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Investigating Effects of Composite Dielectric Material Components and Temperature on Breakdown Strength

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***Abstract* – Breakdown measurements under applied AC voltage stress at a constant temperature are presented for pure epoxy, epoxy containing mica tape and epoxy containing glass mat tape. These form the individual components of the composite insulation system as used in the main dipole bending magnets at the ISIS neutron and muon source. Results are presented as Weibull plots from which characteristic breakdown fields (scale), and shape parameters are calculated. Subsequently the measurements are repeated over temperature on epoxy samples containing mica. A slight decrease in breakdown strength occurred when glass fibre mat was included, whereas the presence of mica caused a significant increase. The difference in breakdown strength between the different sample types are discussed in terms of the theories of electrical breakdown, and ultimately were related to the tensile strength of the corresponding materials.**

***Keywords* — Breakdown, mica, epoxy, characteristic breakdown field, Weibull plot.**

I. Introduction

The ISIS neutron and muon source is a high energy particle accelerator located at the Rutherford Appleton Laboratories in Oxfordshire, UK. To produce neutrons, H^- ions are accelerated in a linear accelerator up to approximately 70 MeV. These are then injected into a synchrotron, where they are stripped of electrons and the remaining protons are accelerated up to 800 MeV [1]. These high energy protons are constrained by substantial electromagnetic fields, which are generated by electromagnets. There are several types of magnets – quadrupole, dipole, AC, DC and pulsed, each with a different function. The magnets of primary interested here are dipole bending magnets (DBM's) driven with AC voltages of up to 15 kV with a small DC voltage component of around 100 V. The DBM's are 4 m long, and consist of a series of copper conductors arranged in six stacked "racetrack" coils. The coils themselves are individually wrapped in mica backed tape and glass tape. The entire stack is then wrapped in successive mica tape and glass tape, and embedded in an epoxy resin by vacuum impregnation, resulting in a "composite" dielectric. The composite is subjected to multiple stress factors that affect the DBM's during normal operation; namely electric field, temperature cycling, mechanical vibration at various frequencies (predominantly 50Hz), moisture ingress, ionising radiation and physical ageing. The primary stress factor is the AC / DC electric field, as this drives the breakdown. However, any of the given stress factors will induce a change in the physical and chemical properties of the system if they are of a sufficient magnitude, and given sufficient time. The resultant changes in the structure of the composite will then change the overall electrical performance of the system, which can be observed in many parameters such as the material dielectric permittivity or its electrical breakdown strength.

Here, the breakdown strength of the composite was examined by isolating each of the glass and mica components individually within epoxy resin and comparing them with pure epoxy. These were subjected to AC voltage stress tests at room temperature. Additionally, the mica containing component was investigated over a range of temperatures. To establish a suitable geometry for the test samples the historical failures of the DBM's were examined, where the most common failure site had an insulation thickness of 6.5 mm.

Given:

$$E = \frac{V}{d} \tag{1}$$

where E is the electric field, V is the voltage and d is the distance between conductors. The breakdown voltage of epoxy resin is 26 kV / mm [2] and so from (1) the voltage required to breakdown the pure epoxy is 169 kV. Consequently, scaled samples were manufactured to allow lower test voltages whilst maintaining the same electric field.

II. Experimental

A. Sample preparation

Three types of samples were prepared: pure epoxy (EP), epoxy containing mica (EM), and epoxy containing glass fibre (EG). The epoxy formulation was identical to that used in the DBM's, and is shown along with mixing proportions in Table 1. The mica tape (Kremica.por K3015-14) and the glass fibre tape (Vidatape AS) were identical to those in the DBMs.

Twenty EM and EG samples were prepared, and five EP samples (due to the difficulty of removing them from the mould without breaking) for the room temperature tests. Separate EM samples were prepared for the elevated temperature testing. Five EM samples were tested at 40 °C and 80 °C, and six tested at 60 °C. All samples measured 75 x 75 x 0.5 mm. The thickness was measured at 5 points across each sample using a micrometer and an average taken.

TABLE 1: Components Of Epoxy Resin And Relative Proportions By Weight

Component	Product	Chemical name	Proportion by weight
Epoxide resin	MY740	Diglycidlether of bisphenol A (DGEBA)	100
Hardener	HY906	Methyl Nadic Anhydride (MNA)	80
Accelerator	DY073-1	Tributylamin Phenol Diethylphthalate	10

The mica layer profile consisted of two layers of half lapped paper backed mica tape. The glass fibre profile consisted of two layers of butt lapped glass tape. In both the EM and EG samples, the tapes were hand wound around an aluminium form prior to vacuum impregnation. The DGEBA and MNA were mixed in the proportions shown in Table 1 and degassed in a vacuum (2.3 x 10^{-1} mBar) at 50 °C for 16 hours. Accelerator was added and the mixture was returned to the vacuum chamber for an hour to remove any trapped volatiles. Next, the mixture was flowed (under vacuum) into moulds, and over the aluminium, tape wrapped, plates. These were then gelled in between hot plates mounted in a large press at 95 °C for 16 hours. Finally, they were removed from their moulds and placed on curing plates in an oven at 122 °C for a further 15 hours.

Prior to testing samples were conditioned at 50 °C in a vacuum oven to remove any residual moisture. To confirm that all moisture had been removed the samples were weighed several times over a 48-hour period until the mass had stabilised. The samples were stored in an airtight container with desiccant.

B. Breakdown measurements

Testing was carried out under oil (Silicon Allcosil 200/350) to prevent surface tracking. The test set up was contained within an oven to control temperature. The oven was set to the test temperature with the oil bath in situ and left to stabilise. The temperature of the oil bath was verified using a Fluke thermocouple reader (using K-type thermocouples). Measurements were taken with the thermocouple submerged and in contact with the electrode to ensure a uniform temperature throughout the oil. The dried samples were individually placed in the oven 15 minutes before testing began to ensure they were at thermal equilibrium with the apparatus. The electrode configuration consisted of a brass cylindrical HV electrode with a 1 mm edge radius fillet, and a larger, flat plate ground plane with a 1 mm edge radius fillet. The fields generated by the electrodes were uniform neglecting edge effects, which were partially moderated by the fillets. An AC high voltage (50 Hz, 100 kV_{rms},100 mA Haefely dielectric test set) source was connected across the electrodes, with the smaller electrode at the high potential. The sample under test was sandwiched between the electrodes. Voltage was then applied in 1 kV_{rms} steps from 0 kV with a constant ramp rate and a 30 s dwell time at each test step until breakdown occurred. Breakdown was considered to have occurred when the current limit was tripped on the test set (fixed at 100 mA).

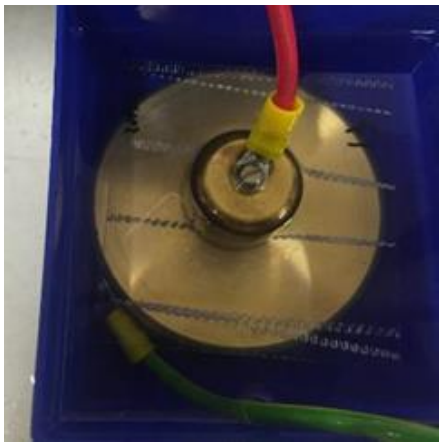

Fig. 1: Sample between HV (upper) and ground (lower) electrodes under oil.

C. Differential scanning calorimetry (DSC) measurements

To determine the glass transition temperature of the fully cured epoxy resin DSC measurements were carried out on a dried EP sample. The instrument used was a NETZSCH DSC 200F3. Heat-flow scans were obtained over the temperature range of 20 °C to 150 °C at a heating rate of 10 °C / min.

D Dielectric measurements

Broadband dielectric spectroscopy (BDS) was carried out on EM samples in air as a function of temperature. The range was 30 °C to 90 °C. Measurements were carried out over the frequency range 1 mHz to 65.5 kHz as the upper frequency limit for the frequency response analyser used was 65.5 kHz. Full details of the test regime are given in [3].

III. Results

A. DSC results

From the DSC heat flow curves, the onset of glass transition, Tg, for the EP samples was 75.3 °C, the midpoint 85.0 °C and the end point 94.6 °C.

B. Relative breakdown strengths of individual components

The breakdown strengths of the three samples were analysed using the 2 parameter Weibull distribution (2) to determine the cumulative probability of failure distributions of the samples, and hence assess the effective contribution of the individual components: mica, glass and epoxy resin, to the overall breakdown strength.

$$P_F(t) = 1 - exp\left\{-\left(\frac{V}{a}\right)^{\beta}\right\} \quad (2)$$

The cumulative probability of breakdown is shown for each of the sample types, EM, EG and EP at room temperature in Fig. 2. The mica samples, EM, over a range of temperatures are shown in Fig. 3. In both cases the data is presented on Weibull plots.

The characteristic breakdown fields (E_{brc}), alpha in (2), were estimated from the breakdown fields, E_{br}, corresponding to P_F value of 0.632 [4] and are given for each of the three sample types in Table 2. The shape parameter values, beta in (2), are shown in Table 2 and correspond to the slope of the best line fits in Fig. 2. This demonstrates that the EM samples exhibit significantly improved breakdown strengths compared to both the EP and EG samples. The EG samples, and to a lesser extent the EM samples in Fig. 2 show divergence from a single straight line on a two parameter Weibull distribution. This may suggest the presence of two or more mechanisms, or the existence of a threshold field in the breakdown statistics [5]. The characteristic breakdown field (E_{brc}), as shown in Table 2, for the EM samples is around 100 % higher than that of the EP samples. The EG samples E_{brc} is approximately 10 % less than the EP samples E_{brc}. However, it is clear that there is significant overlap of the confidence limits of the EP and EG samples.

The beta values shown in Table 2 for the three different types of samples are 7.9, 11.2 and 18.5 for EG, EP and EM samples respectively. However, considering the 95 % confidence limits the beta values for the EG and EM are the only values that are significantly different. Sample sets containing greater numbers of breakdown measurements than that used here would be required to gauge any significant difference in the beta values for the different sample types and as such it is not possible draw any statistically significant

TABLE 2: FITTED WEIBULL PARAMETERS

ID	Alpha (Scale) kV / mm	95% Confidence		Beta (Shape)	95% Confidence	
		Low	High		Low	High
EG	**27.6**	26.0	29.3	**7.9**	5.8	10.7
EP	**30.5**	28.5	32.6	**11.2**	5.70	21.9
EM	**57.2**	55.8	58.7	**18.5**	13.2	25.9

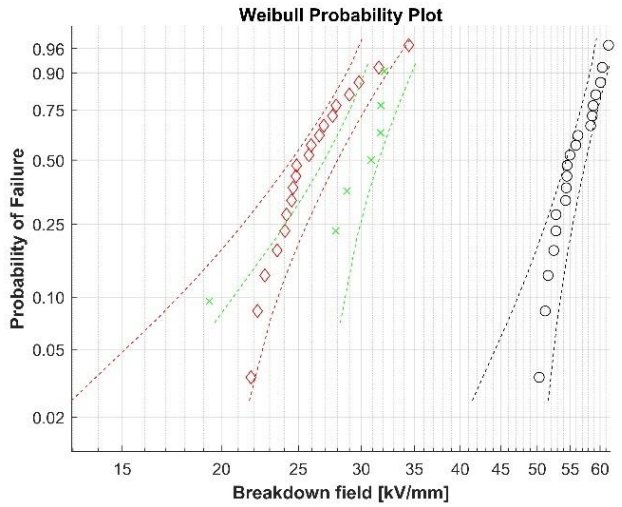

Fig. 2: Cumulative probability of electrical breakdown of composite components at room temperature. EM (o), EG (◇) and EP (x). Dashed lines delineate 95 % confidence limits.

conclusions regarding the relationship between the shape and scale parameters despite their seemingly similar trends.

C. Temperature dependence of the breakdown strength of the mica component

As the EM samples showed the greatest breakdown strength it was of interest to observe the change in E_{br} as a function of temperature over the DBM's ambient operating temperature (25 °C), up to the epoxy resin Tg (~ 80 °C). In Fig. 3 the cumulative probability of failure for the samples at four temperatures are shown, along with the 95 % confidence limits. Fig. 4 shows the temperature dependence of E_{brc} of the EM samples.

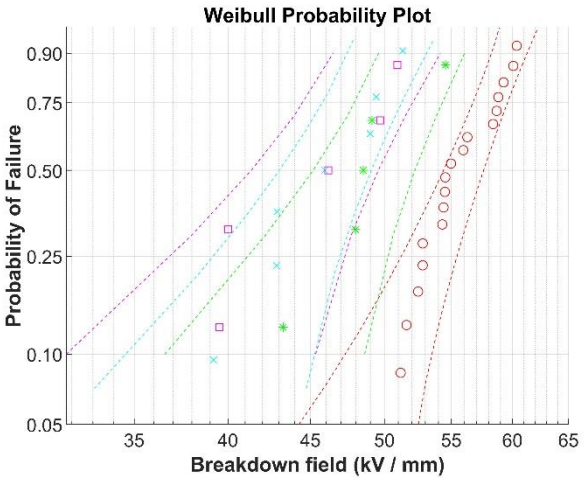

Fig. 3: Cumulative probability of electrical breakdown of mica component as a function of voltage and temperature: 25 °C (o), 40 °C (*), 60 °C (x) and 80 °C (□)

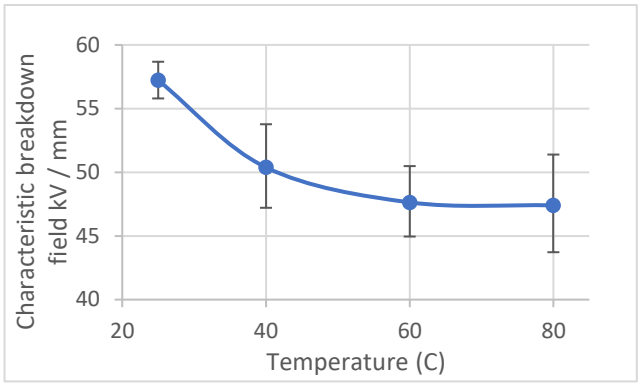

Fig. 4: E_{brc} of EM as a function of temperature with error bars showing confidence limits.

As shown in Fig. 3 there is clearly a large overlap in the breakdown fields (E_{br}'s) of the three higher temperature samples, although the E_{br}'s of the lowest temperature samples fall outside the confidence limits of all the other test temperatures.

In Fig. 4 the E_{brc}'s of the EM samples at each of the four tested temperatures were determined from the best straight-line fits to the Weibull distribution at each temperature. Despite the large range of the confidence limits it is apparent that the E_{brc} is monotonically decreasing as a function of temperature and approaches a constant value at approximately 60 °C, i.e. at temperatures around 15 °C to 20 °C below the glass transition temperature of the epoxy resin.

D. Relative permittivity of EM samples as a function of temperature

The dielectric response of the EM samples as a function of frequency across a range of temperatures are shown in Fig. 5. At the frequency of interest (50 Hz) there is a clear tendency of the imaginary part of the relative permittivity, ε_r, to increase with increasing temperature. A corresponding but smaller increase in the real part is also shown. The loss peak seen centred around 1 Hz at 25 °C shifts to higher frequencies with increasing temperature until it is mostly swamped out by a conduction process at 90 °C, which becomes dominant when Tg is exceeded [3].

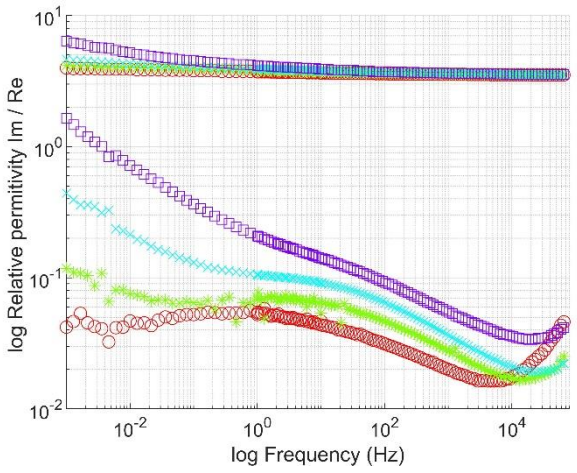

Fig. 5: Relative permittivity of EM sample as a function of frequency over temperature: 25 °C (o), 40 °C (*), 60 °C (x) and 90 °C (□)

IV. Discussion

The significant increase in E_{br} values for the EM samples over the EP and EG samples at 25 °C demonstrates that the presence of the mica tape has a profound effect on the electrical strength when compared to that of the pure epoxy or epoxy samples containing glass fibre tape. It is tempting to relate this increase to the mica layer acting as a barrier to charge flow in the epoxy layers thereby causing the electric field within the mica to increase, and consequently reduce in the epoxy regions. Breakdown in the EM samples would therefore ultimately be related to the electrical properties of the mica component. However, there is little evidence for this as the dielectric spectra measurements as shown in Fig. 5 at 30 °C show only a weak dispersion centred at 1 Hz. Therefore, the presence of the mica gives rise to only a minor impact on the dielectric properties at the test frequency of 50 Hz.

The dielectric spectra measurements of the EM samples taken over a range of temperatures (Fig. 5) give values of tan delta that increase from 10^{-2} at 30 °C to 3×10^{-2} at 90 °C which may be a contributing factor in accounting for the decrease in E_{brc} as temperature increases (Fig. 4). However, the small increase in the real part of the permittivity over this temperature range, at 50 Hz, suggests that the mica layer is not being significantly charged due to dc conductivity in the epoxy regions. It is therefore doubtful that the electric field across the mica layer is significantly enhanced with increasing temperature.

The likelihood of any form of electronic breakdown is low due to the field strengths involved. It is suggested in [4] that $E > 10^{10}$ V / m is required for intrinsic breakdown or electron avalanche breakdown. It is worth noting that the average energy gained by free electrons depends on the applied electric field and the mean free path, while the current density will depend on the applied electric field and number of free carriers [4]. It is possible that at breakdown, the applied field may be of sufficient strength to cause charge injection at the electrodes and boost the concentration of free carriers (and hence electrical conductivity) in the epoxy regions. However, it is not possible to relate this to the dielectric spectroscopic measurements over the temperature range investigated here (Fig. 5) as these were undertaken at low applied field.

A similar analysis applies to electrothermal breakdown; although the change in V_{brc} with temperature is clear, the small changes in effective 50 Hz current seen (as estimated from the tan delta measurements) do not support this mechanism: the tan delta is ~ 10^{-2}, which is insufficient to cause thermal runaway through Joule heating. However, as pointed out above, the high electric fields at breakdown may be sufficient to enhance electrical conductivity above that found in the low field dielectric measurements.

An alternative viewpoint is that electromechanical breakdown is at least partly responsible for the observed V_{brc}'s. In the theory of Stark and Garton [4] the principal material property affecting the magnitude of the electromechanical breakdown voltage, V_{br}, is the Young's modulus (Y). For pure epoxy Y ≈ 4 GPa, for mica Y ≈ 5.4 GPa, and for glass Y ≈ 80.5 GPa. Given these values one obtains values of breakdown voltage in the range $3 – 11 \times 10^9$ V / m, which is well in excess of the measured values found by experiment in this work. However, importantly, it is also the mechanical strength of the material that matters; as the samples are compressed by the electrostatic force, they will be in tension laterally in directions normal to the electrostatic force. The tensile strength of epoxy, glass and mica are 26 - 85 MPa, 30 - 90 MPa and 120 - 170 MPa respectively [6] [7]. In relative terms, these values are in line with the measured electrical breakdown fields. This supports crack formation as the origin of electrical breakdown results found in this work. It is found that the tensile strength in polymers in general decreases with temperature [8], as does the adhesive strength at the mica epoxy interface [9]. Either of these factors can account for the observed decrease in breakdown strength of the EM samples with increasing temperature.

The presence of voids, along with asperities and contaminants may give rise to local field enhancement, partial discharge damage and the onset of electrical breakdown. This may account for the measured breakdown strengths being much lower than the values predicted by the theory.

V. Conclusion

The influence of mica and glass tapes in thin epoxy resin samples on the electrical breakdown strength has been investigated. It has been found that the characteristic breakdown strength of epoxy samples is ~ 30 kV / mm. The glass fibre containing samples have a similar, albeit slightly lower value, and the mica containing samples exhibited a characteristic breakdown strength approximately double that of the pure epoxy samples ~ 60 kV / mm. The dielectric properties of the epoxy containing mica tape were also investigated as a function of temperature. These results were discussed in terms of the various accepted breakdown mechanisms: electronic, electrothermal, electromechanical, and the onset of partial discharges within regions of free volume. The observed electric breakdown measurements were related to the tensile strength of the material components of the samples. The mica containing samples tested over temperature indicate that the adhesive strength of the epoxy and mica may also have an influence on the breakdown field.

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