IMPACT OF IMMERSION COOLING ON THERMO-MECHANICAL PROPERTIES OF PCB'S AND RELIABILITY OF ELECTRONIC PACKAGES

By

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THESIS

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ABSTRACT

IMPACT OF IMMERSION COOLING ON THERMO-MECHANICAL PROPERTIES OF PCB'S AND RELIABILITY OF ELECTRONIC PACKAGES

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Immersion cooling technique is used for the thermal management of high-density data centers to avoid overheating of components and failure of servers. However, to use this as a viable cooling technique, the effect of dielectric coolants on the reliability of server components needs to be evaluated. Previous work reported contradicting findings for Young's modulus of PCBs, providing motivation for this work. This study focuses on effect of immersion cooling on the thermos-mechanical properties of printed circuit board (PCB) and its impact on reliability of electronic packages. Changes in thermo-mechanical properties like Young's modulus (E), Glass transition temperature (Tg), Coefficient of thermal expansion (CTE) of PCB and its layers due to aging in dielectric coolant are studied. Two types of PCBs using different material namely 370HR and 185HR are studied. To characterize Young's modulus, Tg and CTE, dynamic mechanical analyzer (DMA) and Thermo-mechanical Analyzer (TMA) is used. Major finding is Young's modulus and CTE is decreasing for PCBs after immersion in dielectric coolant which is likely to increase reliability of electronics package.

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Chapter 1

1.1 INTROCDUCTION

Data centers are facilities that house the computing, storage, and networking equipment, IT equipment that serve the Information Technology (IT) needs of modern society. Almost all industries, ranging from finance, health care, entertainment, government, to various businesses rely on these services [1]. Data center facilities range in size from a few hundred square feet to over one million square feet. In United States since last five years, capacity of data center has been increased greatly with little rise in data center total energy consumption, according to the results of new study of data center energy use by US government released on Jun 27th,2016. US data centers have consumed about 70 billion kWh in 2014 representing 2 percent of country's total power consumption. That's equivalent to the amount of electricity consumed by 6.4 million average American homes that year [2]. For cooling of such big data centers, usually, air cooling is used to cool servers and other IT equipment's. In the air-cooled data centers, about 40% energy is used by refrigeration system i.e. CRAC units, HVAC fans, HVAC cooling. By using immersion cooling as a cooling method for servers, we can directly save this energy which will result in significant cooling energy savings in data center and hence will save the operating cost required for data centers [3].

By submerging all servers in dielectric coolant can save the energy required for HVAC cooling, HVAC fans and CRAC units. ASHRAE TC 9.9 reports that typical air-cooled rack power densities are in the range of 6 to 30 kW per rack [4]. For power densities above this, Immersion cooling can be viable option which will result in significant cooling energy savings in data center. Compared to air, many mineral oils, synthetic fluids have a heat capacity roughly 1200 times greater [1]. Despite recent findings about improved cooling efficiency and cost savings of dielectric fluids as a cooling fluid, this technique is still not widely used due to lack of information available. There is information available about immersion cooling from thermal perspective but there is not much literature regarding effect of immersion cooling on reliability of IT equipment's like PCB's and Electronic packages. The presented work depicts useful information about impact of immersion cooling on thermo-mechanical properties like Young's modulus, glass transition temperature and of Printed circuit boards and its effect on reliability of Electronic packages. The bulk thermo-mechanical properties of PCB's can be measured with DMA, TMA, tensile tester, Nano indentation etc. [5]. The change in thermo-mechanical properties like Young's modulus, glass transition temperature is being shown in the paper for thermoplastic materials.

For efficient cooling of servers in data center, immersion of servers and IT equipment's like PCB in dielectric fluid results in saving energy required for air cooling. When power densities are above 30kW then immersion cooling can be efficiently used over traditional air-cooling due to its availability and cost effectiveness **[6]**. Immersion cooling will be efficient for high rack power densities beyond 30 kW where air-cooling will be inefficient **[7]**. Immersion cooling of servers increases the prospects for improved reliability in working of servers as it minimizes common operational issues and reduces causes of failure like solder ball joint failure, excessive warpage, less operating temperatures for Printed circuit boards and its components. As there will be no moving parts like fans, it will save the energy required to operate them, no oxidation/corrosion of electrical parts, the reliability advances include a reduction in corrosion and electrochemical migration, reduction of contamination of dust, debris and particulates **[7]**.

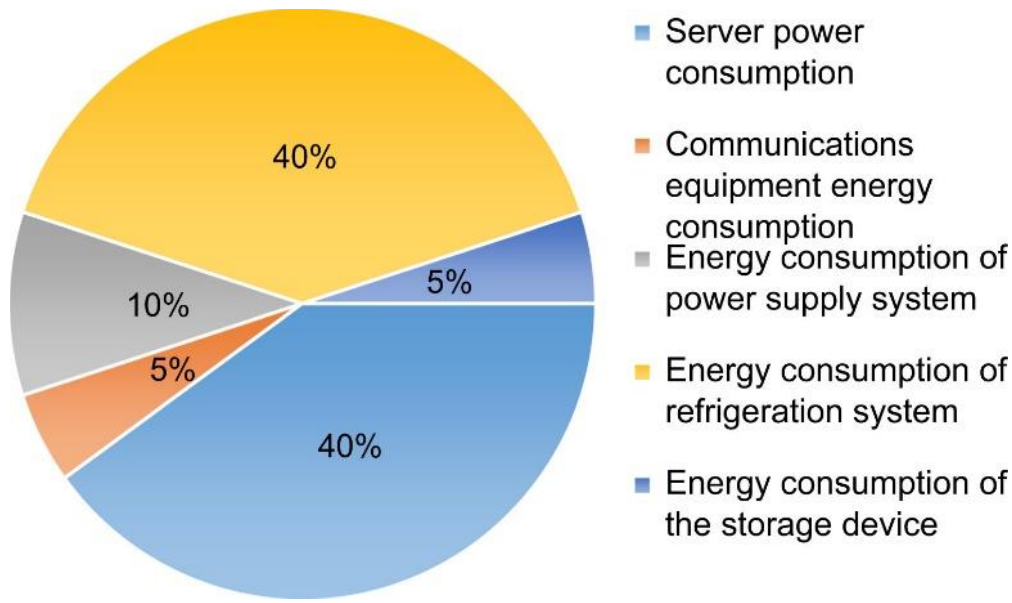

Figure 1: Typical Breakdown of Energy Consumption in Air-Cooled Data Centers [3]

About 40% energy is used by refrigeration system i.e. CRAC units, HVAC fans, HVAC cooling. By using immersion cooling as a cooling method for servers, we can directly save this energy which will result in significant cooling energy savings in data center and hence will save the operating cost required for data centers [3].

This study focuses on the impact on thermo-mechanical properties of PCB's when they are immersed in dielectric fluid and its effect on reliability of Electronic packages. Changes in the material property, failure of components or change in reliability of components is a result of changes in thermal, mechanical, electrical properties of material when introduced to new operating environment. When we use immersion cooling as a cooling method for servers, it affects the reliability at device and component level [6]. So, with the concern of performance and working life of servers, the study of reliability of IT equipment's like PCB's is necessary. The components considered for this study are two different types of PCB's, 370HR and 185HR. 370HR and 185HR are type of prepregs.

1.1.1 Cooling of Electronic Packages

In the data center there are IT equipment's like electronic packages and PCB's which are typically the main sources of power consumption and heat generation. These are the primary motivator for cooling needs in the data center. For safe operation of devices, the functional limit temperature range is between 85 to 105°C. At temperatures higher than this, damage to the device begins to occur. The electronic package is made up of different material like PCB, Solder mask, die attach, underfill material, silicon die etc. Due to which it makes package complex system. In electronic package reliability is dependent on numerous factors like the thermo-mechanical properties of different materials, CTE of different materials and difference between them, temperature changes and environmental conditions [8]. The buildup layer of PCB affects the reliability of solder joints; it affects the creep strain range, stress range, creep strain energy density ranges and the thermal fatigue life [9]. The solder balls on a populated PCB absorb all the strains due to the expansion of the package and by the PCB in thermal excursions. At high temperatures, there is a high possibility of the solder joint to fail due to the CTE mismatch between the PCB and the package [10]. Also, the stiffness of a PCB is higher than the package which affects the reliability of a solder joint and results into failure package. In this study effect of oil immersion cooling on stiffness and CTE of PCB board is presented.

1.1.2 Air Cooling for Servers

Air cooling uses cooled air for cooling is traditional and widely used method for cooling data centers. Heat rejected from servers and IT equipment's is rejected outside to ambient temperature, mixed with outside fresh air or pass through refrigeration system and can again use to cool the data centers [1]. These techniques are matured fields and well documented with safe environmental conditions established by ASHRAE TC 9.9. Generally, cold aisle and hot aisle floor layout are most commonly used in cooling of data center. In cold aisle arrangement cold air is supplied through an underfloor plenum from a computer room air conditioning (CRAC) unit and the hot exhaust circulates back to the return side of the CRAC [11] .There are different methods available to distribute cold air in data centers and cool them. There is plenty of literature available on understanding dynamics of air flow in the data center. Below figure 2 shows tradition air cooled data center.

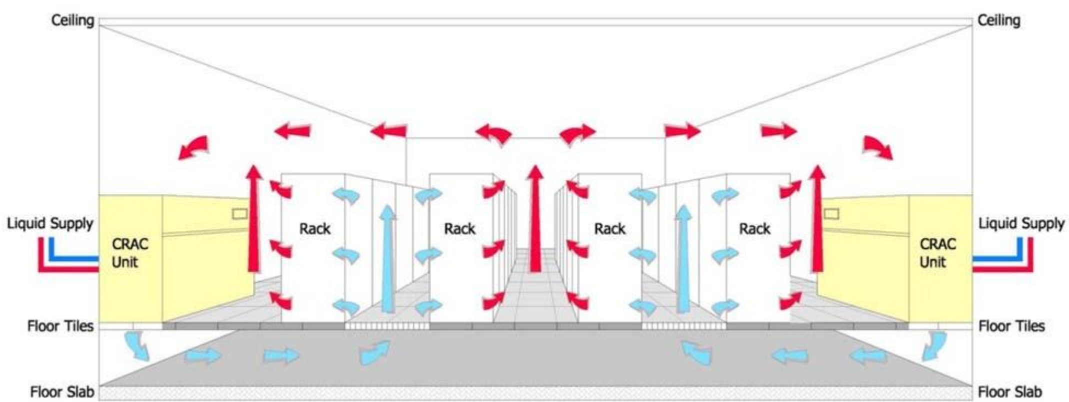

Figure 2: Typical Raised floor data center layout [1]

1.1.3 Limitation of Air cooling

ASHRAE TC 9.9 reports that typical air-cooled rack power densities are in the range of 6 to 30 kW per rack [4]. Rack densities above this range will typically be beyond the cooling capabilities of air-cooling system and will be very costly to cool air and then pass through such racks to cool them. Previous studies by M. Iyengar showed that it is possible to cool high-density equipment with air cooling methods; however, the use of water-cooling techniques provided anywhere from 50.1% to 92.2% operational energy savings [12].

1.1.4 Liquid Cooling for Servers

Liquid cooling both direct and indirect liquid cooling offers many advantages over traditional air cooling when rack power densities are above 30 kW. Also, dielectric fluids used in immersion cooling has very high heat capacities compared to air cooling. Compared to air, many mineral oils have a heat capacity roughly 1200 times greater [1] .Several liquid coolants are available and have been used in the cooling of electronic equipment with varying thermal and hydraulic properties. Indirect methods, water is used as a cooling medium. In this water is used through cold plates or rear door heat exchangers. In liquid cooling, the whole server is directly immersed in dielectric fluid which offers cooling solution in which the server can be cooled by a single fluid medium. Some of the most common forms of liquid cooling for data centers are discussed below.

1.1.4.1 Water Cooling

Water being an excellent conductor of electricity, so, it cannot be directly used to contact heat generating components and cool them. So, we use ‘Cold-Plate’ for heat transferring from heat generated components. Cold plates are placed on the top of heat generating components like processors etc. bottom of the cold plate is made up of copper which is high heat conducting material. It is generally used to extract the heat from heat generating components. The gap between heat generating component and cold plate is filled with heat spreader. Heat generated from components like processor is conducted through heat spreader to cold plate. Heat conducted to cold plate increases the temperature of cold plate. Water is distributed through cold plate which extracts the heat from cold plate and temperature of water increases. The high temperature water is then passed through the water chillers and heated water is cooled down. The cooled down water can again use to extract the heat from cold plates and finally cool down the heat generated components. The vital benefit of using cold-plate is the requirement of less space as compared to heatsink resulting in more compact design of server as well as power required to operate cold plate is less as compared to air cooling technique [13] . Water cooling allows increased efficiency through use of higher temperature fluids and possible use of waste heat for other applications [14].

Figure 3: Cold plate [15]

1.1.4.2 Immersion Cooling

Immersion cooling method consists of submerging the servers in the thermally conductive but electrically non-conductive liquid called dielectric liquid. Heat transfer continuously takes place between dielectric liquid and server. The flow of dielectric liquid is maintained with the help of flowmeter. Some most commonly used dielectric liquids are mineral oil, white oil, electric cooling oils and non-purpose oils. Oil immersion cooling can be further classified based on the characteristic properties of dielectric liquid [16].

i. Single Phase Immersion Cooling

ii. Two Phase Immersion Cooling

Many mineral oils have heat capacity 1200 times greater than air [1]. Dielectric nature of mineral oils, high heat capacity compared to air and enhanced thermal properties make them possible alternative fluids for server cooling applications [6].

Liquid immersion cooling is the technique of removing the excessive heat generated by electronic components in servers by fully immersing servers in dielectric liquid bath. Single phase oil immersion cooling is highly efficient, less costly compared to air cooling when power densities are beyond 30kW and simple technique of cooling the servers and its components. In this technique server is fully submersed into dielectric fluid bath. This fluid is circulated by natural convection or by pumping the fluid around the server and its heat generating components which are to be cooled. The heat generated is absorbed by the dielectric fluid and then this high temperature fluid is passed through the heat exchanger where it rejects the heat to cool water. Now, hot water is passed through the cooling towers where its rejects its heat and this water can again use in heat exchanger [17].

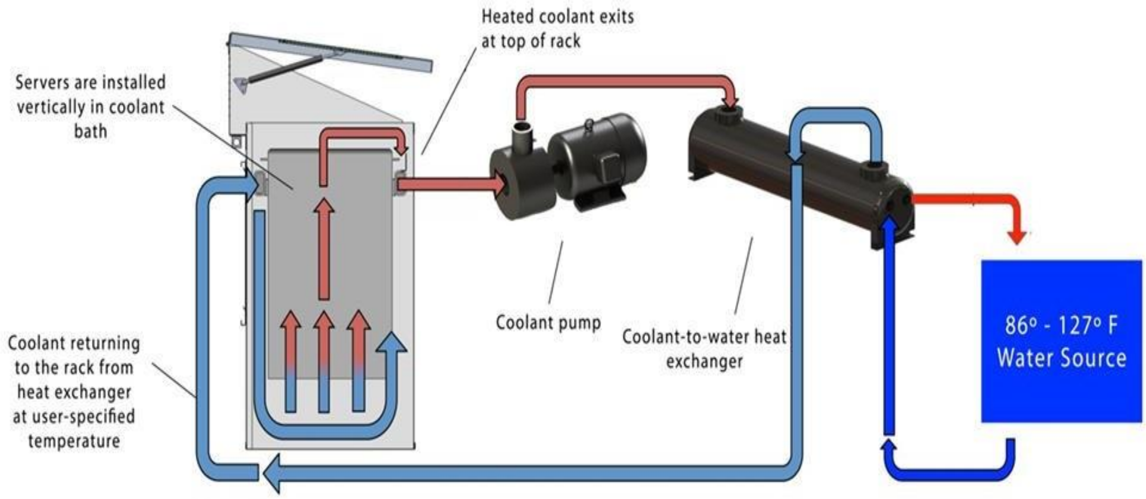

Figure 4: Single phase Immersion cooling [7]

In the two-phase immersion cooling system, servers are immersed in a bath of dielectric fluid having much better thermal conductivity as compared to air. Dielectric fluid boils and hence exists in both state liquid and gaseous form. Working dielectric fluid gets heated by absorbing excessive heat from server, heat generating electronic components and results in boiling. The dielectric fluid in gaseous form moving upward comes in contact with condenser coils which is maintained at temperature lower than saturation temperature. Cold water is made to flow through condenser coil. Condenser coil causes the condensation of dielectric fluid vapor and dielectric fluid in liquid fall back into the dielectric fluid pool. It is required to be operated in the form of semi-open bath to avoid the loss of liquid as working fluid changes its state [18].

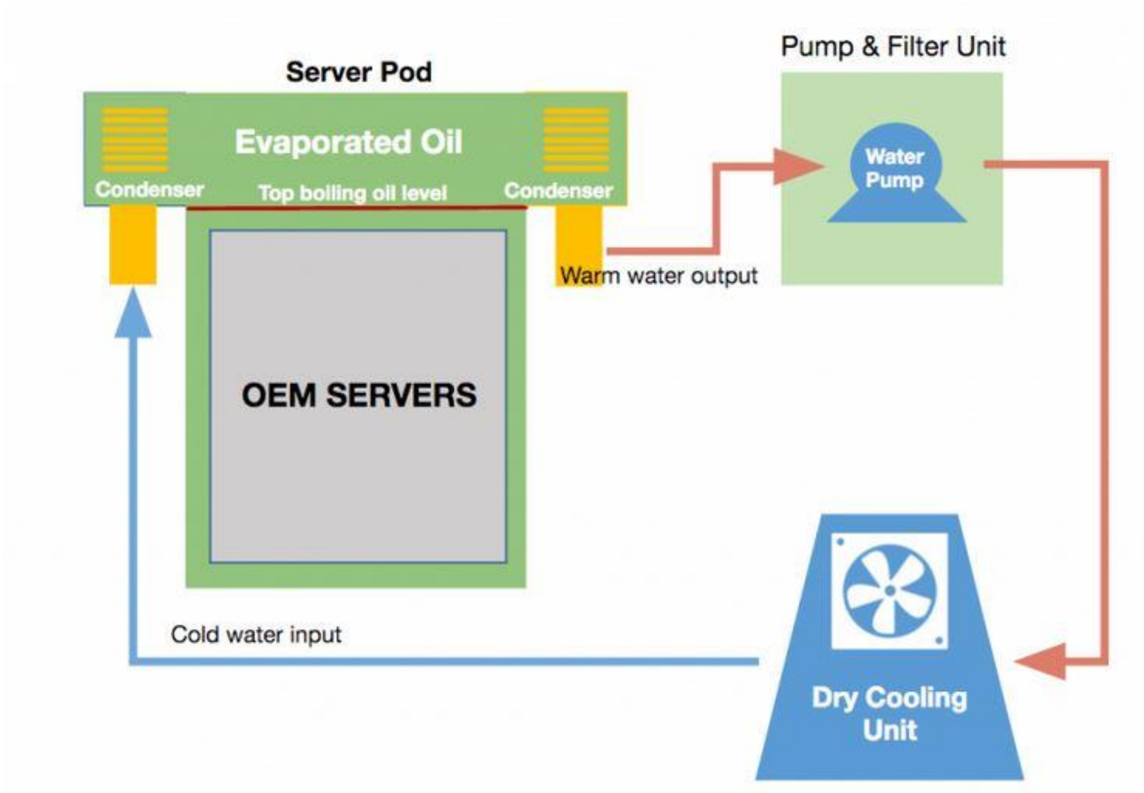

Figure 5: Schematic of Two-Phase Immersion Cooling [19]

A primary concern regarding immersion cooling techniques is the impact of the dielectric fluids on electronic components from Reliability point of view. Current industry data regarding the reliability of server systems after immersion in mineral oil suggest that there is no detrimental impact to components [6]. Previous work reported by Shah et. Al. three servers were fully immersed in the mineral oil for six month of time period, samples of motherboard PCB's from air cooled and oil cooled servers were taken and characterized for young's modulus on Instron tester and have observed significant increase in Young's modulus after immersion in mineral oil [6]. In second study PCB's were taken from air cooled and oil cooled servers and characterized and observed that Young's modulus is decreasing for oil immersed PCB's [7]. Both the results are contradicting. In this paper we have characterized two PCB's 370HR and 185HR before immersion in dielectric fluid and after immersion in dielectric fluid and have compared the changes occurred in thermo-mechanical properties of PCB samples.

1.1.5 Types of Printed Circuit Boards

PCB is a copper laminated and non-conductive material, it is a stack up of different layers like core layer, prepreg Solder mask etc. Core layer is FR 4 sandwiched between two copper layers. PCB is a composite material in which all electrical and electronic components are connected together in one common board with physical support for all components with base of board [20]. PCB is used to provide electricity and connectivity between the components, by which it functions the way it was designed. PCBs can be customized for any specifications to user requirements. There are several types of PCB available for the circuit. Out of these types of PCB, we have to choose the appropriate type of PCB according to our application [20].Some of the types of PCB's are Single-layer PCB, double layer PCB, multilayer PCB, aluminum backed PCB, flex-rigid PCB, flexible PCB etc. [20]

This study focuses on the impact on thermo-mechanical properties of PCB's when they are immersed in dielectric fluid and its effect on reliability of Electronic packages. Changes in the material property, failure of components or change in reliability of components is a result of changes in thermal, mechanical, electrical properties of material when introduced to new operating environment. When we use immersion cooling as a cooling method for servers, it affects the reliability at device and component level [6]. So, with the concern of performance and working life of servers, the study of reliability of IT equipment's like PCB's is necessary. The components considered for this study are two different types of PCB's, 370HR and 185HR. 370HR and 185HR are type of prepreg.

370 HR PCB is lead free compatible material and used for high-reliability applications. 370HR laminates and prepregs are manufactured using high performance 180°C glass transition (Tg) FR-4. It is multi-functional epoxy resin system and it is designed for multi-layer Printed circuit Board (PCB) applications. It is used where maximum thermal performance required. 370 HR provides superior thermal performance with low Coefficient of Thermal Expansion (CTE) and the mechanical, chemical and moisture resistance properties that equal or exceed the performance of traditional FR-4 materials [21].

370HR is used in thousands of Printed Circuit Board designs and has proven to be best in class for thermal reliability, CAF performance, ease of processing and proven performance on sequential lamination designs. Following are some of the thermal and electrical parameters of 370 HR laminate [21]. Following are some of the properties of 370 HR PCB:

Table 1: Properties of 370HR PCB [21]

Property		Typical Value	Units	Test Method
			Metric (English)	IPC-TM-650 (or as noted)
Glass Transition Temperature (Tg) by DSC		180	°C	2.4.25C
Decomposition Temperature (Td) by TGA @ 5% weight loss		340	°C	2.4.24.6
Time to Delaminate by TMA (Copper removed)	T260	60	Minutes	2.4.24.1
	T288	30		
Thermal Conductivity		—	W/mK	ASTM E1952

Thermal Stress 10 sec @ 288ºC (550.4ºF)	. Unetched . Etched	Pass	Pass Visual	2.4.13.1
Dk, Permittivity	. @ 100 MHz . @ 1 GHz . @ 2 GHz . @ 5 GHz @ 10 GHz	4.24 4.17 4.04 3.92 3.92	—	2.5.5.3 2.5.5.9 Bereskin Stripline Bereskin Stripline Bereskin Stripline
Df, Loss Tangent	. @ 100 MHz . @ 1 GHz . @ 2 GHz . @ 5 GHz @ 10 GHz	0.0150 0.0161 0.0210 0.0250 0.0250	— — —	2.5.5.3 2.5.5.9 Bereskin Stripline 2.5.5.5 2.5.5.5
Volume Resistivity	. After moisture resistance . At elevated temperature	3.0×10^8 7.0×10^8	MΩ-cm	2.5.17.1
Surface Resistivity	. After moisture resistance . At elevated temperature	3.0×10^6 2.0×10^8	MΩ	2.5.17.1
Dielectric Breakdown		>50	kV	2.5.6B

Arc Resistance		115	Seconds	2.5.1B
Electric Strength (Laminate & laminated prepreg)		54 (1350)	kV/mm (V/mil)	2.5.6.2A
Comparative Tracking Index (CTI)		3 (175-249)	Class (Volts)	UL 746A ASTM D3638
Peel Strength	. Low profile copper foil and very low-profile copper foil all copper foil >17 µm [0.669 mil] . Standard profile copper 1. After thermal stress 2. At 125ºC (257ºF) 3. After process solutions	1.14 (6.5) 1.25 (7.0) 1.25 (7.0) 1.14 (6.5)	N/mm (lb/inch)	2.4.8C 2.4.8.2A 2.4.8.3 2.4.8.3
Flexural Strength	. Length direction . Cross direction	90.0 77.0	ksi	2.4.4B
Test data generated from rigid laminate	. Length direction . Cross direction	3744 3178	ksi	ASTM D790-15e2
Poisson's Ratio	. Length direction . Cross direction	0.177 0.171	—	ASTM D3039
Moisture Absorption		0.15	%	2.6.2.1A

Flammability (Laminate & laminated prepreg)	V-0	Rating	UL 94
Max Operating Temperature	130	°C	UL 796

185HR laminate and prepreg materials are high-performance resin system. It has a Glass transition temperature (Tg) of 180°C for multilayer Printed Circuit Board (PCB) applications where maximum thermal performance and reliability are required. 185 HR are reinforced with electric grade (E-glass) glass fabric. It has a lower expansion in Z axis. It has a decomposition temperature of 340°C and it offers lower loss. It has a high thermal reliability. 185 HR has applications in Automotive and transportation, consumer electronics, medical, aerospace, defense industries [22]. Following are some of the thermal and electrical properties:

Table 2: Properties of 185HR PCB [22]

Property	Typical Value	Units	Test Method
		Metric (English)	IPC-TM-650 (or as noted)
Test data generated from rigid laminate	50	%	2.3.16.2
Glass Transition Temperature (Tg) by DSC	180	°C	2.4.25C
Glass Transition Temperature (Tg) by DMA	185	°C	2.4.24.4
Decomposition Temperature (Td) by TGA @ 5% weight loss	340	°C	2.4.24.6

Property		Typical Value	Units	Test Method
			Metric (English)	IPC-TM-650 (or as noted)
Time to Delaminate by TMA (Copper removed)	T260 T288	60 >15	Minutes	2.4.24.1
Thermal Conductivity		0.4	W/mK	ASTM E1952
Thermal Stress 10 sec @ 288ºC (550.4ºF)	Unetched Etched	Pass	Pass Visual	2.4.13.1
Dk, Permittivity	@ 100 MHz @ 1 GHz @ 2 GHz @ 5 GHz @ 10 GHz	4.13 4.04 4.01 3.88 3.88	—	2.5.5.3 Bereskin Stripline Bereskin Stripline Bereskin Stripline Bereskin Stripline
Df, Loss Tangent	@ 100 MHz @ 1 GHz @ 2 GHz @ 5 GHz	0.0158 0.0192 0.0200 0.0235	—	2.5.5.3 Bereskin Stripline Bereskin Stripline

Property		Typical Value	Units Metric (English)	Test Method IPC-TM-650 (or as noted)
	@ 10 GHz	0.0236		Bereskin Stripline Bereskin Stripline
Volume Resistivity	. C-96/35/90 . After moisture resistance . At elevated temperature	— 3.0×10^8 7.0×10^8	MΩ-cm	2.5.17.1
Surface Resistivity	. C-96/35/90 . After moisture resistance . At elevated temperature	— 3.0×10^6 2.0×10^8	MΩ	2.5.17.1
Dielectric Breakdown		>50	kV	2.5.6B
Arc Resistance		115	Seconds	2.5.1B
Electric Strength (Laminate & laminated prepreg)		54 (1350)	kV/mm (V/mil)	2.5.6.2A
Comparative Tracking Index (CTI)		3 (175-249)	Class (Volts)	UL 746A ASTM D3638

Property		Typical Value	Units	Test Method
			Metric (English)	IPC-TM-650 (or as noted)
Peel Strength	Low profile copper foil and very low-profile copper foil all copper foil >17 µm [0.669 mil]	0.969 (5.5)	N/mm (lb/inch)	2.4.8C
	Standard profile copper	1.06 (5.9)		2.4.8.2A
	1. After thermal stress	1.06 (5.9)		2.4.8.3
	2. At 125ºC (257ºF)			2.4.8.3
	3. After process solutions	0.969 (5.5)		
Flexural Strength	Length direction	97.1	ksi	2.4.4B
	Cross direction	54.1		
Test data generated from rigid laminate	Length direction	3770	ksi	ASTM D790-15e2
	Cross direction	3337		
Poisson's Ratio	Length direction	0.172	—	ASTM D3039
	Cross direction	0.155		
Moisture Absorption		0.15	%	2.6.2.1A
Flammability (Laminate & laminated prepreg)		V-0	Rating	UL 94

1.1.6 Failures in Electronic Packages

One of the common failures in Electronic package is due to CTE mismatch between different components in package. In package, silicon has 2.6 ppm/ C, copper has 16.5 ppm/ C, aluminum 22.7 ppm/ C, PCB has 14 ppm/ C [23]. Due to such mismatch in CTE, at high temperatures PCB expands and at low temperature PCB contracts [23]. With PCB the attached components to PCB like substrate, solder balls, silicon die etc. tends to extend and contract. Also, if the PCB are stiff then it will give high resistance to bending and will result in failure. This creates the warpage in PCB and excessive warpage creates strain on solder ball joints and makes them to fail. In figure: 2 and 3, we can clearly see the PCB warpage and solder ball joint cracking. Solder ball cracks at interface between solder ball and substrate, solder ball and PCB. This type of crack in solder balls finally results in failure of package. If the PCB are flexible, then it will give low resistance to bending and due to low elasticity, it can regain its shape after bending. By decreasing mismatch between different components in package and by making PCB flexible we can counter the problem of CTE mismatch and solder ball joint failures. Also, if there is less mismatch between CTE of different components like silicon die, substrate, PCB's etc. then we can prevent the failures due to CTE mismatch in Electronic packages.

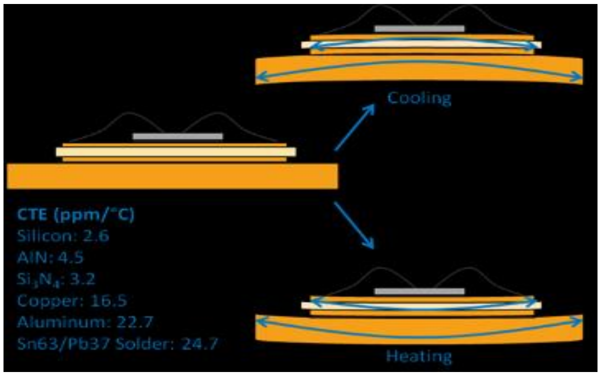

Figure 6: Warpage due to CTE Mismatch [23]

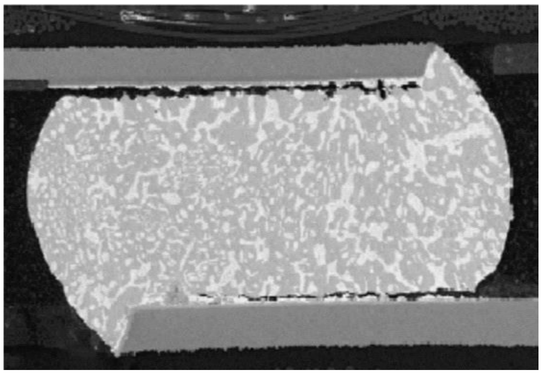

Figure 7: Crack propagation at top and bottom edges of solder ball [23]

1.2 Motivation and Objective

The Stiffness and CTE mismatch between PCB and package effects the reliability of solder ball joints [24]. Region where solder ball connects substrate and solder ball connects PCB are most prone to fail [23]. At high temperatures, there are high chances of failure of package due to CTE mismatch between PCB and Electronic package. Also, Young's modulus of PCB is higher than package i.e. Stiffness of PCB is higher which effects the solder ball joint reliability and becomes reason to failure. In this work effect of oil immersion cooling on thermo-mechanical properties like Youngs modulus and CTE on PCB is presented. To calculate thermal properties like CTE Thermo Mechanical Analyzer (TMA) and to calculate mechanical properties like storage modulus, loss modulus, glass transition temperature Dynamic Mechanical Analyzer (DMA) are extensively used. In this work, we have investigated the thermo-mechanical properties of two different PCB's, 370HR and 185HR and its core layer. Change in thermo-mechanical properties before oil-immersion and after oil immersion are studied to check its effect PCB's. Previous work reported by Shah et. Al. three servers were fully immersed in the mineral oil for six month of time period, samples of motherboard PCB's from air cooled and oil cooled servers were taken and characterized for young's modulus on Instron tester and have observed significant increase in Young's modulus after immersion in mineral oil [6]. In second study PCB's were taken from air cooled and oil cooled servers and characterized and observed that Young's modulus is decreasing for oil immersed PCB's [7]. Both the results are contradicting. In this study we have characterized two PCB's 370HR and 185HR before immersion in dielectric fluid and after immersion in dielectric fluid and have compared the changes occurred in thermo-mechanical properties of PCB samples.

1.3 Outline

Dynamic Mechanical Analyzer (DMA) and Thermo-Mechanical Analyzer (TMA) are leveraged for calculating thermo-mechanical properties of two PCB's and its core layer. Samples of PCB's and core layer were prepared by cutting PCB in to sample size with the help of high-speed cutter. DMA samples were cut in the size of 50 x 8 x 1.5 mm and TMA samples were in size of 8 x 8 x 1 mm. half of the samples were immersed in dielectric oil EC 100 for period of 720 hours at room temperature and then tested on DMA and TMA. Remaining half Pre-immersed samples were tested on DMA and TMA to calculate Young's modulus and CTE. For DMA testing samples were tested from 25° to 200° C and for TMA testing samples were tested from 25° to 160° C. Four samples of each PCB and core layer were tested and averaged value is taken. Young's modulus and CTE of Pre-Immersed and Post-Immersed samples were studied and compared to check its effect on PCB's.

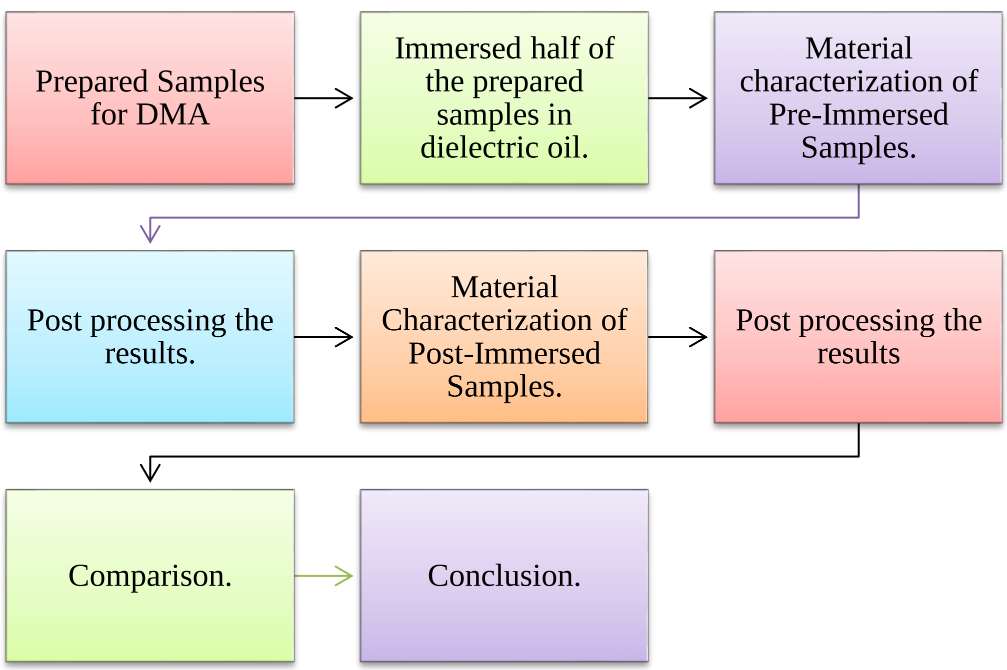

Figure 8: Outline of Research work

Chapter 2

2.1 Material Characterization

Material characterization is very important step to evaluate thermo-mechanical properties of PCB. For lumped analysis, it is very necessary to predict precise material properties for boards. In this work, we are going to evaluate Storage modulus, loss modulus, complex modulus, glass transition temperature and CTE. Different test setups and arrangements were used to calculate material properties. For material characterization samples were prepared with high speed cutter. For DMA testing samples were tested from 25° to 200° C and for TMA testing samples were tested from 25° to 160° C. Four samples of each PCB and core layer were tested and averaged value is taken. Samples of PCB's and core layer were prepared by cutting PCB in to sample size with the help of high-speed cutter. DMA samples were cut in the size of 50 x 8 x 1.5 mm and TMA samples were in size of 8 x 8 x 1 mm.

*Table 3**:** DMA and TMA working Parameters*

Parameters	**DMA**	**TMA**
Temperature range	25°C to 200°C	25°C to 160°C
Minimum tension/compression force	100mN	-100mN
Tension/compression force gain	1.5	-
Force amplitude	100mN	-100mN

2.1.1 Sample Preparation

For material characterization samples were prepared with high speed cutter. Four samples of each PCB and core layer were tested and averaged value is taken. Samples of PCB's and core layer were prepared by cutting PCB in to sample size with the help of high-speed cutter. DMA samples were cut in the size of 50 x 8 x 1.5 mm and TMA samples were in size of 8 x 8 x 1 mm.

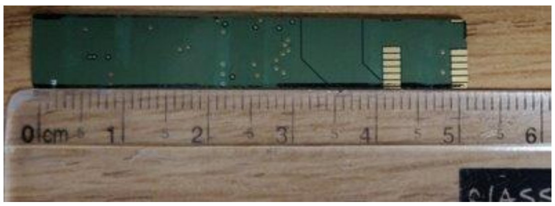

Figure 9: DMA PCB Sample

Figure 10: DMA Core layer Sample

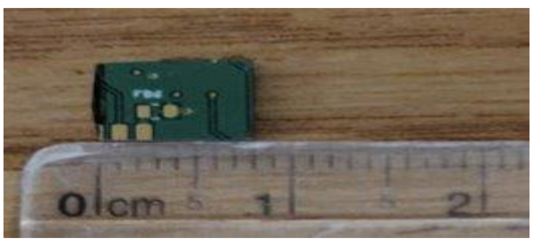

Figure 11: TMA PCB Sample

Figure 12: TMA Core layer Sample

Table 4: Dimensions of DMA Samples

Parameters	**DMA**			
	PCB Samples (in mm)		**Core Samples (in mm)**	
	370HR	**185HR**	**370HR**	**185HR**
Length	50	50	50	50
Width	8	8	8	8
Thickness	1.62	1.68	0.4	0.24

Table 5: Dimensions of TMA Samples

Parameters	**DMA**			
	PCB Samples (in mm)		**Core Samples (in mm)**	
	370HR	**185HR**	**370HR**	**185HR**
Length	50	50	50	50
Width	8	8	8	8
Thickness	1.62	1.68	0.4	0.24

2.1.2 Dynamic Mechanical Analyzer (DMA)

Dynamic Mechanical Analysis measures the mechanical properties like Young's modulus, glass transition temperature etc. of materials as a function of time, temperature, and frequency. It is measurement technique of relationship between temperature and mechanical properties of material. DMA is consisting of measurement head, heater, thermocouple, displacement detector and force generator. Sample is attached to the measurement head; heating is applied through the furnace and probe is introduced through the force generator to apply stress to the sample. Stress is set as one measurement condition as sine wave force, so the sample strain amplitude is constant. Sample deformation amount i.e. strain that occurs from sinusoidal oscillation force gets detected in the displacement detector unit. Stress applied and strain detected is used to calculate elasticity. In DMA the results are output as a function of temperature. The dynamic mechanical analysis is method used to measure mechanical properties of material by evaluating stress and strain that is generated for the stress or strain applied in vibration over time to the sample. DMA can go from 25° C to 600° C and with using DMA can go from -150° C to 600° C. Static mechanical analysis is method used to measure the changes of stress and strain by applying a constant stress or strain over time

Table 6: Sample dimensions for different types of measurement modes in DMA

Sample Dimensions	Tension mode	Bending mode
Length	25 to 55 mm	50 ± 2 mm
Effective length	5 to 35 mm	20 mm
Thickness	3 mm	5 mm
Max. width	10 mm	16 mm

without changes. Following table shows desired sample dimensions for tension mode and dual cantilever mode.

DMA gives us the values of storage modulus and loss modulus. From storage and loss modulus we can calculate complex modulus and this complex modulus can be relate to Young's modulus. Here, E' is storage modulus, E" is loss modulus and E* is complex modulus. Equation (1) is used to calculate complex, modulus:

$$E^{*}= E' + iE'' \qquad (1)$$

Figure 12 Shows the Schematic of DMA. The sample is clamped in the measurement head of DMA instrument. During measurement, sinusoidal force is applied to the sample via the probe. Deformation caused by the sinusoidal force is detected and the relation between the deformation and the applied force is measured. Properties such as elasticity and viscosity are calculated from the applied stress and strain plotted as a function of temperature or time.

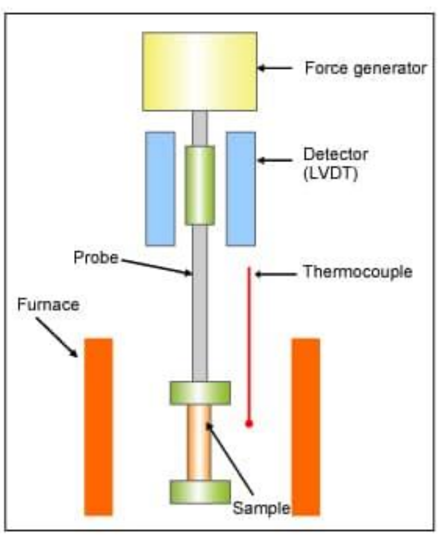

Figure 13: Schematic of DMA [29]

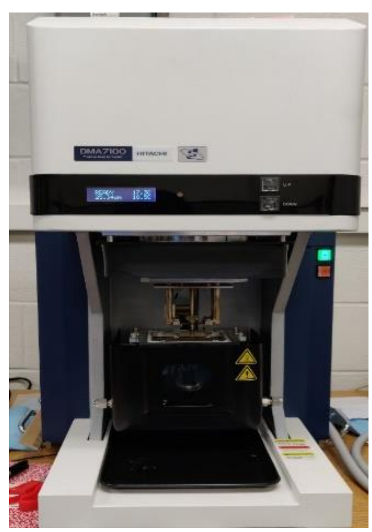

Figure 14: DMA

DMA is used for measurement of various types of materials using different deformation modes. There is tension, compression, dual cantilever bending, 3-point bending, and the most suitable mode should be selected depending upon the sample shape, type, thickness, measurement purpose. In this study, for thick samples like PCB dual cantilever bending mode is used and thin samples like core layer tension mode is used for measurement of modulus.

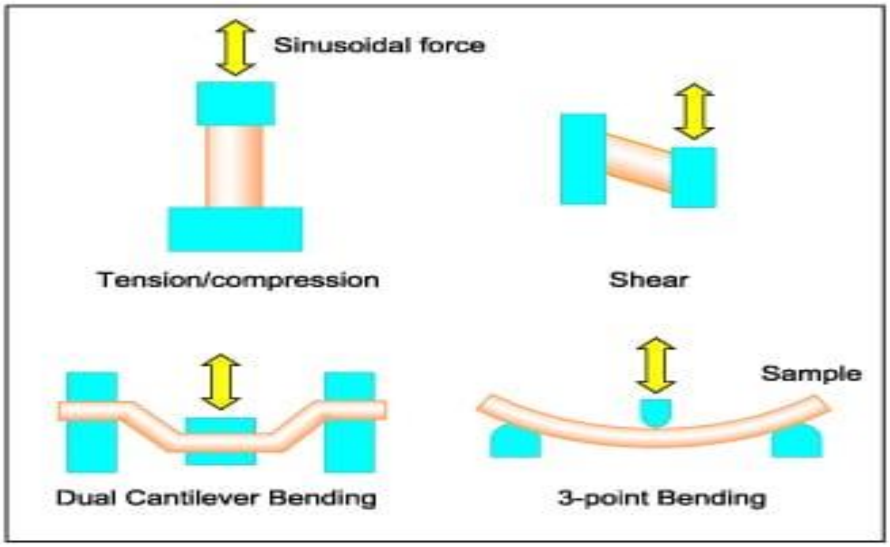

Figure 15: Schematic of measurement modes in DMA [29]

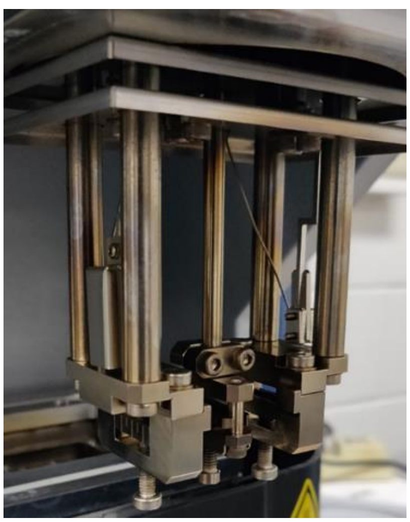

Figure 16: Dual Cantilever bending mode

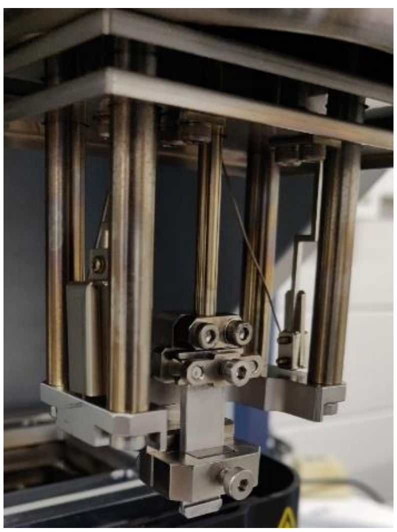

Figure 17: Tension mode

2.1.3 Thermo-Mechanical Analyzer (TMA)

Thermo-Mechanical Analyzer (TMA) is a device used to measure thermal properties of material like CTE, glass transition temperature, melting point etc. TMA has working temperature range of 25° to 600° C, if liquid nitrogen is used then we can test the sample from -150° to 600° C. In this study, the PCB samples were tested from 25° to 160° C. TMA is used to measure In-plane as well as out of plane CTE for different materials. For this study, TMA samples are cut in square shape with the help of high-speed cutter. For our study samples are cut in the size of 8 x 8 x 1 mm. Probe of TMA is quartz which touch the sample and after applying heat movement of probe in Z direction gives the CTE of material. For the experiment temperature range of 25° to 160° C is used with temperature increment of 2° C/min. Total four test were conducted for each sample and then average value is taken.

Following are the Specifications of the TMA:

Table 7: TMA Specifications

Module	**TMA/ SS6100**
Unit Composition	TMA/SS6000 Base Unit+100H Heater+ Measurement unit
Heater type	100H Heater
Connected Sample tube	Quartz, K thermocouple
Connected Probe	Quartz
Probe Support	Cantilever
TMA Range (Sensitivity)	±5 mm
Program Speed	0.01 to 100 C/ min
Sample Length	Auto measurement

Below Figure 17 shows Schematic diagram of TMA. The sample is kept on the sample tube seat which is surrounded by the furnace and probe is touched to the sample which is connected with the Length Detector and the Force Generator. The probe touched to the sample measures the length i.e. thickness of sample. The thermocouple for temperature measurement is located near the sample which measures the sample temperature when heat is applied through the furnace. With increase in temperature the force is applied from force generator through the probe on the sample. The thermal expansion of sample i.e. thermal deformation of the sample with change in temperature is measured by the length detector as the probe displacement. For Length Detection Sensor Linear Variable Differential Transformer (LVDT) is used.

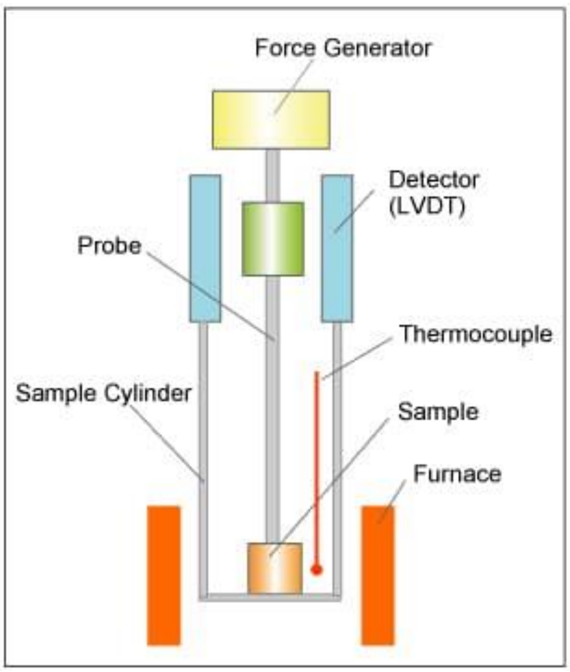

Figure 18: Schematic of Thermo-mechanical analyzer (TMA) [30]

Figure 19: TMA

There are various types of probe used in TMA. The use of each probe depends upon purpose of measurement. In this work expansion/compression probe is used for all the experiments. Following are the different types of probe used in TMA,

Expansion/Compression Probe: It is used to measure transition of the material under the compression force and also to measure deformation of the sample by thermal expansion.

Penetration Probe: This probe is usually used for softening temperature measurement.

Tension Probe: For the measurement of thermal expansion and thermal shrinkage of materials like film and the fiber tension probe is used.

Depending upon purpose of measurement and temperature range used for evaluating material properties, the type of probe is used. The materials used for probe are quartz glass, alumina and metals. In our study we are using quartz type of probe.

Following Figure 20 shows types of Probe used in TMA Study.

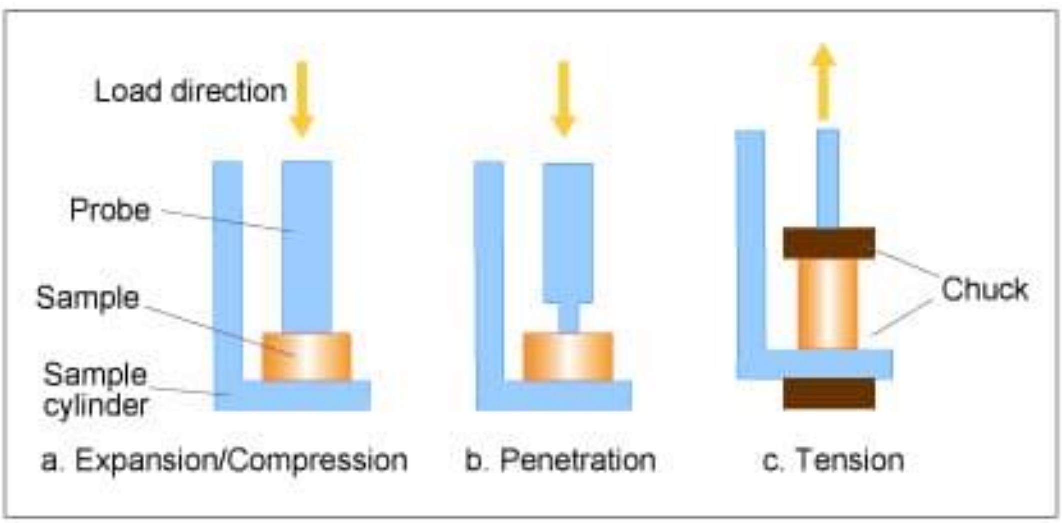

Figure 20: Types of Probe in TMA [30]

Chapter 3

3.1 Experimental Procedure

For conducting experiments on PCB sample, total fifty samples were prepared from 370 HR and 185 HR PCB's and their core layer. Half of the samples were immersed in the dielectric fluid. For testing on DMA to evaluate Young's modulus and glass transition temperature, four samples of each PCB, 370HR and 185HR and their core layer were tested, and averaged value is taken. Also, four samples of each PCB were taken and were tested on TMA to evaluate CTE. Samples of PCB's and core layer were prepared by cutting PCB in to sample size with the help of high-speed cutter. Core layer of PCB is assembly of FR4 sandwich between two copper layers. Samples were prepared suitable to DMA and TMA measurement setup and are in length and width given in the manual of DMA and TMA. For the study samples prepared from 370HR and 185HR PCB were kept in dielectric fluid EC 100 for period of 720 hours (one month) at room temperature 22° C. Material characterization is very important step to evaluate thermo-mechanical properties of PCB. For lumped analysis, it is very necessary to predict precise material properties for boards [24].

In this work, we are going to evaluate Storage modulus, loss modulus, complex modulus, glass transition temperature and CTE. Different test setups and arrangements were used to calculate material properties. For DMA testing, samples were tested from 25° to 200° C. Four samples of each PCB and core layer were tested and averaged value is taken. Samples of PCB's and core layer were prepared by cutting PCB into a sample size with the help of high-speed cutter. To test the sample from 25° to 200° C, each test took 89 min. Minimum tension force used was 100mN, force gain 1.5 and force amplitude 100mN. Before testing, samples were polished on polish paper to remove rough edges and cleaned with ethanol to make sure that there is no dust on the samples. For material characterization, DMA was extensively used. Four samples of each PCB and its Core layer were tested on DMA. More than 32 tests were conducted on pre-immersed and post-immersed samples and obtained values were averaged to get the results.

For evaluating CTE of PCB samples, TMA was extensively used. Total 16 samples were prepared for TMA testing in dimensions according to manual. Half of the samples were kept in dielectric fluid EC 100 for period of 720 hours (one month) at room temperature 22° C. For TMA, samples were tested from 25° to 160° C, each test took around 63 min. Minimum force used was -100Mn. Before testing, samples were polished on polish paper to remove rough edges and cleaned with ethanol to make sure that there is no dust on the samples. For each test probe and base on which sample sits were cleaned with ethanol. More than 32 tests were conducted on pre-immersed and post-immersed samples and obtained values were averaged to get the results. Following images shows the Immersed PCB and Core samples in dielectric fluid EC100 for period of 720 Hours (one month).

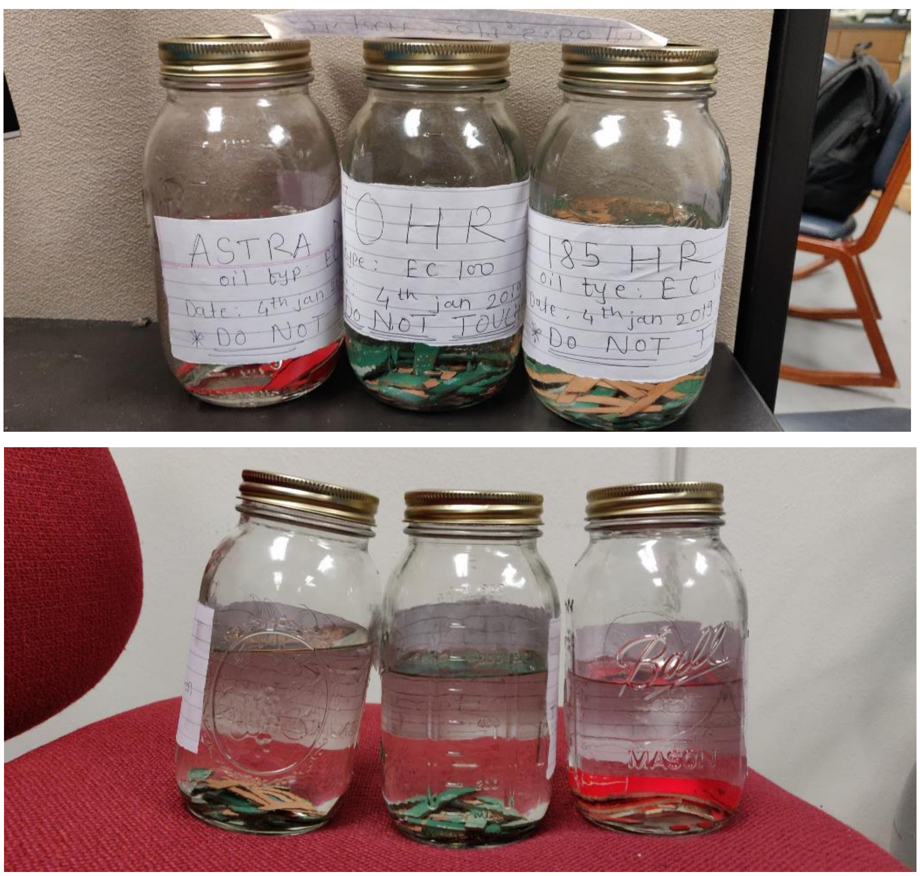

Figure 21: Samples immersed in dielectric fluid

Chapter 4

4.1 Experimental Results

4.1.1 Results of DMA 370 HR PCB Samples

Figure 22 below shows the complex modulus of 370HR PCB Pre-Immersed samples. At room temperature it is 18 GPa. The error bar shows the standard deviation. So, the values are in ±1 GPa. Figure 23 below shows the complex modulus of 370HR PCB Post-Immersed samples. At room temperature it is 12 GPa. The error bar shows the standard deviation. So, the values are in ±1 GPa.

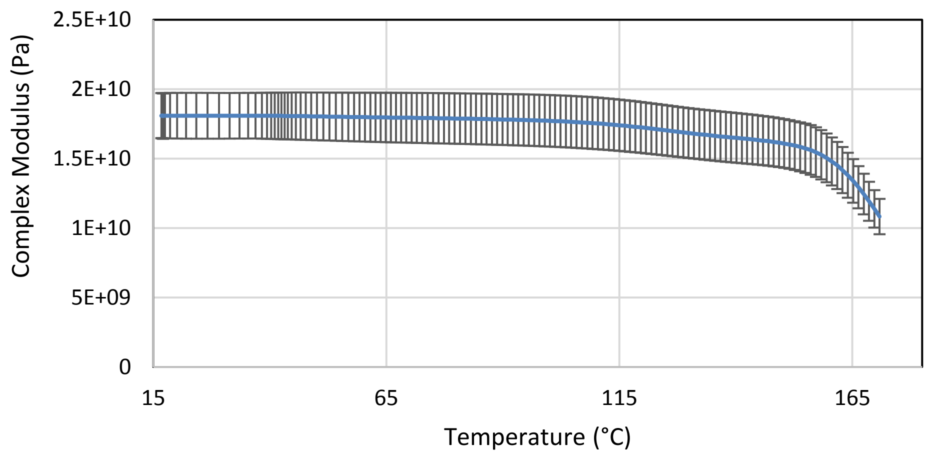

Figure 22: Graph of Complex modulus for 370HR Pre-Immersed DMA PCB Samples

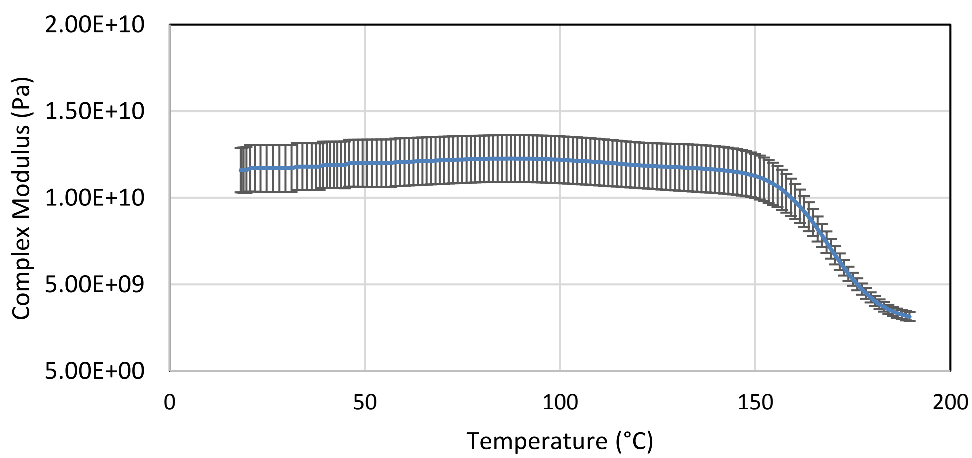

Figure 23: Graph of Complex modulus for 370HR Post-Immersed DMA PCB Samples

From below Figure 24 of comparison of 370HR pre-immersed and 370 HR post-immersed DMA samples, we can see that at room temperature complex modulus of Post-Immersed samples decreased by 33.33% compared to Pre-Immersed samples.

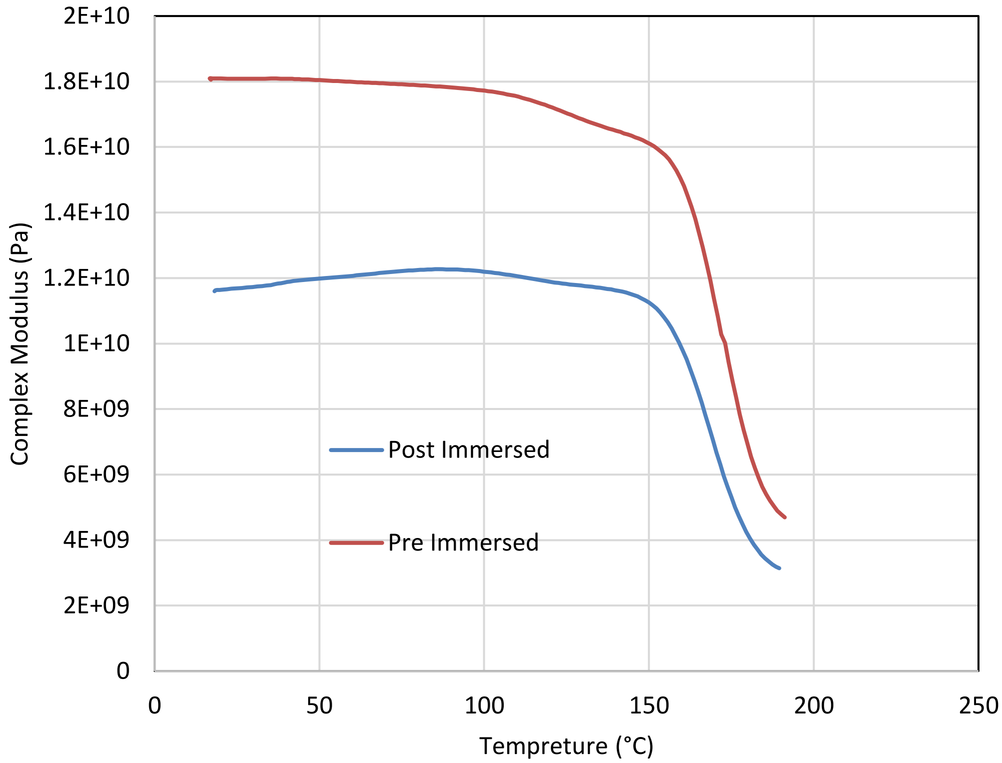

Figure 24: Comparison of 370HR pre-immersed and 370HR post-immersed DMA PCB samples

4.1.2 Results of DMA 370 HR Core Samples

Figure 25 below shows the complex modulus of 370HR DMA Core Pre-Immersed samples. At room temperature it is 46 GPa. The error bar shows the standard deviation. So, the values are in ±1 GPa. Figure 26 below shows the complex modulus of 370HR Core Post-Immersed samples. At room temperature it is 42 GPa. The error bar shows the standard deviation. So, the values are in ±0.5 GPa.

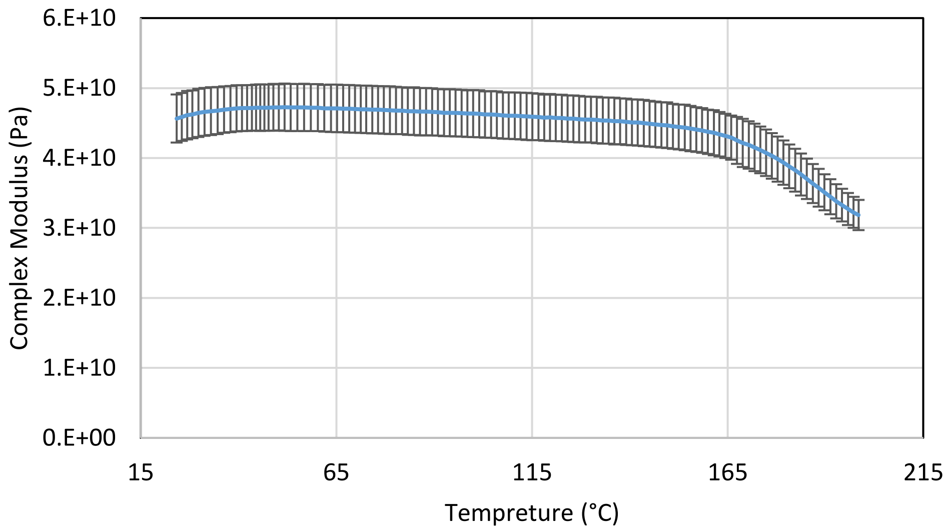

Figure 25: Graph of Complex modulus of 370HR DMA Core pre-immersed samples

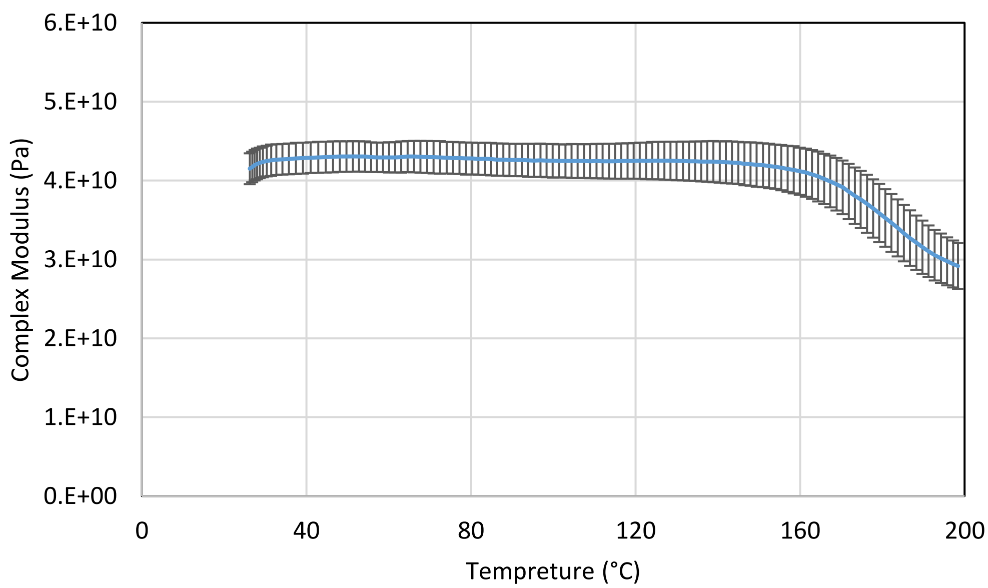

Figure 26: Graph of Complex modulus of 370HR DMA Core post-immersed samples

From below Figure 27 of comparison of 370HR DMA Core pre-immersed and post-immersed samples, we can see that at room temperature complex modulus of Post-Immersed samples decreased by 8.69% compared to Pre-Immersed samples.

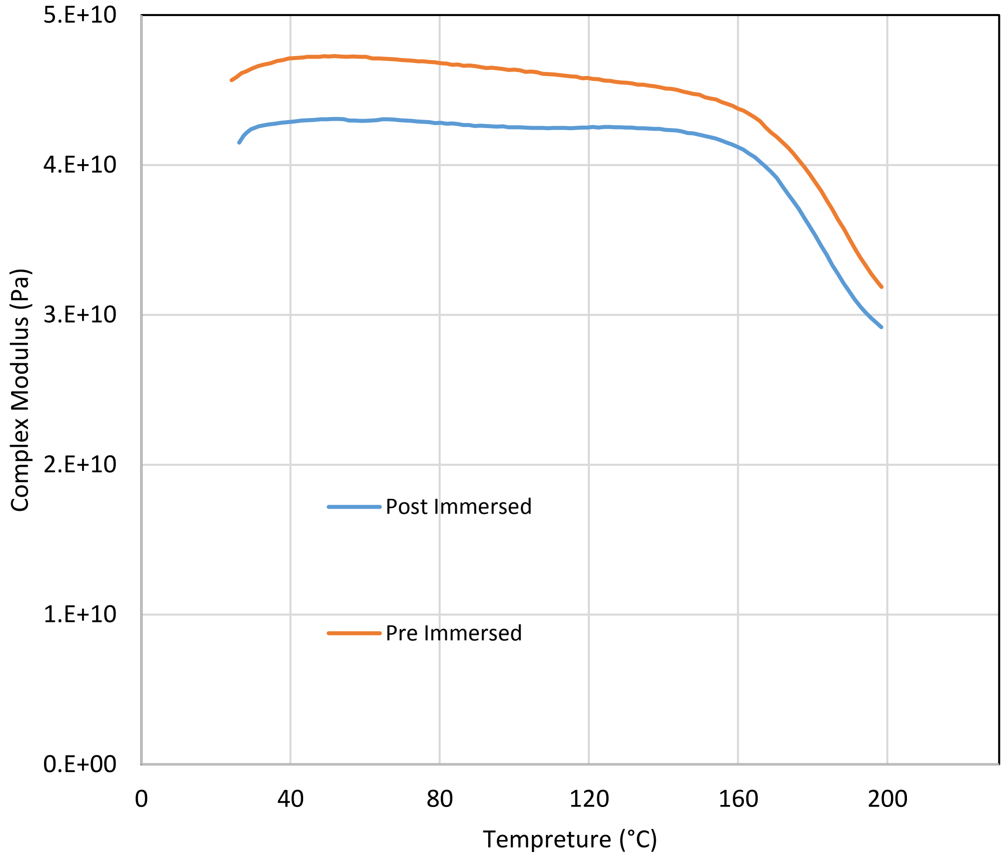

Figure 27: Graph of Comparison of 370HR DMA Core pre-immersed and post-immersed samples

4.1.3 Results of DMA 185 HR PCB Samples

Figure 28 shows the complex modulus of 185HR DMA PCB Pre-Immersed samples. At room temperature it is 10.2 GPa. The error bar shows the standard deviation. So, the values are in ±1 GPa. Figure 29 shows the complex modulus of 185HR PCB Post-Immersed samples. At room temperature it is 8.2 GPa. The error bar shows the standard deviation. So, the values are in 0.5 GPa.

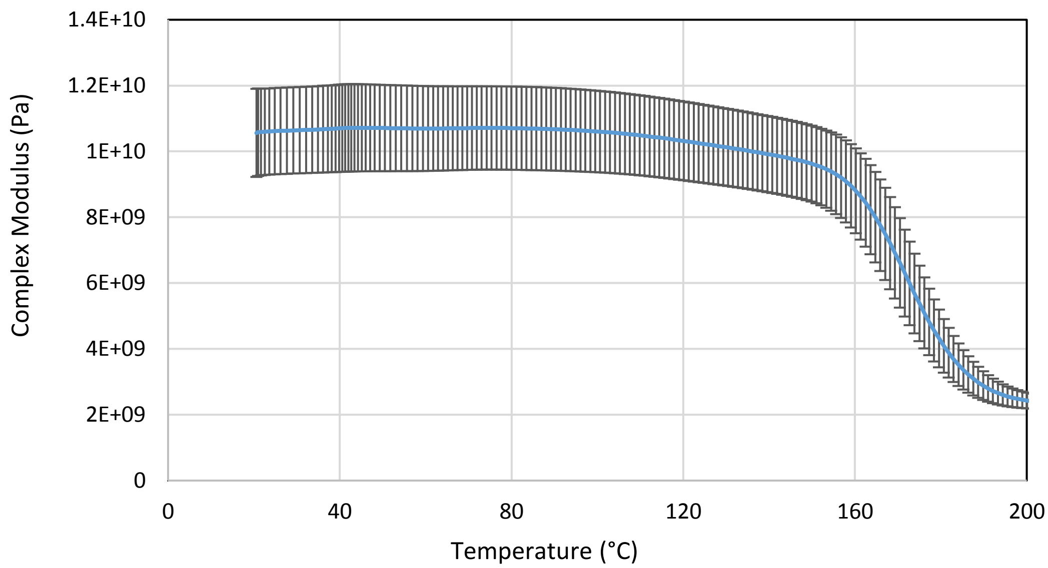

Figure 28: Graph of Complex modulus of 185HR pre-immersed DMA PCB Samples

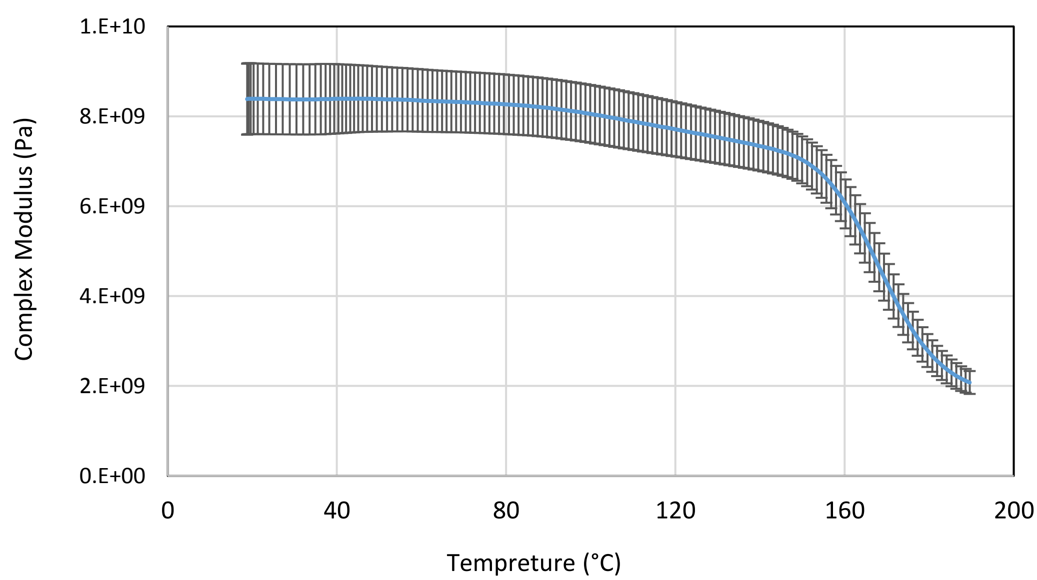

Figure 29: Graph of Complex modulus of 185HR Post-immersed DMA PCB Samples

From Figure 30 of comparison of 185HR DMA PCB pre-immersed and post-immersed samples, we can see that complex modulus of Post-Immersed samples at room temperature is decreased by 19.04% compared to Pre-Immersed samples.

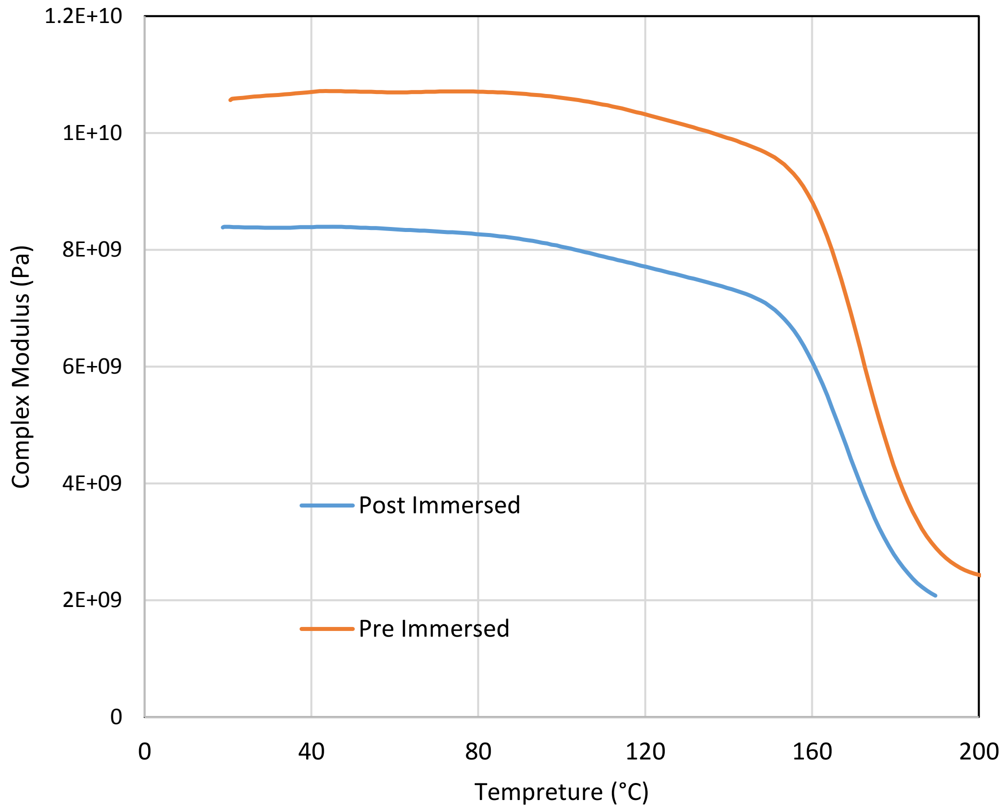

Figure 30: Graph of comparison of 185HR DMA PCB pre-immersed and post-immersed samples

4.1.4 Results of DMA 185 HR Core Samples

Figure 31 below shows the complex modulus of 185HR DMA Core Pre-Immersed samples. At room temperature it is 48 GPa. The error bar shows the standard deviation. So, the values are in 0.5 GPa. Figure 32 below shows the complex modulus of 185HR DMA Core Post-Immersed samples. At room temperature it is 46 GPa. The error bar shows the standard deviation. So, the values are in ±1 GPa.

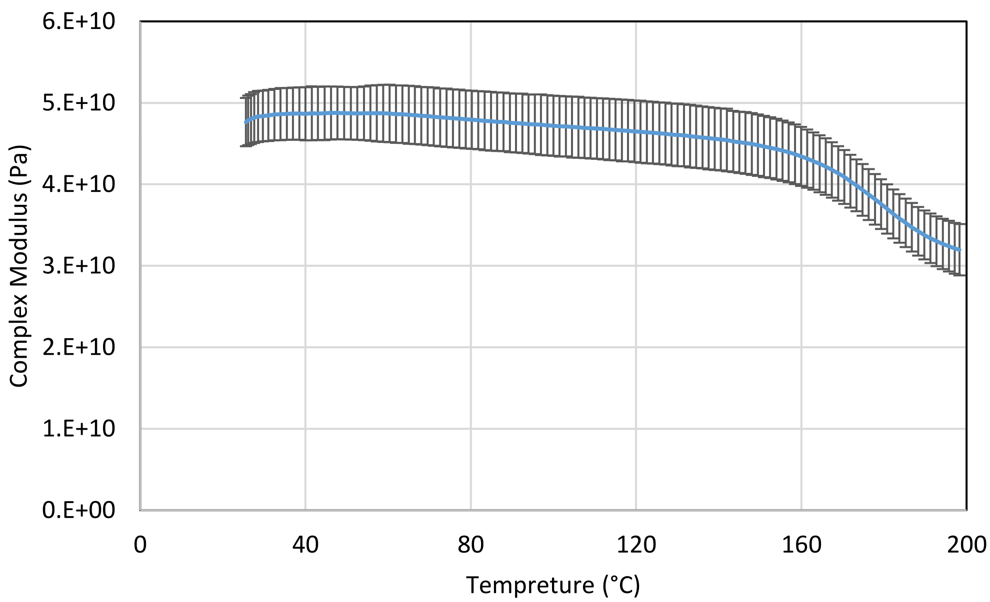

Figure 31: Graph of 185HR DMA core pre-immersed samples

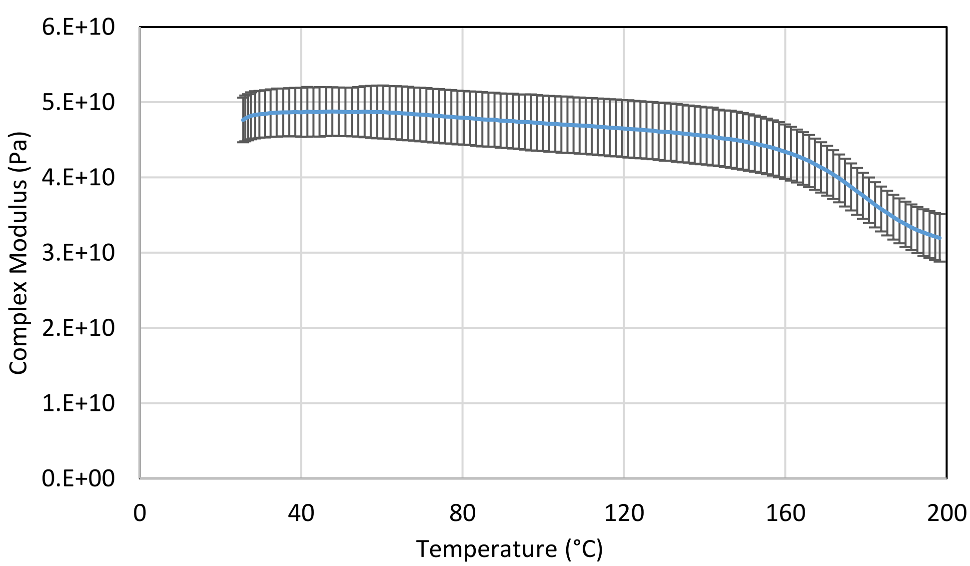

Figure 32: Graph of 185HR DMA core post-immersed samples

From the below Figure 33 of comparison of 185HR Core pre-immersed and post-immersed samples, we can say that, at room temperature there is no significant change in complex modulus of Post-Immersed 185HR Core samples compared to Pre-Immersed samples.

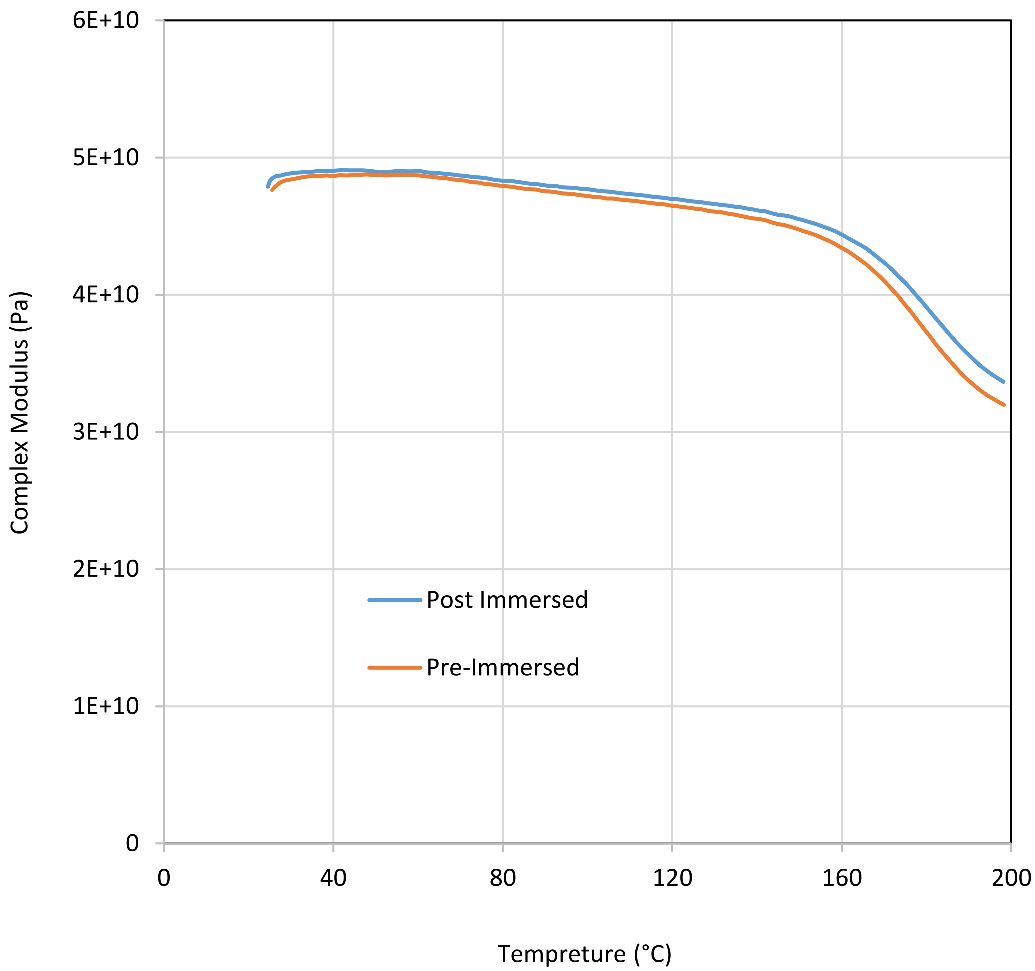

Figure 33: Graph of comparison of 185HR DMA Core pre-immersed and post-immersed samples

4.1.5 Results of TMA 370 HR PCB Samples

Below Figure 34 shows the comparison of out of plane CTE of 370HR pre-immersed and post-immersed PCB samples. From figure we can see that CTE of post-immersed PCB samples is decreasing compared to 370HR pre-immersed samples.

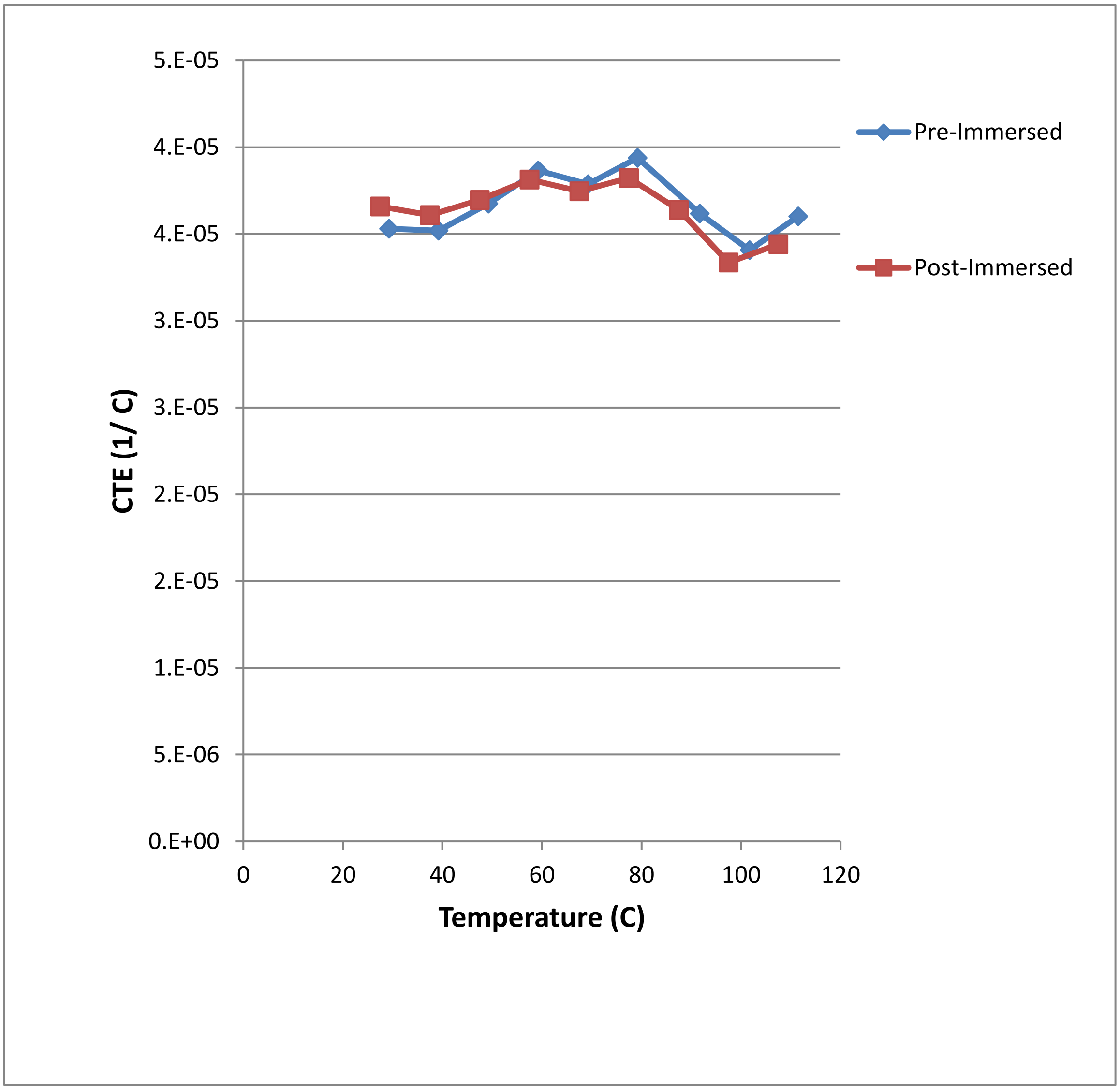

Figure 34: Comparison of CTE of 370HR pre-immersed and post-immersed PCB Samples

4.1.6 Results of TMA 185 HR PCB Samples

Below Figure 35 shows the comparison of out of plane CTE of 185HR pre-immersed and post-immersed PCB samples. From figure we can see that CTE of post-immersed PCB samples is decreasing compared to 185HR pre-immersed samples

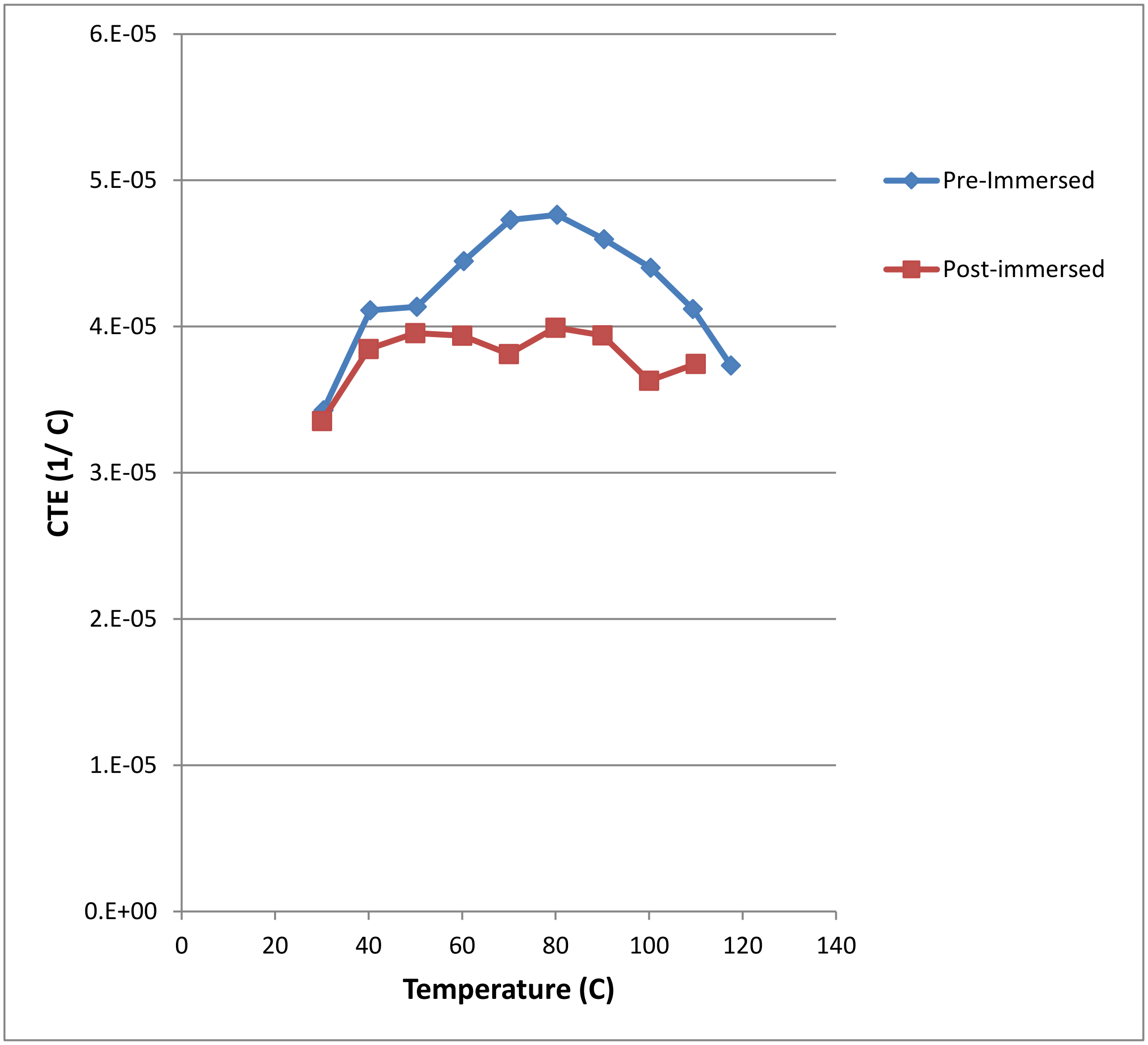

Figure 35: Comparison of CTE of 185HR pre-immersed and post-immersed PCB samples

4.1.7 Effect of Copper and FR4 Content in Core Samples

Core layer in PCB is assembly of FR4 sandwiched between two copper layers. The below image is cross-section of core layer captured from Polarized microscope. The top and bottom golden layers are two copper layers and in between them wavy structure like fibers are FR4. In this study core layer of 370HR and 185HR has different thickness. In this section we will see how percentage content of copper and FR4 affects the Young's modulus of sample. For this study we have used OLYMPUS BX60 polarized microscope. Samples were cut on high speed cutter and then well-polished on bottom and top surface and edges. Polished Core samples were kept and observed under polarized microscope to see structure and content of copper and FR4 present in PCB core sample. Following images shows the cross-section of 370HR and 185HR core samples:

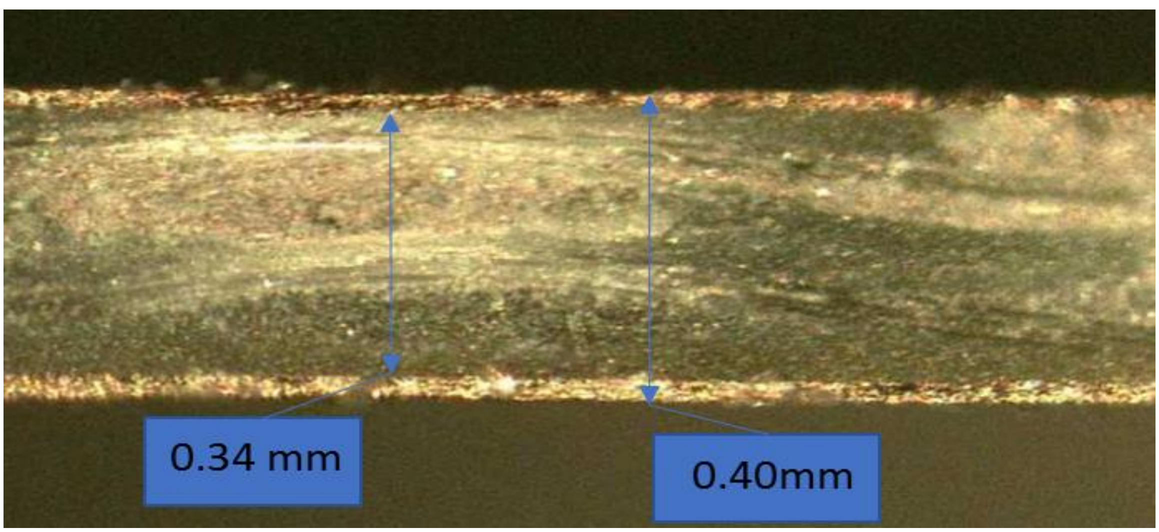

Figure 36: Cross-section of 370HR Core sample

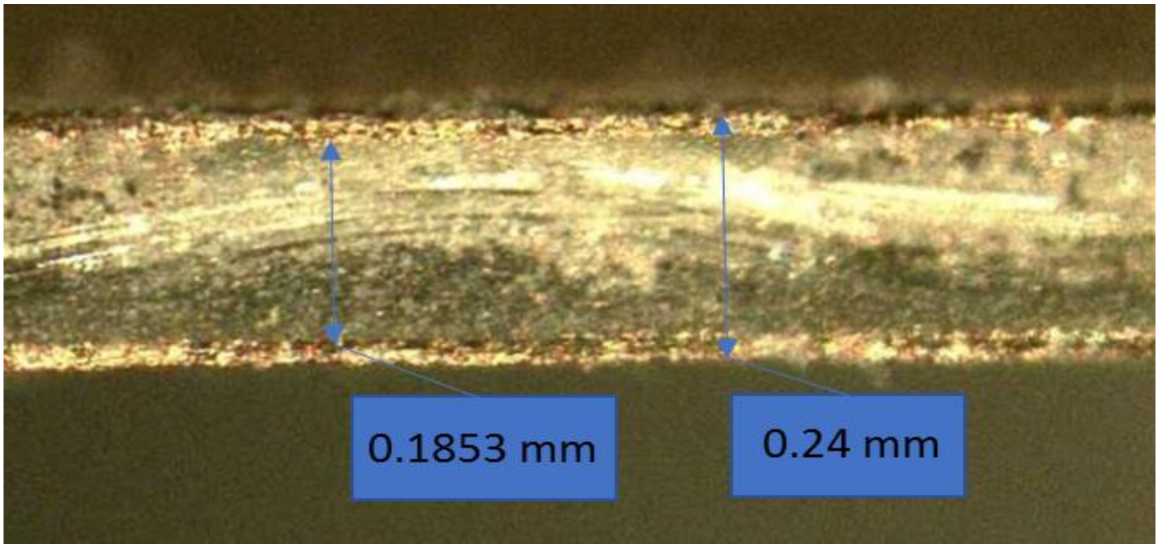

Figure 37: Cross-section of 185HR Core samples

Table 8: FR4 and Copper percentage in 370HR Core sample

Description	370HR	Percentage amount
Total Thickness	0.40 mm	-
FR4 Content	0.34 mm	85
Content	0.06 mm	15

Table 9: FR4 and Copper percentage in 185HR Core sample

Description	185HR	Percentage amount
Total Thickness	0.24 mm	-
FR4 Content	0.1853 mm	77.20
Copper Content	0.0547 mm	22.8

Above tables 8 and 9 for 370 HR and 185 HR core samples shows the percentage amount of copper and FR4 present in samples. Young's modulus of FR4 is around 24 GPa and Copper is 128 GPa [25]. In 370HR Core sample FR4 content is 85% and it is greater than FR4 content in 185HR which is 77.20%. From the experimental data, Young's modulus of 370 HR Core layer is 46GPa and 185 HR is 48 GPa. Therefore, we can say that as amount of FR4 in PCB increases, Young's modulus will decrease.

Chapter 5

5.1 Result Discussion

After the experimental study, thermo-mechanical properties of pre-immersed and post-immersed 370HR and 185HR PCB and their core layer we have seen that Complex modulus of both PCB's decreased after immersing them in dielectric oil for period of 720 hours (one month). Also, after immersion of both 370HR and 185HR PCB's, CTE of post-immersed PCB's is decreasing compared to pre-immersed PCB's. This kind of decrease in CTE will reduce the CTE mismatch between different components like PCB's, substrate, Silicon die etc. of Electronic packages and can prevent the failure of packages due to warpage. Stiffness of 370HR and 185 HR PCB's and their core layer decreased due to absorption of oil when submerged in dielectric oil. Amount of Copper and FR4 content in core layer affects the complex modulus of 370 HR and 185 HR core layer. Amount of oil absorbed by PCB's and core layer during immersion in dielectric oil can be evaluated by Thermo gravimetric analysis (TGA) study. There was no change in glass transition temperature (Tg) of 370HR and 185HR PCB and their core layer after immersion in oil compared to samples before immersion. As the Young's modulus decreases it will make PCB's less stiff. Due to less stiffness and more flexibility there will be less warpage in PCB at higher or lower temperature. The flexible PCB's will result into flexible assembly. Flexibility of PCB will make the assembly warp flexibly. On the other hand, stiff PCBs, by opposing the warpage behavior cause more stresses on the solder which will result into decreased life [26].

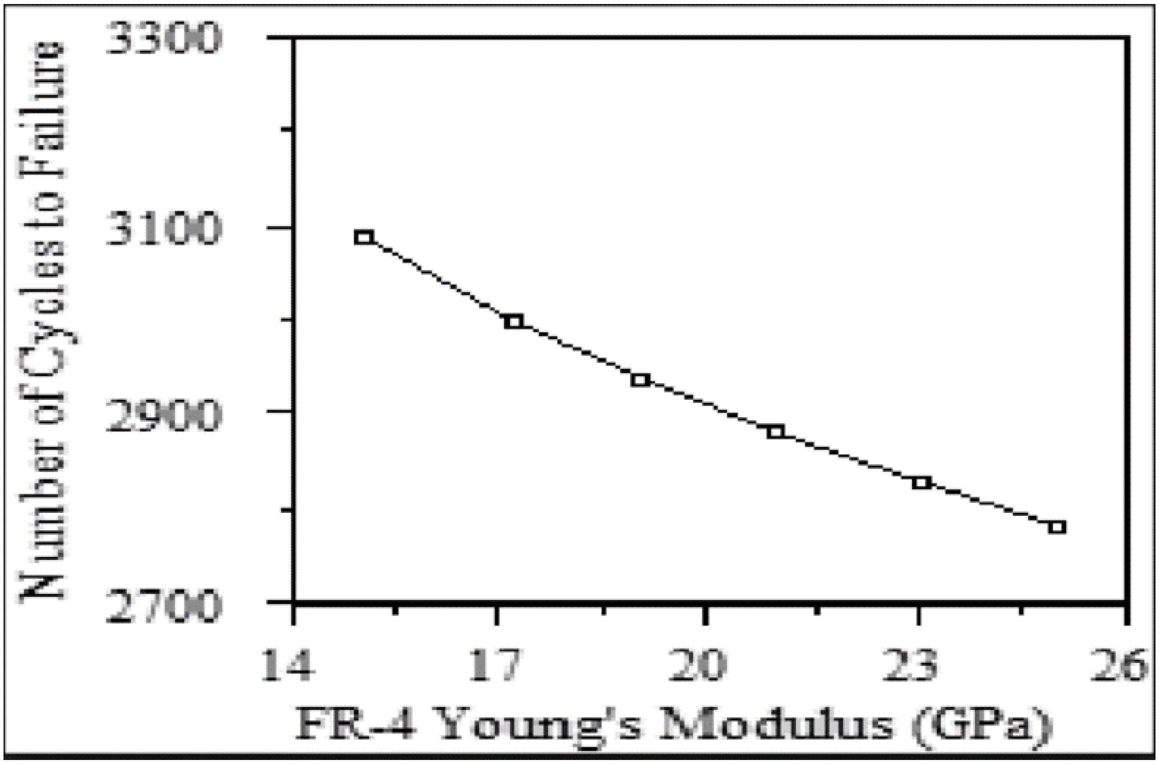

Figure 38: Typical relation between Number of cycles to failure and Young's modulus [6]

Above figure 38 indicates that, as the Young's modulus increases then number of cycles to failure will decreases [27]. In the presented study from experimental data we can see that for both PCB's 370HR and 185HR Young's modulus is decreasing. In case of 370HR core layer Young's modulus is decreasing but there is no significant decrease in Young's modulus of 185HR core layer.

Such kind of decrease in Young's modulus will result in increase of number of cycles to failure which will result in increased reliability of electronic package.

Chapter 6

6.1 Conclusions and Future Work

The information presented in the work is on the basis on strong experimental data and literature review. The study provides the useful information about change in material properties of PCB's when they are immersed in the dielectric fluid EC100, and its effect on reliability of Electronic packages. From the experimental data we can clearly see that Young's modulus of PCB' is decreasing and this will result in reduced number of cycles to failure and therefore increase the reliability if electronic package. As the stiffness of PCB's decreasing, it will result in less warpage. From reliability point of view, there are no detrimental effects on PCB's when immersed in dielectric fluid EC 100. The lower stiffness of PCB's after immersion in dielectric fluid is due to absorption of fluid. The amount of fluid absorbed can be evaluated by TGA study. The objective of TGA is to measure the change in mass of a sample as the sample is heated, cooled or held at a constant (isothermal) temperature [28]. As there is not much literature available for immersion cooling from reliability perspective, there is good scope for future work in this study. Currently, we are testing 370HR and 185HR PCB's on Thermo mechanical analyzer (TMA) to evaluate there out of plane and in-plane Coefficient of thermal expansion (CTE). Different types of minerals oil, synthetic fluid can be used to study their effect on thermo-mechanical properties of PCB's. Time period and temperature can be increased to check its effect on PCB's. The obtained data from experiments can be input to FEA model and simulation can be done to study warpage failure and solder ball joint failure computationally. We can use different types of PCB's like Megtron 6 to study changes in its properties when immersed in different dielectric fluids. Delamination study can be carried out on different PCB's to check effect of immersion cooling on bonding between different layers of PCB's. This work will provide valuable insight in the feasibility of using immersion for cooling from the reliability standpoint and will enable the thermal design team to select oil as a viable cooling solution for high-end data center servers.

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Biographical Statement

Shrinath Ramdas received his bachelor's degree in Mechanical Engineering from University of Pune, India, in the year 2016. After his Bachelors, he worked for one year in Omega Engineer, Pune as a Graduate Engineer Trainee in Machine Design field. He pursued his Master's in Mechanical Engineering in University of Texas at Arlington from Fall 2017. He joined the Electronics MEMS & Nanoelectronics Systems Packaging Center (EMNSPC) under Dr. Dereje Agonafer in Summer 2018 and developed a keen interest in Immersion cooling, reliability and failure analysis of electronic packages. His research interest includes reliability, Material characterization, thermo- mechanical simulation. As a Secretary of Surface Mount Technology Association (SMTA) UT Arlington student chapter, he was actively involved in all the events and a technical meeting of SMTA. Upon graduation, Shrinath Ramdas will be working as Senior, SI Package Engineer at Inphi Corporation, CA and will continue his career in the field of electronic packaging, mainly focusing on electronic components reliability and analysis.