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Linear Thermal Expansion Coefficients for an Epoxy/Glass Matte-Insulated Solid Cast Transformer[1]

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Glass matte/epoxy-reinforced composites provide high-quality electrical insulation, structural integrity, and environmental protection in solid cast transformers. The thermal expansion characteristics of those composites are very important; the thermal expansion must be compatible with the conductor of the transformer in order to minimize stresses and prevent decohesion between the composite and the copper. The glass matte orientation and loading greatly influence the thermal expansion characteristics of the composite. A section was removed from a glass matte/bisphenol A epoxy-insulated, copper conductor wound cylindrical transformer coil. The linear expansion coefficients of the glass matte/epoxy composite were determined by differential dilatometry for three mutually perpendicular orientations with respect to the cylindrical coil. The expected reduction in thermal expansion of the epoxy in the tangential and axial directions due to the glass matte, which produced improved thermal expansion compatibility with the copper windings, was demonstrated. The measured linear thermal expansion coefficients were compared with theoretical values derived from a model for thermal expansion of a two-dimensional isotropic composite filled with fibers randomly oriented in a plane. An alternate composite system used for solid cast coil transformers, consisting of a cycloaliphatic resin filled with silica flour, was also investigated for comparison.

KEY WORDS: composites; dilatometry; epoxy; glass matte; thermal expansion.

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1. INTRODUCTION

High-performance solid cast coil transformers are produced by the vacuum impregnation with epoxy resin process. In that process, copper windings are permanently embedded between layers of glass matte cloth. The glass matte/copper winding assembly is then vacuum impregnated with an epoxy resin. One of the desirable characteristics of this cast coil transformer design is its high thermal overload capability. The glass matte/epoxy composite provides a very high resistance to cracking and prevents decohesion from the copper windings.

It is expected that the good thermal expansion compatibility of the glass matte/epoxy composite and the copper windings would contribute to the resistance to thermal overload damage resulting from thermal expansion and contraction. A typical design criterion for transformer coils is to incorporate a filled epoxy system which would allow for well-matched thermal expansion characteristics as well as suitable electrical and mechanical properties. However, because of the complex orientation of the glass fibers, the thermal expansion behavior of the composite is not readily predicted from the individual thermal expansion coefficients for the glass fibers and epoxy. Therefore, an experimental differential dilatometry study was carried out to determine the thermal expansion coefficients for the epoxy composite in each of the three mutually perpendicular principal directions for the cylindrical coil geometry.

An alternate composite system used for solid cast coil transformers, consisting of a cycloaliphatic resin filled with silica flour, has also been investigated for comparison.

2. EXPERIMENTAL

The samples of glass-filled epoxy were obtained from a standard commercial resin cast transformer coil (Square D solid cast type) which was sacrificed for the purposes of the test program. Each of the coil samples was composed of a bisphenol A-type epoxy consisting of an epichlorohydrin–bisphenol A resin (DGEBA) which was cured with a hexahydrophthalic anhydride (HHPA) hardener. The filled samples contained approximately 30 wt% E-glass fiber matte. Table I lists the values of the basic physical parameters for both of these materials [1–3]. Samples also were prepared with the unfilled bisphenol A epoxy under similar casting and curing conditions. For the purposes of comparison with the alternate composite material, a sample was prepared from a cycloaliphatic epoxy block filled with approximately 50 wt% silica flour.

The geometry of the transformer coil and the definitions for the sample

Table I. Physical Properties of the Glass Matte/Bisphenol A Epoxy Composite

Property	E-glass fibers[a]	Bisphenol A epoxy
Young's modulus (GPa)	72.4	3.6[b]
Poisson's ratio	0.20	0.33[c]
Bulk modulus (GPa)	40.0	3.6[d]
Shear modulus (GPa)	30.3	1.3[d]
Linear thermal expansion coefficient ($\mu°C^{-1}$)	4.9	70[b]
Density ($g \cdot cm^{-3}$)	2.54	1.20[e]

[a] See Ref. 1.
[b] See Ref. 2.
[c] Standard assumption of $\nu = 1/3$ used.
[d] See Ref. 3 for relationship among bulk modulus, shear modulus, and Young's modulus.
[e] Determined by mass and volume measurements.

orientations (C = circumferential, Z = axial, R = radial) are shown in Fig. 1. Cylindrical samples were machined with nominal diameters of 0.635 cm and lengths of 1.0 cm. The lengths of the samples were chosen so as to align with each of the three principal axes of the coil. In terms of the coordinate system defined in Fig. 1, the copper windings and the glass-fiber mattes are wound in the circumferential direction. There is no apparent preferential orientation for the fibers in the glass matte; the fibers essentially are oriented randomly on the cylindrical surface at a specific value of the radius.

The values for the thermal expansion coefficient of the epoxy samples were determined with a Theta Industries (Dilatronix IX) quartz rod differential dilatometer. The instrument operates on the usual basis of monitoring the relative motion of a sample probe during thermal expansion by means of LVDT (linear variable differential transformer). The temperature of the sample was varied by inserting it in a tube furnace where a Chromel/Alumel thermocouple monitored the sample temperature. Several values for the heating rate were used, but the majority of the test runs was performed at a heating rate of 3°C/min. Each of the samples (three coil, three unfilled bisphenol A, one cycloaliphatic) were run through at least two complete heating and cooling cycles. The information obtained from these repeat runs was used to compute approximate values for the uncertainty in the values of the linear expansion coefficient.

The output voltage of the thermocouple was used both for the furnace controller operation and for data acquisition. In an effort to increase the sensitivity of the expansion measurement, all values were obtained with

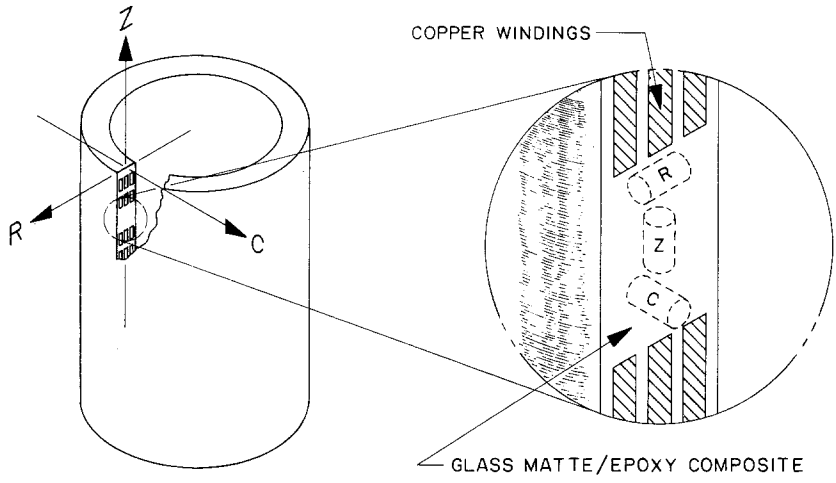

Fig. 1. Transformer coil geometry and sample orientation.

respect to a well-characterized platinum standard [4]. The LVDT output (mV), corresponding to the differential expansion of the epoxy samples with respect to the platinum standard, was plotted versus the thermocouple output (mV). These values were converted to the relevant expansion values and temperatures; therefore, it was possible to obtain a continuous measurement of percentage expansion, $\Delta L/L$, versus temperature.

3. RESULTS

Typical traces obtained from all three of the glass-filled bisphenol A epoxy samples were superimposed in Fig. 2 to provide a single graph of transducer output versus sample temperature. By viewing these three traces simultaneously, it is apparent that the linear thermal expansion coefficient for the glass matte-filled epoxy resin is strongly affected by the orientation of the reinforcing fibers. Individual traces were digitized and the transducer response was converted into values of relative expansion versus temperature. These data, in turn, were used to compute the average thermal expansion coefficient over the temperature ranges 20 to 80 and 115 to 185°C. The net expansion ($\Delta L/L$) was computed at 80, 115, and 185°C. The results of these computations, for all of the samples, are shown in Table II. In that table, $\bar{\alpha}$ refers to an average value of thermal expansion coefficient over the indicated temperature range, and $(\Delta L/L)_T$ refers to the percentage total length change observed at the temperature T. All expan-

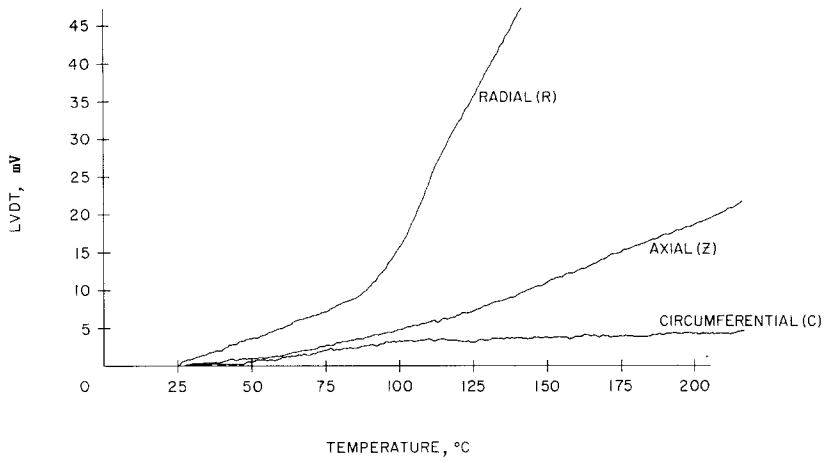

Fig. 2. Dilatometer response versus temperature for oriented glass matte/bisphenol A transformer coil samples.

sion coefficients have units of $10^{-6}\,°C^{-1}$ ($\mu°C^{-1}$), and $\Delta L/L$ values are reported as percentage. Based on the variability observed in the repeat measurements for several of the samples, it has been determined that the uncertainty in $\bar{\alpha}_{20\text{–}80}$ is $\pm 10\,\mu°C^{-1}$, while $\bar{\alpha}_{115\text{–}185}$ has an uncertainty of $\pm 20\,\mu°C^{-1}$.

Table II. Results of Thermal Expansion Measurements

Sample No.	Description	Average expansion coefficient ($\mu°C^{-1}$)		Net expansion (%)		
		20–80°C	115–185°C	80°C ($\Delta L/L$)	115°C ($\Delta L/L$)	185°C ($\Delta L/L$)
1	Unreinforced bisphenol A	73	208	0.39	1.04	2.52
2	30% glass matte-reinforced bisphenol A (Z direction)[a]	42	89	0.22	0.41	1.02
3	30% glass matte-reinforced bisphenol A (C direction)[a]	32	23	0.17	0.26	0.37
4	30% glass matte-reinforced bisphenol A (R direction)[a]	62	387	0.33	1.06	3.72
5	50% silica flour-filled cycloaliphatic epoxy	63	140	0.35	0.80	1.76

[a] Relates to Fig. 1.

4. THEORETICAL CONSIDERATIONS

A thorough theoretical model for predicting the coefficient of thermal expansion for composite materials has been proposed by Christensen [5, 6]. The primary objective of the model is to predict, from the individual thermal and mechanical properties of the separate phases (epoxy resin, glass filler), the effective (average) coefficients of thermal expansion of the complete composite material. The model used here was developed for predicting formulas for fiber systems that are isotropic in a plane. In using that model, it has been assumed that the cylindrical configuration of the transformer coil presents a curvature small enough so that a modification of the derivation would not be required.

Christensen's two-dimensional model yields an expression for the in-plane value of the quasi-isotropic coefficient of thermal expansion, $\bar{\alpha}_{2D}$, in terms of the properties of the two phases. For the transformer coordinate system, subscript 2D corresponds to any direction in the C–Z plane. The final expression of interest is

$$\bar{\alpha}_{2D} = \frac{E_{11}\bar{\alpha}_1 + E_{22}(\bar{\alpha}_1 + \bar{\alpha}_2)\nu_{12} + E_{22}\bar{\alpha}_2}{E_{11} + E_{22}(1 + 2\nu_{12})} \tag{1}$$

where the various expressions presented in this equation are as follows:

$E_{11} = 15.2$ GPa = Young's modulus for the composite in tension along the fiber length;

$E_{22} = 5.1$ GPa = Young's modulus for the composite in tension along any direction perpendicular to the fiber length;

$\bar{\alpha}_1 = 18.2\ \mu°C^{-1}$ = the coefficient of expansion for the composite in the direction of a fiber;

$\bar{\alpha}_2 = 69.7\ \mu°C^{-1}$ = the coefficient of expansion for the composite in any direction perpendicular to a fiber; and

$\nu_{12} = 0.317$ = Poisson's ratio (lateral strain in the 2 direction due to the strain in the 1 direction).

Complete expressions for computing the quantities indicated above are available in Ref. 6. Those quantities depend on the individual material properties, and the volume fractions, of the glass matte and epoxy.

The values for these expressions have been computed using the values of the glass and epoxy physical properties presented in Table I. The calculations were restricted to only the low-temperature range, where linear elastic behavior is most closely followed. For typical glass loadings of 30 wt % found in the glass matte/bisphenol A epoxy composite in the transformer, the value of volume fraction of glass was $X_f = 0.168$ and the volume

fraction for the epoxy matrix was $X_m = (1 - X_f) = 0.832$. With the values for volume fractions given above, the equation for the isotropic two-dimensional coefficient of expansion yields a value of $\bar{\alpha}_{2D} = 32.8\ \mu°C^{-1}$.

5. DISCUSSION

The measurements of thermal coefficients for the glass-filled epoxy composite have provided several interesting points for discussion. Initial measurements performed on the cured but unfilled bisphenol A-type epoxy have yielded an average value of thermal expansion coefficient in the range 20 to 80°C of $73\ \mu°C^{-1}$. This compares quite closely to the value stated in the resin manufacturer's guideline [2] of $70\ \mu°C^{-1}$. At temperatures above the glass transition, the average expansion coefficient increases to $208\ \mu°C^{-1}$.

Referring to Table II and Fig. 2, it is seen that the presence of the oriented glass matte reinforcement dramatically influences the thermal expansion properties of the composite. For temperatures below the glass transition, the transformer circumferential (*C*-direction) and axial (*Z*-direction) samples exhibited measured thermal expansion coefficients, $\bar{\alpha}_{20\text{–}80}$, which were significantly lower than that of the unfilled bisphenol A epoxy, i.e., 32 and 42 vs $73\ \mu°C^{-1}$. Those much lower expansion coefficients produce improved thermal expansion compatibility with the copper windings ($\bar{\alpha}_{Cu} = 18\ \mu°C^{-1}$) in the transformer coil.

The contact area between the composite and the copper windings is greatest along the *C* direction and is also significant in the *Z* direction. Thus, the observed thermal expansion compatibility for these two directions can be expected to contribute to an improved thermal overload capacity for the transformer. The thermal expansion coefficient for the transformer radial sample (*R* direction), below the glass transition, was also lower, but to a lesser degree, than that of the unfilled epoxy.

In the upper temperature range (115 to 185°C) the axial sample (*Z* direction) had $\bar{\alpha}$ reduced to $89\ \mu°C^{-1}$, as compared to the initial expansion coefficient of $208\ \mu°C^{-1}$ for the unreinforced material. The circumferential sample (*C* direction) had an even larger reduction: a decrease from $208\ \mu°C^{-1}$ to a new value of $23\ \mu°C^{-1}$ (a net reduction of 89%).

A surprisingly large increase in expansion coefficient, at temperatures above the glass transition, was observed for the *R*-direction sample. The low-temperature region shows a slightly reduced expansion coefficient; but for temperatures in the range 115 to 185°C, it is observed that $\bar{\alpha}$ has increased from $208\ \mu°C^{-1}$ to a new value of $387\ \mu°C^{-1}$. This observed effect is suspected to have been produced by the Poisson expansion which

results from the relatively large elastic strains in the epoxy matrix in the circumferential and axial directions.

The measurements on the cycloaliphatic epoxy filled with silica flour yielded an isotropic expansion, with average thermal expansion coefficients of 63 and 140 $\mu°C^{-1}$ in the 20–80 and 115–185°C temperature ranges, respectively. Although more highly filled than the glass matte/bisphenol A epoxy composite, the cycloaliphatic epoxy exhibited higher thermal expansion than did the axial and circumferential glass matte/bisphenol A samples. That result illustrates the greater effectiveness of fibers versus particulate fillers for reducing expansion of an epoxy matrix.

The calculations based on the model by Christensen tend to confirm the values obtained from the dilatometer measurements. As compared to the matrix (epoxy) expansion coefficient, the average isotropic two-dimensional expansion coefficient for the composite decreased from 70 to 33 $\mu°C^{-1}$.

It is interesting to note that the average of the two "planar" low-temperature thermal expansion coefficients ($\bar{\alpha}_c$, $\bar{\alpha}_z$) yields a value of 37 $\mu°C^{-1}$. That close agreement between experiment and theory is reassuring, especially after considering theηnumber of assumptions required to obtain the theoretical model and justify its use for evaluating this particular composite system. However, significant differences are still evident, particularly the observed nonisotropic expansion in the C–Z surface.

The observation that the measured $\bar{\alpha}_c$ and $\bar{\alpha}_z$ are not equal indicates that the assumption of planar isotropy for the glass fibers was not obtained for the transformer samples. The lower value for $\bar{\alpha}_c$ indicates some degree of fiber alignment in the C direction. The degree of fiber alignment was not pronounced, in that the observed values for $\bar{\alpha}_c = 32\ \mu°C^{-1}$ and $\bar{\alpha}_z = 42\ \mu°C^{-1}$ did not approach the theoretical values for complete fiber alignment, i.e., $\bar{\alpha}_1 = 18\ \mu°C^{-1}$ in the fiber direction and $\bar{\alpha}_2 = 70\ \mu°C^{-1}$ in the direction normal to the fibers.

At temperatures above the glass transition, the epoxy matrix does not exhibit linear elastic mechanical behavior. Therefore, it is not feasible to use the theoretical model to predict thermal expansion above that temperature.

6. CONCLUSIONS

The measurement of linear thermal expansion coefficients is an important design tool for the proper choice of reinforced epoxy resin composites to be used as insulators in solid cast transformer coils. Theoretical models have proven to be useful for understanding the mechanical processes occurring during thermal loading but are not sufficient, in themselves, to predict completely the thermal expansion produced by the addition of

various fillers. The model proposed by Christensen was shown to predict closely the average expansion coefficient in the plane of the reinforcing fiber matte; however, it did not allow for consideration of expansion in the radial direction (perpendicular to the glass matte surface). The observed differences between the experimental values and the predictions of the model can be attributed to a lack of true isotropic fiber loading and orientation. Other factors, such as inelastic fiber to matrix interfacial effects, may also have contributed to the differences between theory and experiment.

For the glass matte/bisphenol A epoxy system, it has been shown that the thermal expansion coefficient is reduced substantially by glass-fiber fillers. This is desirable in order to produce a more compatible thermal expansion for the epoxy composite insulator and the copper windings in the transformer. Furthermore, in the case where oriented glass-fiber mattes are utilized, the resulting changes in thermal expansion will vary between the principal directions of the coil. The largest reduction in the composite's average thermal expansion coefficient is produced in the circumferential direction, where the matching of material expansions is most important, in order to prevent cracking of the composite insulating material and decohesion from the copper windings.

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