor is reduced. Values between 0.9 and 0.95, in which 90-95% of the stack is metal, are typical. To obtain good results in a motor, the lamination steel stacks must be oriented such that the plane of the sheet is the plane of magnetic flux. Magnetic permeability quickly drops when the direction of magnetic flux changes from within the plane of the sheets to a normal direction where the insulation must be crossed, Figure 1 [3]. The outcome is that virtually all electric motors are radial flux motors. If a motor design utilizing magnetic flux in a different orientation is desired, a lamination stack becomes difficult and a different solution is required.

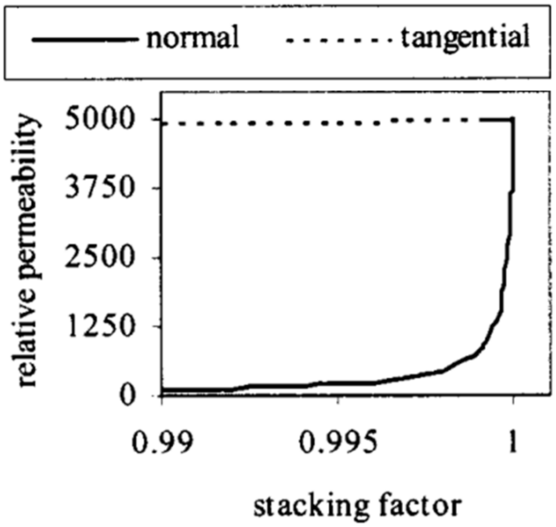


Figure 1: Relative permeability for a lamination stack with a single sheet permeability of 5000. [3] Flux orientation is either in the plane of the sheets (tangential) or perpendicular (normal) to the sheets.

PM-based soft magnetic composite (SMC) materials consist of iron powder and an insulation layer on the surface of the powder. The insulation is often phosphate based and may contain other layers and/or organic coatings. The thickness of the coating is typically less than 1 micrometer but the total amount of insulation in the PM component may be greater than the lamination stack due to the sheer number of interfaces throughout the compact. The material also contains a lubricant to aid in compaction and ejection. Compact densities up to 7.5 g/cm^3 are typically reported. The three-dimensional insulation of SMC's more easily enables production of axial and transverse flux stators and could lead to higher torque and more efficient motor production. However, the nominal reported magnetic properties of SMC material pales in comparison of that reported for lamination steels and remains a barrier to wide-spread adoption.

Two very different methods are used to report magnetic properties for lamination steel and SMC. Lamination steel magnetic properties are developed from single layer samples taken from both the transverse and longitudinal orientations, per ASTM A343. The condition of the steel is often in the as-sheared state and the Epstein test is used to measure magnetic properties. This test is a fast and convenient test for documenting sheet production in a steel mill but does not necessarily represent properties of an assembled lamination stack. Relative permeability of single sheets can range from 2500 to over 5000. Additionally, core loss for single sheets, often quoted at 1.5 Tesla and 50 Hz, ranges from 1-4 W/kg. Use of a toroid ring composed of a lamination stack is more representative of the final application. It can be seen in Figure 2 [4] that core loss of a single sheet sample and a wound toroid lamination ring for a 0.35mm thick M19 steel (or EN 10196 grade M270-35A) is substantially different. At 1 Tesla, the single sheet test results in a core loss of just under 20 W/kg, whereas the toroid test results in roughly 33 W/kg. Since SMC magnetic properties are reported via a toroid test, it is important for users to understand these important differences when comparing both technologies. This study is an expansion of an earlier study [5] that was presented in Europe that compares lamination and SMC materials in toroid tests to further understand where these materials can best be used. Content is being republished for the North American market. Additionally, the effect of ring size and test repeatability is addressed.

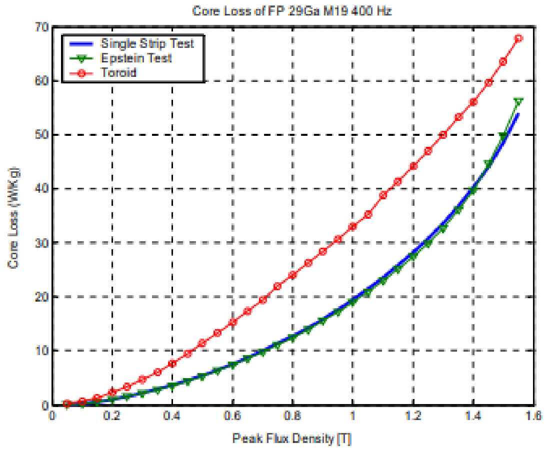


Figure 2: Difference in core loss at 400Hz when testing a single sheet sample and a wound lamination stack toroid of 0.35 mm tick M19 (M270-35A) steel. [4]

Experimental Procedure

Two grades of SMC, AncorLam® (referred to as 'standard SMC' hereafter) and a developmental high permeability grade (high perm SMC), were used in the study. Both are based on water-atomized iron powder and contained 0.4% lubricant. Additionally, the effect of lubricant content used from 0.1% to 0.4% was also studied for the high perm SMC. Two different ring geometries were produced with SMC powders: small torroids were 23 mm ID and 36 mm OD and larger torroids that meet an upcoming geometry standard were 45 mm ID and 55 mm OD. The toroid samples were pressed to a density of 7.4 ± 0.01 g/cm^3 and nominally 5 mm tall, followed by a two step curing at 400 °C for 60 minutes plus 490 °C for 10 minutes in a Gasbarre batch furnace. The cured density was measured prior to testing.

For the lamination samples, ring samples measuring 45 mm ID and 55 mm OD were produced from two different grades of non-oriented lamination steels, Table 1. Rings were laser cut to minimize deformation and stacked to form a 5 mm tall toroid. No joining technique was used to make the lamination stack other than initially clamping the toroid until it was wound, so this represents an ideal lamination stack. Normal fabrication methods such as welding or stamping would further degrade properties. Nominal Si plus Al content listed for the lamination grades are from the ASM Handbook [2].

Table 1. Lamination steel sheet information

Designation	ASTM A677 Designation	EN 10106	Thickness	Si+Al Content
M-19	36F155	M270-35A	0.35 mm	3.3
M-36	36F185	M330-35A	0.35 mm	2.7

The toroids were wrapped using inner windings (0.51 mm thick wire) and outer windings (0.64 mm) sufficient to induce the desired magnetic response. Insulating tape was applied beneath each set of windings. The DC properties were measured at both a magnetizing force of 10,000 A/m and at a flux density of 1 Tesla using an SMT700 hysteresis graph. AC properties were measured at 1 Tesla. The lamination sheets and SMC cured samples were metallographically cross-sectioned, polished and etched to reveal the microstructure.

Results and Discussion

Comparison of Lamination and SMC Materials

The materials tested under direct current (DC) conditions exhibit significantly different behaviors. The B-H curve for the M19 lamination stack is narrower, has a steeper slope and reaches saturation faster than the high permeability SMC material, Figure 3. Similar behaviors were observed for the M36 and standard SMC samples. Maximum magnetic flux density (B_{max}) for the lamination stacks was 1.77 T and 1.78 T for M19 and M36 and for the SMC materials was 1.64 T and 1.58 T for the high perm SMC and standard SMC at 10,000 A/m. Maximum relative permeability (hereafter permeability) for the same four samples was 1386, 1745, 548 and 401, respectively. Significantly less magnetizing force (H) is required to increase flux density above 1 T. Under these test conditions, the lamination stacks clearly outperform the SMC materials.

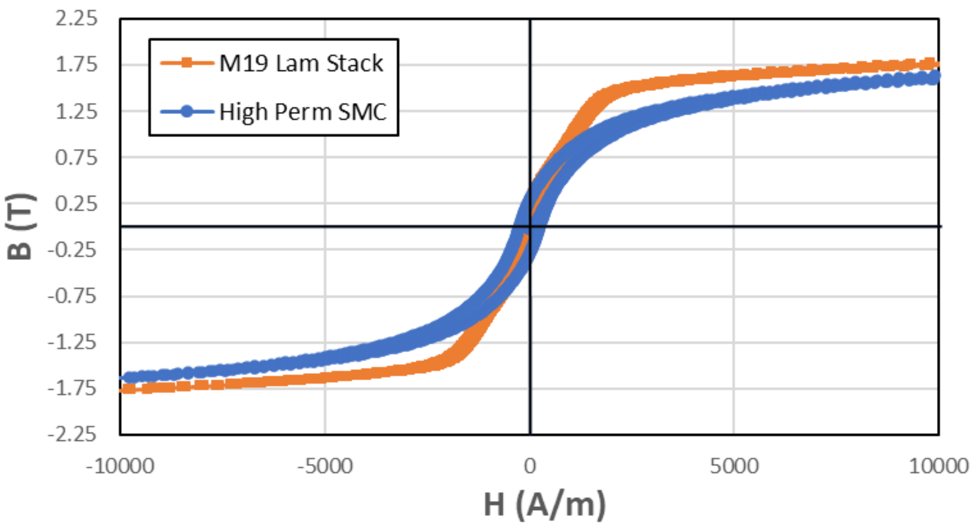


Figure 3: DC B-H curve for M19 lamination stack and the high permeability SMC material at 10,000 A/m.

It is also useful to evaluate materials at a given flux density, and in this paper a value of 1 T was chosen. Figure 4 better illustrates the differences between the M19 and high perm SMC at lower magnetizing force. The magnetizing force required to reach 1 T increases from nominally 1250 A/m for the lamination steel to 2000 A/m for the SMC material and is largely independent of test conditions. The DC curve for the lamination steel (orange) is clearly narrower (lower coercivity) than the SMC material (blue). However, as the frequency is increased to 400 Hz, the width of the lamination steel B-H curve (magenta) greatly increases, indicating a greater core loss due to eddy currents. The SMC material does not exhibit much change from DC to 400 Hz test conditions (blue to green curves) as the SMC material has more extensive insulation to limit eddy current losses.

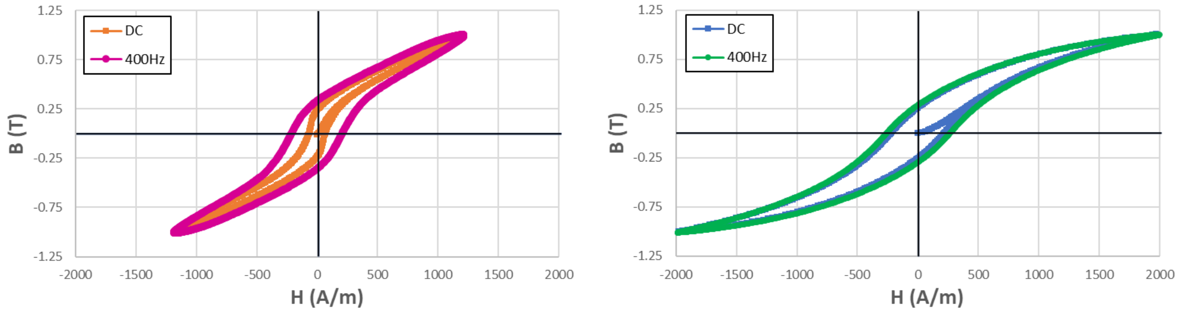


Figure 4: DC and 400 Hz B-H curves for (a) M19 and (b) high perm SMC at 1 Tesla.

The permeability is a useful measure of the material to determine how quickly the flux density increases with a change in magnetizing force and can be determined as the slope of the steepest line from the origin to the tangent of the positive, increasing B-H curve relative to that of the B-H curve with air or vacuum as the core material. This is most often given under DC conditions where lamination steels greatly outperform SMC materials. However, as seen in Figure 4a, the slope from the origin to the magenta line is much lower than to the orange line, resulting in a drop of permeability. The same analysis of the SMC material results in little change to permeability. It is therefore interesting to examine this change for all four materials. Figure 5 shows the change in permeability with test frequency. The lamination steels exhibit a strong decay in permeability with test frequency whereas the SMC materials show a much smaller change. The delta in permeability between lamination steel and SMC becomes much smaller at higher frequency, indicating that SMC materials become relatively more attractive at these conditions. The authors are unaware of literature showing this different behavior between the two material types and it would be interesting to know if motor manufacturers are aware of and account for these differences in simulation and design.

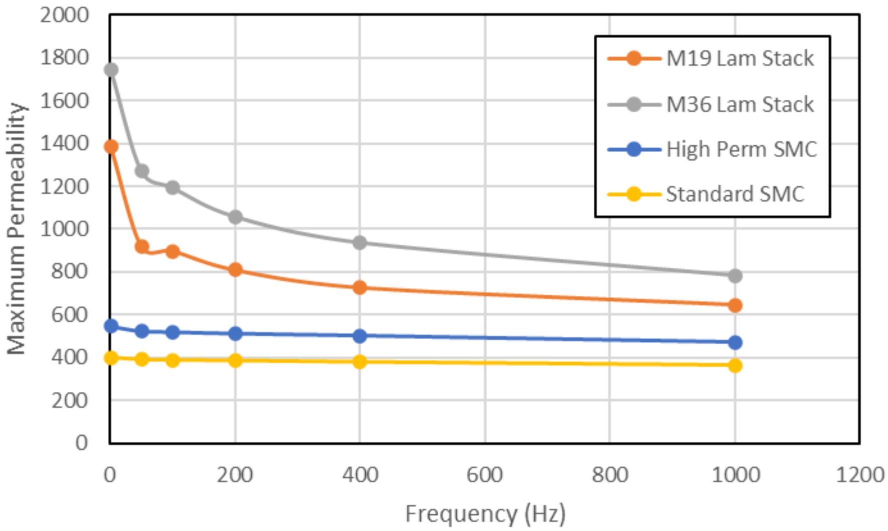


Figure 5: Change in permeability from DC conditions (shown at 0 Hz) and AC conditions up to 1000 Hz

It was also noted earlier from Figure 4 that the width of the B-H curve increased with higher frequency, and as the area enclosed by the B-H curve increases, energy loss, aka core loss, increases. The core loss was plotted versus frequency in Figure 6. It can be seen that core loss for the lamination stacks is lower than the SMC materials at frequencies from 50 to 400 Hz. The M19 steel that contains higher Si+Al content (higher resistivity) has a lower core loss than the M36 steel. Above 400 Hz, there is a crossover where core loss for the SMC material is lower than the laminations. The high perm SMC crossover with M36 and M19 is nominally 500 and 610 Hz, whereas the standard SMC crossover is closer to 700 and 1000 Hz, respectively. Figure 6b shows the core loss of the lamination steels rapidly increases above 1000 Hz and significant separation between SMC and lamination steel is evident.

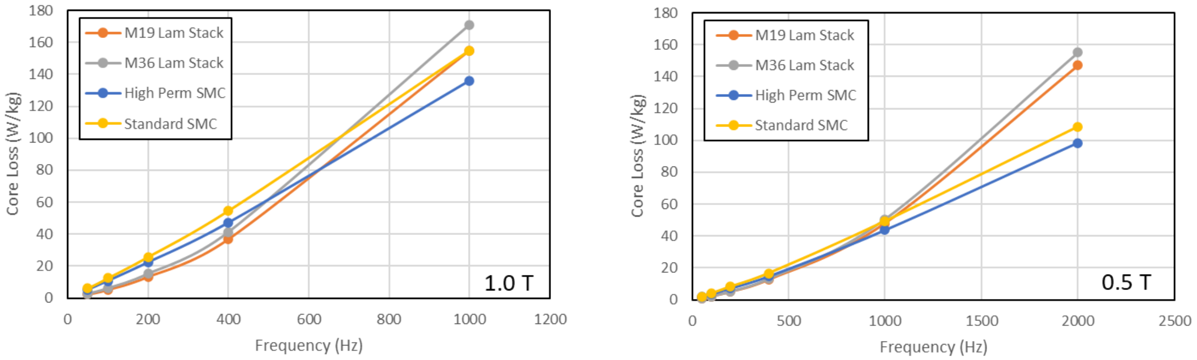


Figure 6: Change in core loss with increasing frequency. (a) 50 Hz to 1000 Hz at 1T and (b) 50 Hz to 2000 Hz at 0.5 T.

Effect of Lubricant Content

Work presented in 2022 showed that lubricant plays an important role in the insulation layer of the SMC [6]. The addition of 0.4% lubricant compared with 0% lubricant (die wall spray only) greatly reduced permeability and also significantly reduced core loss. The amount of lubricant, however, was not studied, and therefore the high perm SMC was tested with 0.1, 0.2, 0.3 and 0.4% lubricant, all at 7.4 g/cm^3 density. Figure 7a shows that permeability increased slightly with less lubricant. Surprisingly, the core loss did not exhibit any appreciable change as the lubricant content was decreased. This would suggest that only a modest 0.1% lubricant is required to yield good insulating properties. For this particular material, the lubricant content can therefore be tailored for sufficient part ejection while also obtaining the best magnetic performance.

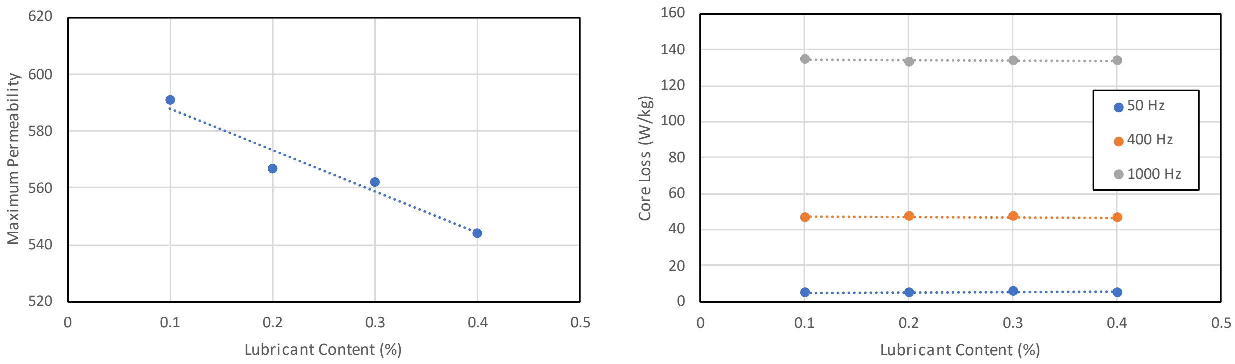


Figure 7: Change in permeability and core loss with increasing lubricant content for the high perm SMC. (a) permeability and (b) core loss.

Test Repeatability

The repeatability of test values was evaluated. The standard deviation in magnetic properties for 5 rings for each SMC material and ring size was measured. It was determined that the average standard deviation for DC permeability at 1 T was 8.5 and the deviation for core loss was 0.07, 0.8 and 3.6 for 50, 400 and 1000 Hz, respectively. The test results were found to be quite repeatable. Additionally, little difference was found in rings made 1 year apart with the high perm SMC. Permeability (DC at 1 T) was measured at 548 and 544 in 2023 and 2024 and core loss at 1000Hz was 136 and 134, respectively.

Ring Geometry

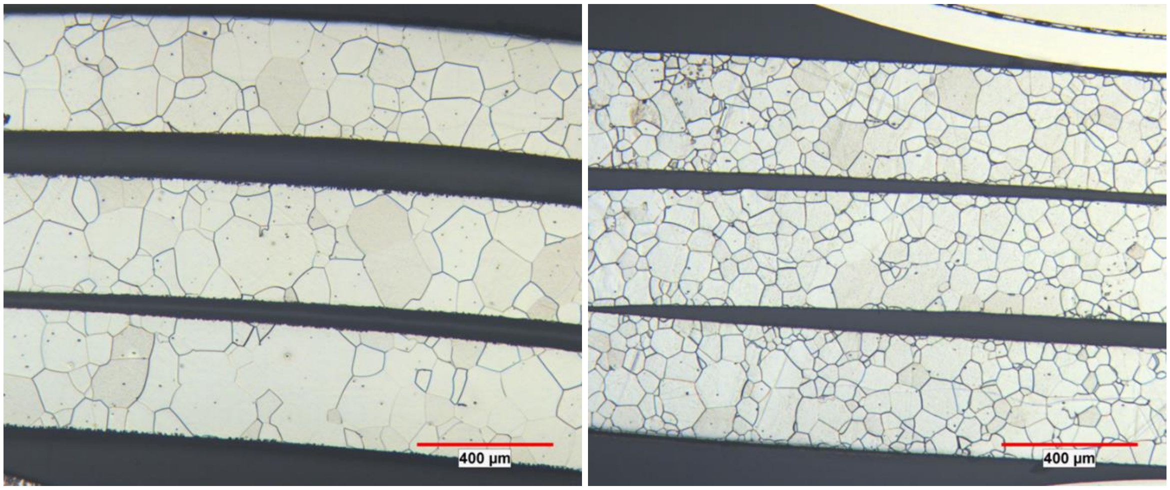
Finally, the effect of ring geometry was evaluated. The test equipment settings were adjusted to accommodate the different sizes and wall thicknesses. Little measurable difference was found between geometries. The results are shown in Table 2 below. All apparent differences due to ring size fall within the standard deviation shown above.

Table 2. Effect of ring geometry on magnetic properties.

Magnetic Property	High perm small	High perm large	Std SMC small	Std SMC large
DC Permeability	544	544	401	396
Core Loss 50Hz (W/kg)	5.2	5.4	6.2	6.4
Core Loss 400Hz (W/kg)	46	47	55	56
Core Loss 1000Hz (W/kg)	134	134	155	157

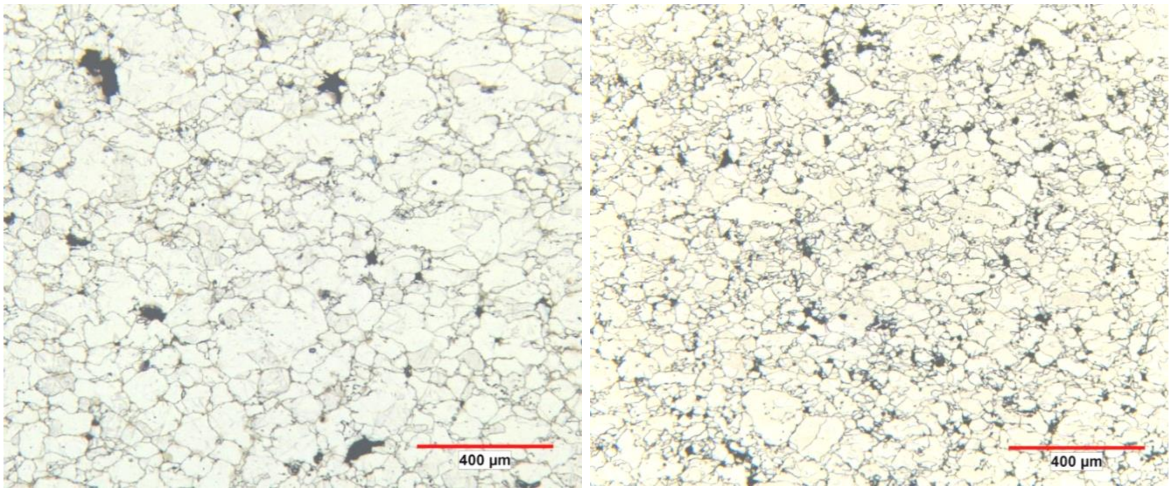
Microstructure

The etched microstructures of the lamination steels are shown in Figure 8. A significant change in grain size between grades is observed, where the M19 has a grain size of 99 μm and M36 a grain size of 58 μm. Per Tumanski [1], the best properties are achievable with a grain size of 100-200 μm, so it is surprising such a large difference was found. Further, based on the permeability results, it was expected that the higher permeability M36 material would have larger grain size. The opposite was found. Since the lamination stacks were lightly clamped prior to winding, a difference in stacking factor may be influencing the permeability result. The small difference in Si + Al between grades is not known to have a large enough effect on permeability to overcome the significant grain size difference [7]. It is possible that slight differences in residual deformation or interstitial elements could drive this difference, but no evidence was found to definitively explain this unexpected result. The microstructure the SMC materials is shown in Figure 9. The outline of the particles is clearly evident due to the insulation layer present on the surface. The high perm SMC material has a coarser microstructure than the standard SMC. The grain size within particles is difficult to resolve under these conditions but is smaller than the particle size. Overall, the grain size of the lamination steels is greater than the grain size of the SMCs and certainly contributes to the better magnetic properties at low frequency.



a *b*

Figure 8: Etched microstructure of (a) M19 and (b) M36 lamination steels.



a *b*

Figure 9: Etched microstructure of (a) high perm SMC and (b) standard SMC.

A detailed analysis of the lamination steel revealed that the coating is not a uniform thickness. Evidence of the non-uniform coating is clearly visible in Figure 10, varying from 1 to 6 μm in thickness. SEM-EDS analysis confirmed the coating to be consistent with a C5-type coating, containing carbon, oxygen, aluminum, silicon and phosphorus. The variable coating thickness will contribute to an air gap between the lamination steel sheets, thereby improving electrical insulation between sheets but reducing the maximum saturation and permeability.

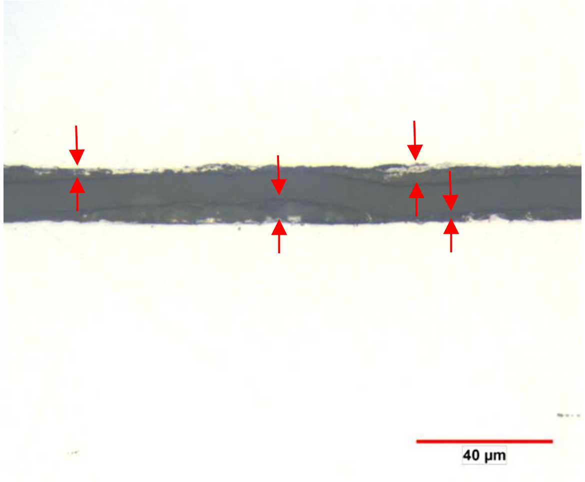


Figure 10: Polished microstructure showing the variable thickness of insulation coating on the surface of the lamination steel.

Conclusions

There is a clear difference between the behavior of lamination steels and soft magnetic composites. Lamination steel stacks have superior properties at low frequency, assuming the laminations are oriented in the proper direction. The permeability, coercivity and core loss are much better than SMC at 50 Hz, for example. Further, soft magnetic composites are at a disadvantage compared with lamination steels based on the way properties are often reported. Lamination steel properties are measured on single sheets at 50 Hz for core loss and permeability is measured under DC conditions. Toroid testing of lamination stacks reveals a larger core loss than that of a single sheet.

At no or low frequency, SMC materials are inferior. However, as frequency increases, the difference between these material types lessens until the SMC outperforms laminations at frequencies around 1000 Hz. The relatively stable magnetic response over a wide range of frequencies should make modeling and design more straightforward, assuming this behavior is understood. Further, the shape making ability of PM processing and the three-dimensional flux carrying capability of SMC provide differentiators from laminations, such that with the best motor design and operating speed, SMC is the superior choice for advanced motors.

Lubricant content between 0.1 and 0.4% was found to have a relatively minor role on magnetic properties at a given density. Additionally, test results within a sample group and between sample groups were found to be consistent. Little difference was found between toroid ring geometries as well.

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