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ANALYZING THE THERMOMECHANICAL PERFORMANCE OF TG400G MATERIAL SUBSTRATE CORE UNDER IMMERSION COOLING

BY

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Venkateswar Vishnu, 15th August 2023

DEDICATION

I would like to dedicate my master’s dissertation

To

My parents

Meenakshi T.V.S.

For their unwavering backing, affection, and concern for me,

And their constant encouragement and support.

ABSTRACT

ANALYZING THE THERMOMECHANICAL PERFORMANCE OF TG400G MATERIAL SUBSTRATE CORE UNDER IMMERSION COOLING

TIRUPATI VENKATACHALAM SOUNDARAPANDI VENKATESWAR VISHNU

The University of Texas at Arlington,2023

The relentless surge in demand for seamless information exchange through consumer electronics, driven by the indispensable role of the Internet, has given rise to an unprecedented need for data centres. Yet, the energy consumption of conventional data centres, where a significant one-third of energy usage is attributed solely to cooling, has triggered an urgent quest for energy-efficient solutions. Immersion cooling technology appears as a promising contender due to its exceptional prowess in managing thermal energy. However, its potential impact on the reliability of IT equipment needs a more profound exploration before widespread adoption can be realized.

This study embarks on a focused mission: to unravel the intricate effects of thermal aging on the thermo-mechanical attributes of low loss printed circuit boards (PCBs), specifically homing in on the TerraGreen 400G variant, within ambient air conditions. The investigation subjects these low-loss PCBs to varying temperatures (85°C and 125°C) and durations (720 hours) of thermal aging, both within EC100 and PAO6 environments. By meticulously scrutinizing alterations in complex modulus and Glass Transition Temperature (Tg) before and after aging, the study endeavours to unearth any shifts in the material's fundamental properties.

Anticipated outcomes of this research stand to give invaluable insights into the dependability and adaptability of TerraGreen 400G PCBs within immersion cooling scenarios. Such insights hold profound implications for the relentless pursuit of energy-efficient and environmentally considerate data centres. Moreover, the study's findings promise to cast a luminous beam on the terrain of electronics mechanical design by illuminating material behaviour amidst the rigors of thermal aging. In a world propelled by digital expansion, this investigation serves as a beacon, illuminating pathways to both greener data infrastructure and a more profound comprehension of materials under demanding thermal conditions.

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Chapter 1

1.1 Introduction

Power consumption by data centres has emerged as a critical challenge that demands unceasing attention and a continuous stream of innovation. Over the past ten years, with the surge in energy requirements and higher processing capabilities, conventional air-cooling techniques have faced constraints in effectively cooling processors operating within lower thermal design power (TDP) thresholds. [1] As society becomes increasingly dependent on digital services, the demand for data centre operations continues to surge, making energy efficiency an ever-more pressing concern. At the heart of these centres, CPUs and GPUs stand as the workhorses powering the servers that facilitate these services. These processors undertake a myriad of computational tasks, spanning from executing applications and parsing through voluminous data to promptly responding to user commands. IT devices must function within prescribed temperature and humidity ranges that are suitable and permissible given the prevailing conditions. [2] As data centres shoulder the escalating burden of processing vast volumes of information, the imperative for robust yet energy-conscious processors become more pronounced. The relentless growth of data centres has prompted industries to intensify their focus on enhancing energy efficiency. As consumer expectations for added features in handheld electronic gadgets grow, the requirement for additional components like memory, CPU, and GPU within compact handheld designs is on the rise. [3] Innovations in hardware design, cooling systems, and data centre architectures are being pursued to mitigate the formidable energy footprint of these facilities.

Modern CPUs/GPUs commonly possess numerous cores, and not all of these cores within the package are active simultaneously. This dynamic generates an uneven dispersion of heat or a thermal gradient across the processor. [4] A pivotal aspect of these efforts is the development of more energy-efficient CPUs and GPUs. The advancements in computational performance following the divergence from Moore's law were attained through the utilization of multicore processors. However, this approach has resulted in uneven power distribution and concentrated high temperatures, further complicating the task of thermal management. [5] Technological breakthroughs are steering chip manufacturers towards producing processors that can deliver exceptional performance while minimizing power consumption. This twin objective necessitates research into novel materials, advanced manufacturing techniques, and fundamentally rethinking the architecture of these processing units. The consequences of not addressing the energy consumption issue are looming large.

Data centres presently account for around 3% of the world's total electricity usage, and projections indicate that this figure could swell to 4% by 2030. As a result, collaboration across industries, governments, and academia is paramount to find sustainable solutions.

This collaboration can involve developing stricter energy efficiency standards for data centres, incentivizing the adoption of renewable energy sources to power these facilities, and promoting research into innovative technologies that could revolutionize energy-efficient computing. The path forward involves a multi-pronged strategy that includes optimizing existing data centre operations, investing in research for next-generation processors, and advancing the use of renewable energy in powering these energy-intensive hubs. In response to demands from data centre operators, manufacturers of information technology equipment such as Dell and IBM are creating products capable of enduring maximum temperature levels reaching 45°C. This exceeds the suggested range and falls within ASHRAE's permissible A4 temperature range. [6]

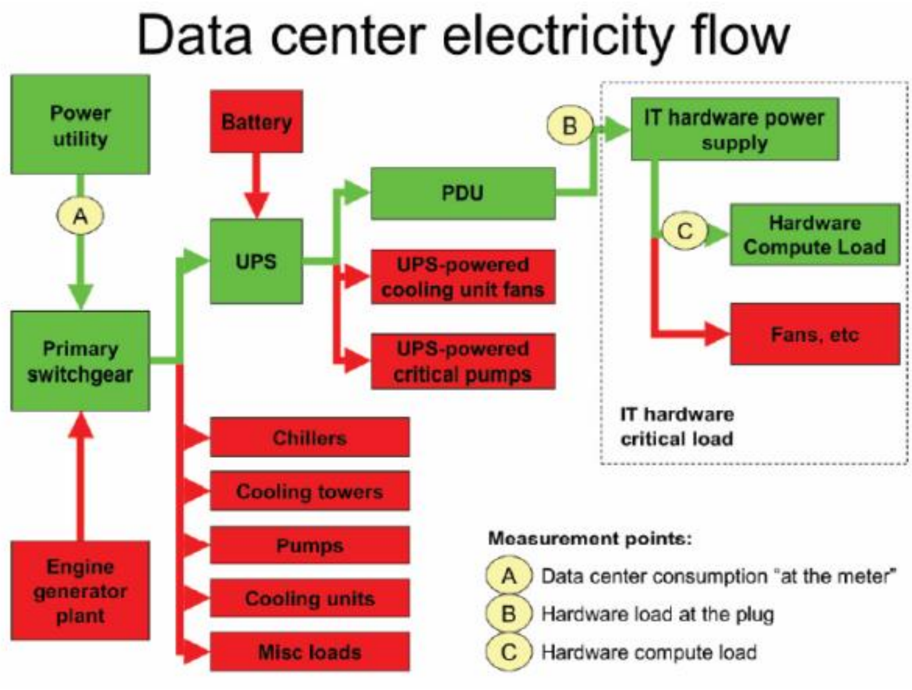


Figure 1: Data Centre Electricity Flow [57]

The goal is to strike a balance between the insatiable demand for digital services and the imperative of environmental stewardship. As the world hurtles toward a future intricately intertwined with digital technologies, it becomes increasingly crucial to ensure that this evolution is underpinned by sustainability. Only through such holistic and concerted efforts can we hope to mitigate the energy challenges posed by the relentless expansion of data centres and secure a greener, more efficient digital future. The relationship between the workload of Information Technology Equipment (ITE) and allocation of chilling resources is complex and exhibits non-linear behaviour in both space and time aspects. [7]

In a data centre, electricity flows through a complex network of components and systems to power the various operations and services shown in figure 1. Starting from the external power grid or power Utility, electricity enters the facility and is distributed through transformers and switchgear for appropriate voltage levels. It then moves through un-interruptible power supply (UPS) systems, which offer alternative power source during outages and regulate voltage stability. From the UPS, electricity is channelled into power distribution units (PDUs) and then directed to racks of servers and networking equipment. Within these racks, power is further distributed to individual servers and their components, including CPUs, GPUs, memory modules, and storage devices. Advanced cooling systems work in tandem to dissipate the heat generated by these components. Efficient power distribution, backup systems, and cooling mechanisms are essential to ensure reliable data centre operation while addressing energy consumption concerns.

1.2 Data Cooling Energy Breakdown

The energy breakdown of data centre cooling encompasses several key components, each contributing to the overall efficiency of temperature management as shown in figure 2. First, precision air conditioning systems play a pivotal role, responsible for maintaining the ambient temperature within optimal ranges for equipment operation. These systems often consume a significant portion of cooling energy. Additionally, the process of circulating and filtering air throughout the data centre requires energy, with fans and blowers contributing to the cooling load. Data-centric modelling or machine learning is a cost-effective and time-efficient approach as compared to alternatives such as validated computational fluid dynamics (CFD) simulations or experimental setups. [8]

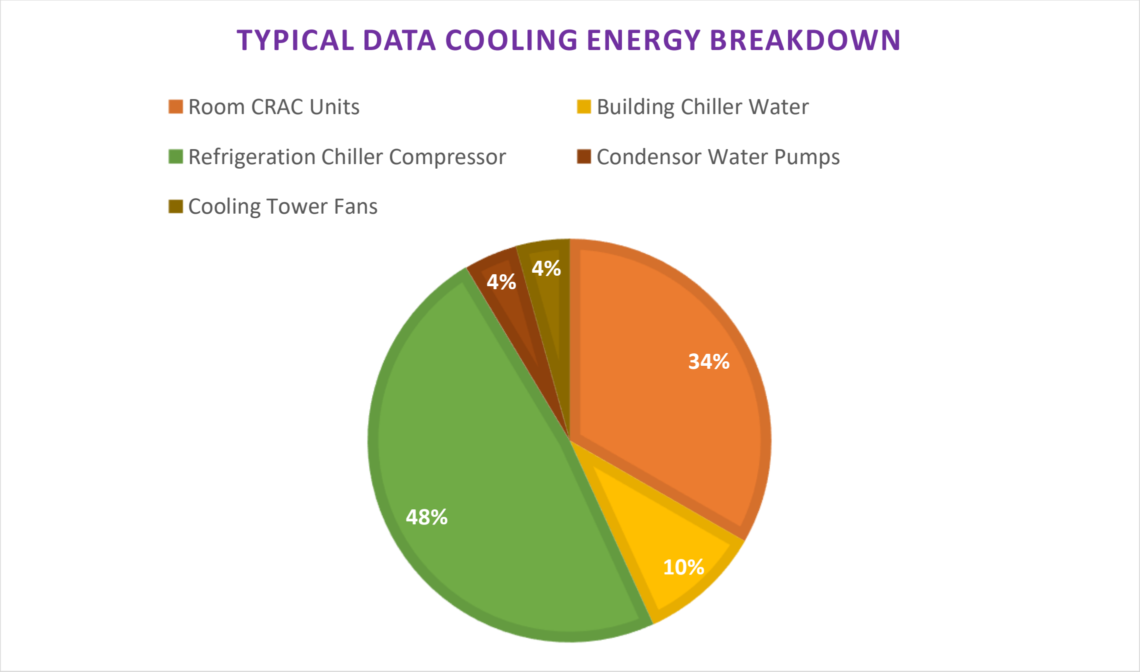


Figure 2: Bar chart for Typical Data Cooling Energy Breakdown

Another substantial aspect is the chillers or cooling towers that transfer heat away from the air conditioning systems. These components require energy to operate and are vital for dissipating the accumulated thermal energy. Furthermore, the layout and arrangement of server racks and aisles affect the efficiency of airflow management. The act of repeatedly powering off and on an electronic device result in a loading scenario referred to as power cycling. [9,10,11]

Effective hot & cold aisle containment strategies aim in decrease the mingling of hot & cold air currents, thereby lessening strain on cooling systems. Modern data centres are increasingly integrating advanced technologies like liquid cooling, Immersion cooling are used to dissipate heat from high-power components. The majority of manufactured electronic devices find application in everyday routines. With the ongoing miniaturization of these devices, there is a potential risk of failure due to impacts from drops in daily use. Therefore, the analysis and assurance of electronic device reliability under various loading conditions have become crucial. [12] While these innovations can significantly enhance cooling efficiency, they also introduce their own energy requirements for pumping and distributing coolants. The cooling energy breakdown in data centres encompasses the energy consumed by precision air conditioning systems, air circulation equipment, chillers or cooling towers, and innovative cooling solutions. Optimizing each facet of this cooling ecosystem is essential to strike a balance between maintaining optimal operating temperatures for equipment and conserving energy to address the overall sustainability challenges posed by data centre operations.

1.3 Failure and Stress Distribution in Power Electronic Systems

Within power electronic systems, the deterioration of a single component can have a cascading effect on the performance of others as shown in figure 3. For instance, a decrease in capacitance might lead to a higher voltage ripple, subsequently subjecting switching devices to overvoltage stress. The prevalent mode of failure in commonly employed microelectronic devices is the development of interface fractures caused by fatigue connecting solder joints and components. [13] This occurs even if the capacitor itself remains operational within standard parameters. Likewise, the decline change in the inputs and outputs of a power electronic converter could initiate malfunctions in interconnected subsystems. Due to a cohesive, protective, and naturally occurring oxide layer, aluminium and its alloys have good adhesion properties to many surfaces. [14] Establishing failure criteria for parts or systems in power electronics is more difficult than in other fields due to its complexity.

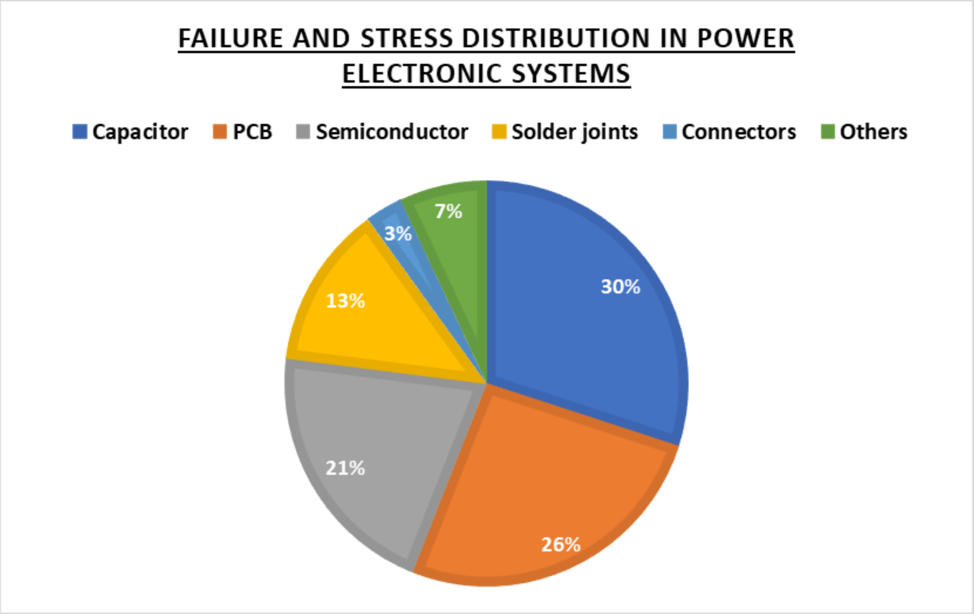


Figure 3: Bar Chart for Failure and Stress Distribution in Power Electronic Systems [58]

Failures in printed circuit boards (PCBs) within a single-phase immersion cooling environment are an essential consideration in the quest for reliable and efficient data centre solutions. As the process of minimizing planar devices progresses towards its ultimate thresholds, the intricate nature of circuit interconnections in two-dimensional devices imposes a constraint on performance and contributes to increased power dissipation. [15] Immersive cooling, involving the utilization of dielectric fluid for cooling purposes electronic components, which presents special difficulties that may affect PCB performance and durability. PCBs core and basic component which acts as a support as shown in figure 4.

One primary concern is the potential for dielectric fluid ingress into the PCB, which can lead to short circuits and corrosion of electrical connections. While immersion cooling systems are designed to prevent such occurrences, any breach in the system could result in fluid reaching the PCB surface. PCB boards are experiencing higher levels of component density, incorporating an array of smaller hardware elements. As a result, the demand for effective cooling is on the rise. [16] This could compromise insulation and cause electrical disruptions, leading to system failure.

Reliability testing under immersion conditions becomes vital to assess the impact on PCBs. Accelerated life tests involving prolonged exposure to elevated temperatures and fluid environments help gauge the resilience of PCBs. To satisfy impending interconnection demands, employing through silicon vias (TSVs) within a three-dimensional (3D) packaging has shown promise. [17,18] Monitoring electrical performance, insulation resistance, and integrity of solder joints are key metrics. The investigation of package technique like System-on-Chip (SoC) and System-in-Package (SiP) is typically driven by rising consumer expectations, the opportunity for improved collaboration between PCB and packaging, and the need to accelerate time-to-market. [19] In summary, single-phase immersion cooling offers promising thermal management benefits, but it introduces unique failure mechanisms for PCBs.

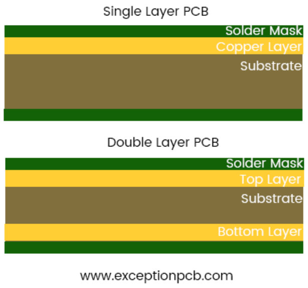


Figure 4: Types of PCB [59]

1.4 Cooling Technologies

Air cooling requires ensuring that the heat-intensive components within a server or hardware receive optimal airflow to effectively dissipate heat. To achieve this, ducting is implemented to direct air towards these components for efficient cooling. [20] Different cooling technologies possess differing capabilities in effectively handling the maximum power density per rack. The cooling system itself accounts for approximately 30% to 40% of the overall energy consumption. [21] Air-cooled data centres require multiple cooling methods to prepare and regulate the air before it reaches the IT equipment. [22] In order to meet increasing demands, Rear Door Heat Exchangers (RDHx) is introduced into operational data centres in conjunction with Computer Room Air Handling/Conditioning (CRAH/CRAC) units. [23] Air cooling can support approximately 30 kW per rack, while passive liquid cooling is cable to accommodate upto 60 kW/rack. Accelerated Thermal Cycling (ATC) tests specified by ATC JEDEC pertains specifically to air cooling, with no equivalent standard established for immersion cooling. [24] Meeting the rising performance requirements involves elevating CPU and GPU power densities, necessitating the adoption of enhanced cooling methods in contrast to conventional air-cooling methods. [25] When power density surpasses these thresholds, the implementation of direct liquid cooling or immersion cooling becomes imperative. According to the ASHRAE standard (2009b), the airflow into the data centre needs to be restated. undergo continuous filtration using MERV 11 or preferably MERV 13 filters, while air within data centres should meet the cleanliness criteria specified in ISO class 8. [26] In terms of power usage efficiency (PUE), immersion cooling outperforms air cooling and indirect cooling methods, showing the highest level of efficiency as shown in figure 5. While the deployment of airside economizers (ASEs) is highly efficient, it introduces potential concern of contamination in data centres, while compromising dependability of IT equipment. [27] Cold plate-oriented liquid cooling facilitates effective dissipation of high heat fluxes due to its notably elevated convective heat transfer coefficients. [28] The method of directly cooling chips with liquid has been extensively adopted to manage the heat generated by high thermal design power processors. [29] Within a hybrid-cooled server configuration, components generating substantial heat are cooled through the use of water or water mixed fluids, while remaining components get chilled via airflow utilizing fans situated at the server level. [30] Airside economization, also known as free air cooling, decreases the expenses associated with mechanical cooling by employing external air to cool IT equipment during favourable atmospheric conditions. [31]

Making use of natural air cooling and economization on the air side significantly decrease the power consumption attributed to cooling information technology equipment (ITE), a segment that constitutes roughly 40% of active energy usage in a conventional air-cooling data centre. [32]

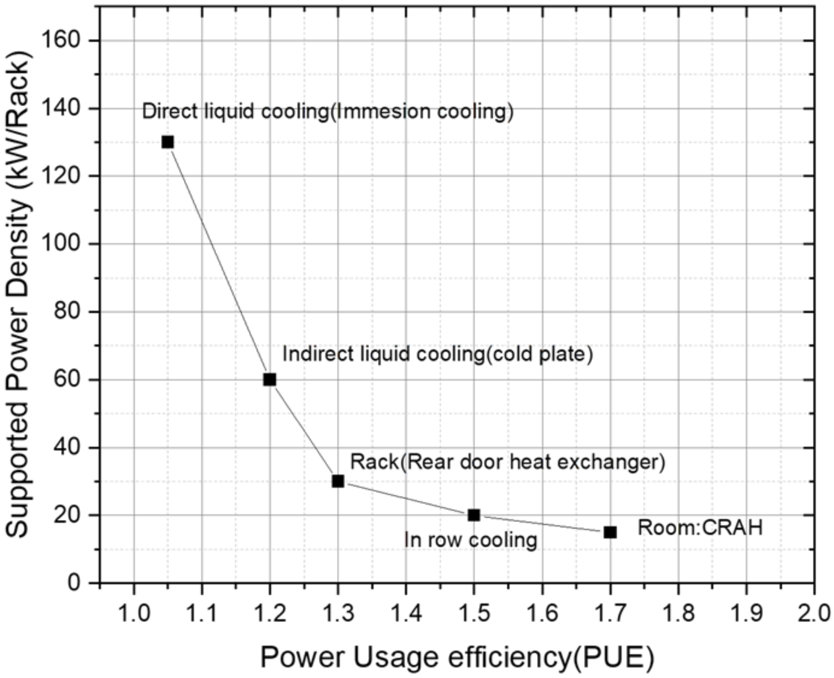


Figure 5: PUE graph for different types of cooling

The constraints of air cooling's ability to manage rising power densities in processors have prompted researchers to shift their focus towards more effective and efficient liquid cooling alternatives. [33]

Although the implementation of Airside Economizers offers high energy efficiency, it introduces the potential threat of contamination within data cooling centres, thereby Undermining the dependability of IT hardware. [34]

Conventional high-performance servers that rely on air cooling necessitate lower air-supply temperatures and increased airflow rates, which becomes inefficient for thermal design power values beyond a certain threshold. [35]

1.4.1 Liquid Cooling

The concept liquid-cooled system used in automobiles, where water Moves back and forth between the heat origin and the cooling radiator, has found an analogous application in computer devices and data centres. Utilizing cold plates for direct-to-chip liquid cooling has demonstrated itself as one of the most effective approaches to efficiently manage the substantial heat fluxes generated by contemporary high-power CPUs and GPUs. [36] The prevalent technique for dissipating heat from high-density data centre is the adoption of direct-to-chip liquid cooling, which employs cold plates. [37] In these setups, a cooling liquid is directed towards the central processing unit {CPU}, which is responsible for generating the bulk of the energy, while other parts are cooled using air. Air cooling is a not a good option for data centre cooling because of how little heat it can carry. [38] The enhanced effectiveness of mineral oil could potentially streamline facility design in contrast to conventional air-cooling methods, offering a viable avenue for cost reduction. [39] The operational parameters of the CDU are altered based on different conditions, including consistent flow rate, unchanging differential pressure, and steady pump speed. [40] For instance, let's take a personal computer, wheCPU) and graphics processing unit (GPU) serve as the main contributors to heat generation. This is evident from the notable heat emission observed during their operational activities. Liquid-to-liquid heat exchangers employed in data centres that use liquid cooling are also known as coolant distribution units (CDUs). [41] High-density data could potentially be thermally managed using the extremely effective thermal management technology known as immersion cooling. [42]

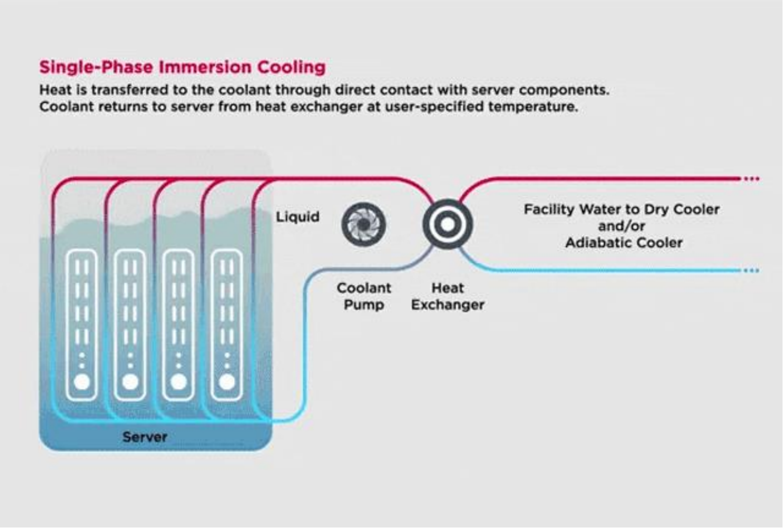


Figure 6: Single phase Immersion Cooling [60]

Notably, the rapid progress in technology and communication has led to a notable expansion of data centres and increased global energy consumption in recent years. This has underscored the need to give more significance to cooling systems within data centres, considering that these systems reportedly eat up more than 50% of energy due the process involved. Moreover, the escalating power density of microprocessors has been driving a significant rise in the cooling requirements of data centres. Utilising single-phase immersion cooling with a fluid with excellent heat characteristics and a high boiling point is a more efficient way to remove heat from these powerful components. [43]

Water cooling stands as a promising cooling solution, notably in data centres, to effectively manage processor and component temperatures like graphics cards. Airside Economization, also known as free air cooling, has been used for a while to lower the price of mechanical cooling. [44] The necessity arises due to the escalating processor speeds in recent years, resulting in heightened heat generation. The utilization of water in this context is driven by its exceptional heat absorption capability, approximately 30 times faster than air. This characteristic enables processors to operate at higher speeds and with reduced noise. The term "liquid cooling system" is sometimes used interchangeably, as alternative liquids can replace water. Numerical inverse analysis is applied to anticipate properties of heat-producing materials by gauging temperatures at the external boundary. The precision and effectiveness of this approach are elevated through the utilization of precise sensitivity details, achieved by employing the Semi-Analytical Complex Variable Method (CVSAM). [45,46,47,48,49] A notable advantage of this method is its heightened heat transfer effectiveness per unit, resulting in a diminished temperature difference between the CPU and cooling apparatus. Furthermore, it can accommodate higher input temperatures, thus decreasing the demand for heat dissipation techniques & facilitating reutilization of produced heat. Within the framework of single-phase immersion cooling, a fluid is revolved within a sealed circuit to efficiently draw out energy from IT equipment. This captured heat is subsequently released into the atmosphere from the dielectric fluid through a secondary loop, as depicted in figure 6. Immersion cooling exhibits the most favourable power usage efficiency (PUE) compared to all other cooling methods employed in data centres. There remains ongoing interest of refining immersion cooling techniques to fully capitalize on their capabilities. [50] Unlike air cooling, where the medium is in a gaseous state, the dielectric fluid in single-phase immersion cooling stays in its fluid state. In order to improve server thermal management and reduce operational and cooling costs, numerous industries are looking into the use of single-phase immersion cooling with a variety of dielectric fluids. [51] Notably, it possesses a volumetric thermal mass that is 1200 times massive compared to air cooling.

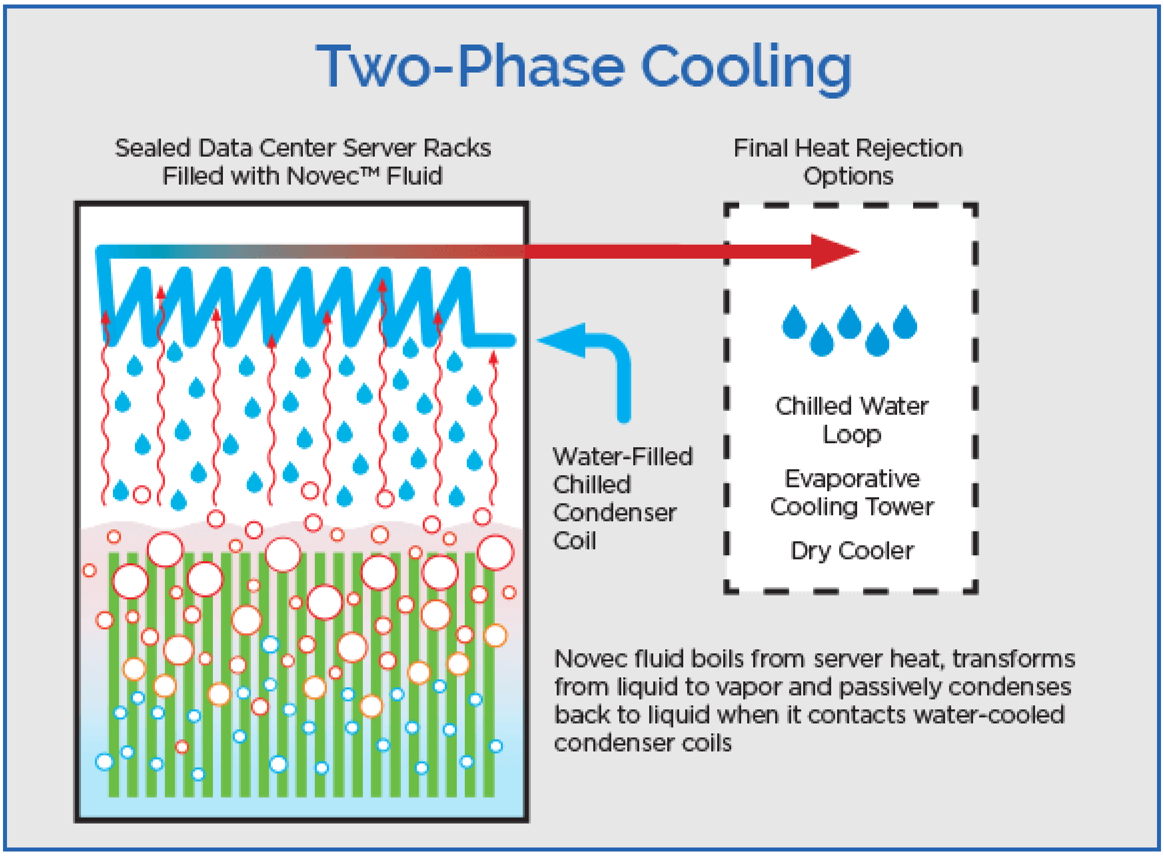
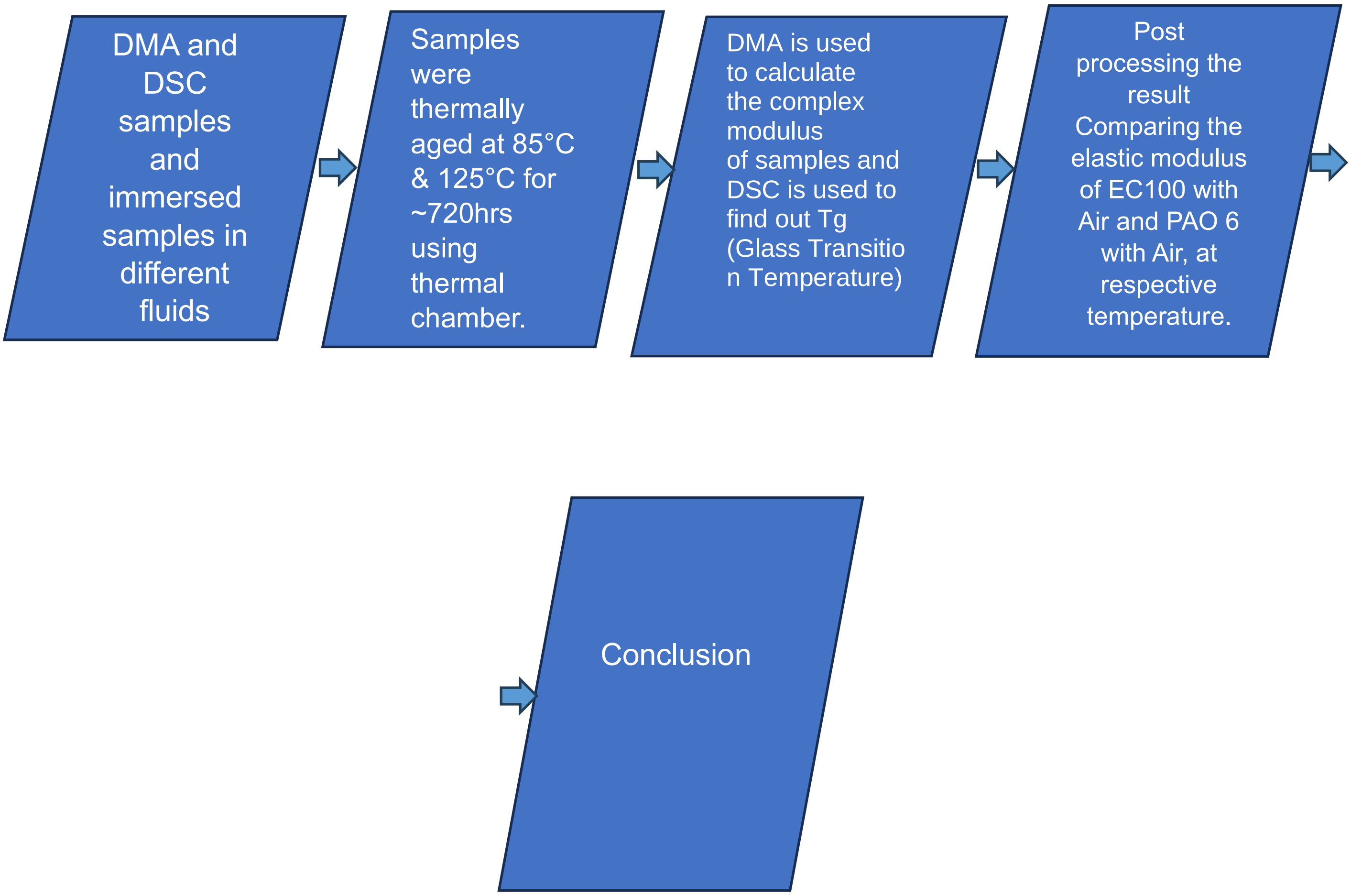


Figure 7: Two Phase Immersion Cooling [61]

Conversely, two-phase immersion cooling entails a fluid that transitions into a liquid to a vapor state, undergoing a phase change while absorbing heat energy from IT equipment and surpassing its temperature. The full immersion of servers in artificial fluids is quickly gaining popularity as a method to reduce energy needed by data centres for chilling. [52] Subsequently, the vapor condenses back into a liquid state by releasing heat to a condenser, ultimately leading to heat dissipation into the surrounding environment shown in figure 7.

1.5 OUTLINE



DMA and DSC samples and immersed samples in different fluids

Samples were thermally aged at 85°C & 125°C for ~720hrs using thermal chamber.

DMA is used to calculate the complex modulus of samples and DSC is used to find out Tg (Glass Transition Temperature)

Post processing the result Comparing the elastic modulus of EC100 with Air and PAO 6 with Air, at respective temperature.

Conclusion

Chapter 2

2.1 Materials and Methods

2.1.1 Dynamic Mechanical Analyzer (DMA):

Dynamic Mechanical Analysis (DMA) serves as a method for gauging a sample's kinetic attributes, encompassing qualities like elasticity and viscosity. This technique involves subjecting the sample to a sinusoidal load through a probing mechanism, resulting in stress/strain effects. These induced sinusoidal stress/strain reactions are then gauged and plotted over time or temperature. Several investigations have been undertaken to examine how different board thicknesses influence the thermo-mechanical reliability of BGA packages. [53] Distinct DMA modes, spanning tension, bending, shear, and fil shear attachments, are employed to assess varying material characteristics contingent on factors such as sample dimension, elastic modulus, and measurement objectives. DMA facilitates the evaluation of viscos and elastic traits such as storage modulus and loss modulus. By leveraging storage and loss modulus, one can compute Complex Modulus, whose extent aligns with Young's modulus.

$$E^* = E' + iE'' \qquad \text{(i)}$$

$$E^* = \sqrt{(E')^2 + (E'')^2} \qquad \text{(ii)}$$

$$Tan\ \delta = E''/\ E' \qquad \text{(iii)}$$

Above equations (i), (ii), and (iii) establish E* as the complex modulus, E' as the storage modulus, and E" as the loss modulus. The Dynamic Mechanical Analysis (DMA) apparatus utilized in this research functions across a temperature spectrum encompassing roughly -150°C to 600°C. To attain temperatures lower than room temperature, a cooling mechanism is employed that relies on automated LN2 gas injection, providing liquid nitrogen to the furnace. The key components of the DMA arrangement are visually illustrated in Figure 7.

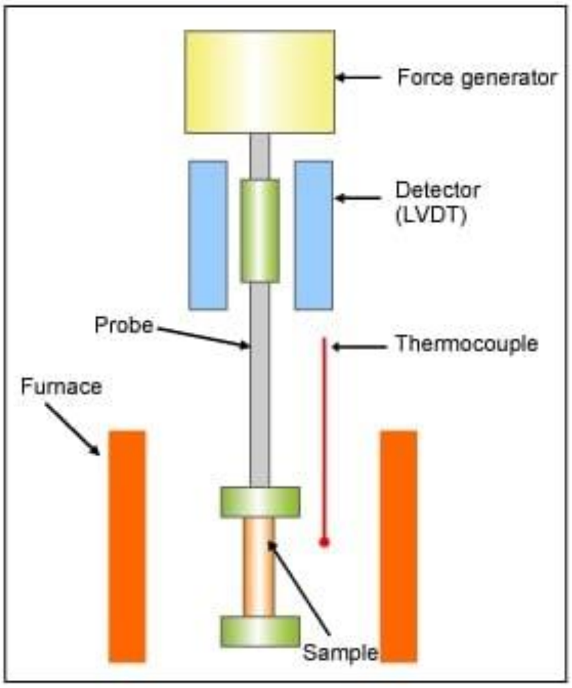


Figure 8: Block diagram DMA [62]

Chapter 3

3.1 Sample Preparation

3.1.1 Cutting the samples

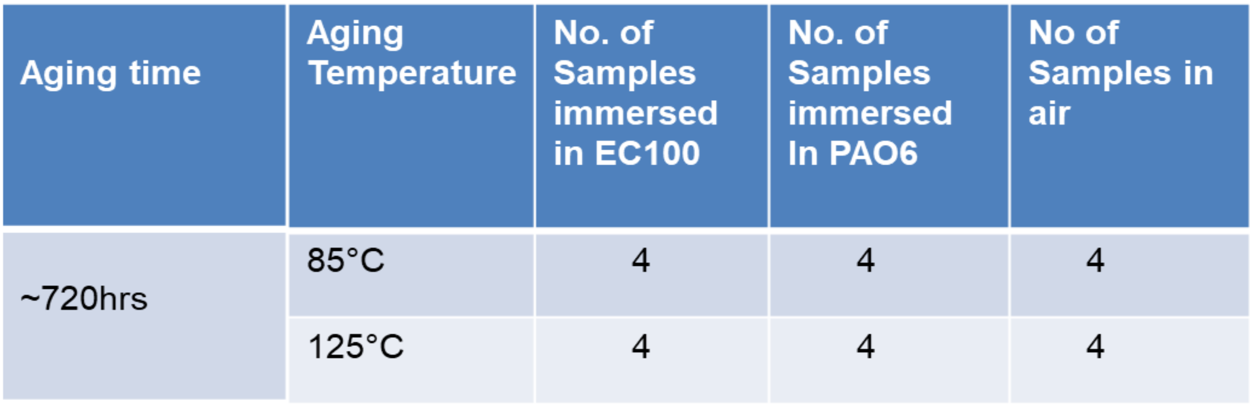
(a) (b)

Figure 9: (a) Sample length and (b) Sample width

The TG400G Substrate, with a thickness of approximately 2 mm, underwent division into four samples for each case examined in DMA analyses, ensuring statistical precision. For the DMA Tension tests, substrate was divided into approximately 50 mm x 5 mm samples as show in in figure 9 (a) and (b), resulting in a total of 32 samples for DMA assessments by cutting. Figure 9 depicts a representative sample configuration for DMA.

3.1.2 Thermal Aging

A total of 3 distinct aging scenarios were executed, differing in aging environment conditions, specifically for aging both temperature, and fluid. For each of the 3 cases, 4 samples from the substrate were subjected to both DMA and DSC analyses. The aging process was conducted across four distinct temperatures (85°C & 125°C) and within three various fluids (Air, EC100 & PAO6). The precise number of samples aged for a duration of approximately 720 hours for in each case is provided in Table 1 for DMA. Figure 10 displays the standard configuration used in aging, wherein substrate samples are immersed in Air, EC100 & PAO6 are placed within a furnace. The Figure 11 shows samples kept in different bottles for all different conditions.



Aging time	Aging Temperature	No. of Samples immersed in EC100	No. of Samples immersed In PAO6	No of Samples in air
~720hrs	85°C	4	4	4
	125°C	4	4	4

Table 1: TG400G samples subjected to the aging process within both air and dielectric fluids at 85ºC and 125ºC.

Figure 10: Thermal Chamber

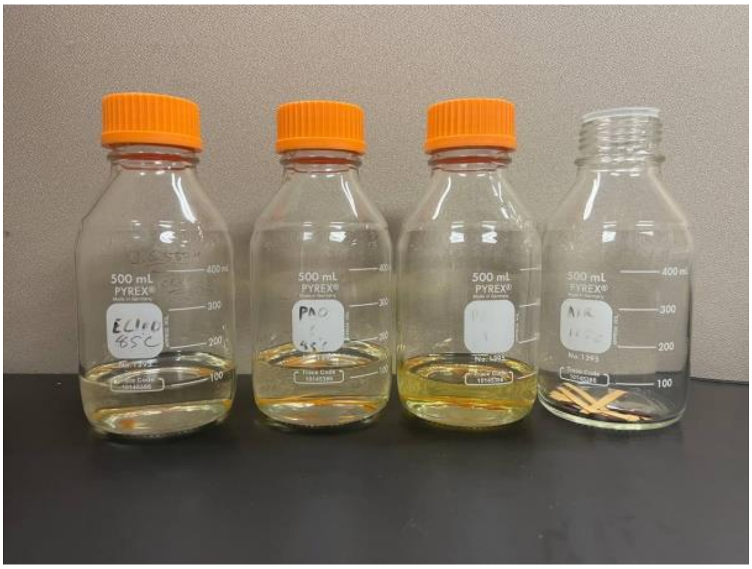


Figure 11: Immersed and non-immersed samples

Property		Typical Value	Units	Test Method
			Metric (English)	IPC-TM-650 (or as noted)
Glass Transition Temperature (Tg) by DSC		200	°C	2.4.25C
Decomposition Temperature (Td) by TGA @ 5% weight loss		>380C	°C	2.4.24.6
Time to Delaminate by TMA (Copper removed)	A. T260			
	B. T288	>60	Minutes	2.4.24.1
Z-Axis CTE	A. Pre-Tg	37	ppm/°C ppm/°C	
	B. Post-Tg	170	%	2.4.24C
	C. 50 to 260°C, (Total Expansion)	1.8		
X/Y-Axis CTE	Pre-Tg	12/13	ppm/°C	2.4.24C
Thermal Conductivity		0.54	W/m·K	ASTM E1952

Table 2: Properties of TerraGreen 400G [65]

Chapter 4

4.1 Experimental Procedure

4.1.1 DMA

Parameters	Values
Maximum Force	2000 mN
Temperature Ramp	4°C
Sample Thickness	0.25mm~0.3mm
Sample Length	50mm
Sample Width	5 mm

Table 3: Experimental Parameters for DMA

Figure 12: Tension Attachment

The samples subjected to DMA testing had dimensions of approximately 50 mm in length, 5 mm in width, and a thickness of around 2 mm. Measurement was conducted using digital callipers with a precision of 0.02 mm. The choice of the bending attachment for the investigation was determined by considering the projected material modulus and the geometry factor of the sample, which was derived from its dimensions.

After aging and immersion in fluid, the post-aging samples were delicately wiped using a serviette before being mounted onto the DMA apparatus for testing. The parameters employed for testing the samples in the tension mode are detailed in Table 3. The experiment covered frequencies of 0.5, 1, 2, 5, & 10 Hz, spanning a temperature range from -35°C to 200°C. These chosen frequencies are commonly used within the industry in account for the material's behaviour influenced by both frequency and temperature.

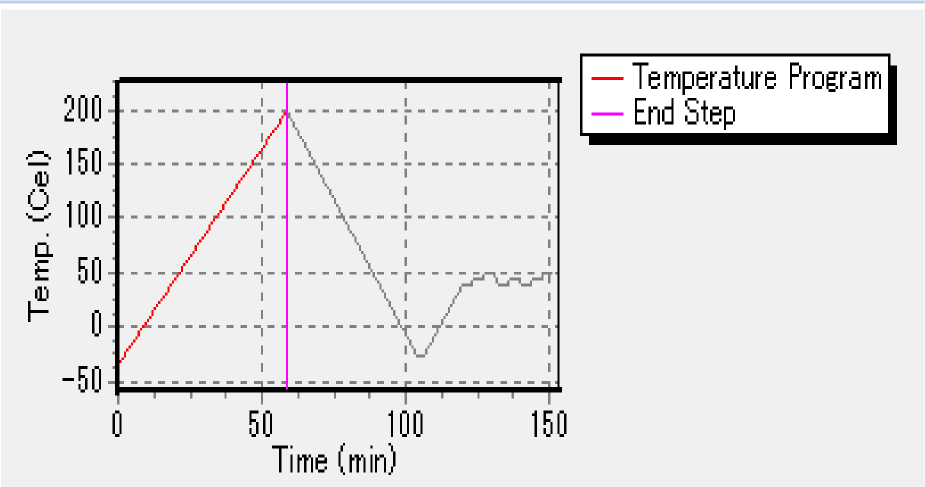


Figure 13: Test Sequence

The duration of the sample testing process encompassed a period of approximately two hours. This included an initial phase of one hour dedicated to isothermal holding, during which a constant temperature was maintained. Subsequently, an additional hour was allocated for the gradual attainment of the specified temperature, culminating in the conclusion of the testing procedure which is shown in the figure 13.

Figure 14: Dynamic Mechanical Analyser [63]

Evaluations of the characteristics of samples before and after aging were carried out at a frequency of 1 Hz. A constant temperature pause was initially performed at -35°C to stabilize temperature fluctuations within a range of +/- 3°C. To account for the sample's thermal property and reduce time lag between sample and the furnace, a slower heating rate of 4°C per minute was employed while performing experiment, contrasting with the faster 10°C per minute rate. The configuration of sample for testing used in tension attachment is illustrated in Figure 12.

4.1.2 DMA Test Output Graph

The accompanying Figure 15 showcases outcomes of a Dynamic Mechanical Analysis (DMA) performed on samples submerged in an air environment at 85°C. Within this graph, storage modulus (E') is represented by this green line, the loss modulus (E") by this red line, and damping ratio of the sample is represented by blue line. These values are graphed for frequencies spanning 0.5, 1, 2, 5, & 10 Hz.

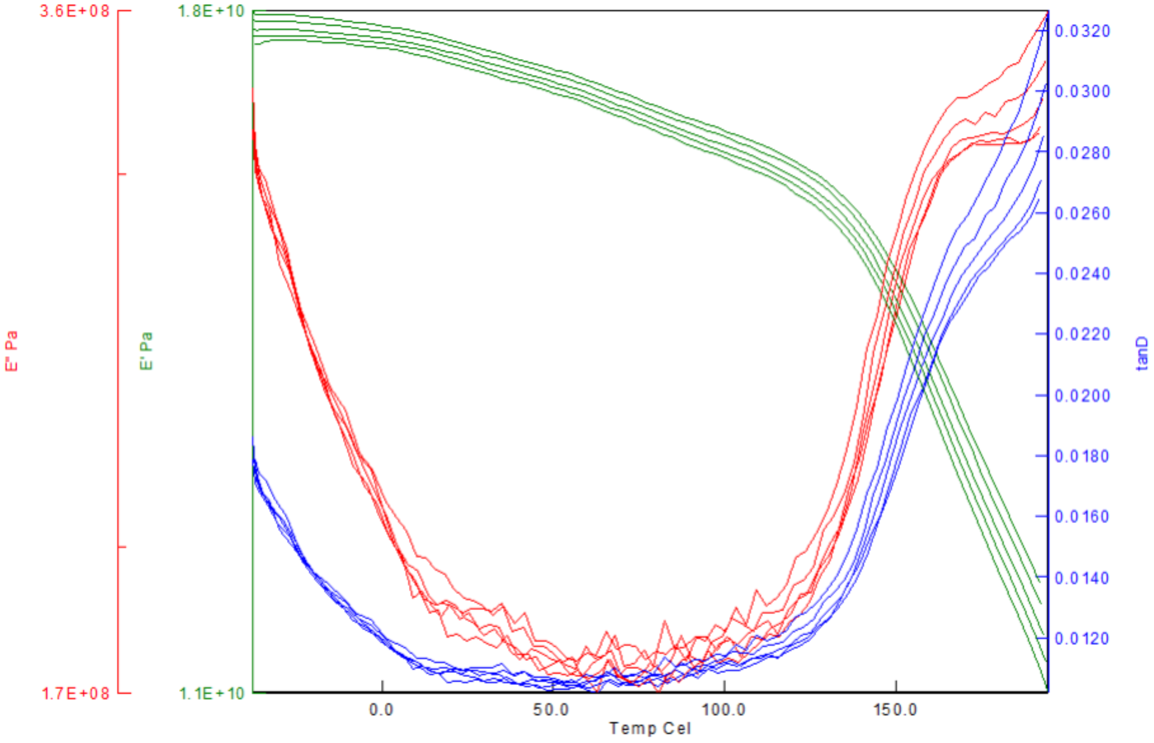


Figure 15: DMA Test Output

4.2 DSC (Differential Scanning Calorimetry)

Differential scanning calorimetry is a utilized technique for thermal analysis to quantify heat exchange linked to physical and chemical transformations within a substance under controlled alterations in temperature. The test takes place inside a closed chamber in which the sample in kept with the reference. Both the crucibles are placed over the heat flux sensor as shown in figure 16.

This technique is commonly used to study phase transitions (such as melting and crystallization), glass transitions, reactions, and other thermal events in materials like polymers, pharmaceuticals, foods, and more. It is a valuable tool for characterizing the thermal properties and behaviour of materials.

The Samples for DSC were carefully prepared by thermally aging the existing samples at 85ºC and 125ºC. For each fluid, a minimum of three samples were prepared and immersed in the fluid. Following that, the samples were stored in the thermal chamber for 720 hrs.

For measuring the glass transition temperature from DSC, the mass of the sample is required which can be calculated using a digital weighing scale. It was taken into consideration that all the masses were as equal as possible for each fluid with respective temperature of 85ºC and 125ºC. So, the samples were cut from immersed and non-immersed material and then measured.

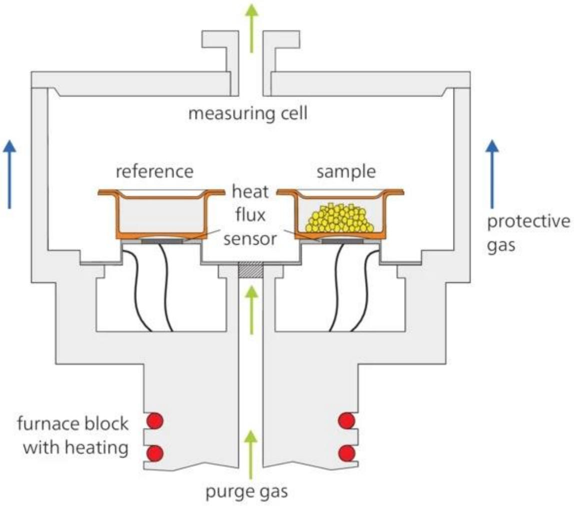


Figure 16: Block Diagram of DSC [64]

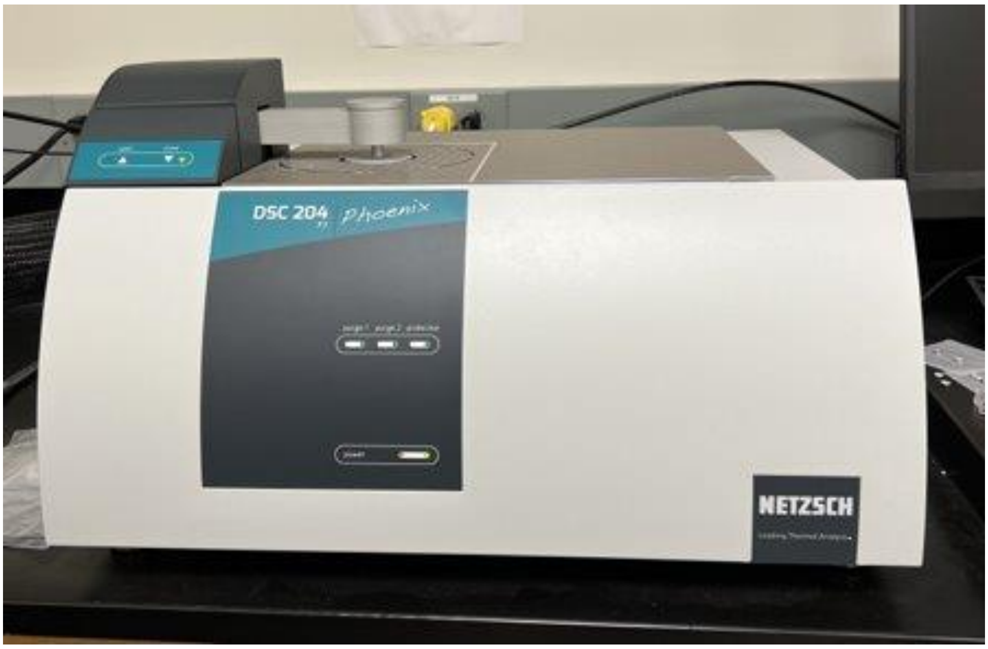


Figure 17: NETZSCH DSC 204 F1 Phoenix

4.2.1 Experimental Procedure

The samples that were cut and separated into equal masses were placed inside a closed crucible and then set inside the chamber as illustrated in figure 19 & figure 17. Temperature range used for the test was from 90ºC to 300ºC. Since the Tg (glass transition temperature) was given from the company. All three different samples which are air, EC100 and PAO6 were compared for changes in the glass transition temperature for both 85ºC and 125ºC. Liquid nitrogen was used to return the chamber to room temperature once the experiment is done. The main purpose for performing this DSC was to observe if the glass transition temperature remains unchanged after immersion or not, that being the reason for choosing a specific temperature range from 90ºC to 300ºC. As the test was finished the chamber was opened as shown in figure 18 and the crucible was taken out.

Sample	**Sample Mass**
Air	7.81mg
EC100	7.65mg
PAO6	7.91mg

Table 4: Mass of Samples for DSC

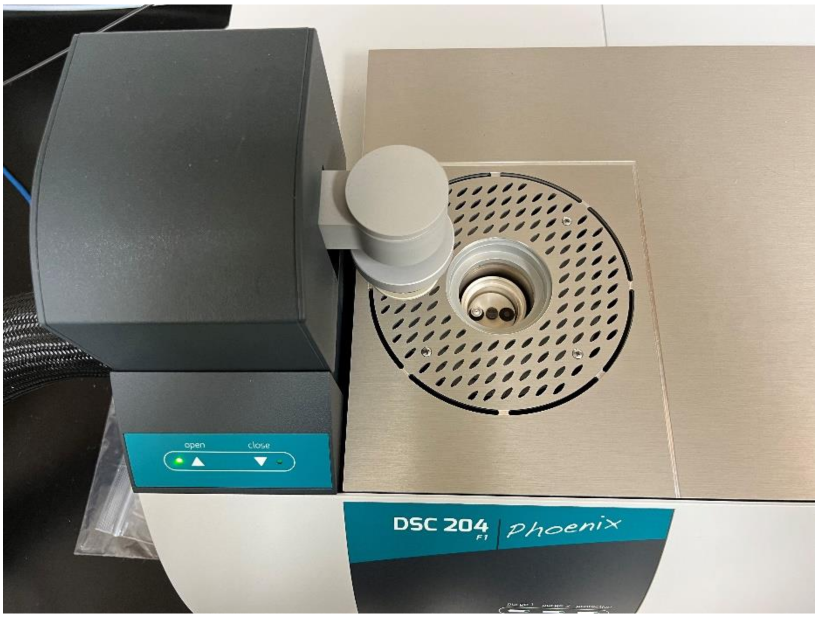


Figure 18: Open Chamber

Figure 19: Closed Crucible

4.2.2 DSC Test Output

The provided figure 20 illustrates the results of a Differential Scanning Calorimetry (DSC) conducted on samples exposed to air at a temperature of 85°C. The result shows the temperature change from 90ºC to 300ºC. The x-axis denotes the DSC value, and the y-axis represents the temperature as illustrated in Figure 20.

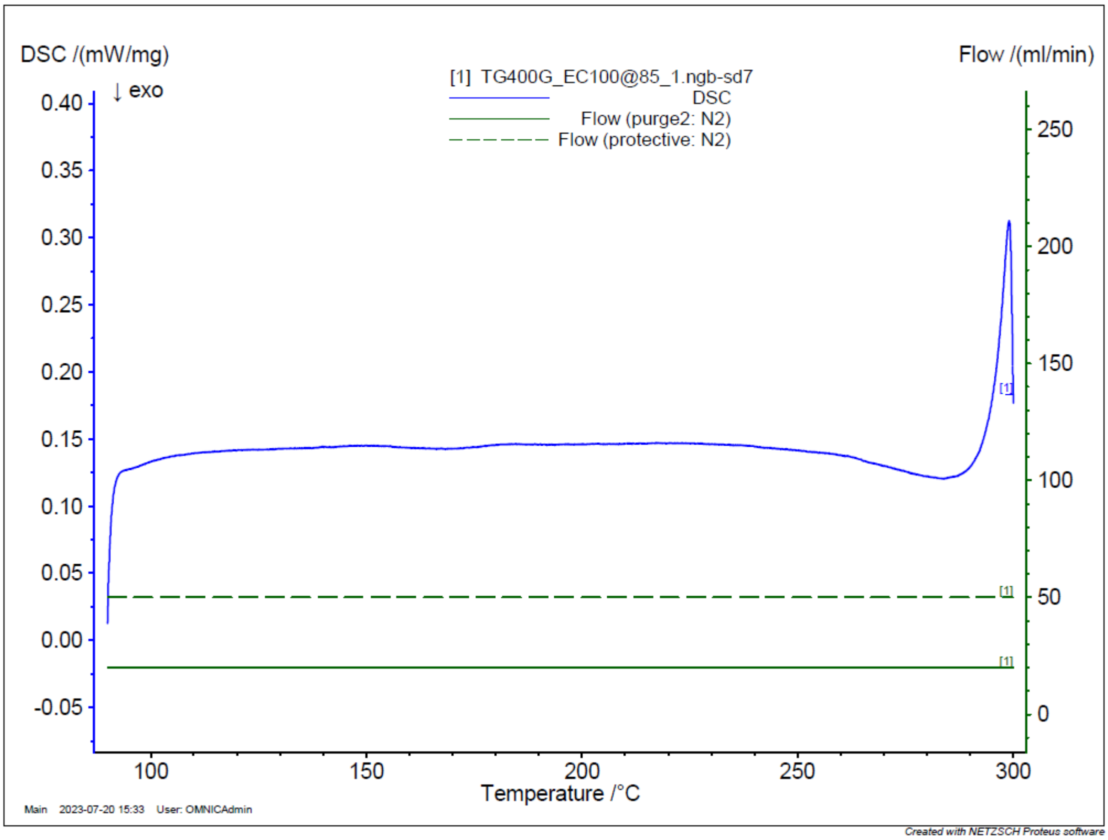


Figure 20: DSC Test Output Graph

Chapter 5

5.1 Results

5.1.1 DMA Result

Figures 21 through 25 illustrates the contrast in DMA evaluations of the complex modulus between samples subjected to immersion and those that were not immersed. These comparisons were conducted at temperatures 85°C & 125°C, respectively. Each measurement was executed a minimum of 4 times for the immersed samples and 4 times for the non-submerged counterparts. Figures below display the average complex modulus, accompanied by standard deviation, encompassing temperature span from -35°C to approximately 200°C.

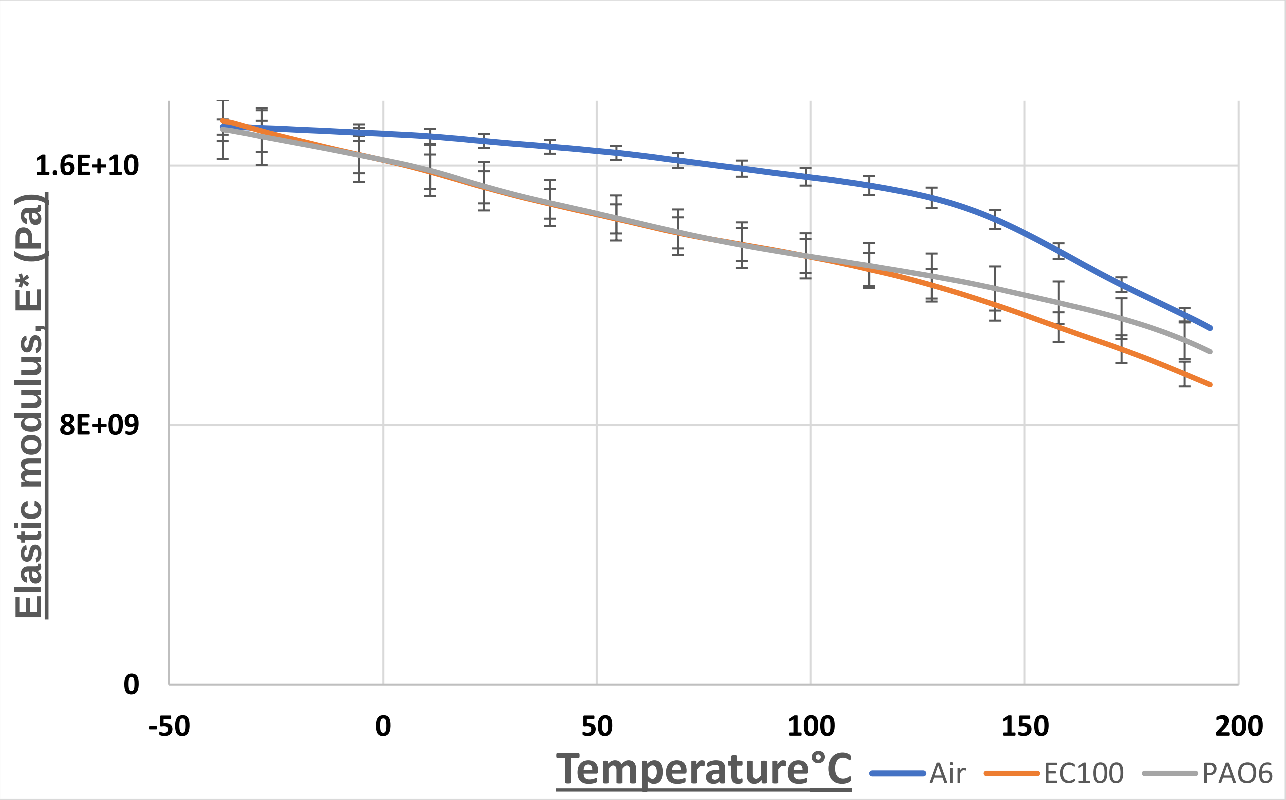


Figure 21: Comparison of non-immersed & immersed sample (EC100 & PAO6) at 85ºC

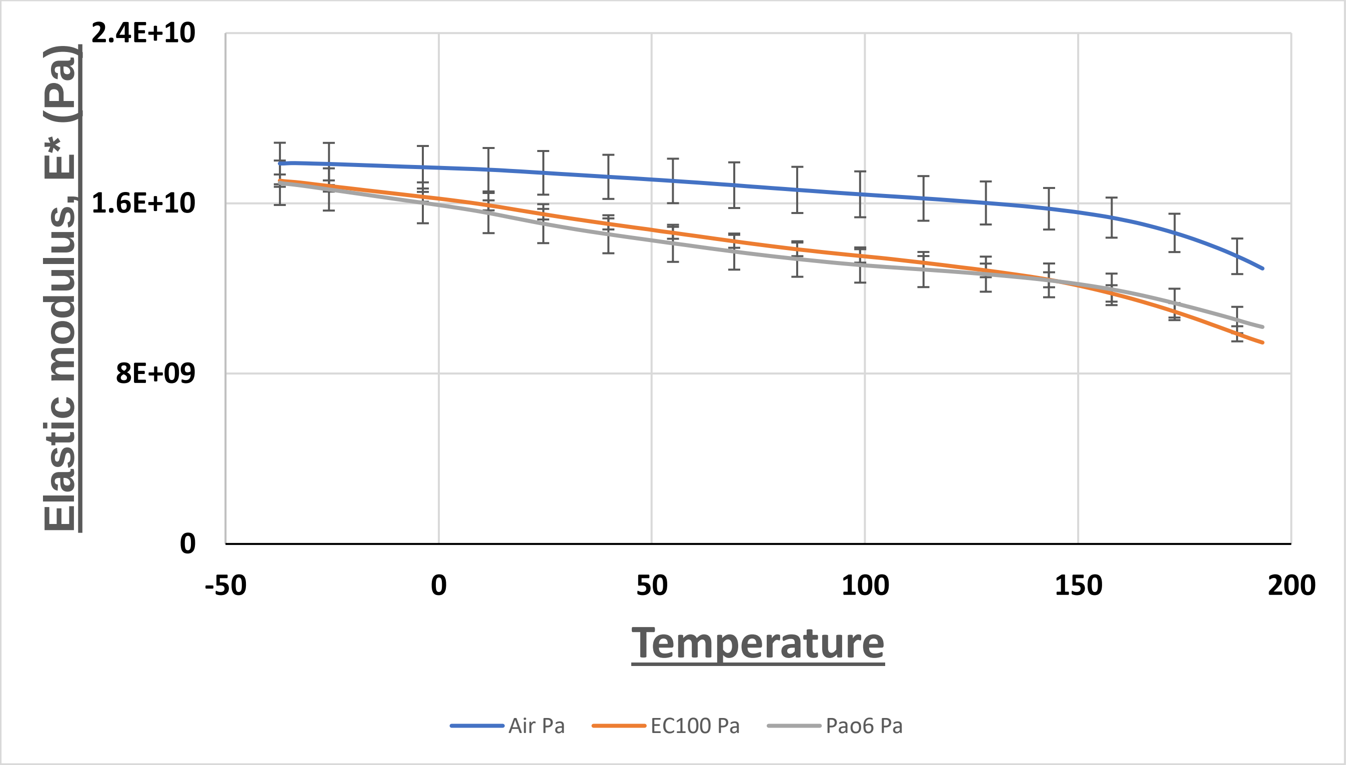


Figure 22: Comparison of non-immersed & immersed sample (EC100 & PAO6) at 125ºC

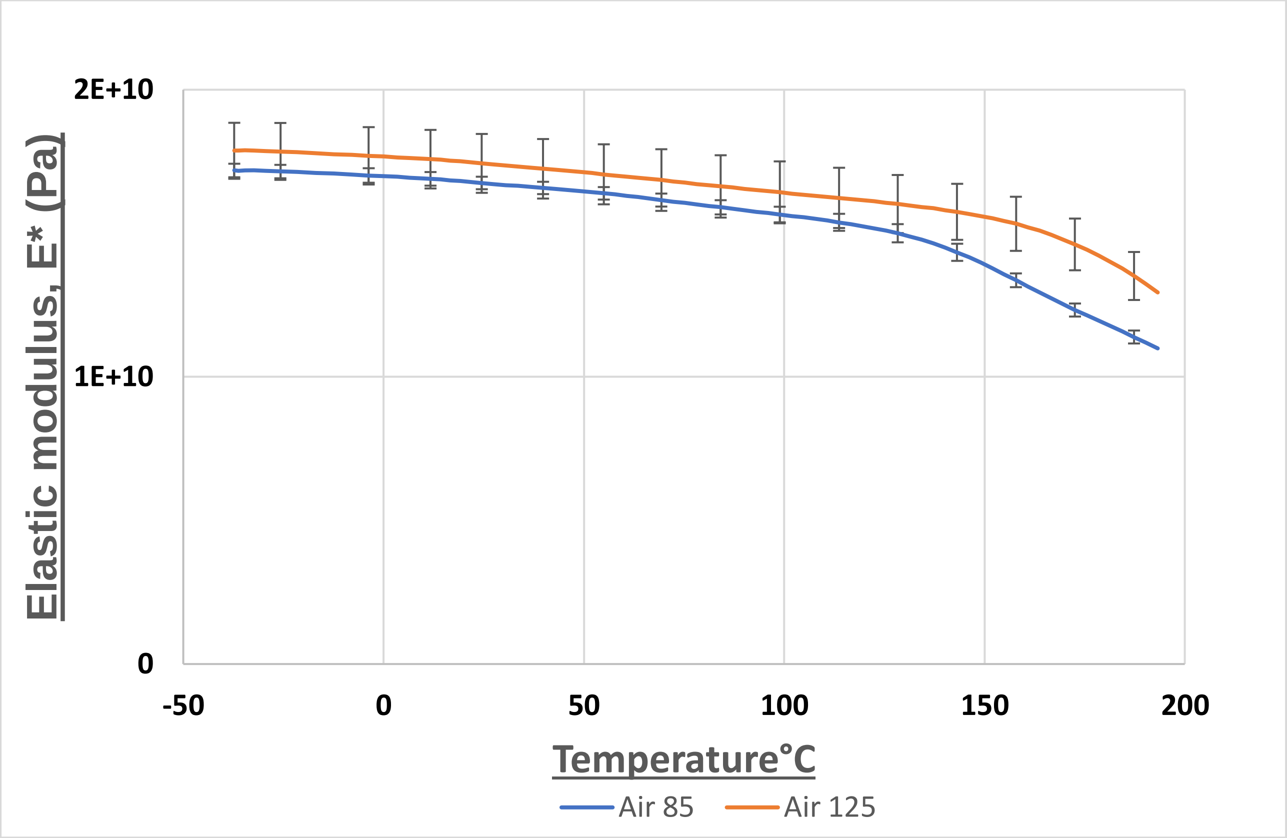


Figure 23: Comparison of air at 85ºC and 125ºC

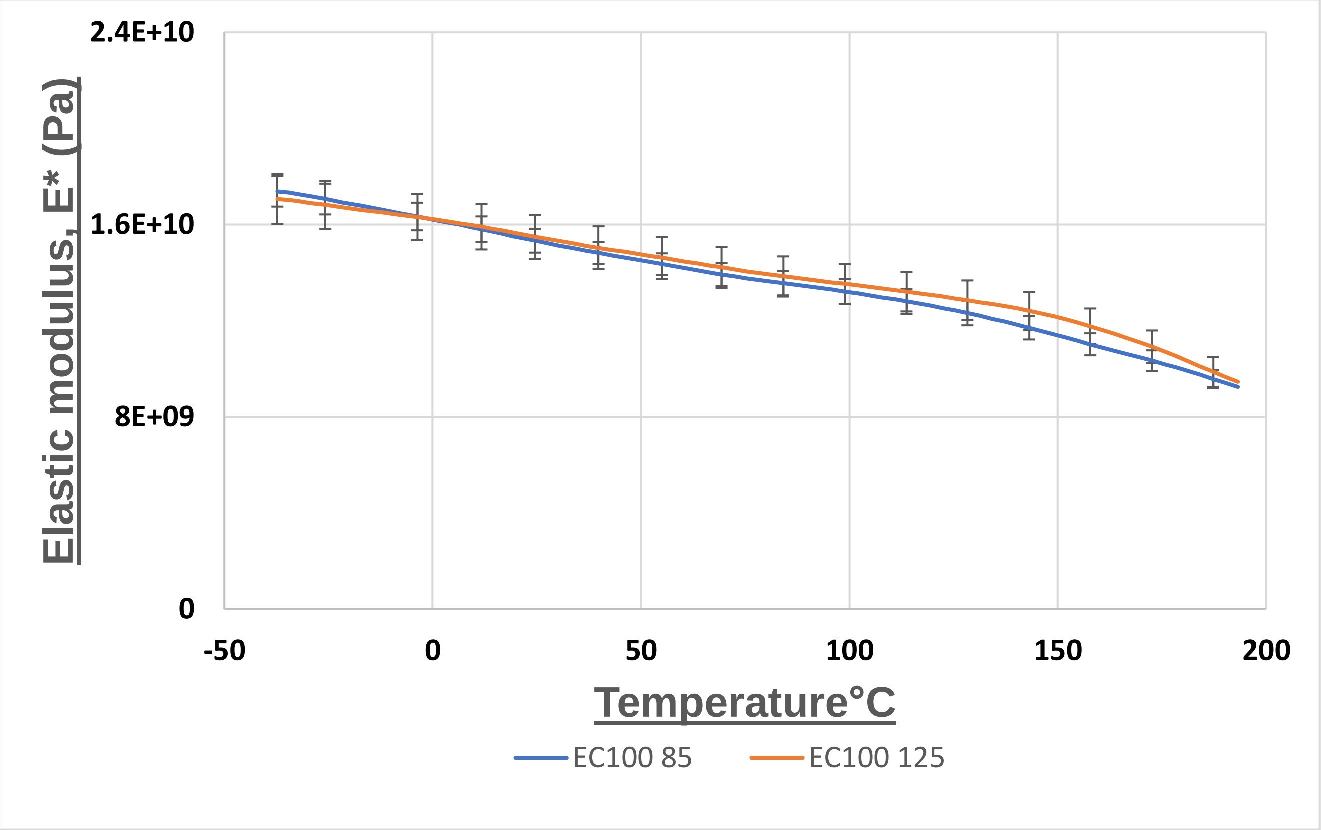


Figure 24: Comparison of EC100 at 85ºC and 125ºC

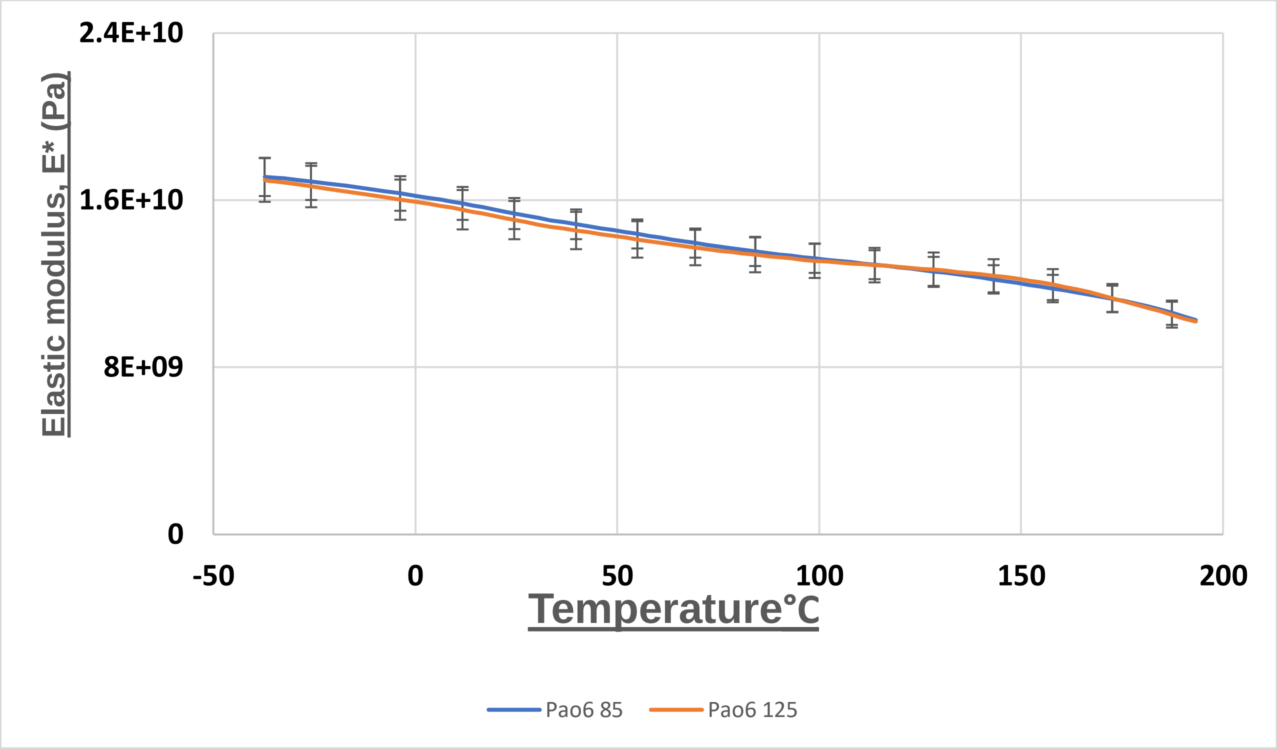


Figure 25: Comparison of PAO6 at 85ºC and 125 ºC

5.1.2 DSC Result

This figure 26 depicts the post processing result from NETZSCH DSC 204 F1 Phoenix. The comparison graph for 3 scenarios was plotted using a python code for 85°C. The graph depicts how the glass transition temperature remained the same as its original value around 200ºC.

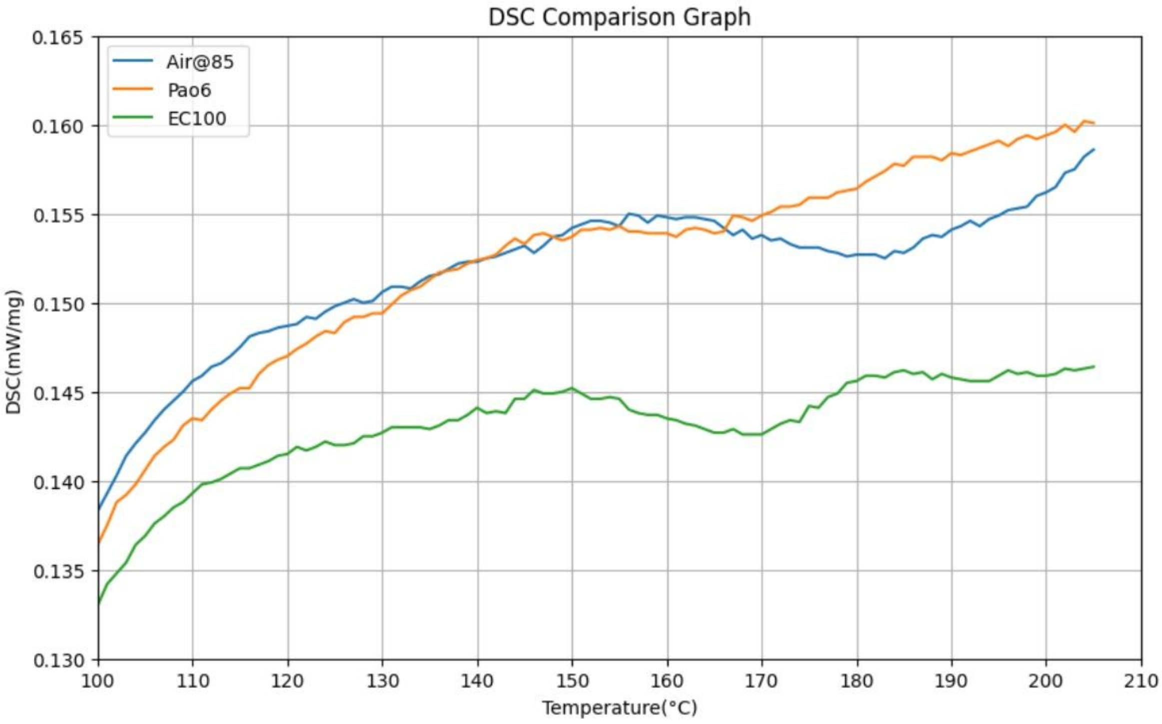


Figure 26: Post Processing DSC Graph

Chapter 6

6.1 Discussion

Within the results section, a comprehensive comparison of DMA measurements is presented, detailing the impact of aging TG400G samples in both dielectric liquid and air at distinct temperatures, namely 85°C and 125°C. For each graph depicting samples aged under varying temperature-fluid conditions, four samples were subjected to testing and their averages were utilized. The standard deviation for each circumstance is calculated and displayed along the temperature axis as the complex modulus is plotted against temperature.

Each sample's computed standard deviation takes into consideration differences brought on by things like different copper connections, minute differences in sample dimensions, and density fluctuations. To ensure consistent conditions, a predefined torque was applied during sample attachment, and an isothermal pause was executed at -35°C. Dynamic mechanical analysis (DMA) was carried out within a temperature range from -35°C to a maximum of 200°C. This choice of range aligns with the operational temperatures of most IT equipment, spanning from -40°C to 85°C. Moreover, the extreme conditions experienced locally by the substrate can exceed 125°C. The decision to include -35°C was driven by the goal of capturing a comprehensive material profile. The upper temperature limit, 200°C, was chosen in consideration of the material's glass transition temperature (Tg). The data presented reveals the Tg of the TG400G substrate core to be 200°C. Notably, the complete testing process, including the initial isothermal hold, spans approximately 2 hours, with the main test duration lasting around 1 hour.

Figures 21 and 22 present a summarized illustration indicating standard deviation of complex modulus at temperatures 85°C and 125ºC, respectively, samples submerged in Air, EC100, & PAO6. Examination of mean complex modulus (E*) implies that air-exposed samples display most amount modulus, whereas those immersed in EC100 and PAO6 exhibit the least. Material reliability is often deduced from its elastic modulus, with lower E* values signifying heightened substrate flexibility and dependability. Accordingly, samples that were kept in EC100 and PAO6 at 85°C reveal an improved level of flexibility and reliability contrasted to those submerged in air under the same circumstances.

Figures 23 to 25 extend the comparison to modulus values across 2 different temperatures that is Air at 85°C versus 125°C, EC100 at 85°C versus 125°C, & PAO 6 at 85°C versus 125°C

Figure 26 depicts about glass transition temperature, Tg which is a thermal property of material. The Tg was provided by the company as 200°C, and the expected results were same as the original for all the different conditions and temperatures.

Chapter 7

7.1 Conclusion and Future work

For both samples aged at 125°C and 85°C, it was noted that the elastic modulus of samples immersed in a liquid was lower compared to those exposed to the air. Upon graphing the data, it became evident that the elasticity of samples in air at 125ºC was greater than in air at 85ºC. Remarkably, the graphs illustrating EC100 and PAO6 at both temperatures closely resembled each other.

The glass transition temperature remained unchanged after the samples were submerged in the dielectric liquid. The unaltered glass transition temperature after submersion highlights the material's robust nature and its ability to resist structural changes even in the presence of the dielectric liquid. This property further underscores its potential for prolonged and reliable service in relevant applications.

After conducting a comprehensive series of tests, it was observed and deduced that this material boasts high reliability and flexibility. It has the capacity to maintain its performance and structural integrity throughout its intended service life, provided it can sustain its glass transition temperature over an extended duration. In comparison with prior research, the outcomes indicated that immersing the printed circuit board (PCB) in the dielectric liquid did not yield significant results due to the lack of material absorption. However, when the substrate was directly exposed to the dielectric fluid, the outcomes were distinct and clear.

Further research opportunities lie in exploring the substrate's response when exposed to various fluids commonly utilized in industrial data centre cooling applications. Thermomechanical properties of substrate might be examined in depth in this inquiry. The work should be expanded to examine the impacts of prolonged exposure at high temperatures, which will help clarify how these variables affect thermomechanical properties.

Furthermore, because delamination is a common failure type, non-halogenated substrates could go through delamination experiments. Thermal interface materials (TIMs) play a crucial role in electronic packaging, and there is a focused endeavour to comprehend their durability when subjected to different environmental stress conditions. [54,55]

Research indicates that Megtron 6 currently exhibits the lowest levels of dielectric losses, minimal transmission loss, excellent heat resistance, and lower weight reduction compared to

FR-4 boards. [56] Such efforts would advance knowledge of substrate behaviour and possible vulnerabilities under diverse circumstances.

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BIOGRAPHICAL STATEMENT

Venkateswar Vishnu Tirupati Venkatachalam Soundarapandi graduated from SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu with a bachelor’s degree in mechanical engineering. Obtained knowledge through internships with respected manufacturing companies. In Fall of 2021, he joined University of Texas at Arlington for his master’s degree in mechanical engineering. During this period, he joined Electronics MEMS & Nano Electronics Systems Packaging Centre (EMNSPC) under the guidance of Dr. Dereje Agonafer and worked as a volunteer. His research endeavours cantered on different types of cooling and material reliability related. In the Spring of 2023, he undertook a role as a Manufacturing Engineer at Volvo Trucks as part of Co-op program. Upon completing his studies, Venkateswar Vishnu will be working as a manufacturing engineer and pursue his career in the field of reliability.