IMPACT OF IMMERSION COOLING ON THERMOMECHANICAL PROPERTIES OF LOW-LOSS MATERIAL PRINTED CIRCUIT BOARDS

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For traditional data centers, one-third of the total energy consumed is directed toward cooling information technology equipment. High demand for new data centers, vast amount of energy consumption, and their impact on the climate requires the data center industry to make them energy efficient and opt for immersion cooling technologies. From a thermal energy management perspective, immersion cooling is better than traditional air-cooling technology. However, detailed study of material compatibility of the various electronics packaging materials for immersion cooling is essential to understand their failure modes and reliability. The stiffness and thermal expansion are critical material properties for the mechanical design of electronics. Printed circuit board/substrate is a critical component of electronic package and heavily influences failure mechanism and reliability of electronics both at the package and board level. This study mainly focuses on two major challenges. The first part of the study focuses on the impact of thermal aging in dielectric fluid for single-phase immersion cooling on the low-loss material printed circuit board's (PCB's) thermomechanical properties. The PCB sample weight is compared to quantify absorption of the dielectric fluid into PCBs or leaching of the plasticizers into the fluid. The second part of the study is the impact of thermal aging on thermomechanical properties of low-loss PCBs in the air. The low-loss PCBs, Megtron6 are aged in mineral oil, and air for 720 hr at four different temperatures: 22, 50, 75, and 105°C. The complex modulus and coefficient of thermal expansion are characterized before and after aging for both parts and compared.

KEY WORDS: *CTE, complex modulus, TMA, DMA, Megtron, low-loss PCB, immersion cooling*

1. INTRODUCTION

The heat generated by electronics equipment in a data center has been consistently increasing due to convergence and miniaturization in the semiconductor industry. It is further exacerbated by the advances in technologies and online services (Alkharabsheh et al., 2015). Out of total energy consumed by a data center, $\sim$ 52% is consumed by demand-side systems within information technology (IT) equipment, such as processors, server power supply, storage, communication, and other services; whereas, 48% is consumed by the supply-side system, including uninterruptible power supply (UPS), switch gears, lighting, protocol data unit (PDU), and cooling. The traditional cooling alone consumes $\sim$ 38% of total data center energy consumption (Cho et al., 2012), as shown in Fig. 1. The electricity consumption of data centers is increasing all over the world, with an annual increase rate of 10% since 2005. As per the Japanese ministry of economy, the electricity consumption will be five times greater by 2025 (Nadjahi et al., 2018). In 2014, U.S. data centers consumed $\sim 7 \times 10^{10}$ kWh, which is 1.8% of total U.S. electricity consumption. The electricity consumption of data centers in the U.S. has increased by 4% from 2010 to 2014 (Shehabi et al., 2016). The energy consumption of China's data center industry was 160.89 TWh in 2018 and is expected to reach 266.79 TWh by 2023 (Bashroush, 2020). The carbon footprint of the data centers from 2002 was 76 metric tons of carbon dioxide equivalent (MtCO2e) and is expected to increase to 259 MtCO2e, with an annual increase rate of 7% (Webb, n.d.). Because of the strong electricity usage of data centers, especially cooling, the reduction of the energy consumption is increasingly becoming a top priority for IT businesses and policy makers (Garimella et al., 2012).

Despite impressive progress being made during past decades, there are still serious technical challenges in thermal management of electronic devices or microprocessors. Two main cooling challenges are adequate removal of increased heat flux and highly nonuniform power dissipation (Sohel Murshed and Nieto de Castro, 2017). The maximum power dissipation and heat flux for the high-performance microprocessors are increasing and have reached $>$ 300 W and $>$ 190 W/cm^2. The heat dissipation of the chip is increasing $\sim$ 7% annually (Nadjahi et al., 2018). The air cooling is not able to cope with this increasing heat flux density. There is a need for the data center industry to explore and implement different energy-efficient cooling technologies.

Figure 2 shows the approximate maximum power density per rack supported by respective cooling technology and power usage efficiency (PUE). An air cooling and indirect liquid cooling can handle up to 30 and 60 kW/rack, respectively. Beyond this power density, the direct liquid cooling/immersion cooling is required (Zhong, 2019). The PUE is highest for the immersion cooling with respect to air cooling and indirect cooling technology. Two-phase and evaporative

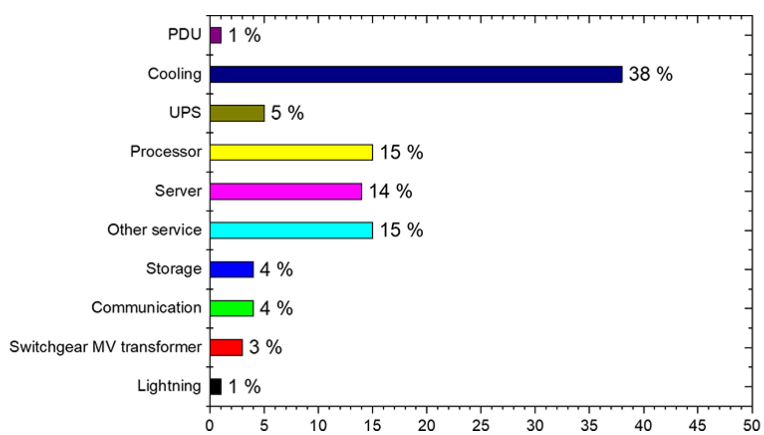

FIG. 1: Analysis of typical data center energy consumption

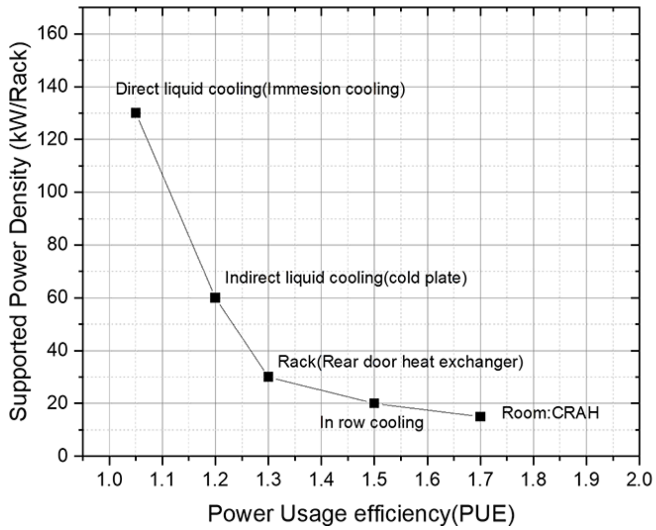

FIG. 2: Cooling techniques for data center and supported power densities and PUEs (based on the results of Zhong, 2019)

cooling also offer significantly higher performance over traditional cooling but may not be implementable as easily as single phase immersion cooling (Agonafer et al., 2021; Nahar et al., 2021).

Immersion cooling is classified based on the phase of the dielectric fluid, single-phase immersion cooling, and two-phase immersion cooling. Furthermore, it has been classified based on the enclosure into enclosed chassis, open bath, and hybrid (Brink et al., 2019). For the single-phase immersion cooling, the dielectric fluid is circulated in a close loop to absorb heat from IT equipment and in a secondary loop the heat is rejected to the atmosphere from dielectric fluid, as shown in Fig. 3. The dielectric fluid remains in the liquid phase and provides 12×10^2 times higher volumetric thermal mass than the air-cooling phase (Pierce, 1992). Mineral oils derived from petroleum have long been utilized for liquid insulation in high-voltage equipment due to their superior dielectric qualities, which include strong electric field strength, minimal dielectric losses, and long-term performance (Darma, 2008). Immersion cooling is one of the primary

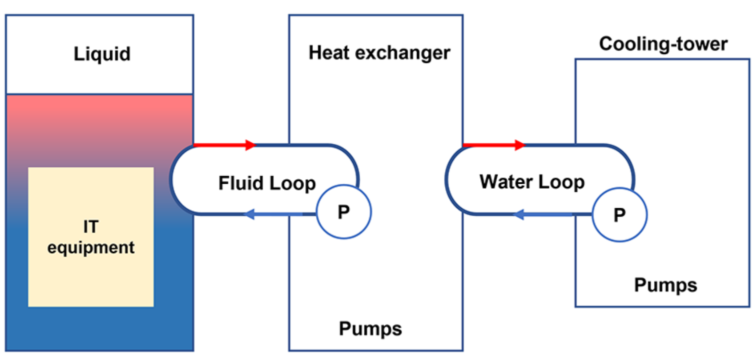

FIG. 3: Single-phase immersion cooling conceptual diagram

options for cooling components beyond the capability of air cooling, and mineral oil plays a significant role in achieving that. Researchers are also investigating the addition of nanoparticles to dielectric fluid to increase the thermal conductivity (Niazmand et al., 2020). In two-phase immersion cooling, dielectric fluid changes phase from liquid to vapor upon absorbing heat from IT equipment beyond its boiling temperature. It again condenses back to liquid phase from vapor by rejecting heat to the condenser; the heat will be rejected to ambience ultimately.

Controlled impedance and specific transmission line performance are necessary for design, and the high-performance materials for circuit boards lead the electronics industry to invent FR-4 grade dielectric materials to meet the need. High-speed designs requiring a low-loss tangent and lower dielectric constant have steered material research and development to invent advanced FR-4 laminates like Panasonic Megtron6, Isola FR408, Nelco N4000-13, and even e-glass engineered to a lower dielectric constant, such as Nelco's SI (for signal integrity) cloth (Advanced Circuits, 2013) (Panasonic, 2019a). The main advantage of Megtron6, the low-loss materials printed circuit board (PCB) compared to traditional FR-4 PCBs are low transmission loss, low dielectric constant, low dielectric dissipation factor, and high heat resistance. The dielectric constant and dissipation factor for Megtron6 is 3.5, and 0.003 compare to 4.2, and 0.018 for traditional FR4 PCBs respectively (Panasonic, 2019a,b). Megtron6 PCBs are used for crucial applications such as ICT infrastructure equipment, supercomputers, measuring instrument, antenna (Panasonic, 2019a).

The reliability study for the air-cooled ITE is mature. The dominant failure modes and the mechanisms are established and defined for the air-cooled IT equipment and electronics packaging in the form of the JEDEC standard (JEDEC, 2016). The operating conditions for immersion cooling are different than air cooling, as the ITE is immersed in fluorocarbon- or hydrocarbon-based dielectric fluids (Saylor et al., 1988). The various failure-prone parts, namely, silicon die package, back end of line structure, underfill, die attach, solder balls, substrate, and printed circuit board, remain in contact with the dielectric fluid constantly replacing the air. Immersion-cooled systems also undergo temperature change due to load fluctuation. Change in the cooling fluid from air to dielectric fluid entails the detail investigation study of reliability and material compatibility for immersion cooling. Different types of mechanical failure modes have been observed in electronics packaging. The most dominant mechanical failure mechanisms for electronic packages are fatigue failure due to temperature cycling, instantaneous fracture due to thermal shock, and tin whiskers (JEDEC, 2016). An electronic package contains various materials stacked together having different coefficient of thermal expansion (CTE). This CTE mismatch along with changing temperature within the system induces mechanical stresses. The impact of mechanical stresses must be studied to gain a better understanding of the reliability of electronics packaging for immersion cooling systems.

There are three major ways to study the mechanical reliability of immersion cooling: experimental, analytical, and numerical. The experimental analysis is the most expensive among all three, and the problem at hand is too complex to study analytically. The numerical method proves itself as the cost- and time-effective approach, and as such, the finite element method is a popular and widely adopted numerical method. One of the key factors for failure analysis using the finite element method is the accuracy of the material properties of electronic packages to formulate the problem. The change in the material properties with aging in the dielectric fluids at high temperatures is crucial information for such a numerical study of failure analysis under various loading conditions, namely, temperature cycling and creep.

Kennedy et al. (2016) demonstrated, for epoxy/E-glass after aging in sea water, the fatigue strength decreased by 20% and tensile stress was decreased by 25%. Kumarasamy et al. (2019)

concluded the tensile strength and modulus of glass-fiber-reinforced polymer deceased after aging in aviation fuels, namely, kerosene, biodiesel, and blend fuel. It is important to study the impact of aging electronic materials in the various dielectric fluids on their material properties.

Ramdas et al. (2019) showed the modulus decreased for 370HR and 185HR printed circuit boards after aging them in EC-100 dielectric fluid for 720 hr. Shah et al. (2019) concluded that the Young's modulus decreased significantly, and there was also increase in CTE for printed circuit boards of a server immersed in mineral oil for eight months compared to an air-cooled server. Shah (2018) aged a printed circuit board in mineral oil and EC 100 dielectric fluid for 288 hr at 45°C and found an increase in Young's modulus and CTE. This study focuses on the impact of thermal aging of a Megtron6 printed circuit board in dielectric fluid, mineral oil. Megtron6 PCB was aged for 720 hr in mineral oil and in air at four different temperatures, namely 25, 50, 75, and 105°C. Modulus and CTE were measured for the samples aged in mineral oil and for samples aged in air using a dynamic mechanical analyzer (DMA) and thermomechanical analyzer (TMA), and compared.

2. MATERIALS AND METHODS

2.1 Methods

2.1.1 Dynamic Mechanical Analyzer

Dynamic mechanical analysis is the technique used to measure a sample's kinetic properties, such as elasticity and viscosity. The sinusoidal load is applied to the sample via a probe in the form of stress/strain, and the sinusoidal stress/strain caused is measured and plotted as a function of time or temperature (Hitachi, 2021a). Different modules of DMA, including tension, bend, shear, and compression deformation attachment, are used to measure different material properties depending on sample shape, modulus, and measurement purpose. The viscoelastic properties, such as the storage modulus and loss modulus, can be measured by DMA (Hitachi, 2021a). The Complex modulus, whose magnitude is comparable to Young's modulus can be obtained using Eq. (1), using the storage and loss moduli (Misrak et al., 2020).

$$E^* = E' + iE'' \tag{1}$$

$$|E^*| = \sqrt{E'^2 + E''^2} \tag{2}$$

$$\tan\,\delta = \frac{E''}{E'} \tag{3}$$

In Eqs. (1)–(3), E* is complex modulus, E' is the storage modulus, and E'' denotes the loss modulus. The DMA used for this study has a temperature range of approximately –150 $\sim$ 600°C. An auto LN_2 gas cooling unit dispenses liquid nitrogen to reduce temperature of the furnace below room temperature (Hitachi, 2013). Figure 4 shows major components of DMA.

2.1.2 Thermomechanical Analyzer

Thermomechanical analysis is a technique in which the deformation of the sample is measured as a function of time or temperature while nonoscillating stress is applied (Hitachi, 2021b). The TMA module is used to measure thermal mechanical characteristics, such as thermal expansion, thermal contraction, and softening. The thermal stress-strain analyzer is used to measure the stress-strain as function of time or temperature. The TMA has a temperature range of

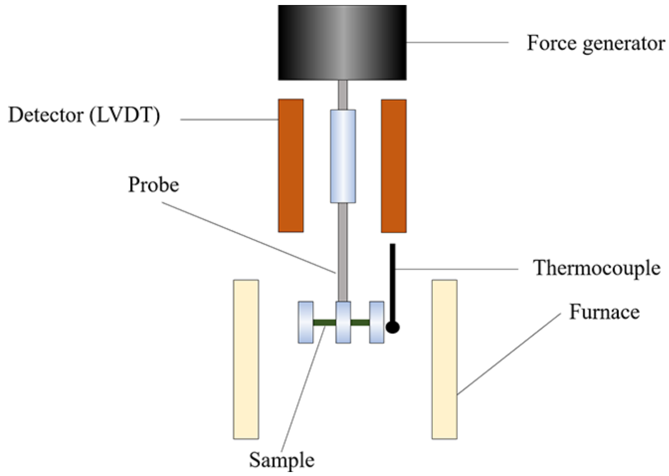

FIG. 4: Schematic of dynamic mechanical analyzer

approximately −150–600°C. One of the three probes—expansion/contraction probe, penetration probe, or tension probe—can be selected based on the analysis and sample type. Liquid nitrogen is used as the cooling agent to bring the temperature in the furnace below room temperature. The sensor is a linear variable differential transformer (SII, 2008). Figure 5 shows the major components of TMA.

2.1.3 Weighing Scale

To study the dielectric fluid absorbance into the PCB sample with respect to thermal aging in dielectric fluid, a digital weighing scale was used. The weighing scale has a stage inside a glass enclosure to avoid the errors caused by the air pressure around the stage (see Fig. 6). It has a

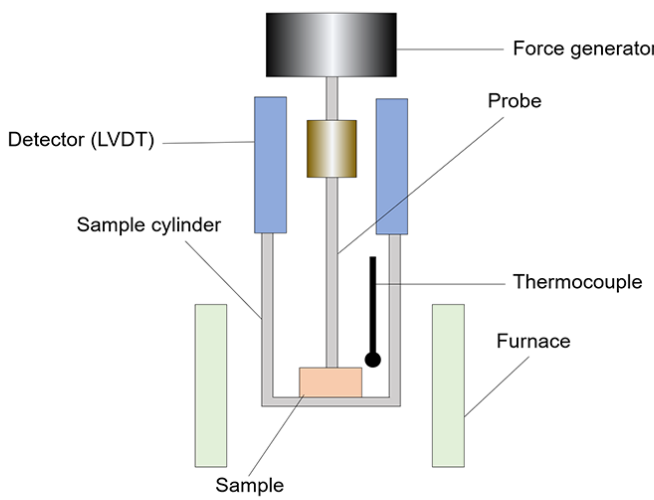

FIG. 5: Schematic of thermomechanical analyzer

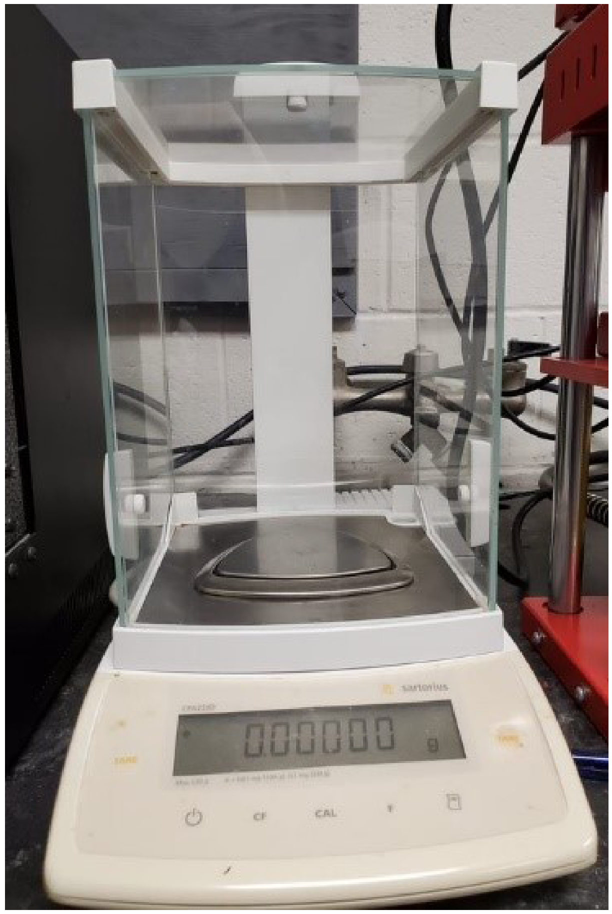

FIG. 6: Weighing scale

readability of 0.01 mg and repeatability (standard deviation) of $\leq \pm 0.02$ mg to measure the slightest change in weight of the PCB sample (Misrak et al., 2020).

2.2 Sample Preparation

2.2.1 Cutting of Samples

The $\sim$ 2 mm thick Megatron6 PCB was cut into at least four samples each, for each case studied for TMA and DMA, to ensure statistical accuracy. For the DMA bending attachment, the PCB was cut into samples of approximately 50 $\times$ 4 mm. A total of 32 samples were prepared for DMA measurements. For CTE measurement using TMA, the PCB was cut into samples of approximately 8 $\times$ 4 mm. A total of 32 samples for TMA measurement were prepared. Figure 7 shows the typical sample for DMA and TMA. In addition to 32 PCB samples, two dummy samples were prepared to study the dielectric fluid absorbance into PCB.

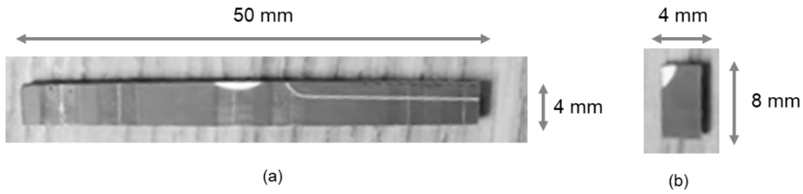

FIG. 7: (a) DMA sample and (b) TMA sample

2.2.2 Thermal Aging

There were eight different cases of aging performed based on aging environment parameters, namely, aging temperature and aging fluid. Four PCB samples each for DMA and TMA were aged at four different temperatures (25, 50, 75, and 105°C) and in two different fluids (air and mineral oil). Details of the number of samples aged for ~ 720 hr for each case is given in Table 1. Figure 8 shows the typical aging setup of PCB samples immersed in mineral oil and placed into furnace.

TABLE 1: Aging of the Metron6 PCB samples in air and dielectric fluid (mineral oil) for ~ 720 hr

Aging Temp.	No. Samples Aged in Mineral Oil	No. Samples Aged in Air
25°C	4 DMA + 4 TMA	4 DMA + 4 TMA
50°C	4 DMA + 4 TMA	4 DMA + 4 TMA
75°C	4 DMA + 4 TMA	4 DMA + 4 TMA
105°C	4 DMA + 4 TMA	4 DMA + 4 TMA

FIG. 8: Aging PCB sample immersed in mineral oil inside a furnace

2.3 Experimental Procedure

2.3.1 DMA

Samples used for DMA tests had a length of $\sim$ 50 mm, width of 4 mm, and $\sim$ 2 mm thickness. The samples were measured using digital calipers having 0.02 mm accuracy. Based on the expected modulus of the material and the sample geometry factor calculated from sample dimensions, a bending attachment was chosen for the current study. The post-aging oil-immersed samples were gently cleaned with a paper towel before mounting to the DMA for testing. The settings used for testing samples in bending mode for the hard sample are shown in Table 2.

The experiment was performed for 0.5, 1, 2, 5, and 10 Hz frequencies and a temperature range from -40 to 220°C. The most used frequencies in the industry were selected to account for the frequency- and temperature-dependent behavior of the material. Measurements for 1 Hz were used to compare the properties of pre-aging (samples aged at 25°C in air) and post-aging samples. An isothermal hold of was performed at the beginning temperature of -40°C to stabilize the temperature fluctuations within the range of $\pm$ 3°C. To account for the thermal mass of the sample and reduce the lag in sample temperature to furnace temperature, a slower heating rate of 2°C/min was used during the experiment compared to 10°C/min. Figure 9 shows the sample mounted for the testing using the bending attachment.

2.3.2 TMA

A typical rectangular sample of $\sim$ 8 mm length, $\sim$ 4 mm width, and $\sim$ 2 mm thickness was used for TMA measurements. The in-plane CTE of the Megtron6 PCB was measured, and samples were mounted such that the length (8 mm) was parallel to the measurement probe of the TMA, as shown in Fig. 10. The TMA probe was cleaned with ethanol before starting the series of measurements to remove any residue on the probe. The post-aging oil-immersed samples were cleaned gently with paper towel to remove access mineral oil on the sample before mounting. The CTE of aluminum was measured to perform and compared to the literature value for sanity check. For the current study, the thermal-mechanical analyzer mode of the TMA and expansion/compression quarts probe of 3 mm diam were used.

Optimum 100 mN force was constantly applied on the sample through probe during the experiment to maintain proper contact between sample and probe and to not constrain the thermal expansion of the sample during the experiment. The experiment was performed for a temperature range of -40 to 220°C. An isothermal hold was performed with stability criteria of having an initial temperature fluctuation within $\pm$ 2°C to attain the desired temperature of the sample at the beginning of the test. The length and thickness of the sample were measured with digital calipers having an accuracy of 0.02 mm. The length of the sample was measured using a TMA with an accuracy of 0.05 mm (SII, 2008). Measurement was performed with a ramp rate of

TABLE 2: Settings use for DMA testing in tensile mode

Parameters	Value
Minimum tension/compression force	200 mN
Tension/compression force gain	1.5
Force amplitude	2×10^3 mN
L Amplitude	10 μm

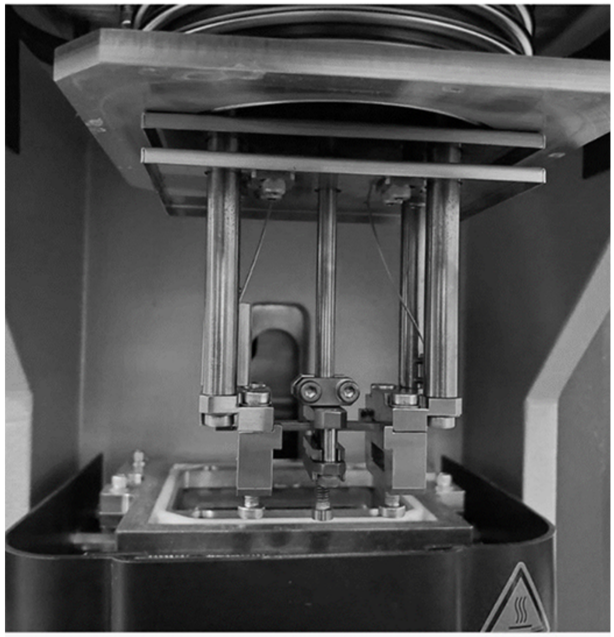

FIG. 9: Megtron6 sample mounted on DMA for testing

FIG. 10: Megton6 PCB sample mounted on the TMA for testing

2°C/min, lower than that found in the literature, to mitigate a little lag between the TMA furnace temperature and the sample temperature.

2.3.3 Weighing the Post-Aging Oil-Immersed Dummy PCB Sample

Two dummy Megtron6 PCB samples of ~ 30 mm length, ~ 4 mm, and ~ 2 mm thickness were used to study dielectric fluid absorbance into the Megtron6 PCB material. One of the dummy samples was immersed in mineral oil at 25°C and the other at 50°C. The samples were taken out at intervals of ~ 24 hr to measure the weight. The process was repeated for ~ 650 hr. The total time from the weight-measuring process was ~ 5 min, including taking out the sample, weighing it, and putting it back. The Megtron6 PCB dummy sample was gently cleaned to remove excess mineral oil on the surface of the sample for precise measurement.

3. RESULTS

3.1 DMA Results

3.1.1 Complex Modulus for Each Temperature for Oil Immersed and Air Case

The comparison of DMA measurement of the complex modulus for immersed and nonimmersed samples at 25, 50, 75, and 105°C are shown in Figs. 11–14, respectively. The measurements were run for at least four times each for both the immersed and nonimmersed samples. The average of the complex modulus along with the standard deviation is shown for the temperature range of −40 to ~ 210°C.

3.1.2 Combined Plot for All Temperatures for Immersed Samples

Figure 15 shows the combined plot for all the temperatures for the immersed samples along with the standard deviation of the complex modulus. Figure 16 shows the combined plot for all the temperatures for the nonimmersed samples along with the standard deviation of the complex modulus.

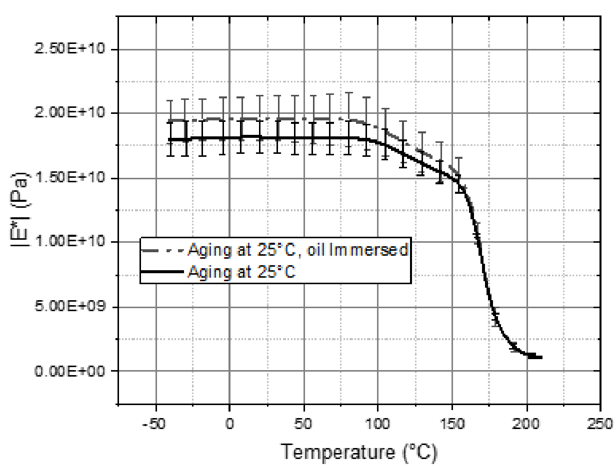

FIG. 11: Comparison of complex modulus aged at 25°C

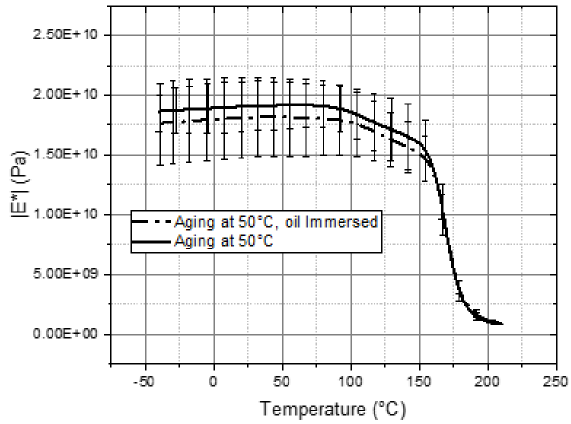

FIG. 12: Comparison of complex modulus aged at 50°C

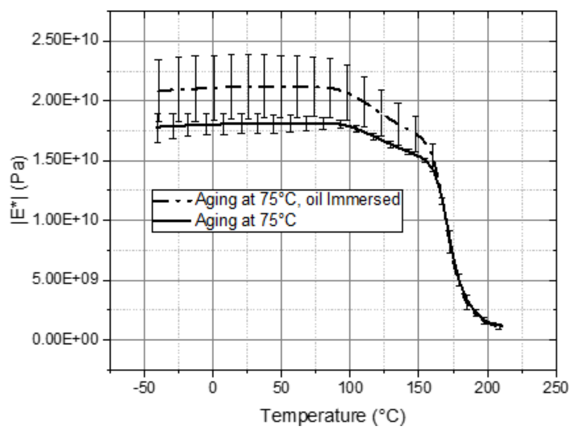

FIG. 13: Comparison of complex modulus aged at 75°C

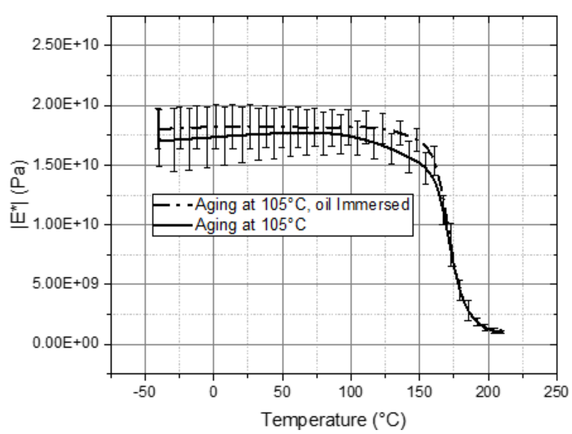

FIG. 14: Comparison of complex modulus aged at 105°C

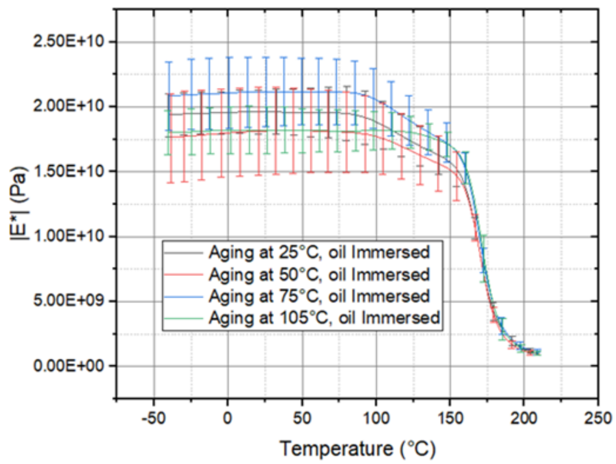

FIG. 15: Complex modulus of the immersed sample at different temperatures

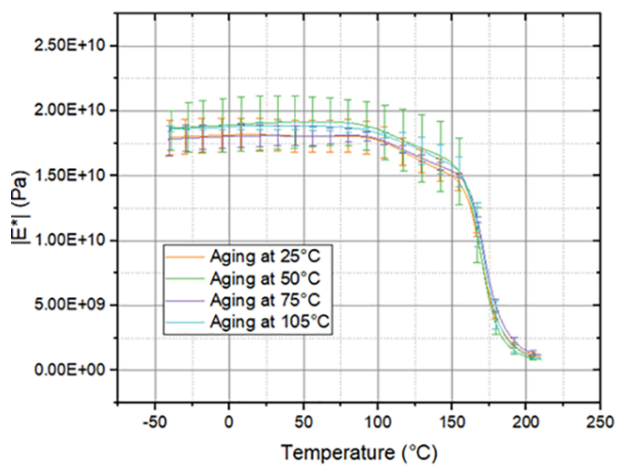

FIG. 16: Complex modulus of the nonimmersed sample at different temperatures

3.2 TMA Results

Figure 17 shows the comparison of CTE for the nonimmersed aged and immersed aged samples at four different temperatures. At each temperature, at least four measurements were completed, and the average and standard deviation are shown in Fig. 17.

3.3 Weight Absorbance Results

Figure 18 shows the weight measurements for the dummy Megtron PCB samples immersed into mineral oil at two different temperatures, 25°C and 50°C, to study dielectric fluid absorbance into the PCB sample. One sample was used for each temperature.

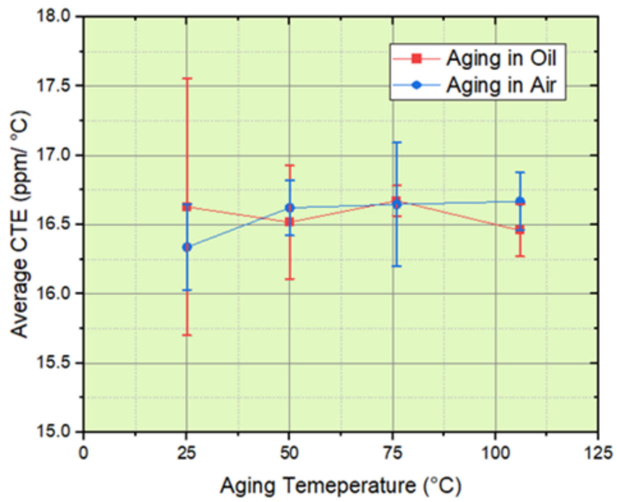

FIG. 17: Coefficient of thermal expansion of the immersed and nonimmersed sample at different temperatures

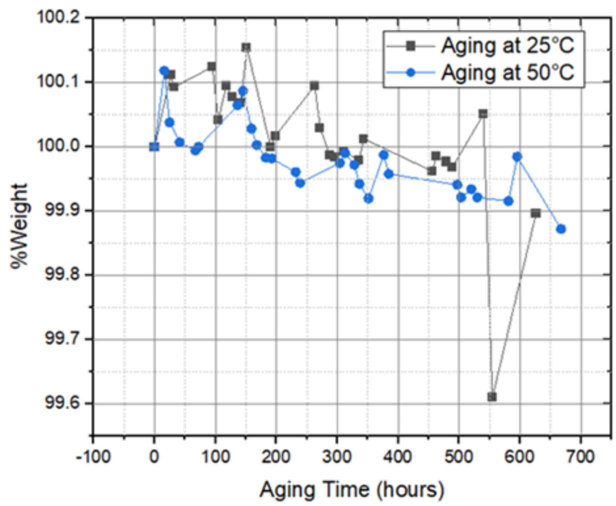

FIG. 18: Change in the weight of Megtron6 sample immersed in mineral oil over time at different temperatures

4. DISCUSSION

In Figs. 11–14, the comparison of results is shown for DMA measurements for Megtron6 PCB samples aged in mineral oil and aged in air at four different temperatures. For each plot, a minimum of four samples was tested and averaged. The standard deviation for the results at 25, 50, 75, and 105°C is respectively 7, 15, 11, and 9% for the oil-immersed samples and 7, 11, 5, and 14% for the samples aged in air. Sample-to-sample variation in terms of copper connections density and slight variation in sample width are potential causes for large error bars. Predefined torque was applied to minimize the variation in the clamping force to attach samples.

At the start temperature, an isothermal hold was applied to attain thermal equilibrium. This increased the measurement time of DMA to $\sim$ 2.5 hr. The presented data shows the glass transition temperature (T_g) of the pre-aging Megtron6 PCB is 155, 171, and 179°C derived respectively from the storage modulus, loss modulus, and loss tangent. Ehrler (2004) studied thermomechanical properties of high-frequency PCB base materials, and the T_g of pre-aging Megtron6 found in this study can be corelated to those found by Ehrler. There is negligible change in the T_g of Megtron6 samples aged in the air, and mineral oil compare to pre-aging sample. From literature, the T_g for the Megtron6 is expected to be 185°C using DSC and 210°C using DMA (Hitachi, 2021a).

The complex modulus of the pre-aging sample (aged in air at 25°C) as shown in Fig. 11 is 18 GPa for the temperature range of -40 to 90°C. From temperatures of 90–155°C, the complex modulus linearly decreases from 18 to 14.4 GPa. After Tg, the modulus decreases rapidly from 14.4 to $\sim$ 1 GPa. There is a slight change in the complex modulus for Megron6 PCB samples aged in air at 50, 75, and 105°C compared to pre-aging sample as shown in Fig. 16. The data presented in Fig. 15 show negligible change in the complex modulus values of the Megtron6 PCB samples aged in mineral oil. This change is within the error margin and could be attributed to sample-to-sample variation. The expected flexure modulus for the Megtron6 PCB pre-aging sample is 18–19 GPa (Panasonic, 2019a). Similar studies in the literature demonstrated a decrease of modulus in the FR-4 PCBs after aging in dielectric fluids (Ramdas et al., 2019; Shah, 2018).

Data presented in Fig. 17 show the comparison of the CTE for the pre- and post-aging samples in air and oil of the Megtron6 PCB for the temperature range of -40 to 160°C. For each measurement, at least four samples were tested to take an average value of CTE. The CTE value for the pre-aging sample is 16.3 ppm/°C, which is significantly higher than the silicon chip in the electronic packaging stack up. For the post-aging samples in air at temperatures 50, 75, and 105°C, the CTE value is $\sim$ 16.7 ppm/°C; the change is negligible compared to pre-aging samples. CTE values for the post-aging samples in mineral oil at temperatures 25, 50, 75, and 105°C are in the range of 16.5–16.7 ppm/°C, as shown in Fig. 17. The change in the CTE value is within the margin of error bars and can be attributed to sample-to-sample variation in terms of copper density. The expected CTE for the Megtron6 from the open literature is 14–16 ppm/°C, which agrees with the results presented.

Figure 18 shows dielectric fluid absorption into the dummy Megtron6 sample at two temperatures, 25 and 50°C, respectively, during $\sim$ 630 hr of aging in mineral oil. There are three possibilities: the weight of the sample will increase, decrease, or remains the same. An increase in the weight of the sample implies absorbing of dielectric fluid into the PCB sample; whereas, a decrease in the weight of the PCB sample implies leaching of plasticizers from the sample into the dielectric fluid. No change in weight of the sample implies either both absorbing and leaching took place at same rate to nullify each other or no absorbing and leaching took place at all. The Metrgon6 sample immersed in mineral oil at 25°C demonstrated that the total weight increased by $\sim$ 0.1% from beginning to $\sim$ 150 hr, and then the weight started to decrease by 0.2% from 150 to $\sim$ 650 hr. The sample immersed into mineral oil at 50°C showed weight increased by $\sim$ 0.05% from beginning to 150 hr and then the weight decreased by 0.15% from 150 to $\sim$ 650 hr. Initially, the data presented indicates the absorbance of the dielectric fluid into the PCB sample was dominant, and after the $\sim$ 150 hr mark, leaching of plasticizers from the PCB sample into dielectric fluid was dominant for aging temperatures of 25 and 50°C. This was a preliminary experiment with one sample for each temperature, which not statistically robust. The focus of this segment of the study is more on defining the methodology for similar future investigations to provide a better understanding of the impact of immersion cooling thermomechanical properties.

5. CONCLUSION

In summary, the thermomechanical properties of low-loss modulus PCBs were studied using dynamic mechanical analysis and thermomechanical analysis. One set of low-loss PCB samples was tested for post-aging in air, and another set of samples was tested for post-aging in mineral oil for 720 hr at four different temperatures, 25, 50, 75, and 105°C. Multiple samples were tested to obtain average values and standard deviations. The CTE values for the post-aging samples in air practically remained the same. The in-plane CTE values for post-aging samples in mineral oils at four temperatures changed negligibly and remained at $\sim$ 16.5 ppm/°C before the glass transition temperature. The complex modulus and glass transition temperature for the post-aging samples in the air and mineral oil at four different temperature did not change. Thus, it is concluded that mineral oil as a dielectric fluid does not have any adverse effects on the thermomechanical properties of a low-loss Megtron6 PCB. This work can be used to understand the impact of immersion cooling on the thermomechanical properties of low-loss PCBs. The dielectric fluid absorbance measurement technique demonstrated in this study may be adopted to gain more understating and insight about impact of immersion cooling dielectric fluid on thermomechanical properties of various electronics packaging materials. Furthermore, modulus, CTE, and glass transition temperature values measured may be used to perform numerical studies, such as finite element analysis to assess the reliability of immersion cooling under different loading conditions.

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