Effect of Machining on the Properties of Resin-Based Soft Magnetic Composites

Maxime R. Dubois, Patrick Lemieux, Charles Cyr and Daniel Massicotte.

Abstract—**This paper investigates the effect of machining on the properties of Soft Magnetic Composite (SMC) materials. A few types of SMC material are pressed with either a lubricating binder or a resin-based binding compound. Resin-based SMC appears to be easily machinable while the SMCs containing lubricating binders are too fragile to be machined properly. Further testing is carried out with ATOMET-EM1, a resin-based SMC. The effect of machining on the mechanical rupture strength, the electrical resistivity, the magnetic permeability, the saturating flux density and iron losses is determined experimentally. Two tool types and two milling speeds are tested. The experiment shows an increase in mechanical strength, resistivity and iron losses for the machined parts, and a reduction in saturating flux density.**

***Index Terms*—Soft Magnetic Composite, Machining, Magnetic properties, Transverse Rupture Strength.**

I. INTRODUCTION

SOFT Magnetic Composite (SMC) materials are used as core material in a growing number of electrical machines requiring isotropic materials or/and unusual 3D core shapes [1].

SMC parts are produced by pressing a blend of iron particles and binding/insulating material at pressures around 600 - 800 MPa. Due to the limitations of the press rating, the parts so produced are generally limited to surfaces below 1000 cm^2 for each individual piece. Hence, the cores of larger machines must be divided into a number of smaller SMC pieces, which must be assembled together. A mechanical assembly comprising a number of smaller SMC pieces fixed together by holes and screws or by the insertion of tapered parts will have a total tolerance equal to the sum of the tolerances of individual parts in a given direction.

A second element affecting the tolerance of machines built with SMC material is the intrinsic precision of the production process. Each SMC part produced by pressing is subject to a springback effect, which expands the part dimensions upon ejection from the die. Also, the resulting mechanical accuracy will be lower in the pressing direction than the accuracy obtained in the axis perpendicular to the pressing direction, since it depends upon the amount of powder in the die. The consequence of these two factors is the difficulty of reaching tight mechanical airgap tolerances. In electrical machines with short pole pitches, like Transverse-Flux PM machines, thin mechanical airgaps are crucial for high force density and high torque to volume ratio [2]-[4]. In such cases, machining of the stator and rotor bore radius may be required to obtain high mechanical precision after assembling separate SMC pieces.

Machining SMC parts will create heat locally, which may affect the insulation between iron particles inside the material, the magnetic properties of the material, and the mechanical resistance of the material. This paper studies the effect of machining on the mechanical and electromagnetic properties of the SMC material.

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M. R. Dubois and C. Cyr are with the Laboratoire d'Électrotechnique, Électronique de Puissance et Commande Industrielle (LEEPCI), Université Laval, Pav. Pouliot, G1K 7P4, Québec, Canada, (phone: 418-656-2131 ext 2982; fax: 418-656-3159; e-mail: mrdubois@gel.ulaval.ca).

P. Lemieux, is with Imfine Corporation, 75 de Mortagne Boulevard, Boucherville, Québec, Canada, J4B 6Y4 (e-mail: plemieux@imfine.ca).

D. Massicotte is with Eocycle Technologies Inc., 49 Belair, suite 106, G6V 6K9, Lévis, Québec, Canada (e-mail: dmassicotte@eocycle.com).

II. SMC MATERIAL TESTED

The electrical machine for which this work was carried out is a Clawpole TFM (Transverse-Flux Machine) with a hybrid stator described in [5] and shown in fig. 1.

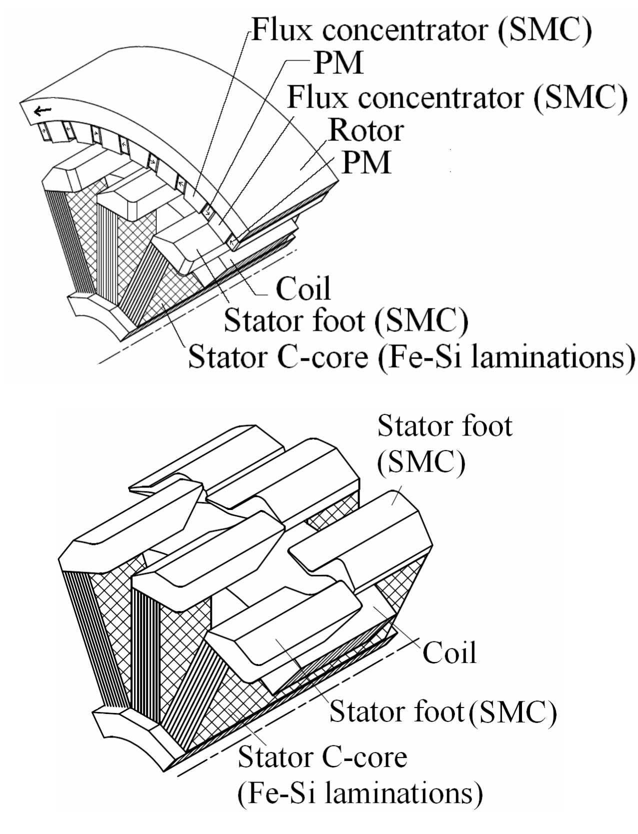

Fig. 1. Clawpole TFM with interior hybrid stator (3 pole pairs of 1 phase, shown with & without rotor).

This type of Clawpole TFM is in many ways similar to the one proposed in [6]. The main difference concerns the use of laminated steel and SMC materials in the stator core. In both cases, however, SMC material is contiguous to the air gap.

In this research, an airgap of 0.5 mm was obtained by machining on a lathe the rotor and stator of the Clawpole TFM machine investigated. Although apparently straightforward, the machining of SMC material could not be applied to all SMC materials available. Various SMC materials were considered for this application:

- SOMALOY 500® with 0.6% LB1®,
- SOMALOY 500® with 0.5% Kenolube®,
- SOMALOY 550® with 0.6% LB1®,
- SOMALOY 550® with 0.5% Kenolube®,
- ATOMET EM-1® (including 1% resin binder),
- ATOMET EM-2® (including 0.7% lubricating dielectrics [7]).

Among the 6 SMC materials tested, ATOMET EM-1® and SOMALOY 550® with 0.6% LB1® were the only two materials not leading to chipping of edges during machining. These can be machined easily because of a good resin content, which gives them good mechanical properties and good resilience.

Fig. 2 shows a part machined from two different SMC materials: a resin-based binder and a lubricant-based binder [7]. It is apparent from fig. 2 that resin-based SMC materials are better suited when machining sharp edges. Hence, only resin-based SMC materials were considered for the Clawpole TFM with hybrid stator of fig. 1.

Die-Wall lubrication is an important concern when pressing SMC parts. This is especially true for a part pressed with a resin-based binder, because it increases the part retention to the die walls and ejection becomes difficult. Ejection forces give a tendency to galling and scoring phenomena that are well known in powder metallurgy. The use of an electrostatic Die-Wall Lubrication method [8] during pressing solves this problem.

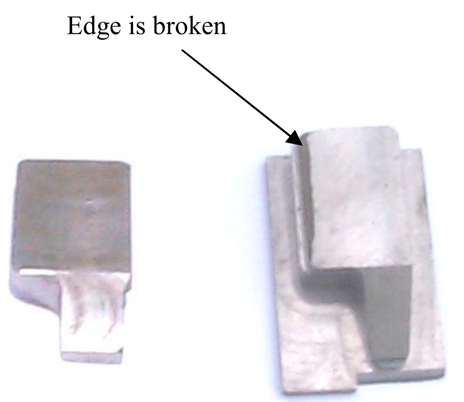

Fig. 2. SMC parts after machining. Left = ATOMET-EM1 (resin-based); right = ATOMET-EM2 (lubricant binder).

This study was held at the IMI (Industrial Material Institute - Montreal) facilities, where an electrostatic Die-Wall Lubrication apparatus Dielube #010116® from Imfine Corporation is available. Because of good previous experience with ATOMET EM-1® at the IMI, the latter was chosen for further study on the effect of machinability.

III. EXPERIMENTAL CONDITIONS

This section describes the methods used to determine the effect of machining ATOMET EM-1® on the following properties of the material:

- Electrical resistivity ρ (μohm-m),
- Mechanical transverse rupture strength σ (MPa),
- Relative magnetic permeability μ_{rmax},
- Magnetic saturation flux density B_{max} (T),
- Iron losses (W/kg).

The measurements of mechanical TRS (Transverse Rupture Strength) and electrical resistivity were performed on a sample of 240 identical rectangular pieces pressed with ATOMET EM-1® at a pressure of 640 MPa, with a 150 ton press, giving a resulting part density of about 7.15 g/cc. Each piece had dimensions of 12.5 mm x 12.5 mm x 77 mm. Fig. 3 shows one such SMC bar. A heat treatment of 200 **°C** in air during 60 minutes was applied to the bars after pressing.

The electrical resistivities were measured with a 4- point micro-ohmeter on all 240 bars before performing the TRS measurement.

Then TRS measurements were performed. The TRS measurement is a destructive test, which consists in the application of three forces across the bar in opposite directions up to the point of destruction, as depicted in fig. 4. The peak force value applied to the bar is recorded. This result is used to determine the TRS of the SMC bar tested. The test was conducted according to the MPIF #15 standard [10].

Among the 240 bar sample, 40 bars were machined after the heat treatment and 200 had no machining at all.

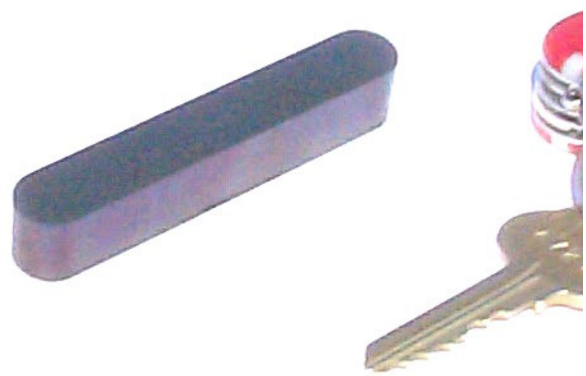

Fig. 3. Bars pressed with SMC for TRS and resistivity measurements.

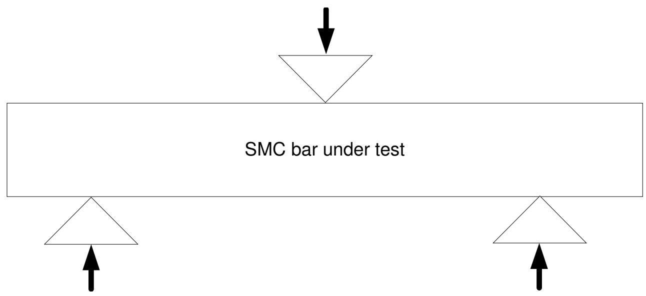

Fig. 4. Principle of TRS measurements.

The 40 bars machined are split into 4 distinct samples as follows:

- 10 bars machined with a "end mill" tool, 7/8 inch diameter, full carbide 4 flute, rotational speed of 1600 RPM; linear speed of 11 cm/minute, milling depth of 0.2 mm (rough machining).
- 10 bars machined with a "face mill" tool, 2.5 inch diameter, rotational speed of 1120 RPM; linear speed of 11 cm/minute, milling depth of 0.2 mm (rough machining).
- 10 bars machined with a "end mill" tool, 7/8 inch diameter, full carbide 4 flute, rotational speed of 1600 RPM; linear speed of 5.9 cm/minute, milling depth of 0.08 mm (soft machining).
- 10 bars machined with a "face mill" tool, 2.5 inch diameter, rotational speed of 1120 RPM; linear speed of 5.9 cm/minute, milling depth of 0.08 mm (soft machining).

The two head types (end mill and face mill) used are shown in fig. 5.

The magnetic properties (permeability μ_{rmax}, saturation flux density B_{max} (T), and iron losses (W/kg)) of ATOMET EM-1 were not tested on bars.

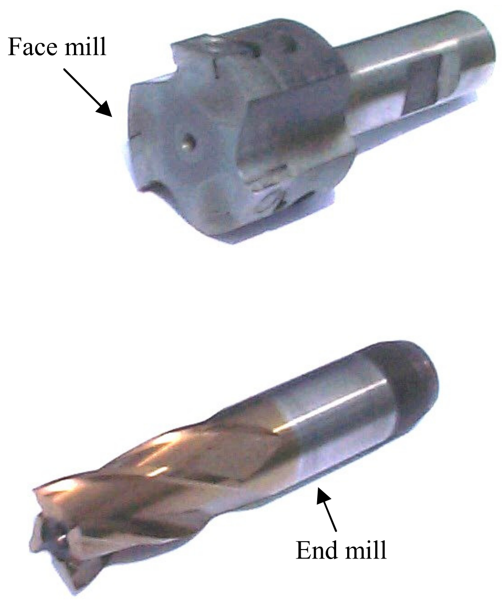

Fig. 5. Milling tools used for the experiment.

These were tested on rings of outside diameter 50 mm, inside diameter 42 mm and thickness 6.35 mm. The pressure applied was 640 MPa and a 200 C / 60 minutes heat treatment in air was applied after pressing. Twelve rings were pressed and six of them were machined as follows:

- 3 rings machined with a "face mill" tool, 2.5 inch diameter, rotational speed of 1120 rpm; linear speed of 11 cm/minute, milling depth of 0.2 mm (rough machining).
- 3 rings machined with a "face mill" tool, 2.5 inch diameter, rotational speed of 1120 rpm; linear speed of 5.9 cm/minute, milling depth of 0.08 mm (soft machining).

For the 6 machined rings, these were initially pressed to a thickness of 10 mm. The machining removed 1.83 mm on both faces, leaving a final thickness of 6.35 mm.

Each ring was wound with a 250-turn primary and a 250-turn secondary. Properties were recorded on a hysteresigraph made by KJS associates, model SMT-500, equipped with a 7385K Fluxmeter.

IV. Experimental Results

Fig. 6 shows the TRS measured on the 200 bar sample with no machining. Values of TRS between 95 and 130 MPa are observed with an average of 112 MPa. The value indicated in ATOMET-EM1 specification [11] is 124 MPa, that is 11% higher than the average observed here, which is within acceptable limits considering that the press and die used are different. Table I shows the average, standard deviation, minimum and maximum TRS values measured for all types of machining experimented on ATOMET-EM1 and described in the previous section. The average TRS value and standard deviations are also plotted in fig. 7. The four types of machining experimented here have a positive effect on the mechanical strength.

An increase of the average TRS value between 14% and 32% is observed, depending on the machining method. The best results are obtained with a soft machining and a face mill. The minimum value observed increases by 44% and the average value increases by 32% compared to the reference values observed with no machining at all.

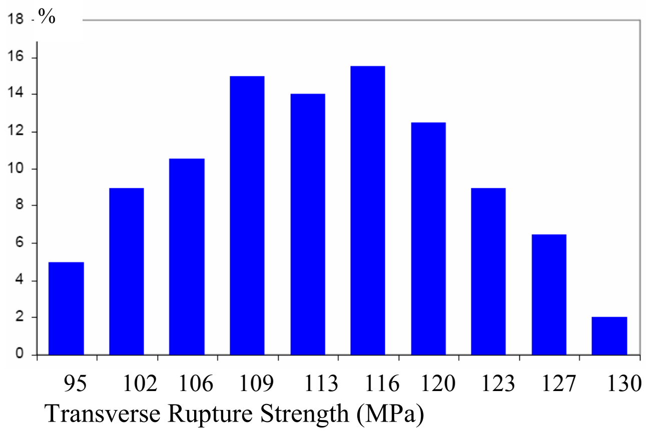

Fig. 6. Percentage of ATOMET-EM1 bars broken in each

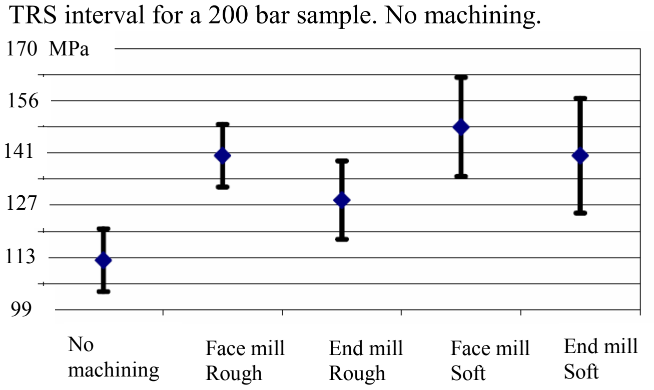

Fig. 7. Average & standard deviation of TRS measured for ATOMET EM-1 bars, with various machining methods.

TABLE I MECHANICAL TRS WITH & WITHOUT MACHINING (TESTED ON ATOMET-EM1 BARS).

	Transverse Rupture Strength (MPa)			
	Average	Standard deviation	Min	Max
-No machining (200 bar sample)	*112*	*8.5*	*89*	*132*
-Rough machining with Face Mill (10 bar sample)	*140*	*8.5*	*128*	*153*
-Rough machining with End Mill (10 bar sample)	*128*	*10.6*	*113*	*149*
-Soft machining with Face Mill (10 bar sample)	*148*	*13.4*	*128*	*162*
-Soft machining with End Mill (10 bar sample)	*140*	*15.5*	*115*	*158*

The electrical resistivity measured for each type of machining is reported in Table II, which indicates an increase of the measured resistivity varying between 0% and 54% depending on the machining method. In particular, the Face Mill gives an increase of the average value varying between 50% (rough machining) and 54% (soft machining), while the End Mill gives an increase of the average value varying between 0% (soft machining) and 23% (rough machining). The standard deviation of resistivity for the samples with no machining is significantly higher than for the machined samples. The surfaces of the machined samples are free of oxide layer, making the resistivity measurements more accurate.

The effect of machining on the saturating flux density B_{max}, the coercive magnetic field H_c, the DC permeability μ_{rmax} , the iron losses is shown in Table III. It is observed that saturation flux density decreases by 5%, while AC losses are increased by 9 – 15%. Coercive magnetic field and permeability are comparable to the values obtained with no machining. For all measurements, the values obtained for soft or rough machining are approximately equal.

TABLE II ELECTRICAL RESISTIVITY WITH & WITHOUT MACHINING (TESTED ON BARS).

	Resistivity (µohm-m)	
	Average	Standard deviation
-No machining (200 bar sample)	*500*	*90*
-Rough machining with Face Mill (10 bar sample)	*770*	*7*
-Rough machining with End Mill (10 bar sample)	*615*	*7*
-Soft machining with Face Mill (10 bar sample)	*750*	*6*
-Soft machining with End Mill (10 bar sample)	*500*	*6*

TABLE III MAGNETIC PROPERTIES WITH & WITHOUT MACHINING (TESTED ON RINGS).

	DC magnetic properties			AC losses (W/kg)	
	B_{max} (T) @ 12 kA/m	H_c (A/m)	μ_{rmax}	60 Hz/ 0.5 T	400 Hz/ 0.5 T
-No machining (6 ring sample)	*1.31*	*401*	*190-210*	*3.4*	*24.5*
-Rough machining with Face Mill (3 ring sample)	*1.25*	*409*	*190*	*3.7*	*26.9*
-Soft machining with Face Mill (3 ring sample)	*1.25*	*414*	*190*	*3.8*	*26.3*

V. DISCUSSION

Changes are observed in the properties of ATOMET EM-1 after machining. First, the transverse rupture strength is increased for all machining methods. The explanation for this enhancement is the removal of the surface layer which presents cracks that will lead to high local stress when subjected to external forces. It seems that soft machining parts have a better surface smoothness since the TRS is better.

Secondly, machining increases the electrical resistivity of the material, except for the case of soft machining with end mill. The increase in resistivity can be explained by the removal of the more conducting surface layer. The lower density in the center of the part can explain an increase in resistivity for most samples.

Thirdly, permeability decreases and coercive field increases after machining. Magnetic permeability and hysteresis losses will be dependent upon the iron density of the part: the lower the density, the lower the permeability and the higher the hysteresis losses. Results seem to demonstrate that machined samples have a lower density, which was expected at the heart of a powder metallurgy part. For this experiment, 40% of the ring thickness was removed by machining. It would be relevant to record the magnetic properties and losses as a function of the percentage of the ring thickness removed by machining. It is possible that removing a lower fraction of the ring thickness would keep iron losses equal to the iron losses with no machining. This is left for further work.

VI. Conclusion

Resin-based SMCs, like ATOMET-EM1 and SOMALOY550 with LB1 are recommended for applications where machining of SMC parts is required.

The effect of machining on the mechanical, electrical and magnetic properties of SMC material ATOMET-EM1 was investigated. A 14 - 32% improvement in mechanical strength is observed after machining. An increase in electrical resistivity up to 54% is also observed. However, machining appears to slightly decrease magnetic properties due to lower iron density in the part center. Saturation flux density decreases by 5%, and AC losses are increased by 9 – 15%. Forty percent of the ring surface was removed by machining. It is expected that losses and magnetic properties may be left unchanged if a lower fraction of the part thickness is removed. But this demonstration has not been made in this paper.

The use of a face mill is recommended for better performance. The choice between rough and soft machining is not a critical parameter.

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