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Soft magnetic composite magnetic component in high efficiency electric motor

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Summary

A 30% cost reduction of the electric motor is required from motor manufacturer to reach the traction drive technical target of the U.S. Department of Energy. To tackle this challenge, new materials and manufacturing technologies must be developed to provide cost-efficient motor design. In the recent year, soft magnetic composites (SMC) shaped by powder metallurgy process has become an alternative approach to produce magnetic component usually made from laminated steel. This paper will report the potential of SMC materials utilization in electric motor and its bench-scale testing versus laminated steel component.

Keywords: Materials; Permanent Magnet Motor; Efficiency

1 Introduction

A recent report from the Department of Energy (DOE) of the United States indicates that the biggest challenge in the development of electric motors for electric and hybrid vehicles is cost reduction, a 30% cost reduction by 2020 is targeted.[1] For an interior permanent magnet motor (IPM) the stator itself and the stator housing represent respectively 12% and 10% of the motor cost.[2] In current high performance electric motor, the stator is fabricated using a stack of Fe-Si laminated steel sheets. However, the high processing cost for thin laminated sheets, the high parts counts (more than 400 sheets per stator) and their limiting 2D design makes them targets for alternative technology. Soft magnetic composites (SMC) start to replace current steel laminates by offering to end-user many design and manufacturing advantages. Indeed, these new ferromagnetic materials allow the magnetic flux to circulate in the three dimensions and offer shape flexibility thru near-net shape powder compaction process, paving the way to efficient and low-cost innovative design.[3-4]

Soft magnetic composites are basically ferromagnetic powder particles separated by an electrically insulated layer. Complex shape products are produced thru the well-established, high volume production and near-net shape powder compaction technologies.[5] Due to their small particle size and the distributed air gap, iron based SMC's provide lower Eddy current losses than conventional electrical steel. On the other hand, their pure iron composition and specific microstructure leads to higher hysteresis losses. Therefore the replacement of laminates by SMC becomes interesting for high frequency applications (> 500 Hz).[4] Also, SMC has lower permeability than the electrical steel counterpart; this difference tends to become negligible for high length air gap motor design.[4] To clearly establish when and how SMC can effectively replace laminated sheet, numerical modelling and bench-scale testing must be carried out.

This paper will discuss the direct comparison of stator made from SMC and electrical steel in a well-established high performance electric motor topology. The performance for two types of SMC materials will be evaluated by numerical modelling and a stator core will be fabricated and bench-scale tested. This should give a clear picture of SMC material strength and weakness and help orientate future material development.

2 Experimental Procedures

2.1 Materials

Two types of SMC powder were used for this study; both were provided by Rio Tinto Metal Powder: EM1 and EM3. The EM1 is a high purity iron powder where the electrical insulation is provided by an organic material that is mix in the powder. This material is pressed at 690 MPa to a density of 7.2 g/cm^3 and cured at 200°C for 30 minutes. For the EM3 the electric insulation is achieved through a powder treatment that creates a fine inorganic layer around each powder particles. The EM3 is warm pressed at 65°C and 827 MPa to a density of 7.4 g/cm^3. The advantages of the EM3, aside from the higher density, is the possibility to cured the material at higher temperature, 480°C for 30 minutes, reducing hysteresis loss and increasing permeability. The material will be compared to a M15 (Fe-2.7%Si) electrical steel with a 0.35 mm thickness. Figure 1 shows the BH curves for each studied soft magnetic materials while table 1 resume saturation induction at 12 kA/m and iron losses at 1T for different frequency.

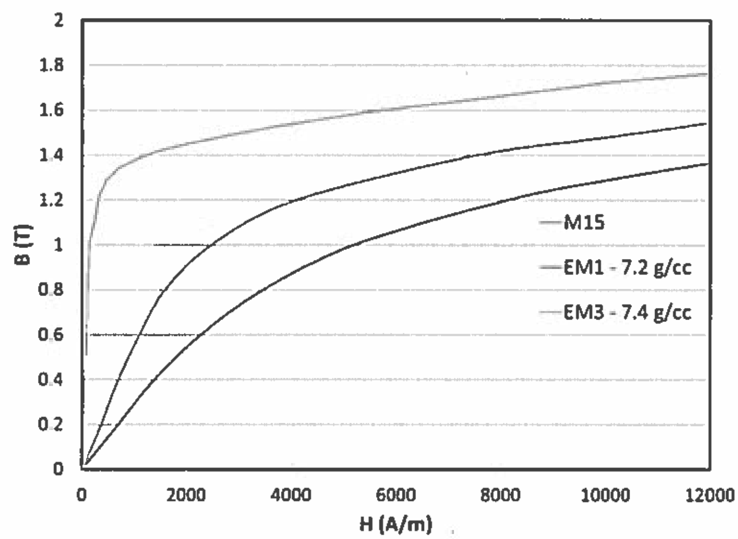


Figure 1: BH curves for all studied soft magnetic materials

Table 1: Materials properties for all studied soft magnetic

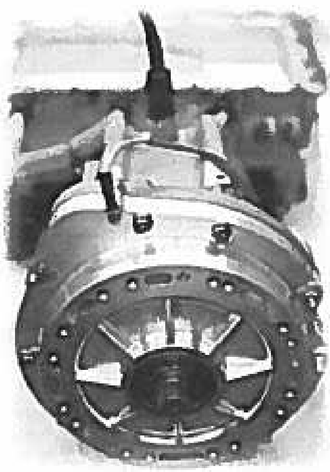
Material	Type	B_{12000} (T)	Losses at 1 T (W/lb)		
			60 Hz	400 Hz	1000 Hz
EM1	Powder	1.36	4.3	35	90
EM3	Powder	1.54	3.3	24	76.5
M15	Laminate	1.75	0.7	10	45

2.2 Magnetic characterization

Magnetic characterization was done on toroid with an outside diameter of 53.6 mm, an inside diameter of 40.6 mm and an height of 6.25 mm. DC and AC magnetic characterization was done on a KJS associates hysteresis graph (model ACT-500, SMT-500, 7385K Fluxmeter), according to ASTM standard A 773. For AC characterization, 250 turns of 24 AWG wire and 250 turns of 30 AWG wire were respectively used for the primary and the secondary windings while 450 turns and 150 turns were used for DC characterization.

2.3 Bench scale testing

The reference motor model for comparison use is the Motive™ motor of TM4. The Motive™ motor is a high performance permanent magnet motor for vehicle application. The system performances include a peak torque of 170 Nm and a peak power of 80 kW. Figure 2 shows image of the tested motor with a description of performance. For this motor, four EM1 pucks were pressed, machined and assembled to replace about 400 laminated sheets.



Torque (Peak*): 170 Nm*

Torque (Continuous): 65 Nm

Power (Peak): 80 kWm*

Power (Continuous): 37 kWm

Operating Voltage: 220-400V

Minimum operating Voltage: 180 V

Cooling: Water/glycol 55°C

* 10 seconds, 25°C, 400 Vdc

Figure 2: Description of TM4 Motive™ motor

3 Results and Discussion

3.1 Electrical losses

The first test was to obtain the electrical losses during a no-load test; figure 3 shows the results for the EM1-SMC material compared to the laminated steel. The losses shown include the mechanical losses. The results show that to compensate for the lower permeability of SMC, flux density needs to be increased to achieve the same electromotive force, thus increasing iron loss. When comparing the results from the EM3 to the M15, the loss is 60% higher at 6000 RPM but the difference is reduced to 25% at 12000 RPM.

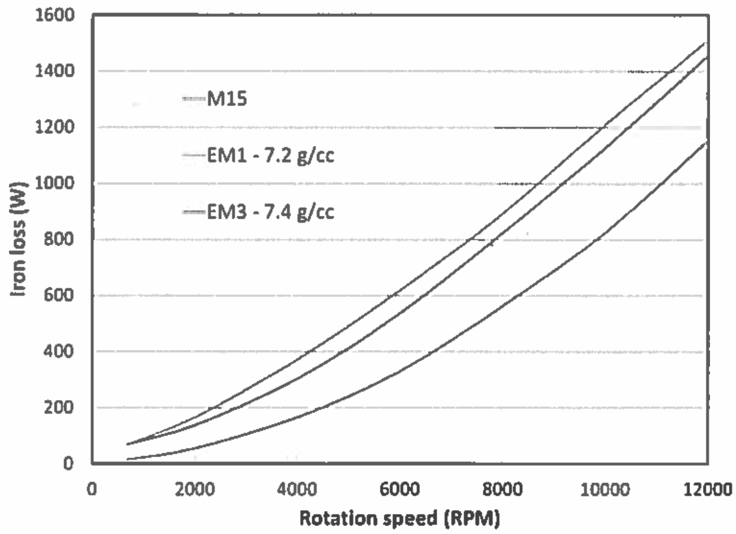


Figure 3: Comparison of electrical losses between SMC materials and laminated steel stator

3.2 Torque

Figure 4 illustrates the simulated results for the continuous and maximal torque at different rotation speed. At low speed the maximal torque is lower by less than 10% for the SMC material compared to the M15. For the continuous speed a difference of 6% is observed. When, rotation speed reaches 10000 RPM, both M15 and SMC materials behave the same way. No major difference was observed between the two types of SMC.

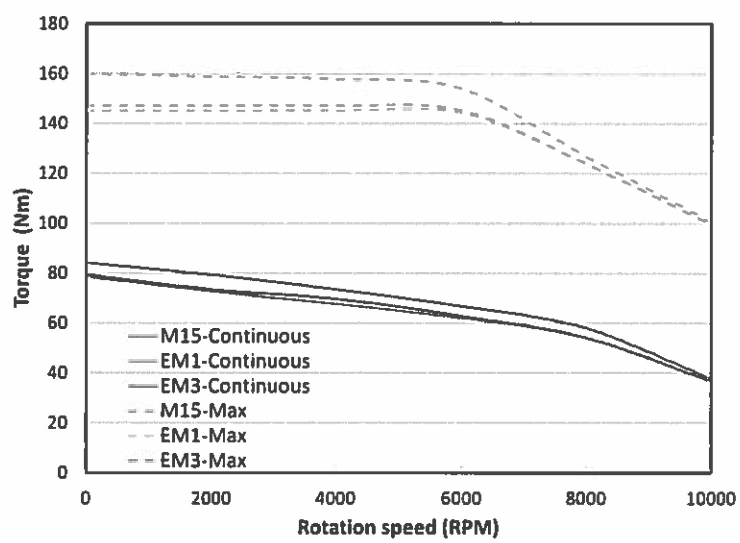


Figure 4: Comparison of simulated motor torque (continuous and maximal) between SMC materials and laminated steel stator

3.3 Efficiency

The efficiency of the motor using the different soft magnetic materials was first simulated. Table 2 and 3 summarize the difference in efficiency between the M15 core and the EM1 and EM3 core, respectively.

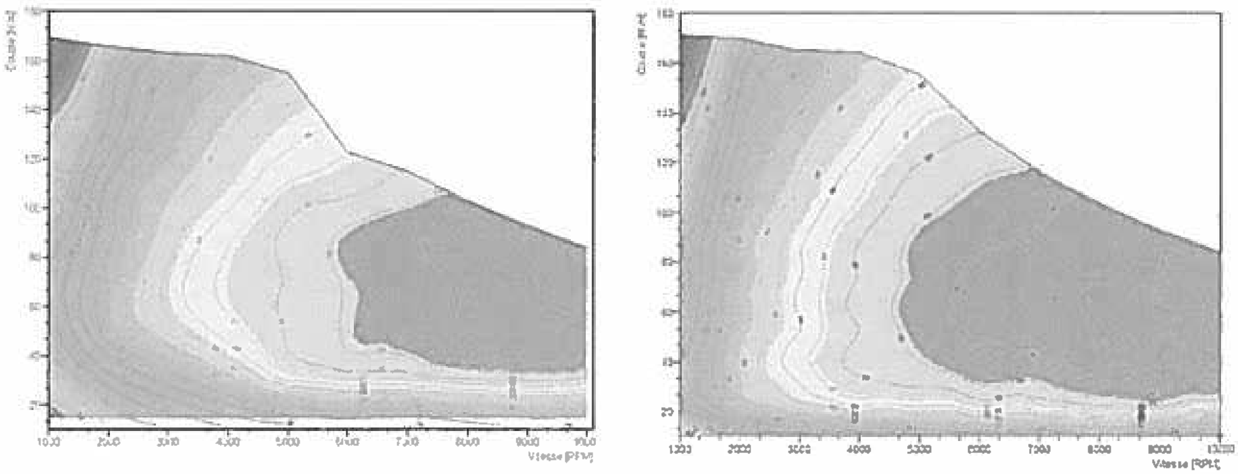
Table 2: Simulated efficiency difference between M15 core and EM1 core, in percentage

Torque (Nm)	Rotation speed (RPM)									
	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
160	4.8	4	3.3	2.8	2.5	1.9				
150	4.5	3.4	2.8	2.4	2	1.8	1.4			
140	4.4	3.3	2.6	2.2	2	1.6	1.1			
130	4.3	3.2	2.4	2.1	1.8	1.6	0.9	1.2		
120	4.2	3.1	2.4	2	1.7	1.6	1	0.7		
110	4.2	3	2.3	2	1.5	1.6	1.3	0.8	0.6	
100	3.8	2.7	2.1	1.8	1.4	1.4	1.2	0.9	0.5	0.3
90	3.8	2.7	2.1	1.7	1.3	1.3	1.2	0.7	0.6	0.7
80	3.4	2.4	1.9	1.6	1.3	1.3	1.1	0.6	0.5	0.4
70	3.3	2.3	1.8	1.6	1.3	1.3	1.2	0.8	0.6	0.3
60	3.2	2.2	1.7	1.4	1.2	1.2	1.1	0.8	0.5	0.3
50	3.1	2.1	1.6	1.3	1.1	1.1	1.1	0.9	0.5	0.4
40	3.2	2.2	1.7	1.5	1.2	1.2	1.2	1.1	0.4	0.1
30	3.2	2.2	1.8	1.6	1.4	1.4	1.4	1.3	0.6	0.3
20	3.6	2.7	2.1	1.8	1.6	1.6	1.6	1.6	0.7	0.2
10	5.9	4.2	3.3	2.9	2.7	2.7	2.7	3	0.9	-0.1

Table 3: Simulated efficiency difference between M15 core and EM3 core, in percentage

Torque (Nm)	Rotation speed (RPM)									
	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
160	3.1	2.4	1.9	1.7	1.5	1.1				
150	3	2.2	1.8	1.6	1.4	1.3	0.9			
140	3	2.2	1.8	1.5	1.4	1.2	0.8			
130	3	2.2	1.6	1.4	1.3	1.1	0.7	0.6		
120	2.9	2.1	1.7	1.4	1.3	1.2	0.7	0.5		
110	2.8	2	1.7	1.4	1.2	1.1	1	0.6	0.6	
100	2.5	1.9	1.5	1.3	1.1	1	0.9	0.7	0.4	0.4
90	2.7	1.8	1.4	1.2	1.1	1	0.9	0.6	0.5	0.5
80	2.3	1.7	1.3	1.2	1	0.9	0.9	0.5	0.6	0.5
70	2.1	1.5	1.2	1	1	0.9	0.9	0.6	0.6	0.3
60	2.3	1.6	1.3	1.1	1	1	0.9	0.6	0.5	0.4
50	2.1	1.4	1.1	0.9	0.9	0.9	0.9	0.7	0.4	0.4
40	2.1	1.5	1.2	1.1	1	1	1	0.9	0.4	0.1
30	2.1	1.5	1.2	1.1	1.1	1.1	1.1	1.1	0.5	0.2
20	2.2	1.7	1.4	1.3	1.3	1.3	1.3	1.4	0.7	0.4
10	3.7	2.7	2.3	2.1	2.1	2.1	2.2	2.6	1	0.2

Finally, the motor efficiency was measured in a bench-scale test for the EM1 and M15 soft magnetic cores, results are shown in figure 5. The operating range for the different stator is similar, for most operating conditions there is a 0.5% reduction in efficiency for the SMC stator, which is clearly better that what was expected from the simulation.



SMC – EM1 M15

Figure 4: Efficiency curves established during bench scale testing for the SMC EM1 and M15 laminated sheet.

4 Conclusion

The following conclusions can be drawn from the direct comparison between SMC and laminated stator core:

- Mainly due to lower permeability and higher hysteresis loss, SMC stator shows higher loss and lower torque than laminated steel cores.
- SMC EM1 stator has similar operating range but with a lower (0-2%) efficiency during bench scale testing.

These results are sufficiently encouraging to pursue research with new material with higher permeability and new motor topologies which utilizes SMC strength.

Acknowledgments

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Authors

Fabrice Bernier is a research officer in the powder forming team at the National Research Council Canada since 2010. He received his Ph.D in 2009 from École Polytechnique de Montréal. His main areas of expertise are soft and hard magnetic materials produced by powder metallurgy technology.