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IMPACT OF IMMERSION COOLING ON THERMOMECHANICAL PROPERTIES OF HALOGEN-FREE SUBSTRATE CORE

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ABSTRACT

The data center's server power density and heat generation have increased exponentially because of the recent, unparalleled rise in the processing and storing of massive amounts of data on a regular basis. One-third of the overall energy used in conventional air-cooled data centers is directed toward cooling information technology equipment (ITE). The traditional air-cooled data centers must have low air supply temperatures and high air flow rates to support high-performance servers, rendering air cooling inefficient and compelling data center operators to use alternative cooling technology. Due to the direct interaction of dielectric fluids with all the components in the server, single-phase liquid immersion cooling (Sp-LIC) addresses mentioned problems by offering a significantly greater thermal mass and a high percentage of heat dissipation. Sp-LIC is a viable option for hyper-scale, edge, and modular data center applications because, unlike direct-to-chip liquid cooling, it does not call for a complex liquid distribution system configuration and the dielectric liquid can make direct contact with all server components. Immersion cooling is superior to conventional air-cooling technology in terms of thermal energy management however, there have been very few studies on the reliability of such cooling technology. A detailed assessment of the material compatibility of different electronic packaging materials for immersion cooling was required to comprehend their failure modes and reliability. For the mechanical design of electronics, the modulus, and thermal expansion are essential material characteristics. The substrate is a crucial element of an electronic package that has a significant impact on the reliability and failure mechanisms of electronics at both the package and the board level. As per Open Compute Project (OCP) design guidelines for immersion-cooled IT equipment, the traditional material compatibility tests from standards like ASTM 3455 can be used with certain appropriate adjustments. The primary focus of this research is to address two challenges: The first part is to understand the impact of thermal aging on the thermo-mechanical properties of the halogen-free substrate core in the single-phase immersion cooling. Another goal of the study is to comprehend how thermal aging affects the thermo-mechanical characteristics of the substrate core in the air. In this research the substrate core is aged in synthetic hydrocarbon fluid (EC100), Polyalphaolefin 6 (PAO 6), and ambient air for 720 hours each at two different temperatures: 85°C and 125°C and the complex modulus before and after aging are calculated and compared.

Keywords: Single phase immersion cooling, Elastic modulus, Low CTE substrate, DMA

NOMENCLATURE

E’	Storage modulus
E”	Loss modulus
E*	Complex modulus/Elastic modulus
tan δ	Damping ratio

INTRODUCTION

Massive amounts of data are gathered, stored, processed, and distributed using data centers (DCs), which may be used for a variety of purposes, including business, amusement, and other requirements [1, 2]. A single CPU's server power will normally be 140 W-190 W by 2020, whereas a single processor for High-Performance Computing (HPC) will exceed 300 W. The heat dissipation of IT equipment accounts for 50%-60% of the data center's heat source [3]. In 2025, DCs will consume 4.5% of the world's electricity, of which 40% will be used for cooling systems [4]. Globally, it is predicted that data centers used 91 billion kWh of energy annually in 2013, 140 billion kWh in 2020, and more in 2025. This would result in annual carbon emissions and operating electricity costing more than 150 million metric tons and $13 billion respectively [5]. Because data centers consume a lot of electricity, particularly for cooling, decreasing energy use is a primary concern for IT companies and policy officials [6].

Despite significant technological advancement over the past few decades, managing the temperature of electronics or microprocessors still presents significant technical difficulties.

The effective removal of increasing heat flux and extremely non-uniform power dissipation are the two key cooling problems [6]. Due to inadequate cooling capacity, high energy consumption, and high operational expenses, traditional air cooling has reached its limits. Immersion cooling offers several benefits such as higher thermal mass and high heat dissipation due to the dielectric fluids being in direct contact with all the components [7]. Single-phase immersion has several advantages such as it shields the ITE from the impact of contaminants, reduces failures due to vibration, and lowers the CapEx as it does not require sophisticated liquid distribution manifold construction, thus making data center architecture easier [7].

Reliability issues may arise when the heat-generating components are immersed in the dielectric fluids. Deformation, warpage, or delamination modes of failure that result in the failure of the complete package may be brought on by a slight variation in the material properties of the components [8]. While providing the material properties, most of the fluid suppliers and vendors send the soak test results. However, they don't consider operational reliability like the mechanical and electrical characteristics of the components unique to the application work environment [8]. The material compatibility may be divided into direct and indirect interactions. Direct interactions are processes that are generated by the fluid itself. They can occur in the fluid or when the fluid interacts with a component material. Dissolution, absorption/swelling, chemical contact of material, environmental stress cracking (ESC), fluid aging, and oxidation are the six basic ways for direct interactions to occur in single-phase fluids. Chemicals released or generated by direct contact with IT components induce indirect reactions rather than the fluid itself [9].

The thermo-mechanical characteristics of low loss printed circuit boards immersed in mineral oil for 720 hours at 25, 50, 75, and 105°C were studied by Tushar et. al [10]. They found that at that the in-plane CTE values of the post-aged samples did not change much at these temperatures. Ramdas et. al [11] performed a similar study with FR-4 PCB immersed in EC-100 dielectric fluid. The results show that the modulus has decreased for post-aged samples which means that PCBs are less stiff and in turn decrease the warpage. Bhandari et al. [12] investigated the effect of single-phase immersion fluid EC-100 on the mechanical properties of non-halogenated substrates after immersion for 720 hours at ambient temperature, 50°C, and 75°C. In this study modulus of the immersed substrate is compared with the modulus of substrates exposed to air at the respective temperatures. It was observed that rising temperatures caused the modulus to decrease but at 75 °C in both air and EC100 fluid, a varying trend was observed.

The fundamental goal of this research is to quantify and characterize the material compatibility of immersed components. As per Open Compute Project (OCP) design guidelines for immersion-cooled IT equipment, the traditional material compatibility tests from standards like ASTM D471 and D2240 can be used with certain appropriate adjustments [9]. The present investigation is bifurcated into two distinct segments: The first stage involves comprehending the effects of thermal aging on the halogen-free substrate core within the dielectric fluid utilized for single-phase immersion cooling, with regards to its thermo-mechanical characteristics. Another goal of the research is to gain an understanding of the impact of thermal aging on the thermo-mechanical properties of the substrate core exposed in air at high temperature. The halogen-free laminate (IS550H) is utilized by individuals who necessitate exceptional thermal stability, as well as elevated power and voltage. The present study involves subjecting the substrate core to synthetic hydrocarbon fluid (EC110), Polyalphaolefin 6 (PAO 6), and ambient air for a duration of 720 hours at two distinct temperatures, namely 85°C and 125°C. The complex modulus of the substrate core is subsequently measured using Dynamic Mechanical Analyzer (DMA) before and after the aging process, and a comparative analysis is performed.

MATERIALS AND METHODS

The halogen-free substrate samples had a thickness of 0.25 mm and were trimmed to dimensions of approximately 50 mm x 5 mm. A set of 24 specimens were fabricated in preparation for Dynamic Mechanical Analysis (DMA) measurements. The selection of experimental parameters, namely temperature (85°C and 125°C) and duration (720 hours or one month), was made in accordance with the OCP guidelines and ASTM 3455. Figure 1 depicts the primary constituents of DMA, while figure 2 illustrates the sample mounted to the tensile probe. Figure 3 shows the thermal chamber which houses substrate samples that are submerged in EC-100, PAO 6, and exposed to air. Table 1 provides information regarding the quantity of samples that are situated in each fluid.

The method of Dynamic Mechanical Analysis is employed to quantify the kinetic properties of a given specimen, including its elasticity and viscosity [10]. Various DMA modules, including tension, bend, shear, and compression deformation attachments, can be employed to examine diverse material characteristics, depending on factors such as sample shape, modulus, and measurement objective. The DMA methodology is utilized to compute both the storage modulus and the loss modulus. Equation 1 and 2 provides the mathematical expression for the correlation among complex modulus, storage, and loss modulus [12]. The complex modulus that has been computed can be subjected to a comparison with Young's modulus. Following is the formula to calculate complex modulus:

$$E^* = E' + iE'' \quad (1)$$

$$E^* = \sqrt{(E')^2 + (E'')^2} \quad (2)$$

$$\tan\delta = E''/E' \quad (3)$$

where,

E^* = Elastic modulus
E' = Storage modulus
E'' = Loss modulus
$\tan\delta$ = Damping ratio

The sample dimensions were measured utilizing a digital caliper that possessed an accuracy of 0.02 mm. The selection of the tensile attachment for the present study was based on the projected modulus derived from the sample dimensions and the material properties. Prior to being mounted onto the DMA for testing, the samples immersed in dielectric were appropriately cleaned using a paper towel. The DMA measurements were conducted with a fixed L amplitude of 10 µm and a force amplitude of 2000 mN for all samples. The experimental data was collected by exposing the specimens to a temperature range spanning from -35°C to 200°C, with a consistent ramp rate of 4°C per minute. Additionally, a range of frequencies, including 0.5, 1, 2, 5, and 10 Hz, were applied during the testing process. The auto LN2 gas cooling unit facilitates the dispensation of liquid nitrogen to lower the temperature of the furnace below ambient temperature [13]. A thermal equilibrium was achieved by subjecting the system to an isothermal hold at the initial temperature i.e. -35°C. This resulted in an extension of the measurement duration of the DMA to approximately 2.5 hours. Table 2 presents the parameters utilized for the purpose of testing.

Table 1: Aging of substrate samples in EC100, PAO 6 and air.

Aging Temperature	**Aging Time**	**No. of Samples immersed in EC100**	**No. of Samples immersed in PAO 6**	**No. of samples in the air**
85°C	~ 720 hours	4	4	4
125°C		4	4	4

Table 2: Testing parameters used in DMA

Parameters	**Values**
Maximum Force	2000 mN
Temperature Ramp	3°C
Sample Thickness	0.25mm~0.3mm
Sample Length	20mm
Sample Width	5 mm

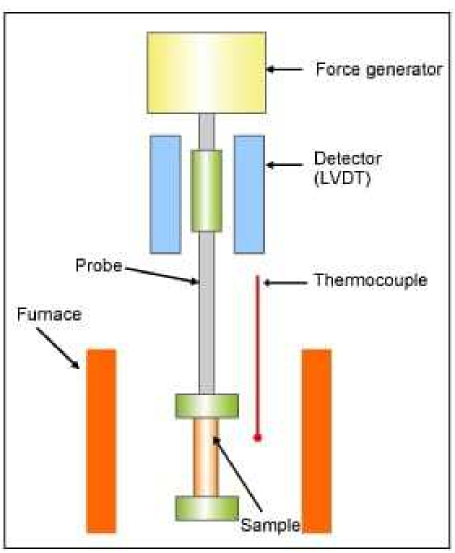

Figure 1: Schematic of DMA

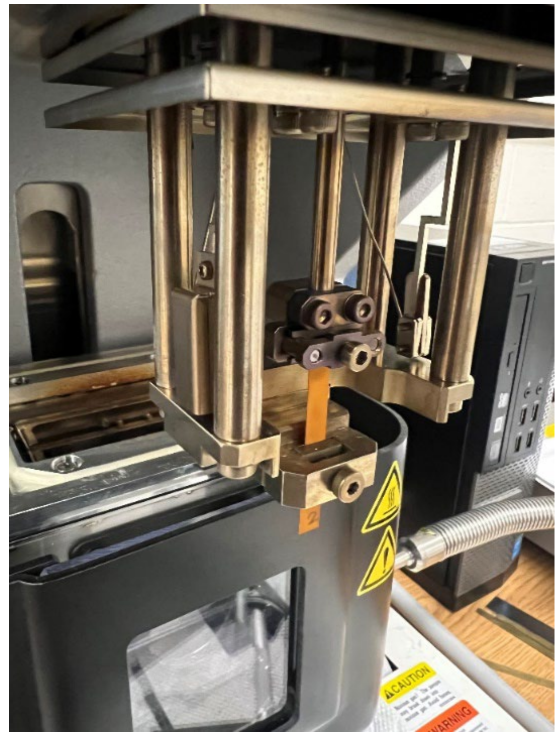

Figure 2: Sample mounted in the tensile attachment on DMA

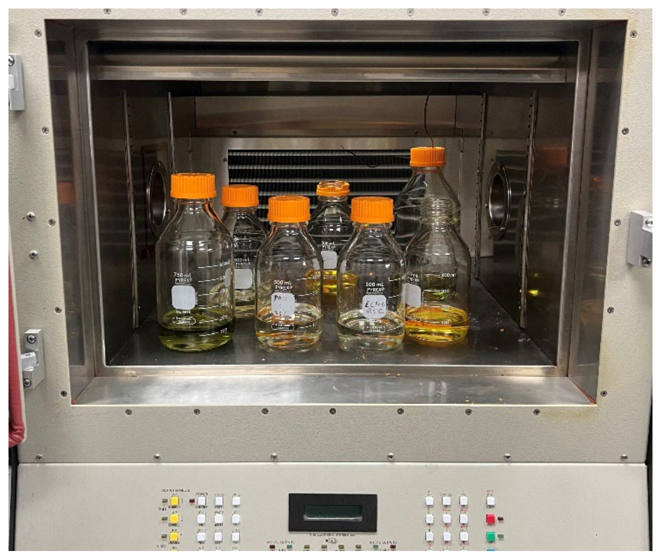

Figure 3: Sample bottles placed in a thermal chamber

RESULTS AND DISCUSSION

The specimens underwent analysis using DMA, and the complex modulus was determined through the examination of the storage modulus and loss modulus data gathered during the testing procedure. Four samples were used for each test case, and the average value was documented. The figures illustrate the values of elastic modulus, with the error bars indicating the standard deviation.

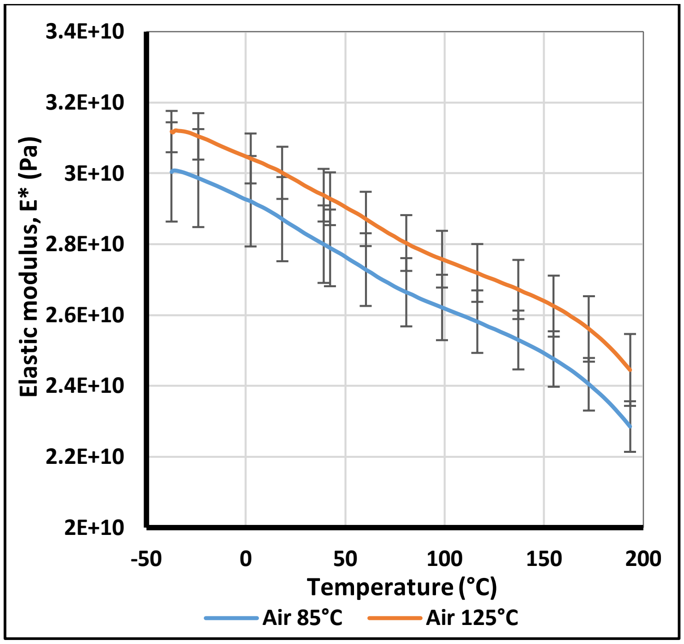

Figure 3: Elastic Modulus of sample exposed in Air at 85°C and 125°C

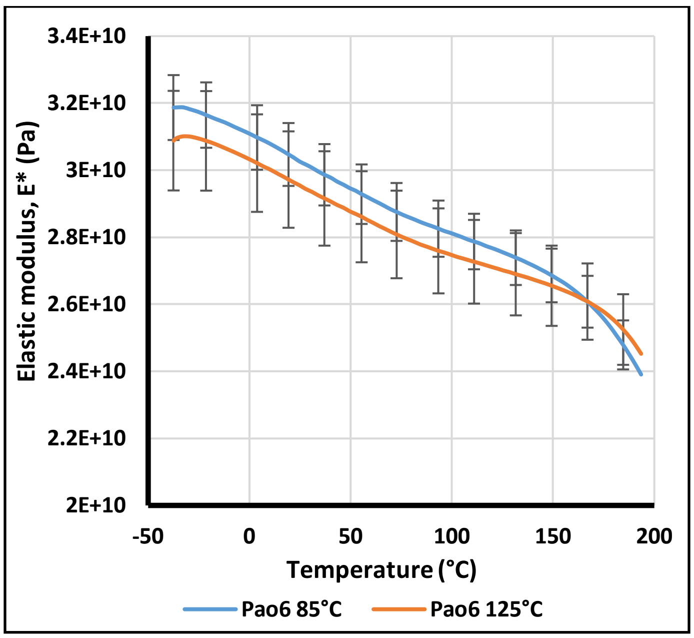

Figure 4: Elastic Modulus of sample exposed in PAO6 at 85°C and 125°C

The elastic modulus of the specimens exposed air at 85°C and 125°C is illustrated in Figure 3. The error bar shows the standard deviation with a value of ±1 GPa. The modulus of elasticity of the sample subjected to air at 125°C is greater than that of the sample exposed to 85°C. Furthermore, the modulus values of both sample variants exhibit a decreasing trend as the temperature is raised from -35°C to 180°C in the DMA. The consistency of the modulus variation between the two samples remains constant within the temperature range of -35°C to 180°C. The data depicted in Figure 4 illustrates an identical trend in samples that were submerged in PAO 6 at both 85°C and 125°C. However, the samples that were immersed in EC100 at 85°C and 125°C chamber temperature as shown in figure 5 exhibit the same modulus at all temperature ranges from -35°C to 180°C.

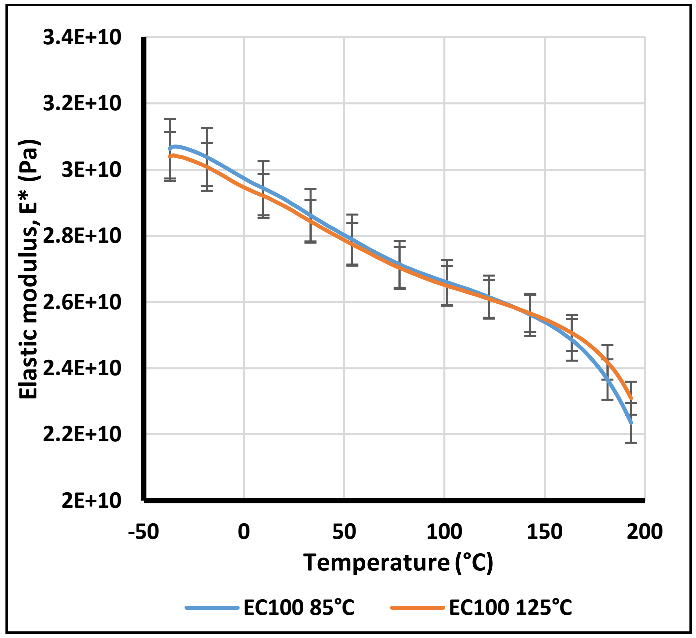

Figure 5: Elastic Modulus of sample exposed in EC100 at 85°C and 125°C

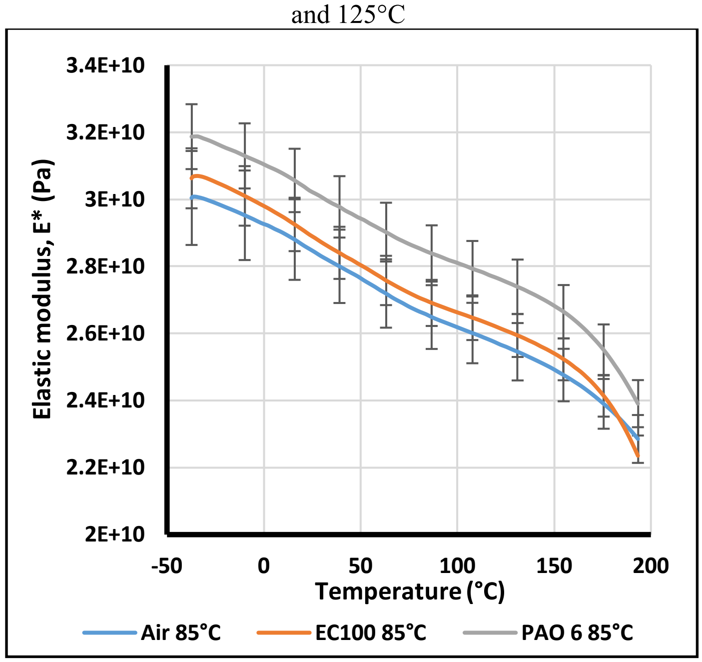

Figure 6: Elastic Modulus of sample immersed in EC100, PAO6 and Air at 85°C

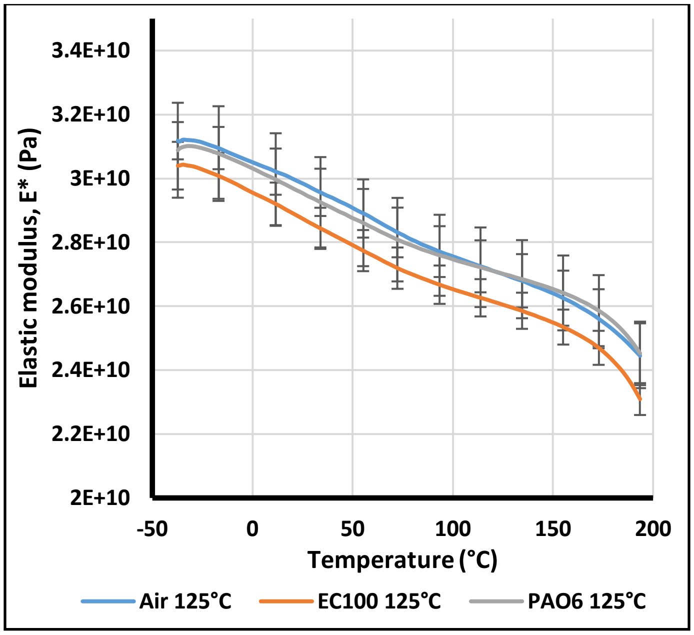

Figure 7: Elastic Modulus of sample immersed in EC100, PAO6 and Air at 125°C

The modulus trend of the samples that were subjected to immersion in EC100, PAO6, and air at a temperature of 85°C is depicted in Figure 6. The observed trend indicates that the elastic modulus of the substrates subjected to immersion in PAO6 is higher than that of the sample subjected to immersion in EC 100. A marginal discrepancy in the modulus is observed between the samples exposed to air and those immersed in EC 100. In Figure 7, when the substrates were subjected to a temperature of 125°C, it was observed that the modulus of the samples immersed in POA6 was comparable to that of the samples exposed to air. On the other hand, the modulus of the samples immersed in EC 100 was found to be lower than that of the air-exposed samples and POA 6 samples. The observed fluctuations in modulus values among samples that underwent thermal aging and air exposure at 85 °C are a matter of concern. The aforementioned conduct was also noted in the analysis carried out by Rabin et al. [12].

CONCLUSION

The surge in immersion cooling's popularity can be attributed to the escalating demand for high-performance computing and the concomitant increase in power density. The matter of reliability is a constant preoccupation within the electronic packaging sector. The present investigation is centered on the reliability of halogen free substrates core. The substrates underwent thermal aging at two different temperatures, namely 85°C and 125°C. The modulus values of these substrates were then compared with those of substrates that were exposed to air at the same temperatures. Consistent with expectations, the modulus exhibited a negative correlation with rising temperature. However, for specimens subjected to a temperature of 85°C in air, POA 6 and EC100 fluid environments, an irregular pattern was detected. Further analysis is necessary to gain a better comprehension of this phenomenon in the halogen free substrates aged at 85°C.

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