

Thermally Conductive MgO-Filled Epoxy Molding Compounds

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Abstract—The use of magnesium oxide (MgO) as a filler in an epoxy molding compound (EMC) was considered to identify the maximum thermal conductivity that could be achieved without compromising rheological or processing control and processing flexibility. MgO is an attractive candidate filler for EMCs used in automotive and other applications because MgO is inexpensive, electrically insulative, has relatively high thermal conductivity, is nontoxic, and is a relatively soft filler material meaning it will be less abrasive to surfaces it contacts during its processing and shape molding. A maximum bulk thermal conductivity of 3 W/mK was achieved with a 56% volume fraction of MgO filler. This 56 vol% MgO-filled EMC has a thermal conductivity approximately twice that of traditional silica-filled EMCs with the same volume fraction of filler and has equivalent electrical insulative, thermal expansion, and water absorption characteristics. It is concluded that if a thermal conductivity greater than 3 W/mK is needed in an EMC, then a much more expensive filler material than MgO must be used.

Index Terms—Epoxy molding compound (EMC), fillers, magnesium oxide (MgO), original equipment manufacturer, thermal conductivity, thermal management.

I. INTRODUCTION

EPHOXY molding compounds (EMCs) are used in a multitude of electronic [1], [2] and electric motor component applications, and for those specifically used or considered for automotive application, low cost has equivalent importance as service performance. The primary functions or desired characteristics of EMCs in automotive applications, at least historically, have been to:

- 1) serve as an electrical insulator;
- 2) have a sufficiently low thermal expansion coefficient so thermal cycling does not induce damage to the

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constituents the EMCs encapsulate or are in contact with, have sufficient mechanical robustness and moisture absorption resistance to protect those constituents from vibration and exterior environments;

- 3) have minimal or no degradation caused by high temperature exposure;
- 4) have insusceptibility to electric and magnetic fields;
- 5) pose no health hazard to the user or consumer.

Cost is of upmost importance along with these listed factors. Any candidate EMC must also be inexpensive; otherwise, the automotive original equipment manufacturers, and their suppliers, will not realistically consider them.

EMCs are a composite material with epoxy serving as the continuous phase and a filler (or particulate) as the secondary phase. Their physical science has been studied for decades [3]–[7]. The volume fraction of filler needs to be sufficiently high, and with high particle packing efficiency, to exploit some desired characteristic(s) of the filler; however, it cannot be so high that rheological control during processing into some final shape (e.g., injection molding) is compromised. Therefore, a compromise must be struck depending on the EMC's application and final use.

An important limiting factor of EMCs is their low thermal conductivity (κ). This in turn limits thermal management options pertaining to the constituents the EMCs are encapsulating or are in contact with. EMCs have a low κ because the epoxy is the continuous phase in the EMC composite structure and the epoxy has a low κ itself ($\kappa < 0.5$ W/mK but typically $\kappa \sim 0.2$ – 0.3 W/mK). An illustration of this is shown in Fig. 1 for a variety of electronic and motor components and the epoxy materials or EMCs used on their exterior. A $\kappa < 1$ W/mK is common, but an EMC can be engineered to have a higher κ with an appropriate choice of filler material and control of its content.

II. EMC THERMAL CONDUCTIVITY AND CANDIDATE FILLERS

It is desirable to have an EMC with a sufficiently high κ so it is not relegated to thermal insulator status, and so the EMC can be a part of the thermal management solution and not an impediment to it. It turns out that the EMC κ may not need to be incredibly high to realize that for some applications.

Using an EMC with a thermal conductivity of 3–5 W/mK in combination with active cooling can substantially lower the maximum temperature of the constituents the EMC is encapsulating or in contact with. An illustration of this effect is shown in Fig. 2 for a hypothetical electronic power module.

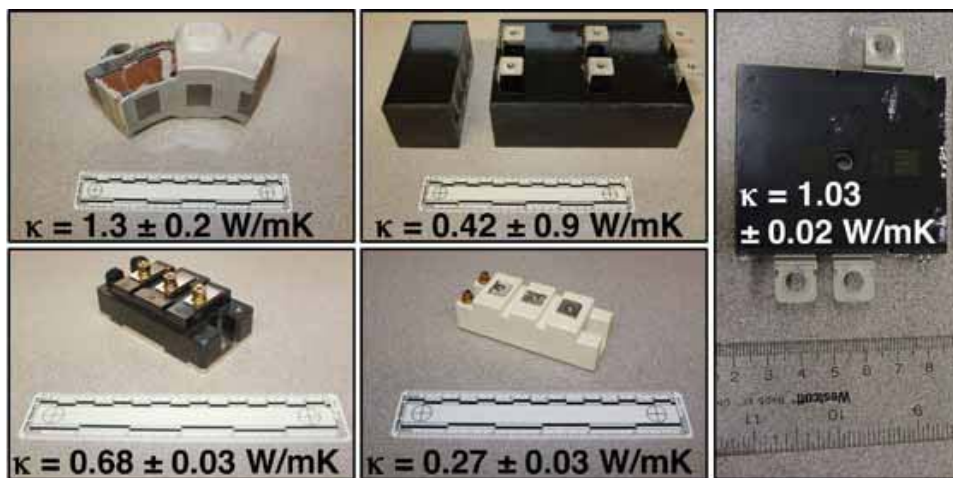


Fig. 1. Thermal conductivities of the encapsulating organic compounds measured with a hot disk thermal constant analyzer using a single-sided mode. Shown from the upper left and clockwise are the sectioned electric generator stator component, film capacitor, transfer molded power module, and two different commercial insulated gate bipolar transistor modules.

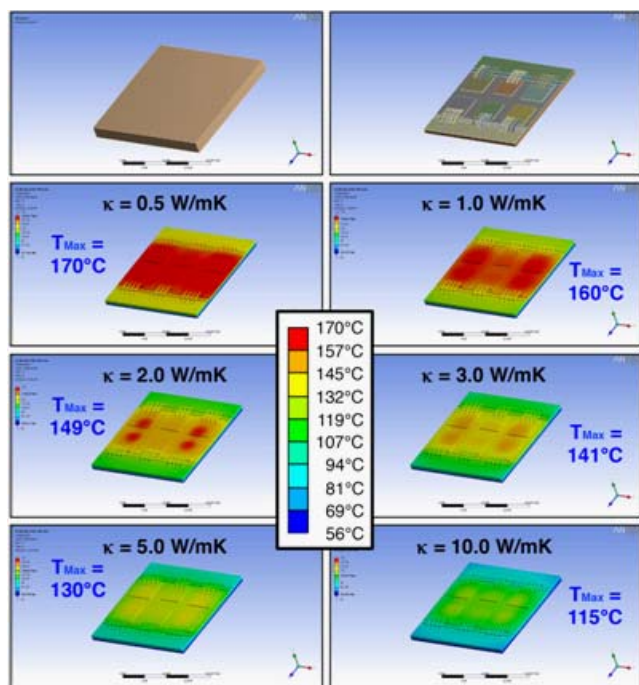


Fig. 2. Modeled temperature distribution and maximum temperature in a hypothetical power module encapsulated by an EMC material with different thermal conductivities.

Keeping all the boundary and power loss generation conditions the same, the use of an EMC with 3–5 W/mK can lower the junction temperature by tens of degrees and thus improve device longevity and performance. The use of an EMC with such a high κ enables the consideration of additional means of cooling and potentially more space- and weight-efficient redesigns of electronic and motor components.

The consideration and choice of the filler material clearly become critical in achieving an EMC with high thermal conductivity. First and foremost, any candidate filler materials must be electrically insulative. This can be a

potential dilemma because most of the materials that have high electrical resistivity also are thermal insulators (i.e., have low thermal conductivity). It must have inherently high bulk or volume electrical resistivity, ρ_E , of $\rho_E > 10^{12} \Omega\cdot\text{cm}$, or even $>10^{14} \Omega\cdot\text{cm}$ when voltage greater than 1 kV is involved. A list of common filler materials that satisfies that electrical resistivity condition is shown in Table I. The listed materials are ceramics or glasses (and thus have desirable high-temperature capability) and include aluminum oxide (Al_2O_3), aluminum nitride (AlN), beryllium oxide (BeO), the hexagonal crystal form of boron nitride (hBN), magnesium oxide (MgO), mullite ($2\text{SiO}_2 \cdot 3\text{Al}_2\text{O}_3$), crystalline silicon dioxide (SiO_2) or crystalline quartz, and amorphous SiO_2 , which is also referred to as fused silica or fused quartz. Zinc oxide and silicon carbide have been considered as filler materials by others; however, they are semiconductive ($\rho_E < 10^6 \Omega\cdot\text{cm}$) and are not considered here because they could be a susceptor (i.e., autogenously heat) in an ac electric or magnetic field.

While all the candidate fillers in Table I have sufficiently high electrical resistivity, no single material is superior among those listed when all the other sought attributes listed in Section I are also considered.

Three filler material candidates have bulk $\kappa > 200 \text{ W/mK}$ (AlN, BeO, and hBN), but they are either very expensive (e.g., tens or hundreds of dollars per kilogram) or pose a health hazard (i.e., BeO), or both. The literature is rich with the consideration of AlN-EMCs [8]–[18] as they could be viable options for noncost-conscious, high-end applications as long as AlN’s hydrophilic nature is managed and if its particle morphology can be controlled to allow desirable flow characteristics. Respiratory concerns (berylliosis) with the use of a BeO filler delegitimizes its candidacy for almost all the applications. The high thermal conductivity of h-BN is attractive and has received attention too as a filler in EMCs [19]–[21]. However, in addition to it being expensive, h-BN can impart less than desirable flow properties. h-BN has a plate-like, anisotropic morphology that affects its rheological

TABLE I
APPROXIMATED PROPERTY VALUES AND ESTIMATED COSTS FOR CANDIDATE MINERAL FILLERS AND EPOXY

Material	Electrical Resistivity, at 25°C (·cm)	Thermal Conductivity, at 25°C (W/m·K)	Heat Capacity, Cp (J/kg·K)	Density, (g/cm ³)	Coefficient of Thermal Expansion, CTE (× 10 ⁻⁶ /°C)	Knoop Hardness (GPa)	Elastic Modulus (GPa)	Estimated Cost (\$/kg)
Alumina (Al ₂ O ₃) or aluminum oxide	> 10 ¹⁴	30	900	3.9	8	14	375	5
Aluminum nitride (AlN)	> 10 ¹⁴	250	700	3.2	5	12	330	50–200
Beryllia (BeO) or beryllium oxide	> 10 ¹⁴	280	600	2.9	9	12	340	800–1000
Boron nitride hexagonal (h-BN) *Anisotropic	> 10 ¹⁴	275*	1600	1.9	1*	4	60*	40–50
Magnesia (MgO) or magnesium oxide	> 10 ¹⁴	40	900	3.6	10	7	250	5
Mullite (2SiO ₂ ·3Al ₂ O ₃)	> 10 ¹⁴	5	900	2.8	6	8	150	5
Silica (SiO ₂) or silicon dioxide <i>crystalline quartz</i> *Anisotropic	> 10 ¹⁴	14*	700	2.6	0.5*	7	95*	0.3
Silica (SiO ₂) or silicon dioxide <i>fused silica or fused quartz</i>	> 10 ¹⁶	1	700	2.2	0.5	5	75	1
Epoxy	> 10 ¹⁴	0.05–0.5	1500	1.2	30–60	N/A	3	5

flow and distribution in the epoxy under the high shear of the compounding and molding processes, and it is therefore difficult to achieve EMC homogeneity in the final form of an h-BN-EMC.

Crystalline quartz is a traditionally used filler material in EMCs because of its low cost, high resistivity, and low coefficient of thermal expansion (CTE). The authors will show the κ of SiO₂-EMCs is only about 1.6 W/mK, so the potential to create new opportunities for thermal management in automotive power electronics and motor components is small. Fused silica or fused quartz is also commonly used because it is very inexpensive, available in high purity, and available in spherical particles that can keep the compound's viscosity relatively low; however, its very low thermal conductivity will not result in an EMC that produces new paradigms of thermal management.

Aluminum oxide has a higher κ than crystalline SiO₂, is inexpensive, and literature shows it is considered as a filler in EMCs [19], [22]. However, Al₂O₃ is one of the hardest ceramics, making it prized as an abrasive material. Therefore, its use in an EMC that is formed under high shear or high speeds may lead to excessively high wear of molds and processing equipment. For this reason, aluminum oxide is more commonly used in liquid epoxy encapsulants that have lower filler loadings and are processed and molded under low shear conditions.

Mullite has a modest thermal conductivity, is inexpensive, and the authors have seen it used in one commercial electronic power module. However, mullite is also hard like aluminum oxide, and its thermal conductivity is less than that of crystalline quartz or crystalline SiO₂, so it is less attractive as a filler than crystalline SiO₂.

MgO has an attractive combination of characteristics as a filler. It has a bulk thermal conductivity greater than alumina and is also inexpensive and nontoxic. MgO already is a commonly used dielectric powder filler for non-EMC applications. For example, it is used as a dielectric filler separating the (coaxial) heating element used in consumer kitchen ovens. One unique and attractive characteristic of MgO, compared with the other listed ceramics in Table II, is that MgO has a low hardness. MgO is a soft ceramic that actually exhibits deformation-like characteristics like those of many metals. In the context of reducing wear during the molding of EMCs, MgO-EMCs would likely wear molds the least among all the other ceramic fillers listed in Table I.

Given the attractiveness of the combination of MgO's attributes, the consideration of MgO as a filler in EMCs was therefore pursued in this paper to specifically determine what maximum thermal conductivity could be achieved without compromise to rheological or processing control. A suite of thermal, electrical, and mechanical tests was completed on the processed MgO-EMCs. In addition, MgO is known to be hydrophilic, so water absorption tests were completed too.

III. EXPERIMENTAL PROCEDURE

A. MgO Filler

Two MgO powders having different particle size distributions were used. The powders were obtained from Ube Material Industries, Ltd., Japan.¹ Images of their size and

¹Certain commercial materials or equipment are identified to adequately specify the experimental procedure. This in no way implies endorsement of materials or equipment by the authors, their institutions, or their sponsor, or that these are necessarily the best for these purposes.

TABLE II
SUMMARY OF MEASURED PROPERTIES OF ALL SIX SETS

Property	Unfilled Epoxy	SiO ₂ 56 vol%	MgO 49 vol% 10C	MgO 52 vol% 50C	MgO 49 vol% 10C-50C	MgO 56 vol% 10C-50C
Filler	None	SiO ₂	MgO	MgO	MgO	MgO
Weight % Filler	0	74	74	76	74	79
Volume % Filler	0	56	49	52	49	56
Spiral Flow (cm)	250+	61	104	101	109	86
Gel Time (sec)	22	24	22	17	19	23
Density (g/cc)	1.19 ± 2%	2.00 ± 2%	2.35 ± 2%	2.42 ± 2%	2.36 ± 2%	2.52 ± 2%
Dielectric Strength of 900 μm thick film (kV/mm)	54	40	37	32	40	32
Surface Resistivity at 500 V (Ω)	4.8×10^{15}	1.5×10^{17}	4.9×10^{15}	5.1×10^{15}	5.0×10^{15}	4.2×10^{15}
Volume Resistivity at 500 V (Ω·cm)	7.2×10^{15}	6.4×10^{16}	4.9×10^{15}	5.9×10^{15}	6.0×10^{15}	5.4×10^{15}
Dielectric Constant at 10kHz	3.54	3.82	5.51	5.13	5.66	6.18
Dissipation Factor at 10kHz	0.0089	0.0060	0.0048	0.0030	0.0063	0.0065
Thermal Conductivity at 25°C (W/mK) ORNL hot disk method	0.24 ± 5%	1.62 ± 5%	2.35 ± 5%	2.00 ± 5%	2.21 ± 5%	2.92 ± 5%
Thermal Conductivity at 110°C (W/mK) SolEpoxy thermal conductance meter	0.23	1.42	1.91	1.81	1.91	2.50
Thermal Diffusivity at 25°C (mm ² /s)		0.68	0.74	0.84	0.83	0.97
Estimated Softening Temperature from Dilatometry (°C)	132 ± 5%	170 ± 5%	145 ± 5%	147 ± 5%	147 ± 5%	146 ± 5%
Coefficient of Thermal Expansion (× 10 ⁻⁶ /°C)	64 ± 5%	32 ± 5%	30 ± 5%	30 ± 5%	32 ± 5%	30 ± 5%
Elastic Modulus (GPa)	3.0 ± 5%	18.4 ± 5%	18.7 ± 5%	19.7 ± 5%	18.1 ± 5%	24.1 ± 5%
Poisson's Ratio	0.32 ± 5%	0.25 ± 5%	0.28 ± 5%	0.25 ± 5%	0.27 ± 5%	0.25 ± 5%
Weight Gain After 800h in Water (mg) [Nominal sample size: 50 mm dia. × 12.6 mm t or Area = 59 cm ²]	90	27	57	59	58	60

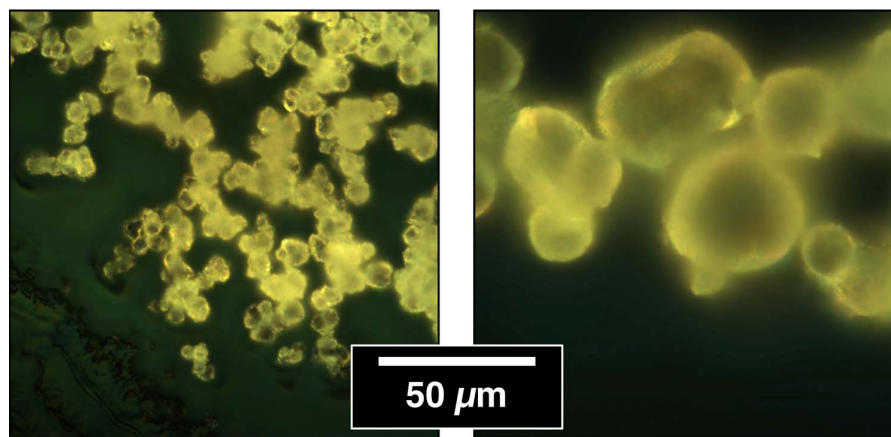


Fig. 3. Optical microscopy images of the two used MgO powders. The powder on the left is designated as 10C and that on the right is 50C.

morphology are shown in Fig. 3. The powders were coated with glycidoxypropyltrimetrixysilane. The primary functions of this organic coating were to promote MgO wetting and bonding with the epoxy matrix.

The particle size distributions of both powders were measured with a laser diffraction analyzer (Microtrac, Montgomeryville, PA). The resulting distributions for the two MgO powder sets, shown in Fig. 4, were chosen to have an idealized

difference in size of 7:1. The 10C powder had a d₅₀ of 10.9 μm and the 50C powder had a d₅₀ of 62.7 μm.

B. Epoxy Matrix Material

The epoxy components for this molding compound include an epoxy resin blend, a phenolic resin hardener, a catalyst blend, two waxes, and carbon black. The fillers were also

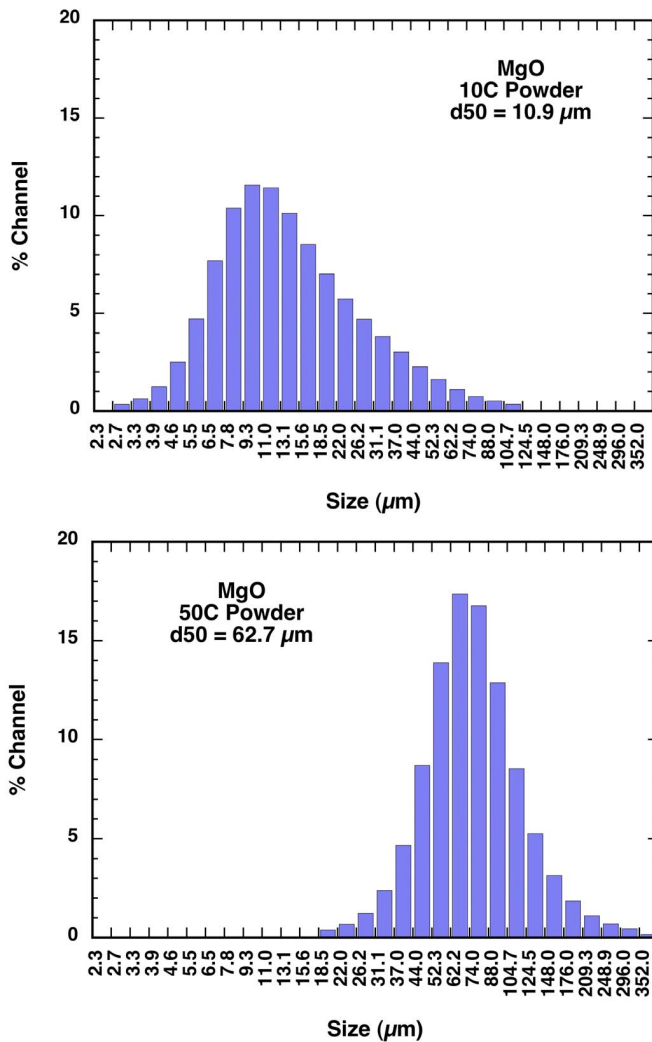


Fig. 4. Particle size distributions of the two MgO particle sets used as measured by a laser-based particle size measuring instrument.

treated with a silane to promote wetting and bonding of the filler into the epoxy matrix. The epoxy resin portion is a combination of an epoxy cresol novolac, a multifunctional epoxy that imparts good high-temperature performance and chemical resistance, and a Bisphenol-A resin, which is a standard epoxy resin. The Bisphenol-A resin helps to improve the toughness of the material. The phenolic hardener reacts with the epoxy resin, in the presence of heat and catalysts, to form an ultrahigh molecular weight, thermoset epoxy polymer. The catalyst blend serves dual purposes. First, since this EMC is a one-component system, there needs to be a catalyst that has low activity or latency, especially under low-temperature conditions, below 20 °C. This low activity is required to provide shelf life for the product so it does not cure while sitting on the shelf waiting to be used. The other part of the catalyst blend provides for a rapid cure and the fast development of physical properties when the compound is transferred to a mold. This is necessary to ensure a high degree of cure in a short time, so the part can be removed from the mold without damage, since an EMC is typically

only cured in the mold for 60–120 s. A postcure is usually included to achieve the maximum properties of the compound. Waxes are included in the formulation to act as a mold release agent and help provide for the overall good processing properties. Carbon black is added for color only and adds a little additional physical properties.

C. EMC Processing

The process of making an EMC generally follows these process steps. First, all the solid materials are weighed and blended together. For some raw materials, pregrinding may be performed to allow for better dispersion in the dry mix. Once all the dry components have been added to a blender, they are mixed together. If a liquid component like a silane is included in the formulation, it gets sprayed into the blender while the dry mix continues to blend. When all of the raw materials have been thoroughly mixed together, they are fed through a twin-screw extruder. The extruder has two blades that rotate and mix the powder blend. The extruder also heats up the material, melting all the solid components and allowing the raw materials to mix together completely. The hot EMC mixture is run over a series of rollers and belts to cool it down to room temperature and form a solid sheet. This sheet is then sent to a grinder where it is grounded into a powder with a specified grain size or coarseness. This ground powder is the EMC in a now usable form. Since it is now a reactive system, it is stored cold (−10 °C to +5 °C) to help in maintaining the shelf life.

The first quality checks that are performed on a material are a hot plate gel and a spiral flow. The setups for these are shown in Fig. 5. The hot plate gel test consists of placing a defined amount of material onto a hot plate that was set at a given temperature. This material was tested at 177 °C. Once the material was deposited on the hot plate, a timer was started, and the material was manipulated on the hot plate with a spatula until the material stopped flowing or gelled, and then the timer was stopped and the reading was taken.

Spiral flow measurements, ASTM D3123 [23], consider the viscosity of the material and the time it takes to gel. A spiral flow mold is a mold with a spiral pattern in it, indexed in 1-in increments. As material is pressed into the mold, it flows into the spiral track. When the mold is opened, the spiral form can be removed and the indexed length is then read from the part. If two EMC systems have the same gel time but different viscosities, the lower viscosity material will yield a longer spiral flow.

One set of processed material was unfilled epoxy. This was processed to provide a baseline. In addition, another processed set was a SiO₂-EMC, and this was included in the matrix because it is a conventional EMC composition.

Four MgO-EMC sets were fabricated in all. Three had nominal MgO filler volume fractions of 50% and were either made with 100% 10C MgO powder, or 50%–50% 10C–50C MgO powders, or 100% 50C powder. The fourth set was also a 50%–50% 10C–50C MgO powder composition, but it had approximately 10% higher total volume fraction of MgO powder in its structure. It was found that increasing the total MgO



Fig. 5. Hot plate gel test (top) and spiral flow mold (bottom).

filler content beyond 56 vol% compromised the rheological control, so this filler content was the highest considered in this paper. This 56 vol% value is near the percolation threshold (when the filler particles would start to contact next nearest neighbors), and the attainment of that percolation limit would desirably increase thermal conductivity but hinder rheological control.

Disks from all the six sets were fabricated. They had a nominal diameter of 50 mm and a thickness of 12.7 mm, and were used for additional characterization. Polished cross sections of the six processed sets of MgO-EMC microstructures are shown in Fig. 6.

Several observations are worth noting regarding Fig. 6. The large black regions in the MgO-EMCs are believed to be grain pullouts from the specimen preparation and polishing. In addition, the microstructure of the EMCs containing 50C MgO did not show the large grain sizes measured in the particle size distribution shown in Fig. 4; it is speculated they might have been comminuted during the mixing and processing with the epoxy. The larger particle sizes in the SiO₂-EMC are quite a bit larger than the 50C MgO grains.

D. Characterization

Four different classes of testing were conducted on the six compositions. They were electrical, thermal, mechanical, and water absorption testing. Properties were measured in

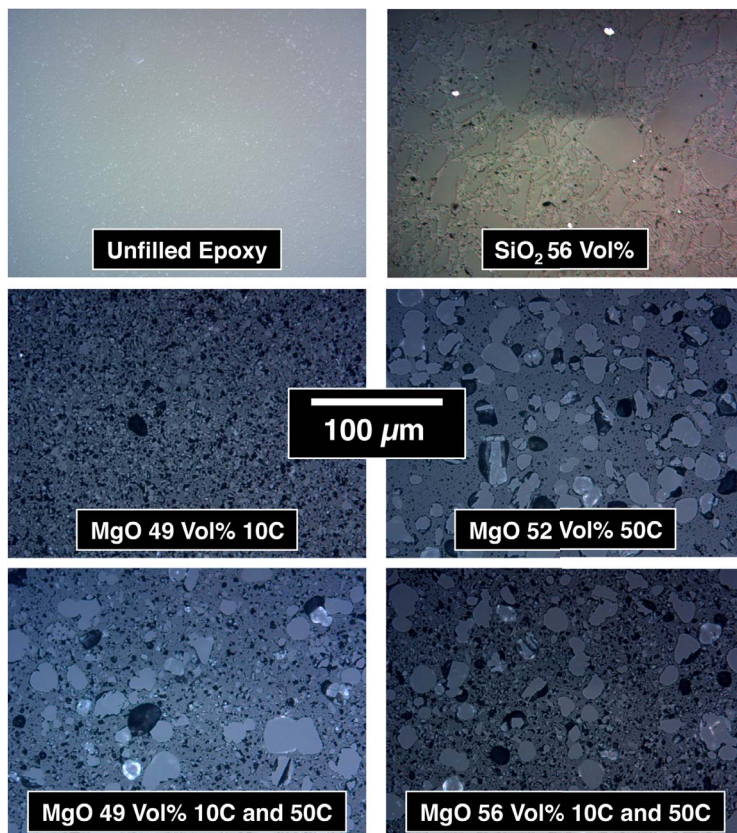


Fig. 6. Polished cross sections of the six different test sets at 200 × magnification.

reference to volume fraction of MgO filler. Volume fraction was simply calculated from the knowledge of the EMC density, namely

$$\frac{Vol_{Filler}}{Vol_{Total}} = \frac{\rho_{Total} - \rho_{Epoxy}}{\rho_{Filler} - \rho_{Epoxy}} \tag{1}$$

where ρ_{Total} , ρ_{Epoxy} , and ρ_{Filler} are the densities of the EMC, the epoxy, and the filler, respectively. A ρ_{Filler} value of 3.58 g/cm³ was used. The apparent densities of the various MgO-EMCs and of an unfilled EMC were calculated by dividing the mass of the processed disks by their volume (dimensions measured with a micrometer).

The procedure for the measurement of dielectric strength is defined by ASTM D149 or IEC 80243 [24]. It is a measure of the electrical strength of a material as an insulator. Dielectric strength is defined as the maximum voltage required to produce a dielectric breakdown through the material and is expressed as volts per unit thickness. A high dielectric strength is required for the material to be a good insulator. Dielectric strength was tested using a Hipotronics ac dielectric test set model 775-5D149-P-B (Hipotronics Inc., Brewster, NY). A film of EMC material is molded to about 0.5-mm (0.020 in or 20 mils) thick. The film is submerged in an oil bath and positioned between two electrodes. The voltage is ramped up until it arcs through the material, creating a short, and ending the test. The peak voltage is measured and divided by the sample thickness to determine the dielectric strength, reported as kV/mm.

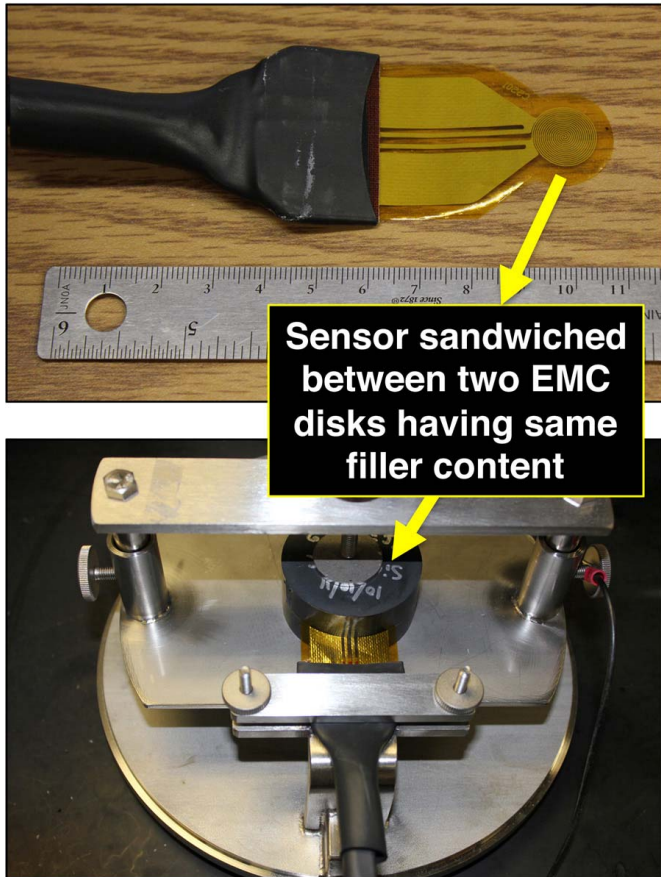


Fig. 7. Experimental layout of thermal conductivity measurement using the hot disk thermal constant analyzer.

Surface and volume resistivity test methods are run according to ASTM D257 or IEC 60093 [25]. The higher the resistance of a material, the better is its insulation to electrical charge. Ionic contaminants on the surface or within the material matrix will ultimately cause failures during these tests. For surface resistivity, electrodes are placed on a smooth test surface at a defined distance. The voltage is increased until an arc occurs across the surface of the material. A Keithley high-voltage supply, a Keithley resistivity adaptor, and a Keithley electrometer were used to perform these tests.

Measurements for dielectric constant and dissipation factor are defined by ASTM D150 or IEC 60250 [26]. The dissipation factor is the amount of energy lost or leaked through a material. A low dissipation factor means that the material is a good insulator and energy is not being lost rapidly. The dielectric constant and dissipation factor were measured with an HP4284A Precision inductance, capacitance, and resistor meter (Hewlett-Packard, Santa Clara, CA).

Room temperature thermal conductivity was measured with a hot disk thermal constant analyzer (Therm Test Inc., Fredericton, New Brunswick, Canada). An isotropic bulk sandwich technique was used to measure the thermal conductivity between two EMC disk samples. The test setup is shown in Fig. 7. A Kapton disk sensor was used with a heating power of 0.2 W and characterization time of 20 s. Per the manufacturer's recommendations, 20–200 data points were

used with an automated time correction, a calibrated specific heat capacity sensor (9.840 mJ/K), and fine-tuned analysis to determine the thermal conductivity. The results of five tests (60-min equilibration time between) were averaged.

Thermal conductivity was measured with a guarded heat flow meter from Netzsch C-Matic thermal conductance meter (Burlington, MA). A sample disk was molded and sanded to a uniform thickness with smooth sides and edges. The sample was coated with a heat-conducting paste to improve surface contact to the test heating elements. The sample was stacked between the two heatflow transducers at a specific compression load. At equilibrium, the heat flow differences were measured and the conductivity was calculated. The device was calibrated to Pyrex and Pyroceram standards prior to sample measurement.

Thermal diffusivity was measured as a function of temperature up to 250 °C using the laser flash diffusivity method (TA Instrument, Pittsburg, PA). Thermal diffusivity response is an indicator of transient thermal transfer, whereas thermal conductivity is more of a steady-state indicator. Disks with dimensions of 12.7-mm diameter and 2-mm thickness were harvested from one disk of each of the six sets. The measurements were carried out in a graphite furnace with a six-sample carousel. The measurement step was every 25 °C. Thermal diffusivity was calculated by the Clark and Taylor method described in ASTM 1461E [27].

The CTE was measured with a dual-rod dilatometer (Theta Industries Inc., Port Washington, NY) and cotedested with a sapphire standard sample. Bars with dimensions of 3 mm × 3 mm × 25 mm were harvested from one disk of each of the six sets. A heating rate of 2 °C/min and a data acquisition rate of 2.4 Hz were used. The softening point was determined to be the temperature at which the elongation temperature curve became nonlinear. The linear CTE was determined by the slope of the specimen elongation temperature curve up to the softening temperature.

The elastic modulus and Poisson's ratio of the disk samples were determined by resonant ultrasound spectroscopy (RUS) (Magnaflux, Albuquerque, NM) and a method developed in [28]. One 50-mm-diameter × 12.7-mm-thick disk from each of the six sets served as the test specimen. Because RUS is a resonance-based method, its resulting estimated elastic modulus and Poisson's ratio are only conclusively relevant for small strain, and are only relevant for larger strains if the material is linearly elastic up through that large strain.

Water absorption responses of the six sets were examined by continually immersing one disk from each set in water at room temperature and periodically removing it from the water to measure its weight gain. The surface area of each disk was 59 cm². This experiment was done over approximately five weeks (800 h). The final weight gain is reported.

IV. RESULTS

The primary finding was that a room temperature κ up to 3 W/mK can be achieved for MgO-EMC with 56 vol% filler without compromising rheological control and characteristics. This is a 10× increase in κ compared with unfilled epoxy and

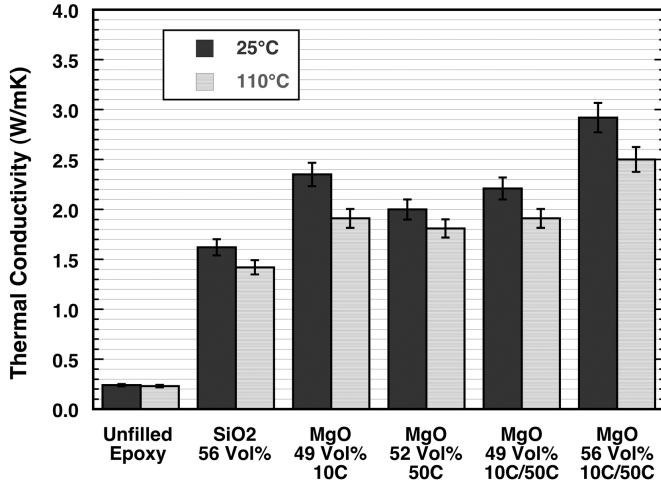


Fig. 8. Comparison of thermal conductivity of the six tested materials. Bars represent $\pm 5\%$. The 25 °C data were generated with a hot disk thermal constants analyzer, and 110 °C data were generated with a Netzsch C-Matic thermal conductance meter.

about twice the κ of a traditional silica-filled EMC for the same vol%, as shown in Fig. 8. The κ s of the three MgO-EMCs having 49%–52% filler content were quite similar, showing either that the particle size distribution differences in their sets did not have a marked effect on κ or that there are some ratios, other than a 1:1 powder blend, that would achieve an even higher κ . Thermal conductivity decreased with increased temperature, which is expected because the κ 's of almost all the materials exhibit this effect.

Obtaining a thermal conductivity >3 W/mK using MgO would require a filler content greater than 56 vol%. This, however, would compromise and limit rheological control during the transfer molding process. Given this, the authors assert that 3 W/mK is the highest thermal conductivity achievable for a low-cost, electrically insulative, nontoxic EMC with versatile flow characteristics and with thermal expansion and water absorption responses equivalent to silica-filled EMCs.

The measured thermal conductivity values of the MgO-EMCs as a function of volume fraction of filler were compared with predictions from the three models, and the results are shown in Figs. 9 and 10.

The classical Eucken–Maxwell model [29], [30] represents EMC thermal conductivity as a function of volume fraction according to

$$\kappa_{EMC} = \frac{\kappa_E V_E + \kappa_F V_F [3\kappa_E / (2\kappa_E + \kappa_F)]}{V_E + V_F [3\kappa_F / (2\kappa_E + \kappa_F)]} \quad (2)$$

where κ is the thermal conductivity, V is the volume, and the subscripts EMC, E , and F are for the EMC, epoxy, and filler, respectively. The Maxwell–Eucken underpredicts thermal conductivity as shown in Fig. 9.

The representation of EMC thermal conductivity using the Lewis–Nielsen model [31]–[33] is

$$\kappa_{EMC} = \kappa_E \left(\frac{1 + ABV_F}{1 - BV_F\Psi} \right) \quad (3)$$

where A is a parameter that describes particle geometry, B accounts for the ratio of κ_F/κ_E [both these parameters

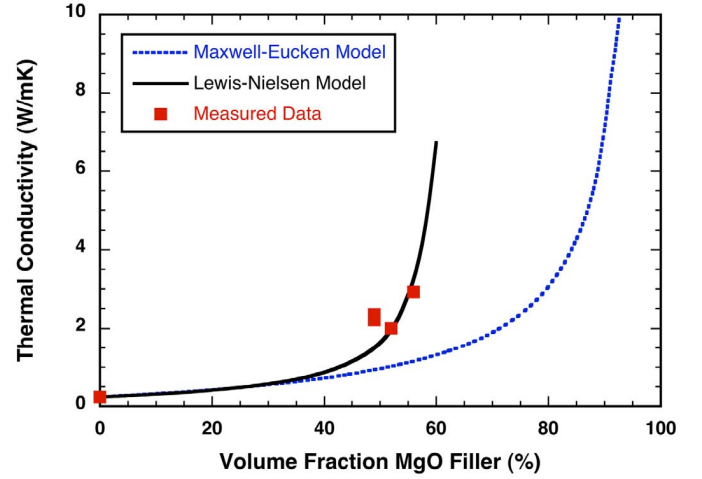


Fig. 9. Maxwell–Eucken model underpredicts thermal conductivity, and the Lewis–Nielsen model can predict thermal conductivity reasonably well if the empirical constants used in its expression are chosen appropriately.

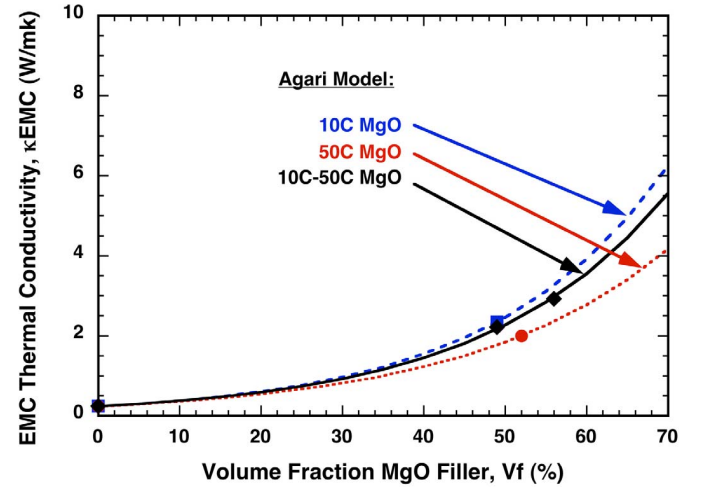


Fig. 10. Agari model fits the data well, which is expected because it uses experimentally measured thermal conductivity data as its input.

were defined for (2)], and Ψ is a function relating V_F to the maximum volume fraction of filler. There are several parameters within A , B , and Ψ that account for particle aspect ratio and different maximum volume fractions for different particle shapes and packings. For these calculations, $A = 1.5$, $B = 0.985$, and Ψ varied between 1.00 and 1.96. Some of those parameters involve some subjectivities, but if they are chosen appropriately, then the Lewis–Nielsen model can reasonably represent k_{EMC} as a function of V_F .

The thermal model of Agari [34], [35] is advocated by many in [6], [7], and [22] for use with EMCs. It is represented by

$$\kappa_{EMC} = \left(\frac{\kappa_F^{C_2}}{C_1 \kappa_E} \right)^{V_F} C_1 \kappa_E \quad (4)$$

where C_1 relates the effect of the filler on the epoxy's secondary structure and C_2 is a measure of how particles form thermally conductive chains. Experimental data of κ_{EMC} as a function of V_F are used to determine C_1 and C_2 so (4) will

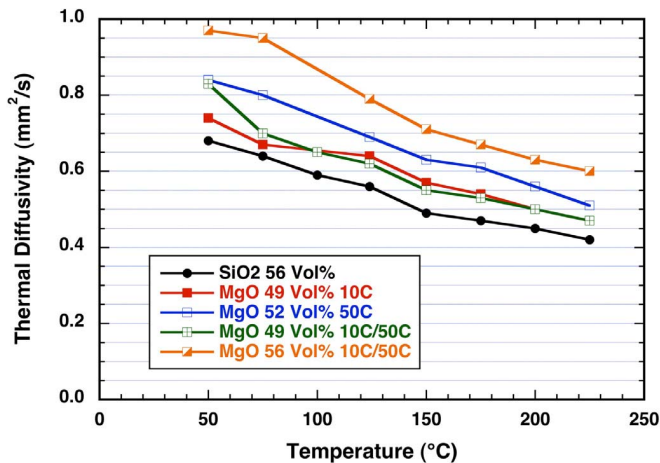


Fig. 11. Thermal diffusivity as a function of temperature for the filled EMC sets. The unfilled epoxy material could not be measured because it was transparent to the laser impulse.

always fit this data well (Fig. 10) and provide tangible physical meaning too.

An insufficient number of test sets at different volume fractions were explored in this paper to make judgments about the effect of the MgO filler, or their size distributions, on the polymer's secondary structure or the formed conductive chain in the context of Agari's model. The separate contributions of the two MgO particle size distributions, if they were indeed operative, were not identified with the admittedly too few sets explored in this paper.

The MgO-EMC with 56 vol% had the highest thermal diffusivity among all the MgO-filled EMCs, as shown in Fig. 11. Its thermal diffusivity was about 30% higher than that of the SiO₂-filled EMC with the same volume fraction filler, and even all the MgO-filled EMCs with lower filler content had a higher diffusivity than the SiO₂-filled EMC. More rapid heat dissipation occurs with higher thermal diffusivity (a desirable characteristic for power modules and electric motors), so the thermal diffusivity response of the MgO-filled EMCs is more effective at rapid heat transfer than that of the SiO₂-filled EMC relative to their volumetric heat capacity.

All the MgO-filled EMCs possessed electrically insulative, thermal expansion, and water absorption characteristics that were equivalent to those of traditional silica-filled EMCs or satisfactory. Support of this is shown in Table II.

The electrical properties of the MgO-EMCs were attractive. The dielectric breakdown strength was very high for all the MgO-EMCs, and their electrical resistivities were desirably high. The dielectric constant and dissipation factor values were good too. Unfilled epoxy has a very high dielectric strength and electrical resistivity, so it is reasonable for the addition of filler to lessen their values somewhat. SiO₂ is traditionally the choice filler for electronic applications due to its good physical and electrical isolation properties. MgO has comparable insulative properties, and the data in Table II show that while not as good as SiO₂, it still has very good insulative properties.

The addition of either SiO₂ or MgO filler to the epoxy caused an expected increase in the softening temperature

compared with the unfilled epoxy. The viscosity of a filled plastic is a function of the volume ratio of the filler to the resin. MgO has a higher density than SiO₂, which results in a lower viscosity. The results show that the percentage of MgO filler in the EMCs has a little effect on softening temperature.

The CTE for a filler is an important property because it affects the overall thermal expansion response of the EMC. All the fillers listed in Table I have a CTE at least 80% lower than that of epoxy, and many are a whole order of magnitude smaller. The compositing effect of CTEs for the filler and epoxy matrix will result in a EMC CTE that is somewhere between the CTEs of both materials. The CTE, in combination with the elastic properties of the EMC, can introduce deleterious stresses in the component it is supposed to protect if the EMC CTE has a sufficient mismatch with the component's encapsulated constituents.

All the filler additions of either SiO₂ or MgO decreased the linear CTE by about half that of unfilled epoxy, to 30–32 × 10⁶/°C. This decrease was expected and is a contributing reason for the routine addition of fillers to epoxy in molding compounds. Despite the CTE of bulk MgO being ~20 times larger than that of bulk SiO₂, equivalent filler contents in their EMCs produced equivalent CTEs. A lower CTE is a positive attribute for EMCs because its mismatch with the (relatively low) CTEs of the constituents that the EMCs are encapsulating or in contact with is lessened and the overall thermomechanical stresses in the electronic or motor component are reduced.

The addition of filler increased the elastic modulus 6–8× over that of unfilled epoxy. As expected, the higher the fraction of MgO filler, the higher was the elastic modulus of the EMC. MgO filler is better at increasing the elastic modulus than is SiO₂, which is not surprising as the elastic modulus of bulk MgO is ~150% higher than that of SiO₂. Despite the elastic modulus of bulk MgO being ~150% larger than that of bulk SiO₂, equivalent filler contents in their EMCs produced equivalent elastic moduli. This effect was the same for both elastic modulus and CTE, and clearly shows that a rule-of-mixture calculation is not valid for their properties in these EMCs. Knowledge of the elastic modulus is needed for modeling thermal-induced stresses in the EMC and the constituents it is encapsulating.

As expected, the addition of filler particles decreased the Poisson's ratio of the EMCs by about 1/3 compared with the unfilled epoxy. The higher the fraction of MgO filler particles, the lower was the Poisson's ratio of the composite. MgO and SiO₂ equally affect the Poisson's ratio compared with the unfilled epoxy. Knowledge of the Poisson's ratio is also needed for modeling thermal-induced stresses in the EMC and the constituents it is encapsulating.

The inclusion of filler in the EMCs lessened the amount of absorbed water. Unfilled epoxy absorbed 90 mg, the SiO₂-EMC absorbed 27 mg, and the four MgO-EMCs had equivalent absorption rates and absorbed 57–60 mg after 800 h of continuous water immersion. The surface area of each test sample was 59 cm², so the amount of water absorbed was very small even for the MgO-EMCs, given that MgO is hydrophilic.

Finally, the observed character of the herein processed EMCs is associated with relatively large bulk coupons. Their further study is warranted for smaller sized application (e.g., dimensions of hundreds of micrometers such as those used in semiconductor packaging) to see if and how thermal conductivity and moisture absorption characteristics are different than what were observed in this paper.

V. CONCLUSION

A bulk thermal conductivity up to 3 W/mK can be achieved with concomitant low cost if MgO is used as a filler in an EMC. This is a 10× increase in thermal conductivity compared with unfilled epoxy and about twice that of traditional SiO₂-filled EMCs. The MgO-filled EMCs also had a higher thermal diffusivity than SiO₂-filled EMCs, meaning thermal transfer occurs more quickly in the MgO-filled EMCs. MgO-filled EMCs possess electrically insulative, thermal expansion, and water absorption characteristics that are equivalent to those of traditional silica-filled EMCs. The results signify that MgO-EMCs would be more effective than SiO₂-EMCs at lowering the maximum temperature of encapsulated components.

Obtaining a thermal conductivity of >3 W/mK using MgO would require a filler content greater than 56 vol%; however, a higher volume fraction would compromise and limit rheological control during the transfer molding process. Given this, the authors assert that 3 W/mK is the highest thermal conductivity achievable for a low-cost, electrically insulative, nontoxic EMC with versatile flow characteristics and with thermal expansion and water absorption responses equivalent to silica-filled EMCs.

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