Electrical isolation of coils in Soft Magnetic Composite applications

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Electrical isolation of coils in SMC applications

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ABSTRACT
Soft magnetic composites based on iron powder have a strong potential for improving both the performance and the manufacturing of various electromagnetic components and devices, such as inductors, induction heaters and electrical machines. A new casting or moulding method we have developed makes use of a modified composite, termed SM^2C, or soft magnetic mouldable composite. Use of it makes it possible to design very complex shapes of magnetic flux conductors and also to achieve a better thermal coupling between electromagnetic components, primarily coils and flux conductors. The latter also creates a new type of problem, concerning the electrical isolation between the coil and the flux conductor. Use of SM^2C, increases the demands on the isolation layer, since the molding compound penetrates every single pinhole, potentially creating leak currents or short circuiting. A comprehensive study of suitable coating materials and processes were carried out, an evaluation of the electrical strength of different configurations being made. A model of the wetting of rough surfaces is introduced here and is applied in the test analysis. This model makes it possible to explain why a certain isolation layer can be insufficient, even if the nominal requirements are fulfilled. Multi layer coatings and certain application adjustments are shown to be necessary, in order for the technical demands placed on isolation to be met.

Keywords: Electrical machines, coating, isolation, SMC, wetting.

1. BACKGROUND

Electromagnetic energy conversion is a key technology in many industrial and domestic applications. Various examples of electromagnetic energy converters are actuators such as rotating and linear electric motors and generators, loudspeakers, several types of sensors, magnetic levitation systems, magnetic forming systems etc, as well as energy converters in general, such as inductors and transformers, and induction heating devices, used to facilitate production, enhance product functionality and increase user-friendliness and comfort. In order to maximize energy efficiency, the magnetic core of most actuators is traditionally laminated by the stacking of soft magnetic iron sheets (0.1 mm – 0.5 mm thick). The actuator function is designed in a 2D-plane and is “extruded” in the 3 rd dimension. This imposes strong limitations on the possibilities of building compact and efficient energy converters that would otherwise be possible from the standpoint of physics.

A new magnetic material technology, Soft Magnetic Composites (SMC), has emerged the last two decades. SMC makes it possible to design 3D electromagnetic circuits showing excellent magnetic performance. Properly used, SMC-based designs can result in smaller, cheaper (fewer parts), more efficient solutions to existing design problems, and solutions to problems that until now have been regarded as commercially unsolvable.

SMC magnetic material possesses a wide range of permeabilities, making it useful in most applications. SMC materials can show permeabilities in the order of 800 and resistivities of up to 6 orders of magnitude higher than homogeneous soft magnetic materials, making SMCs the ideal replacement for laminated magnetic structures. When the three-dimensional flux path for SMCs is compared to the two-dimensional for laminates, it is appealing to select the SMC solution, provided it can be fully utilized in the application.

The static losses of SMCs are their weak spot. Iron-based SMCs shows coercitivities in the order of 300 A/m while standard grade silicon iron sheets can have as low a coercitivity as 40 A/m. This means that the break-even frequency between SMCs and silicon iron laminated structures is often in the order of 1 kHz. Below, the silicon iron has the smallest losses. In applications in which air gap losses dominate, SMC is a very attractive alternative, due to its fully isotropic flux path.

Soft Magnetic Composites (SMC) are compounds consisting primarily of soft magnetic particles usually coated with a thin electrically insulating layer and usually joined by high pressure compaction. Sometimes a non-magnetic polymer binder is used and sometimes thermal processing is sufficient to achieve the desired mechanical properties. Using pressing operations limits the geometrical freedom of the flux conductor design. It is also often desirable to add up to 6% Si to the iron particles, making them very hard and brittle and almost impossible to deform plastically in a pressing operation.

The latter makes it necessary to mould rather than press composites having a high content of silicon, hence the term SM^2C – Soft Magnetic Mouldable Composite. A typical SM^2C material contains spherical iron particles of various sizes, bound together by a suitable matrix material and processed by a suitable moulding technology, such as the Rotocast method, developed by the authors. A more comprehensive account of this moulding or casting process is provided in [1].

In order to fully utilize the potential of SM2C, it is essential to have a stress relieved, crystal wall eliminated and surface-isolated particles. The preparation includes heat treatment in carefully specified atmospheres and use of electro-chemical surface-treatment methods.

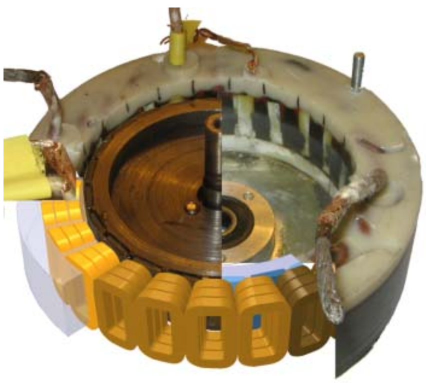

Figure 1: Superimposed picture of a prototype electrical motor showing the electrical windings (coils) and the surrounding cast SM^2C-structure. The white material is an additional isolation layer [2].

Used in a stator circuit of a PM machine, as shown in Figure 1, the resulting PM flux is reduced by 20-50%, depending on the circuit arrangement. This is compensated for to some extent by the reduced thermal barriers in the "slot insulation". Since the winding is present in the moulding process, the core material aligns with the winding in such a way that no pockets of air or excess winding insulation are left. The result is a lower thermal resistance and thus a higher capability to guide heat from the winding into the core and further on to the cooling circuit. This can be used to permit use of a higher current and thus compensate for the reduced flux. Figure 2 shows a sample of the winding and the core material, where the spherical iron particles of different sizes are in immediate contact with the isolation of each wire.

Figure 2: Microscopic picture of the winding and the core material. The wire is 0,7 mm in diameter.

2. PROBLEM DESCRIPTION

Figure 2 illustrates one of the benefits of SM^2C and the moulding technology, but it also reveals one of the technical problems that need to be solved. In a conventional electromagnetic energy conversion unit. the coil can be electrically isolated towards the flux conductor (e.g. the laminated sheet package) by means of a solid isolation material, such as tape or film. In an SM^2C-system this is not sufficient, since the SM^2C particles find their way into each small cavity in the coil structure. Thus, the coil has to be isolated by means of a coating system to cover it, applied by dipping or spraying, for example. Theoretically, it should be sufficient with only one of these coating layers, but in practical applications this is shown to not be the case. The prevent talk addresses this problem, of why a traditional coating procedure is not sufficient, of why more than one single layer of coating is necessary in SM^2C systems, and finally, of what kind of coating materials and coating procedure provide a satisfactory isolation between coil and the SM^2C structure.

3. THEORY

Insulation materials are usually measured in terms of dielectric strength. Dielectric strength is defined as the maximum voltage required to produce a dielectric breakdown through the material. It is expressed in terms of Volts per unit thickness (V/m). This means that the higher the dielectric strength of a material is the better its quality as an insulator. There are different factors that affect the dielectric strength of a material: the thickness of the material, the operating temperature, the frequency and the humidity. There are different test methods to determine the dielectric strength; the most readily used places the material between two copper plates which are energized. What differs in the methods is how the voltage is regulated. One test method starts with 0 volts, this being increased then at a uniform rate until decomposition occurs in the specimen. Other methods have the voltage increase with predefined intervals.

A material can have different dielectric strengths due to possible defects stemming from the coating process, small air bubbles or various defects decreasing the total dielectric strength. Air has a lower breakdown or arc strength than the coating material does. In figure 3 a small defect can be seen in the form of a disc of thickness t located in a coating material of thickness d. In the analog circuit, the capacitance C_c is that of the cavity, the capacitance C_b is that of the material in series with the cavity, and C_a is the capacitance of the rest of the material [3].

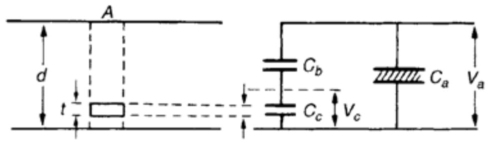

Figure 3: Electrical discharge in a cavity and its equivalent circuit [3].

In reality, most air cavities are spherical. When applying coating on a solid material, the wetting tendency is a factor to take in to consideration. According to the Young equation, the solid-vapor γ_{SV} interface, the surface energy of the liquid-vapor γ_{LV} and the surface energy of the solid-liquid γ_{SL} interface give the surface energy and contact angle θ_e.

$$cos\theta_e = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \quad (1)$$

Another important factor is that of the surface characteristics of the solid, such as its roughness and its porosity. The first of these is dependent on the combination of the coating material and the solid material, whereas the second is dependent upon the handling and the treatment of the material. Theoretical studies as well as experiments on idealized rough surfaces show that peaks and grooves act as energy barriers to the movement of a drop [4,5]. Drops may "jump" when the contact angle exceeds a certain limit. This means that when a drop passes over a top it might entrap an air bubble, as shown in Figure 4 [6].

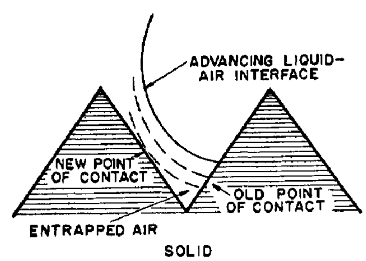

Figure 4: As a liquid advances over a solid, the liquid makes contact with the opposite face and air is entrapped beneath the drop [6].

The air bubble may then be trapped in the coating and, as it hardens, the coating also gets thinner through excess coating material dropping off. If the coating gets thinner than the bubble, it may burst and create a pinhole that becomes a weak spot in the protective layer.

The sequence of breakdown of a sinusoidal alternating voltage is shown in figure 5. V_a is the voltage applied across the material, the dotted line shows the voltage that would appear if the material did not break down due to the defect. When V_c reaches V^+, a discharge takes place, the voltage V_c collapsing. The voltage then starts to increase again across the defect to reach the level V^+ and then collapses again. This can occur several times as the voltage increases as well as when it starts to decrease and reaches V^-. The discharges in the cavity may damage the coating around it due both to the rise in temperature and to chemical degradation of the material.

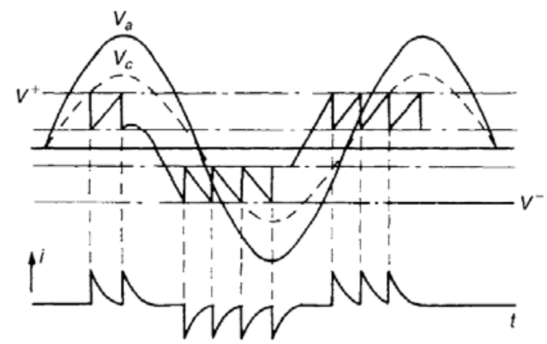

Figure 5: Sequence of cavity breakdown under alternating voltages [3].

4. COATING MATERIALS STUDIED

The coating materials that were tested had to be electrically insulated and have the ability to cover the whole coil evenly without any pinholes. If the coating is not applied with a uniform thickness, the coil may not fit into the mould when it is assembled. Applying the coating to the coil needs to be easy to implement in a manufacturing process. It is also important that the costs of the production process be kept as low as possible. Some of the coatings tested here did not fulfill all of the criteria, but were included in the tests in order to provide an adequate overview of available coating systems.

Ultimeg 2000/380 is a high flash, alkyd phenolic that produces tough, resilient insulating films having excellent electrical and bond strength characteristics at all operating temperatures up to Class H (180°C). The varnish provides excellent penetration into the windings, together with clean drainage and low tendency for secondary drainage to occur. The coating is applied by dipping the coil in the coating material and then drying it at 130°C for 4 hours.

Voltatex® 4250, a one-component impregnating resin, is an unsaturated polyester imide resin specially developed for the Electrical-UV-Process. The resin can also be applied in a conventional Dip & Bake process. The curing time is only 10 – 15 minutes and it provides an insulating system of thermal Class H (180°C). It is specially developed for windings in electrical motors, transformers and high rotating armatures, for example.

INFRALIT PE 8350 is a TGIC-free polyester powder based on a polyester resin. The powder is applied by spraying it on the detail. At elevated temperatures, the powder melts, cures and forms the final paint film. It is suitable for objects that require a weather-resistant coating. It does not have any thermal classification, but it should be able to withstand 180°C for long periods of time.

Epoxy MagComp is an anhydride-free epoxy system for filament winding having good fiber wetting abilities. The coating is applied by dipping the coil in the epoxy it can then be cured at various temperatures for differing amounts of time. Specifics depend on production-related issues and the upper usage-temperature limit.

MF 8001 NV is a monomer-free, one-component impregnating and trickle resin based on a specially modified, unsaturated polyester resin. It is applied by either a conventional Dip & Bake process or by placing the coil in the coating while running a current through it so that the temperature rises and the coating pre-cures before it is later cured in an oven. The coating is of thermal class H (180°C).

Parylene N is a chemical vapor-deposited poly(p-xylylene)-polymer used to provide as moisture and dielectric barriers. The resulting film is thin and conforming, has no pinholes, and resists the effects of organic solvents, inorganic reagents and acids. Parylene serves multiple purposes, including those of electrical insulation, moisture and chemical isolation, mechanical protection, enhanced lubricity, and surface consolidation to avert flaking or dusting.

5. EXPERIMENTAL SETUP

An electrical coil was designed and manufactured in order to be able to test the coating under conditions similar to realistic ones. Coils used in SM^2C applications are usually made of Litz wire. They consist of thin copper wires twisted together so that the threads are evenly distributed over the cross section. The test coil should have a base shape with the same characteristics as a real one in order to emulate all difficulties encountered in the coating operations. Since a round shape was considered to be too simple, a square shape with a relatively sharp corner radius was chosen, see Figure 6.

Figure 6: Uncoated coil.

The copper wire used is bondable and is coated with three layers: THEIC-modified polyester imide as the base, Polyamid-imide as the overcoat and modified aromatic polyamide as the bonding coat. Thus when the coil was wound and was heated to 200 °C, the bonding coat glued it together to prevent it from losing its shape, as shown in Figure 7. Figure 7 also illustrates the surface characteristics of the test coils that were studied.

Figure 7: Illustration of a cross section of an uncoated coil.

On order to investigate the effect of possible fat and other dirt, a cleaning step was performed on half of the coils. They were dipped in ethanol and then air dried for a couple of hours. It is especially important that all the ethanol evaporates so that there are no remainders of it left when the coating is applied, which would interfere with the coating.

Table 1. Overview of the number of coatings on each coil and test setup.

Material	Designation	Number of coatings	Cleaned
Ultimeg 2000/380	CU	1	No
	CUc1	1	Yes
	CUc3	3	Yes
	CUc5	5	Yes
Voltatex® 4250	CV	1	No
	CVc1	1	Yes
	CVc3	3	Yes
	CVc5	5	Yes
INFRALIT PE 8350	CLc1	1	Yes
	CLc2	2	Yes
Epoxy MagComp	CE	1	No
	CEc1	1	Yes
	CEc3	3	Yes
	CEc5	5	Yes
MF 8001 NV	CM	1	No
	CMc1	1	Yes
	CMc3	3	Yes
	CMc5	5	Yes
Parylene N	CP10µ	1	Yes
	CP25µ	1	Yes

Ultimeg 2000/380

The coating was applied by dipping the coil in the coating and then placing it in an oven at 140 °C overnight. For CU and CUc1, the first test was conducted after a single coating. CU then got 2 more layers of coating before a new test (CUc3) was conducted, whereas CUc1 got four more layers of coating before a new test (CUc5) took place, see Table 1.

Voltatex® 4250

This coating was applied by dipping the coil in it and then hanging it in a UV-box. The UV-light was on for 15 minutes. The first test for CV and CVc1 was conducted after a single coating. CV was then given 2 more layers of coating before a new test (CVc3) was conducted, whereas CVc1 got four more layers of coating before a new test (CVc5) took place, see Table 1.

INFRALIT PE 8350

This powder was applied by spraying it on the coil from multiple directions, which was then placed in an oven at 200 °C for 1 hour. Five coils were coated once and 5 others twice, see Table 1.

Epoxy MagComp

This coating was applied by dipping the coil in the epoxy and then hanging it to dry in room temperature for 8 hours before it was then placed in the oven at 65 °C for 24 hours. The reason that the epoxy was first kept at room temperature was that when it is warm its viscosity is low, and it would probably drain off. For CE and CEc1, the first test was carried out after a single coating. CE was then given 2 more layers of coating before a new test (CEc3) was conducted, whereas CEc1 got yet another four layers of coating before a new test (CEc5) was carried out, see Table 1.

Dobeckan® MF 8001 NV

This coating was applied by holding the coil in the coating material for 10 minutes while current were run thru it until the temperature was stable at 130 °C. The coil temperature was calculated by measuring the current and the voltage across the coil. It was then placed in an oven at 130 °C overnight for drying. For CM and CMc1, the first test was made after a single coating. CM then got 2 more layers of coating before a new test (CMc3) was conducted, whereas CMc1 got four more layers of coating before a new test (CMc5) was carried out, see Table 1.

Parylene N

The coating was applied through vapor deposition in a chamber. Due to the complex coating method and the equipment that was needed, the coating was performed at Para Tech Coating Scandinavia AB. Five coils received a 10 µm coating and 5 others a 25 µm coating. One test per coil was performed, see Table 1.

The process of drying the coating differs from coating to coating, but for liquid coatings the way they are placed can make a difference. If the coil is hang-dried, the coating may flow towards the bottom. Since this means that the coating becomes uneven, it is difficult to determine how well the coating works. One of the coatings was thus dried while it was slowly rotated at 1,5 rpm. Twenty-five coils were coated with Ultimeg 2000/380 with differing numbers of layers, see Table 2. One batch, for test coil CUht was exposed to high temperature. The bonding coat on the wires can only withstand 220 °C. If it is exposed to higher temperatures the copper wire loses its shape, Figure 8. Five of these coils were included in the test to determine whether it made any difference whether or not the windings were separated.

Table 2. Overview of the coils that were rotated while curing.

Designation	Number of coils	Number of coatings
CU3	5	3
CU6	5	6
CU9	5	9
CU12	5	12
CUht	5	3

Figure 8: A coil that has lost its shape.

The metal powder in the SM^2C has a diameter of from 10 µm up to 500 µm. This means that the powder has the ability to penetrate almost any pinhole or cavity. The test method must thus be able to emulate this in order for accurate results to be obtained. By experimenting, the research group found that placing the coil in water was quite similar to molding it in SM^2C. This made it possible to sometimes determine where the electrical isolation coating was the weakest, through the bubbles that are created by the leaking current, or through the occurrence of small electric arcs.

The method for testing the coating was to connect one end of the coil to a variable power supplier, and to use accurate current and voltage meters, Figure 9. It is important to place the other end of the coil above the water level, so that it will not short circuit through the water. Connecting the negative pole from the power supply to a conducting container and then placing the coil in the container, which is filled with dielectric tap water makes it possible to measure the leak current. The power supply is programmed to turn off if the current exceeds 10 mA. The voltage is increased incrementally, measurements being made at 100 V steps, starting at 0 V.

According to the directive IEC 61558, the current leakage from all the coils in the machine has to be lower than 10 mA at 3 KV.

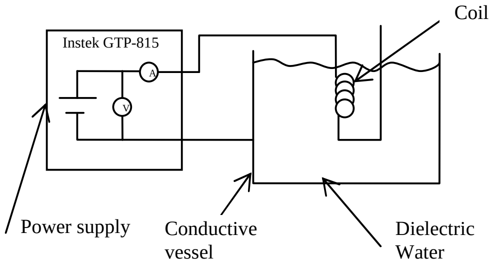

Figure 9: Schematic view of the electrical test setup.

6. EXPERIMENTAL RESULTS

6.1. Limitations

The reason that Parylene were not coated more than once was that, according to the manufacturer, it should withstand 6 KV or more at a thickness of the coating of 25 µm. The reason it did not meet these expectations is not clear at the moment. One reason could be that the coils were only loosely bonded together prior to coating. This would mean that although the coils may have been stable enough to coat, but with the thin layer of 25 µm of coating, there may have been small cracks introduced in the coating while handling. This could explain its failure to pass the test. Even a single layer of Parylene coating takes a long time to apply .Thus, it would not seem reasonable to coat it with a thicker layer.

The coated coil has to be able to withstand 3 KV for one minute. In the testing carried out, a power supply (Instek GTP-815) having a maximum output voltage of 5 KV was used. This is sufficient to test the coating.

6.2. Analysis

As can be seen in Figure 10, none of the single-layer coatings are close to the 5 kV limit. The closest one is INFRALIT PE 8350 at just below 1800 V. When the cleaned coils are compared with the uncleaned ones, no appreciable difference could be observed. In fact, in some cases the uncleaned coils showed higher voltage levels than the coils that were cleaned.

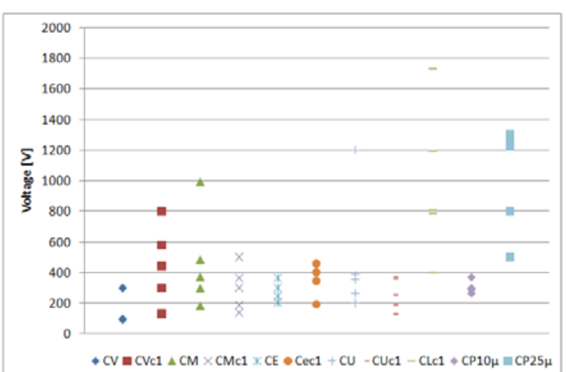

Figure 10: Coils coated with one layer.

The variations in each coating are extensive. It is only CP10µ that shows a small degree of variation, but it also has a low-voltage resistance. CP25µ is the second best, but it shows a strong variation in the results obtained. Both CLc1 and CP25µ are relatively even, but because of cost considerations no further tests on CP25µ will be carried out.

Because of the low voltage that the coils could handle in a single layer, more tests were performed. The coils were thus given new coatings. The results are shown in Figure 11 - 15.

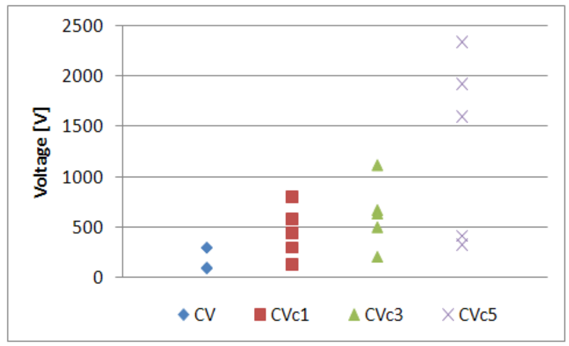

Figure 11: Coils coated with Voltatex® 4250 differing number of layers.

The Voltatex® 4250 coating voltage resistance increases with the amount of layer applied, as can be seen in Figure 11. There is a small difference between CV and CVc1 that could indicate that the cleaning step made a difference. The variation in the case of three and even five layers is rather large, some of the results there being as low as for the coils having only one layer.

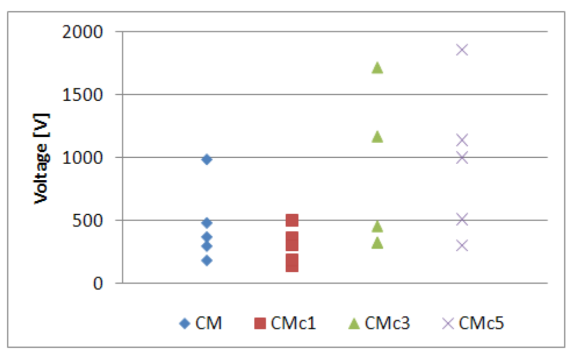

Figure 12: Coils coated with Dobeckan® MF 8001 NV differing numbers of layers.

The Dobeckan® MF 8001 coating shows no important differences based on the coil having been cleaned or not, as can be seen in Figure 12. A coating of several layers results in the voltage resistance being higher, but the difference is not great. The variation are also very large, even with use of multiple layers, some of the coils coated with multiple layers breaking down at the same voltage as the one-layer coils do.

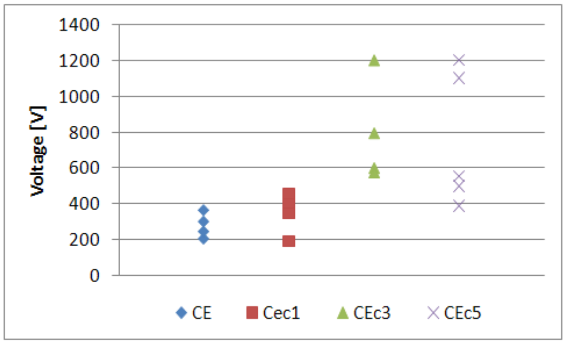

Figure 13: Coils coated with Epoxy MagComp with different numbers off layers.

In Figure 13, a small difference between CE and CEc1 is evident, but it is well within the margin of error, indicating that the cleaning step made no appreciable difference. CEc3 and CEc5 have a higher voltage resistance than CE and CEc1, but there is no significant difference between the first two of these. The maximum voltage is also quite low even with use of five layers, and the degree of variation is high within both CEc3 and CEc5.

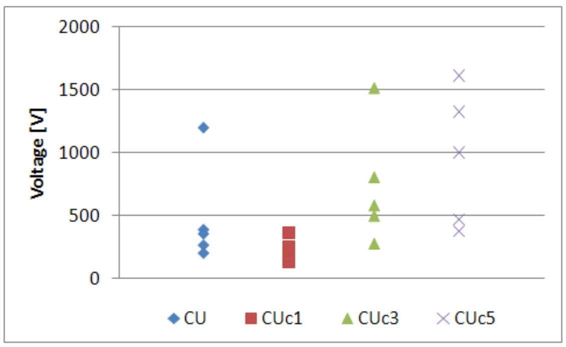

Figure 14: Coils coated with Ultimeg 2000/380 with different numbers off layers.

One of the coils in the test series CU in Figure 14 had more than twice as high a voltage resistance as the others in the same series. This is probably due to nearly perfect conditions during coating, and probably does not occur often. The differences between CU and CUc1 are small and indicate that cleaning does not make any appreciable difference. CUc3 and CUc5 have a high degree of variation, some of the coils tested having the same voltage resistance as CU and CUc1. The difference between CUc3 and CUc5 is small.

The INFRALIT PE 8350 coating layer is quite thick if one compares it with the others. This makes it inappropriate to coat with more than two layers of it. The results are shown in Figure 15.

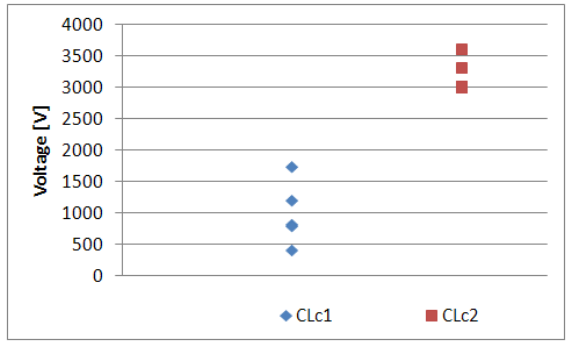

Figure 15: Coils coated with INFRALIT PE 8350.

The variations in CLc1 are high, but the maximum voltage resistance is also high, especially for only one layer. CLc2 shows only a small variation at a high voltage resistance. It varies between 3 kV and 3,6 kV which is the best of the tests so far.

The rotating coils were coated with Ultimeg 2000/380. The results are shown in Figure 16.

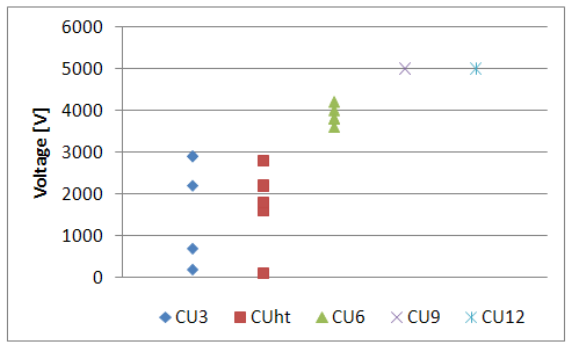

Figure 16: Coils coated with Ultimeg 2000/380 with different numbers off layers while rotating during curing.

As can be seen in Figure 16 there is no significant difference between CU3 and CUht, even though CUht has lost its shape compared with CU3. The curing during rotation appears to improve the voltage resistance there as compared with Figure 14. It was also found that with six layers of coating the variations are quite small and are at an acceptable voltage level. As can be seen in Figure 17, CU12 has a thicker layer of coating than CU3. This means that the mechanical tolerances are affected considerable. As already indicated since the power supply cannot exceed 5 kV no measurements could be made above this level.

Figure 17: From left; CU3, CU6, CU9, CU12.

When examining the coils in a microscope, small air bubbles were discovered. The bubbles are always located in a valley on the coils. This means that air has been trapped there when the coating were applied.

7. DISCUSSION AND CONCLUSIONS

It is shown that the number of coating layers affects the dielectric test result. Yet due to defects, such as air bubbles that get trapped in the coating while the coating is being applied, the voltage required to exceed 10 mV is much lower than in a perfectly coated material.

The variation found in most of the coating tests was high. This is partly due to bubbles that are sometimes found in the coating. When the coils are rotated the coating is more evenly distributed on the coil. It is obvious that a thicker layer helps to protect the coil and reduces the effects of defects. It is also difficult to obtain a uniform thick layer of coating, and it is thus impossible to calculate accurately the dielectric strength.

One way of improve the dielectric strength of the coating is to put on multiple layers so that the pinholes of the one layer are covered by the next layers. Unfortunately, the time this takes involves considerable costs and affects the mechanical tolerances of the coil. It was also shown that putting on several layers does not guarantee the achieving of a high dielectric strength. For Ultimeg 2000/380, there have to be 6 layers of coating, which is cured while rotating, in order to obtain a low degree of variation in the results and a sufficiently high level of dielectric strength to pass the test criteria of 3 KV with a leaking current of less than 10 mV.

The results presented in Figure 15 show that INFRALIT PE 8350 may be a suitable coating material for coils that are to be molded in to SM^2C.

8. ACKNOWLEDGMENTS

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