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ELECTROPHORETICALLY APPLIED DIELECTRICS FOR AMORPHOUS METAL FOILS USED IN PULSED POWER SATURABLE REACTORS.

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ABSTRACT

Amorphous metal foil-wound inductors have been tested as ferromagnetic saturable inductive elements for pulsed-power (multi-terawatt) switching modules in the inertial confinement fusion program at Sandia National Laboratories.

In simulated capacitor testing premature dielectric breakdown of thin polyethylene terephthalate film insulation in the inductor windings occurs at considerably below 2500 V. This appears to be due to inadvertant dielectric damage from micro-spikes on the amorphous foil surface. Electron micrographs and dielectric breakdown data illustrate that electrophoretically-applied dielectric coatings, deposited from organic aqueous colloid dispersions, can be used to provide insulating coatings on the foil which provide a 240% improvement (6000 V) in the breakdown strength of wound amorphous foil inductors.

The theory and operation of a dedicated electrophoretic continuous coating system is described. The machine was constructed and successfully applied for dielectric coating of amorphous metal foil. Additional possible applications exist for practical dielectric coating of metallic films or foils used in various commercial wound-type capacitor structures.

INTRODUCTION

For the past several years, there has been a program at Sandia National Laboratories (SNL) to develop magnetic switches (ie. saturable reactors) for possible use in multi-megavolt, multi-terawatt, pulsed power modules (PPM) of the type that are used to drive many large accelerators (PBFA-II, Hermes-III, Saturn, etc.). In a PPM, energy is taken over a period of a few minutes from the power grid at a relatively low power level and then after several stages of pulse compression, the energy is delivered to a load in a few tens of ns at a very high peak power level. A magnetic switch is simply an inductor with a core of ferrimagnetic or ferromagnetic material. A description of the operation of magnetic switches is described elsewhere [1], but basically it is the nonlinear magnetic property of the core that enables the inductor to operate as a switch in a PPM. A simplified circuit of a typical PPM with 3 stages of pulse compression is shown in Fig. 1. The nonlinear inductors in the last two stages represent magnetic switches. When the 1st switch in the circuit closes, the energy in the 1st capacitor is transferred to the 2nd capacitor in a time determined by the inductance in the 1st loop. During this time the1st magnetic switch, MS1, operates like an open switch because of its very high inductance. By design, when the 2nd capacitor voltage reaches peak, MS1 saturates and its inductance drops by 2-3 orders of magnitude (ie. the switch closes). The energy in the 2nd capacitor is then transferred through the saturated inductance of MS1 to the next stage. Pulse compression is therefore accomplished by designing the circuit such that the saturated inductance of each succeeding stage decreases.

In pulsed power applications, an amorphous ferromagnetic material (Metglas), which has superior magnetic properties, is usually used in magnetic switch cores. Since metglas is only available in ribbon form, cores which use this material must be constructed in a tape wound geometry. As in a conventional inductor core, adjacent layers of magnetic material must be electrically isolated to minimize eddy current losses. In pulsed power applications, the inter-lamination voltage can be as high as a kilovolt. Conventional industrial approaches for core insulation have been found to be inadequate. Consequently, a thin (6-12 micrometer) dielectric film such as Mylar is wound between the Metglas layers to provide inter-lamination insulation. To enhance the performance of the magnetic switch, it is desirable to minimize the thickness of the dielectric material in order to maximize the core cross section ratio of magnetic material area to total area. The successful operation of long lifetime magnetic

switches in PPM's at the 300 kV, 10 GW level has been demonstrated. [2] However, in tests of large (6ft. diameter, 200 kg) magnetic switches at the 2.7 MV, 3.7 TW level, the switches had unacceptably short lifetimes (< 100 pulse shots) due to a uniform distribution of internal lamination dielectric breakdowns throughout the core. [3] This was unexpected because the switches in this experiment had been designed so that the peak electric field in the insulation would be an order of magnitude below the normal failure level of the insulation. The cause of this low level failure has been identified in small scale experiments [4] to be due to the surface roughness of the Metglas ribbon. Since Metglas is a cast rather than rolled material, it has a significantly rougher surface than the smooth aluminum foil conductors found in Mylar capacitors. The degradation to thin (< 25 micrometer thick) dielectric films occurrs during the winding process. This degradation can, however, be eliminated by planarizing the Metglas surface with an electrophoretically (EP) deposited dielectric film prior to winding.

Beginning in approximately 1920, a large number of patented and generic techniques for EP application or deposition of organic or polymer coatings from a liquid bath have been developed. [5,6,7] In principle, any material which can be dispersed with an electrical charge in a liquid can employ EP to deposit coatings onto an electrically conductive substrate. One system employing an aqueous colloidal dispersion of styrene acrylate copolymer has been extensivley investigated at SNL and used in a variety of dielectric coating applications.

EXPERIMENTAL COATING

Fig. 2 schematically illustrates the use of electrophoresis to coat an anodically biased foil. The negativly charged particles in the bath are attracted to the positive anode where they coalesce as a tacky coating. Uniformity of coating thickness is insured due to the self limiting effect produced by the insulation resistance of the coating. Following deposition the coating is cured or crosslinked at elevated temperatures. In this work, a DuPont styrene acrylate copolymer, RK 5004, was used as the EP bath. It contains butyl cellosolve, diethyl ethanol- amine, a proprietary melamine curing agent, and water. One part of the as-supplied resin was diluted with eight parts additional water to make the coating bath. An anodic current density of one mA/cm^2 of foil area was used.

Fig. 3 schematically illustrates the continuous electrophoretic coating apparatus constructed for coating 2 inch wide, one mil thick, Metglas (2605CO) foil. EP deposition took place in a cell 5 inches in depth at a constant current of 87 mA. The foil admittance gland at the bottom of the cell was allowed to leak solution into a catch reservoir whereupon it was filtered and pumped back to the coating cell. Air knives were used to remove excess electrolyte from the emerging foil thereby eliminating the need of a water rinse step. The coating was cured in a 12 foot high cylindrical drying-heating column at approximately 210^{o} C. The column was wound with nichrome heater wire to offset thermal losses throughout its length. The Metglas transport rate through the system was 6.72 inches/min. yielding a dwell time of less than one minute in the EP cell and 42.8 minutes in the curing oven. In order to avoid particulate contamination, the entire system was constructed in an enclosure and pressurized with HEPA filtered air. The heating column was also supplied with HEPA filtered air.

RESULTS

An SEM micrograph of a typical surface defect on bare Metglas at 200X magnification is shown in Fig. 4 To demonstrate the degradation that results when a thin dielectric film is pressed against this surface, 27 small 1 inch diameter, 30 turn, 2 inch wide capacitor structures with Metglas conductors and 12 micrometer thick Mylar insulators were wound. The capacitors were then vacuum impregnated with Flourinert FC-77 and tested in the Capacitor Breakdown Tester (CBT) depicted in Fig. 6. In the CBT, the voltage on the test capacitors was gradually increased at a rate of about 10kV/Minute until the insulation failed. As shown in Fig. 7, the resulting breakdown distribution had a mean of 1.62 MV/cm and a standard deviation, alpha, of 55.7%. When this distribution is compared with the one in Fig. 8 for similar capacitors with smooth-surfaced aluminum conductors (mean = 4.27 MV/cm and alpha =18.7%), the degradation with Metglas is obvious.

When Metglas is EP coated, its surface quality is vastly improved. SEM micrographs at 350X magnification of Metglas samples before and after nominal 12 micrometer thick EP coatings are shown in Figs. 4 & 5. The coarser features are significantly smoothed and the background roughness is masked. In order to assess the value of the improved Metglas surface quality in preventing insulation degradation, 9 small 1" diameter, 30 turn, 2" long capacitors with EP coated Metglas conductors and 0.5 mil Mylar insulators were wound and tested in the CBT. The resulting breakdown distribution, shown in Fig. 9, had an alpha of 5% and an estimated mean breakdown field of 3.97 MV/cm. The breakdown field could only be estimated because the dielectric thickness in the capacitors was not constant. The EP coating had a nominal thickness of about 0.25 mil which is not sufficient to cover the largest protrusions on the Metglas surface. If uncovered protrusions on adjacent conductor surfaces did not align, then the minimum dielectric thickness in the capacitors would have been 0.75 mil. It is this value for dielectric thickness which was used to estimate the breakdown field. Even with the uncertainty in the breakdown field, the tightness of the distribution demonstrates that the mylar is not degraded when wound with Metglas whose surface has been planarized with an EP coating.

CONCLUSIONS

Metglas foil wound with mylar in capacitor-like structures for use in ferromagnetic saturable inductive elements has a surface which yields unacceptable breakdown voltages. This study has demonstrated the use of electrophoretic deposition in applying a thin, uniform polymer dielectric which "planarizes" the surface thereby improving subsequent inter-laminar breakdown potentials by a factor of about 2.4. The electrophoretic coating processor constructed for this study is capable of additional scale-up and may be run continuously for economical coating of large throughput quantities. The system design may have additional value for use in coating a variety of foils for use in other capacitor-like structures.

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TYPICAL PULSED POWER MODULE

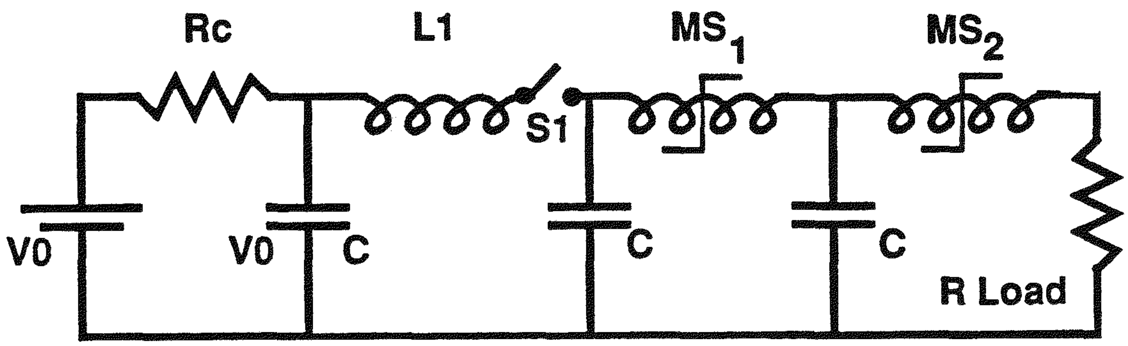

Fig. 1

Simplified circuit, Fig. 1, of a typical pulsed power switching LC network showing three stages of pulse compression. The nonlinear inductors in the last two stages represent magnetic switches.

ELECTROPHORETIC DEPOSITION PROCESS

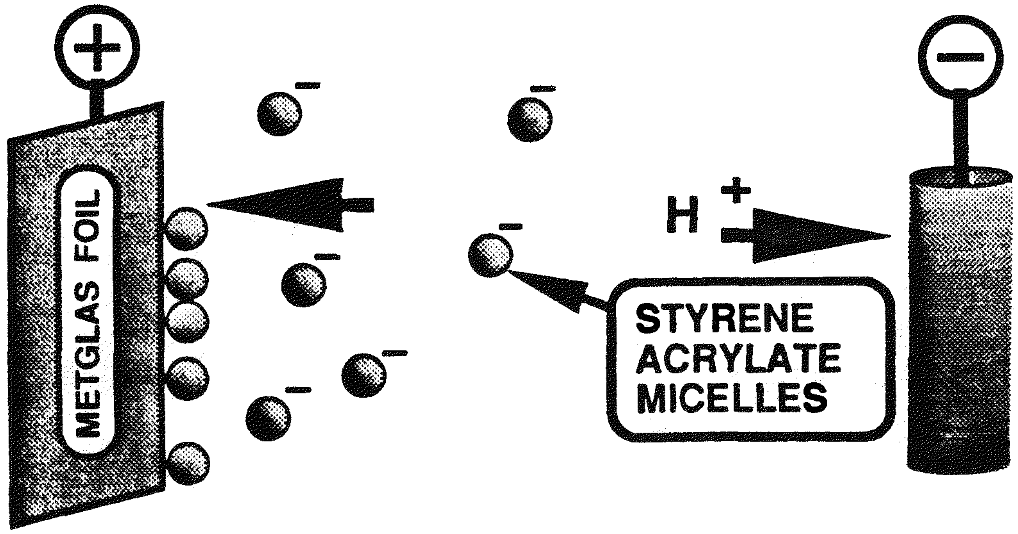

Fig. 2

Negativley charged organic micelles (styrene acrylate) are attracted to and coalesce upon a positive electrode (Fig. 2). The coating is later cured at elevated temperatures.

ELECTROPHORETIC COATING MACHINE

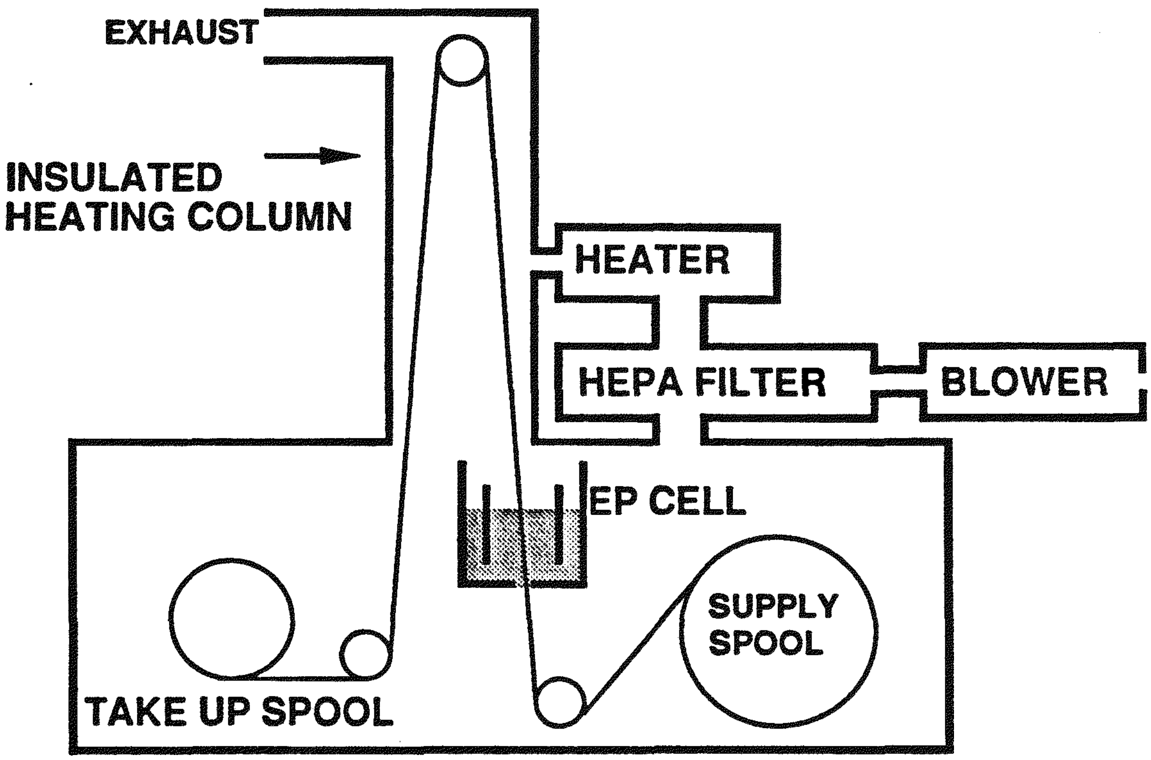

Fig. 3

Electrophoretic coating may be performed continuously. The system shown in Fig. 3 has been used to dielectrically coat hundreds of feet of two inch wide Metglas foil.

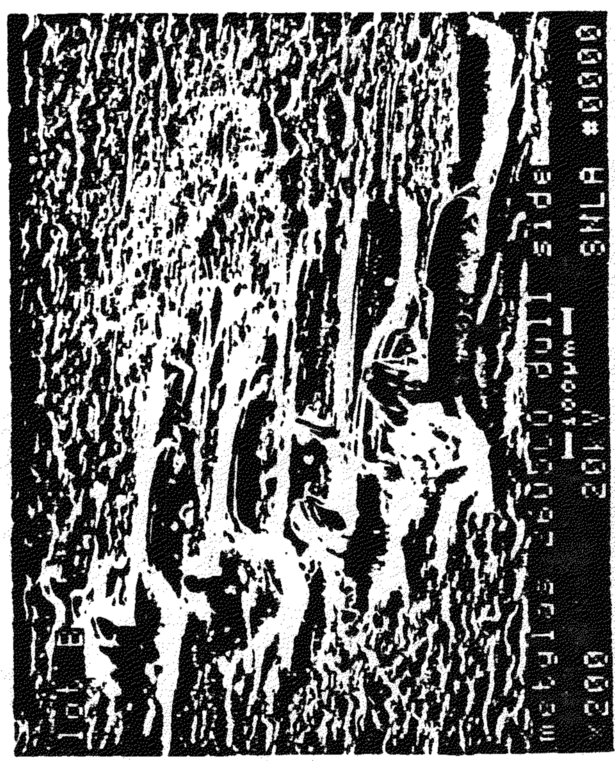

Fig. 4

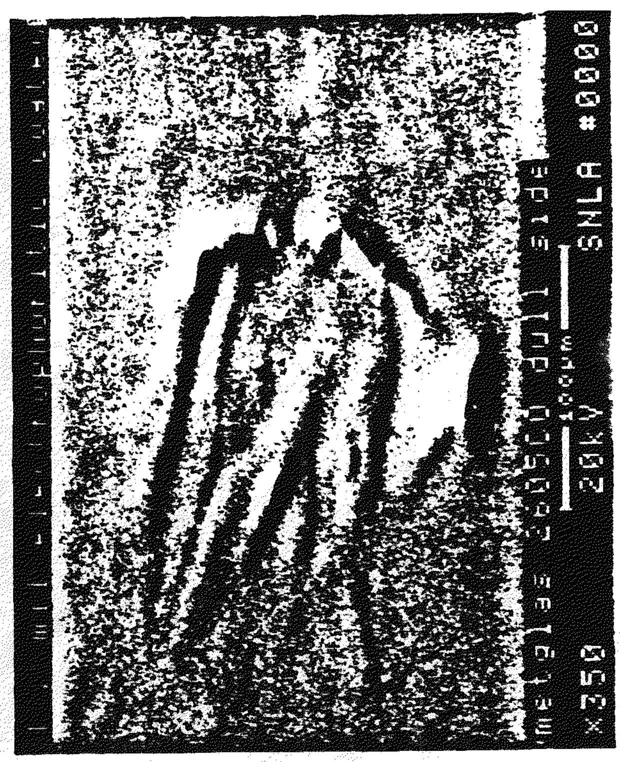

Fig. 5

Before , Fig 4 , and after, Fig 5, SEM micrographs show planarizing effect of electrophoretic coating on Metglas foil samples

Sharp

CAPACITOR TEST CIRCUIT

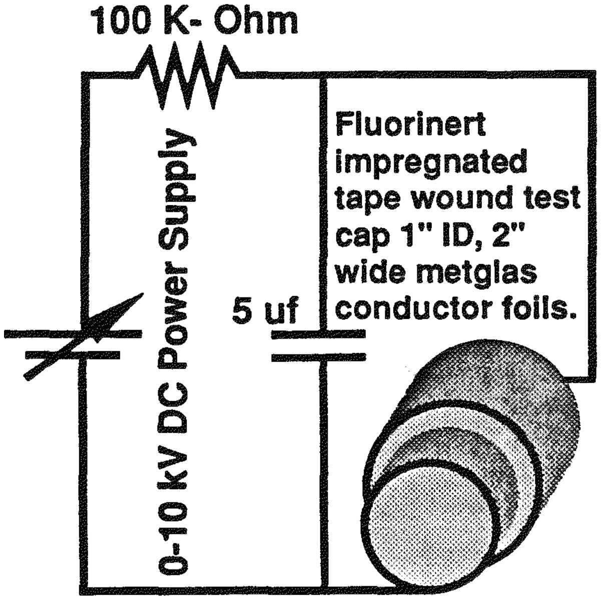

Fig. 6

Capacitor breakdown circuit used to evaluate Metglas foils.

METGLAS

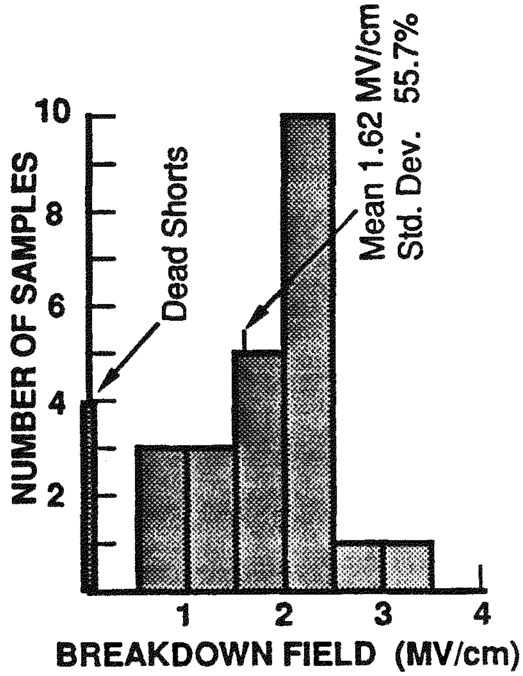

Fig. 7

Dielectric breakdown distribution for non-coated Metglas foil.

ALUMINUM

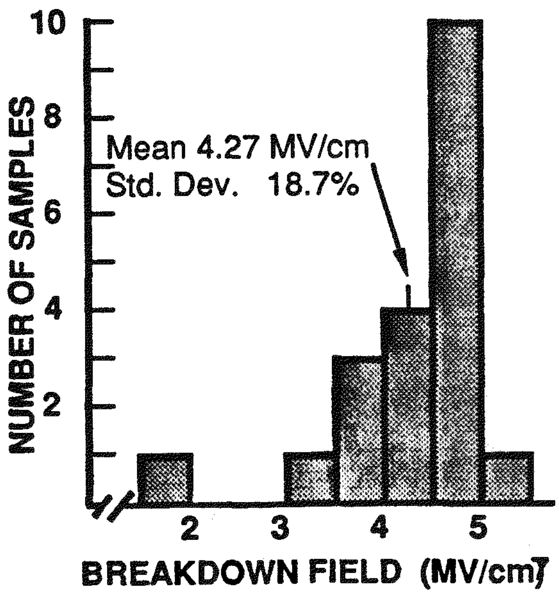

Fig. 8

Dielectric breakdown distribution for smooth aluminum foil.

ELECTROCOATED METGLAS

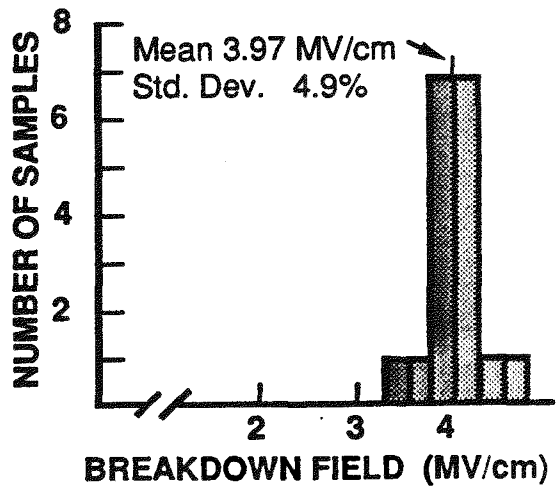

Fig. 9

Improved dielectric breakdown distribution for EP coated Metglas foil.