OVERMOLDED SUBSTRATE ON ALUMINUM METAL BACKING FOR HARSH ENVIRONMENT APPLICATIONS

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OVERMOLDED SUBSTRATE ON ALUMINUM METAL BACKING FOR HARSH ENVIRONMENT APPLICATIONS

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OVERMOLDED SUBSTRATE ON ALUMINUM METAL BACKING FOR HARSH ENVIRONMENT APPLICATIONS

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Date of Graduation

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Joshua David Ridenour, son of Rebecca Jeffries and David Ridenour, was born on March 22nd, 1984, in Huntsville, Alabama. He graduated high school from Westminster Christian Academy as Class President in May 2002. After high school, he attended Auburn University located in Auburn, Alabama in the fall of 2002. In the summer of 2006, he graduated magna cum laude with a Bachelor of Science degree in Mechanical Engineering. After graduation, he remained at Auburn University and entered the graduate program in Industrial and Systems Engineering as a research assistant in the field of automotive electronic reliability. In the summer of 2008, he will obtain his degree in Masters of Science concentrated in Industrial and Systems Engineering.

THESIS ABSTRACT

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Demand for high-temperature electronics in the automotive industry increases daily with the increasing number of electronics going into under-the-hood locations. Along with keeping costs low and reliability high while the electronics are being subjected to environments seeing up to 150^{o}C and beyond, new technologies and methods of production have made there way into the market.

Current designs of transmission controller modules and transfer case controller modules have multipart designs that protect the PC board from the environments. Also, with the increase in the number of flip chip packages being implemented into board PC board design in under-the-hood applications, different techniques have been used to increase reliability. Underfill materials were the first step of increasing these packages

but introduced another step, however a required one for reliability, in production. The effects of applying underfill techniques to overmold the entire PC board to increase reliability are mostly unknown and there is a little information provided to the public about this overmolding approach. This research looks into the quality and production issues of the overmolding process while also looking at the reliability effects. Accelerated life testing will be done on the different material combinations and the outcome of the tests will provide a clearer understanding of the overmolding process and its enhancing capabilities to component reliability.

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CHAPTER 1: INTRODUCTION

In the past decade, the number of electronics in the automobile has steadily increased, with many mechanical systems being replaced with electronic systems. Some systems that have replaced mechanical systems include electronic fuel injection, cruise control, brake-by-wire, throttle-by-wire, and steer-by-wire. Automotive electronic systems have also increased in number, in overall complexity, and in locations within the vehicle. Different locations in the vehicles can have very harsh environments where excess heat, vibration, dust, and liquid can interact with the electronic systems, as shown in Table 1 [1]. However, these systems are decreasing in size, weight, and costs but with increasing performance requirements. With complexity and decrease in size in any electronic system comes an increase in component density on circuit boards. This leads to an increase in heat generation of substrate surface area which requires a method of heat dispersion to increase overall reliability while providing protection from the environment.

Location	Typical Continuous Max Temperature	Vibration Level	Fluid Exposure
On Engine On Transmission	**140°C**	**Up to 10Grms**	**Harsh**
At the engine (intake manifold)	**125°C**	**Up to 10Grms**	**Harsh**
Underhood (near engine)	**120°C**	**3 – 5 Grms**	**Harsh**
Underhood (remote location)	**105°C**	**3 – 5 Grms**	**Harsh**
Exterior	**70°C**	**3 – 5 Grms**	**Harsh**
Passenger Compartment	**70-80°C**	**3 – 5 Grms**	**Benign**

Table 1 – Automotive Temperature Extremes

The method currently used in controller modules is to attach the circuit board to a heat sink to transfer heat away from the components by way of conduction. Then through either forced or natural convection, the heat is transferred to the air. With any automotive electronic, protecting the components of a circuit board from the surrounding environment is essential and often requires complicated fixtures in order to do this, especially in transmission and engine controllers. Plastic or metal fixtures are often designed to attach directly onto the transmission or engine with these fixture designs often attaching a circuit board using screws or adhesives to the fixture in which the fixture acts as a heat sink. The circuit board is then protected from the environment with a plastic covering that is screwed down onto a rubber gasket to create a water tight seal. A ballistic gel is often injected into the remaining area above the circuit board and below the plastic cover to further protect the components from the environment and also to aid in vibration dampening. A general design of this module is seen in Figure 1 [1]. The problems with this design are that the module is often large in size, weight and cost.

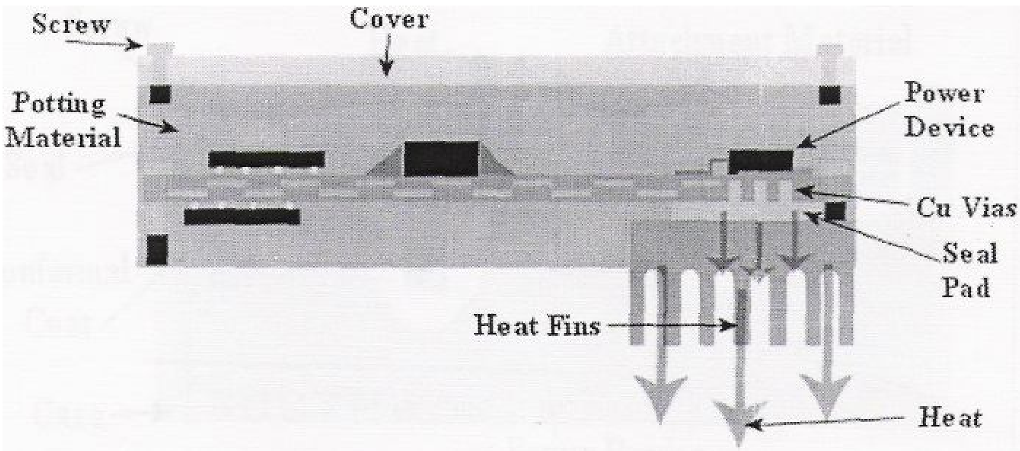


Figure 1 – Controller Module Design with Potting Material

The second generation of controller modules uses a form of overmold but still relies on a case to ultimately protect the circuit board from the elements. The circuit board is bonded to a metal backplane and then a conformal coating or potting is applied to the top of the circuit board. Then the case is attached to the metal backplane to create a water tight seal, as seen in Figure 2 [1]. This allowed for decreasing overall size and weight of the module, decreased the number of steps in the assembly process, and decreases the overall cost. This improvement in cost and assembly lead to the next phase of improvement, and thus the idea of overmolded circuit boards that would eliminate the need for an outer casing was born.

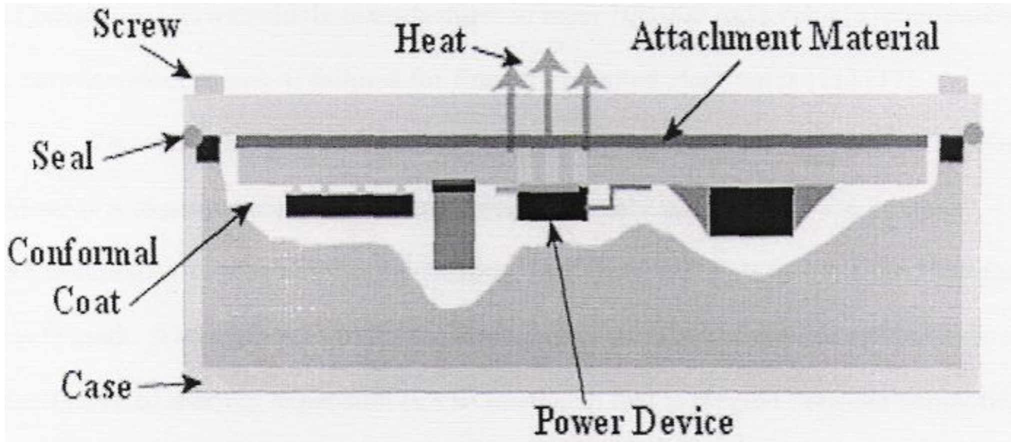


Figure 2 – Controller Module Design with Conformal Coat, Rubber Seal, and Case

The next generation of these controllers is to take a circuit board bonded to a metal backplane and completely overmold it with certain types of materials. As seen in Figure 3, the overmold materials would bond to the substrate material and the components protecting the components from the environment, dampen or eliminate vibrations on the components, and both the overmold and metal backplane would act as heat sinks. The overmolded unit would then be directly mounted to a fixture or even directly mounted onto or in the transmission or engine. Research performed in the area of overmolded circuit boards is nearly non existent, and there is currently no published research done for harsh environment applications.

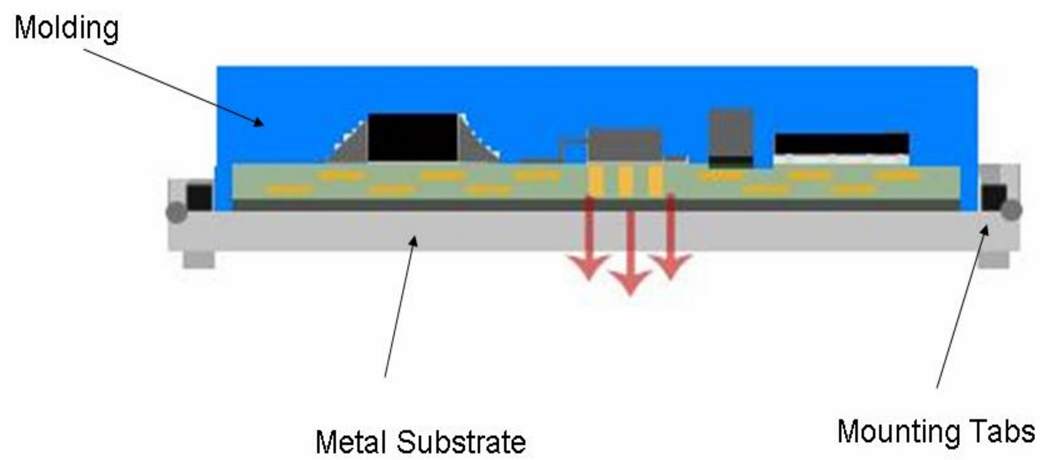


Figure 3 – Overmolded Module Design

This research will look into this next generation of overmolded controllers to answer questions on overmold material types, manufacturing processes, and circuit board quality and reliability issues in harsh environment applications. These answers will create the first step in getting overmolded units from an idea to being used in automotive applications throughout the vehicle, and these answers will be provided by The Center for Advanced Vehicle Electronics (CAVE) of Auburn University. CAVE was formed to work directly with industry to perform research focusing on developing new technologies for packaging, ,materials, and manufacturing of electronics. Research done within CAVE mainly focuses on harsh environment and reliability requirements of the automobile industry.

The main focus of this research will be to investigate the interactions of the overmold materials with the substrate materials and components and the affect of the overmold materials on component and board reliability. To understand why this overmold concept and the test vehicle have come progressed to their current form, past research and testing will be discussed for a better understanding.

Previous research has been performed on the reliability enhancement of FR4-06 fiberglass epoxy laminate substrate circuit boards bonded to metal backplanes [1, 2]. Those works concluded that the metal backplanes acted as a significant heat sink improving thermal performance. However, the backplane attachment increases the overall CTE for the substrate thus decreasing the reliability of the components. The knowledge gained from the increase in thermal performance due to the metal backplane was the first step in creating the test vehicle for this study.

Other research in the area of overmold materials has been done in the area of wire bonding and ball grid array packages (BGAs). Plastic Ball Grid Array (PBGA) packages are usually made with wire bonded interconnects between a silicon die and a fiberglass epoxy laminate substrate. The wire bonds and substrate are then overmolded with an epoxy material, as seen in the Figure 4 [7]. Several areas have research have been performed to determine which overmold materials provide thermal stability, are flame retardant, and provide protection from mechanical damage. Epoxy resin based overmold materials have been deemed as the standard for these types of packages due to their superlative performance in the fore mentioned areas.

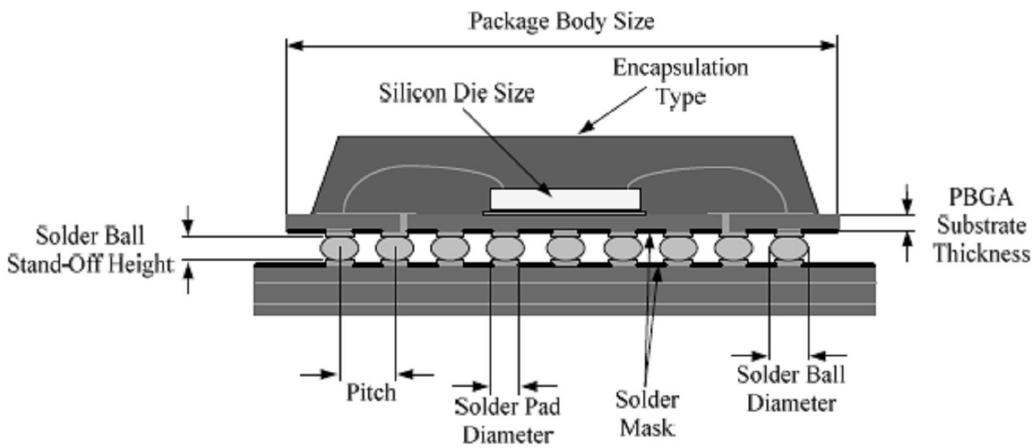


Figure 4 – PBGA Cross Section – Altered Design Parameters

Epoxy protection has been applied to surface mounted components on PC boards in the areas of glob topping and under filling. Studies of underfilling components to determine reliability impact has been performed with the results showing an increase in reliability when dealing with leadless and area array packages such as ball grid array packages and quad flatplacks no-lead packages (QFNs) [8]. This gave rise to glob topping non-area array packages such as resistors and capacitors. Reliability of these components also showed an increase. The underfill materials and glob top materials have been shown to reduce the stress on the solder joints caused by differences in CTE. The materials also aid in vibration dampening, create compressive forces on the solder joints, and protect the components from the environment, even temporarily if the material is not designed to do so.

The overmold concept brings all these advances in electronic component reliability to create the next generation electronic circuit board technology. The theory behind this concept is that all three of these concepts should complement each other to further increase component reliability past the limits of each separate method. Thus, the overmold concept was conceived and the test vehicle design generated.

For this study a test vehicle (TV4 REV 1) was designed and built to investigate the reliability of two different components and two board design issues, which will be discussed in a later chapter in greater detail. The substrate materials used are FR4-06 fiberglass epoxy laminate and a flexible polyimide material called FLEX. FLEX is thinner than most rigid substrates but is designed with exceptional flexing capabilities without board failure. The boards have both SnPb and ImAg plating material with Kester EP256 (Sn63/Pb37) solder paste. An aluminum backplane is attached to the substrates using pressure sensitive attachment material (PSA), which will be discussed in detail later. The circuit boards with aluminum backplane attached will then be overmolded using three different epoxy materials and two thermoplastic polyamide materials which we have named “Hot Melt” materials. The test vehicles will then be subjected to accelerated life testing (ALT) in the form of thermal cycling. Acceptability requirements for the test vehicles are the survival of at least 1000 thermal cycles (-40^{o}C to 140^{o}C) with no failures, which is the requirement for megatronic controllers in under-the-hood applications.

This study hopes to validate the concept of circuit board overmolding by looking at reliability data of the components, the overflow and underfill properties of the overmold materials, and the interactions of the overmold materials to the board design components as well. This will be the front runner for future testing in this area which could lead into applications in other areas of the harsh environment electronics market.

CHAPTER 2: LITERATURE REVIEW

Access to publications of research of completely overmolded circuit boards is nearly non existent to the public, especially with the substrate being attached to a metal backplane. The research performed in this thesis is considered to be a newly developed concept in the automotive industry, with little to no testing public information. However, there are many publications in the areas of harsh environment automotive electronics testing, metal-backed substrate testing, component reliability, substrate alternatives, and overmold materials. This chapter will include a general overview of the topics listed above along with a discussion of previous research dealing with completely overmolded circuit boards.

2.1 Harsh Environment Automotive Electronics

Before the mid 1970's, automobiles had few electronics other than the radio. Today nearly every aspect of a car has electronic components and sensors controlled by an onboard computer system. Barron and Powers et al. [22] discuss how mechatronics has been introduced into the automobile. The paper looks not only into the technologies that are seen in the different automobile systems, but how societal influences and other factors have led to the electronics age of the automobile industry. Environmental issues and fuel price fluctuation were the two main causes for the use of electronic technology. The new requirements that came from these two issues caused the automotive industry to look into new ways of controlling the engine. Thus the automotive electronics industry was born. However, the rise in automotive electronic capabilities has followed the increased improvement of microprocessors in both computing power and size. Continuing improvements in microprocessors and decrease in price has increased the number of applications of electronics within the vehicle. Figure 5 shows this growth of the different electronics within the vehicle. Barron and Powers also discuss the introduction of electronic controllers within the power train. This introduction has increased the performance of the engine but also adds diagnosis capabilities of the different systems. Safety systems, alternative fuel systems, and other applications of electronics being implemented are discussed.

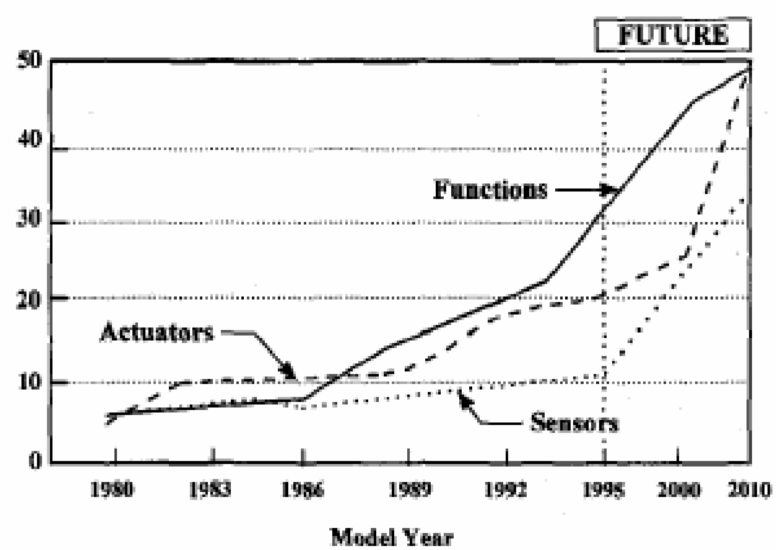


Figure 5 – Growth in Engine Control Functions, Actuators, and Sensors

Kobe et al. [24] discusses how the electronics market has grown and where the future of this market is heading. The article discusses how the automotive market has turned dramatically towards an electronic architecture which will allow for an increase in content into the vehicle and greater flexibility for advances in technology. Increases in demands of consumers' requires an increase in processing power rates, which calls for robust electronic systems in order to provide the needed quality and reliability. Given this, Kobe looks into the convergence of a 42-volt system to provide the power required for the increasing number of electronics in the automobile.

Studies have been performed looking into the different harsh environments for new electronic systems was performed by Johnson et al. [5], Sharp et al. [18], and in the technical article provided by STMicroelectronics [13]. These studies discuss the industry standards for harsh environment electronics and the new technologies seen in providing electronics in these environments. Also, mechatronics and more specifically controller modules and the improvements in this area are discussed along with the challenges of electronics and electronic packaging in these harsh environments. From these studies it is discussed that the use of control modules near their functional component limits the number and length of high-end wiring needed to avoid interference effects in under hood applications. The effects of high temperatures of semiconductors is discussed in STMicroelectronics' technical article which shows that at elevated temperatures semiconductors' electrical properties degrade which results in leakage current. Leakage current is the phenomenon when electrons move easier from the valence band to the conduction band at high temperatures. One suggestion in these papers is to continue the use of electronic assembly advances such as underfill and glob top to use new electronic packages in harsh environment automotive electronics. This has spawned the idea of overmolded control modules in harsh environment applications.

2.2 Metal-Backed Substrate Reliability Testing

Studies done on the effects of metal backed substrates on component reliability were done by Evans et al. [3], Islam et al. [12], Crain et al. [2] and Davis et al. [1]. Crain and Evans looked at determining the best combination of adhesive, backplane metal and component encapsulation material that would be robust enough for use in harsh environment automotive electronics while still meeting reliability, thermal and cost requirements. Aluminum and beryllium copper backplanes connected to FR4 substrates with three different adhesives and 6 different encapsulation materials were tested. Figure 6 shows a Weibull plot of SSA and PSA attachment material on FR4 substrate with aluminum backing under thermal shock cycling. It shows that the aluminum backplane with PSA adhesive and a certain encapsulation material is the best choice due to its reliability increase over SSA, but it was also chosen due to its cheap cost and reliability. This study did prove that the overall component reliability on metal backed substrates is decreased compared to non-metal backed substrates, which is shown in Figure 6 [2].

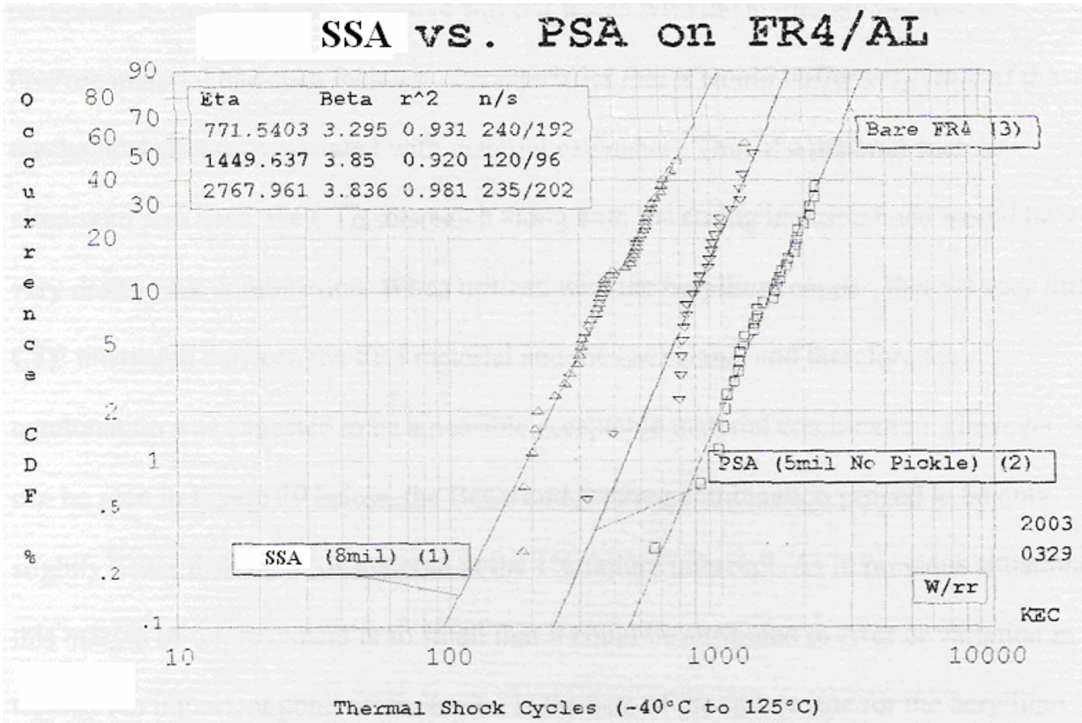


Figure 6 – Weibull Plot of 2512 Resistor With and Without Backplane [2].

Davis continued this work with a look into the reliability of active and passive components on a metal backed substrate. The test used an FR4 substrate attached to an aluminum backplane using pressure sensitive attachment (PSA) material with three passive and six active components using both an electroless nickel immersion gold (ENIG) pad platting or a hot air solder level (HASL) solder. Results were consistent with Crain's testing showing that component reliability is decreased but that some of the components tested meet the requirements for harsh automotive environments (1500 cycles with less than 1% failure). This study also looked into the reliability differences between ENIG and HASL platings used on the boards. Components with ENIG platting showed an overall decrease in reliability compared to the HASL. This study also looked into the reliability affects of placing components on metal backed boards or placing populated boards onto metal backplanes. Results showed normal reflow profiles for non-metal backed boards could not be used due to the metal backplane causing a high rate of temperature conduction away from the components during the cool down phase. Further work showed that metal backplanes would change the assembly process slightly, creating yet another obstacle for manufacturers. Islam et al. [12] furthers these studies with a more in depth look into the failure mechanisms of components on metal back substrates. His findings further exemplify the results of the previous studies using more advanced techniques of analysis.

2.3 Component and Substrate Information

For harsh environment applications in the automotive industry, FR4 substrate is already a standard substrate used in numerous applications especially when metal backplanes are needed. 2512 ceramic resistors have been used in many tests within CAVE as an overall reliability measurement device due to its poor performance in harsh environment testing and extensive test data. Therefore, studies of FR4 substrate material and 2512 components were not deemed necessary to discuss. However, the flexible polyimide substrate or FLEX is used in many applications, and it is making its way into harsh environment applications. Along with substrates, different components are being tested for use in these settings as well. Flip Chip packages are starting to be implemented into harsh environment electronics due to its great qualities. Research looking into the two later topics will be discussed in this section.

2.3.1 Flexible Polyimide Substrate

Bergstresser et al. [20] looks into flexible polyimide substrates for high performance applications to be used for high-density printed circuit (PC) boards. This substrate technology is already used in the production of chip scale packages, flexible circuits, and rigid-flex boards. Reasoning behind using this substrate in these applications is because polyimide is a high performance polymer which has many sought-after properties for automotive electronics. Polyimide substrates have great thermal stability and a CTE close to copper over a wide temperature range. They have great thermal conductivity which makes it very appealing when superior heat dissipation is required in an application. They also have high strength, high modulus, low dielectric constant, low dissipation factor, and have good dielectric strength. Along with these great qualities that would benefit the electrical interconnect reliability, polyimide substrates are also able to withstand harsh chemical environments which are seen in circuit board processing. In short, polyimide substrates demonstrate good thermal, mechanical, chemical and electrical properties for harsh environment PC board use.

2.3.2 Flip Chip Package

Riley et al. [26] gives an overall description of flip chip packages along with a list of advantages. Flip Chip packages consist of a die with solder balls or bumps attaching the pads of the board and the pads of the die, just like a BGA package. In a BGA package, the die pads are facing up and then wire bonds connect the die pads to the substrate pads, as seen in Figure 7. In Flip Chip packages, the die is placed with the pads facing down, hence “flipped”, with solder balls or bumps connected the die pads and the

PC board pads, as seen in Figure 8. Since the distance from the two pads is shortened dramatically by a factor of 100, the electrical performance is increased from that of a BGA. Also, wire bond pads are limited to the perimeter of the die, thus setting a limit on the number of pads per die size before running into problems with wire size and pad size and pitch. Flip Chips allow for the use of the entire die's area which provides a larger number of input/output (I/O) connections per die size. Flip Chip packages are often times the lowest cost package and offer many advantages in automotive applications. However, as Riley points out, Flip Chips have to be underfilled with an adhesive or epoxy in order to become reliable enough for harsh environments which adds a process in manufacturing.

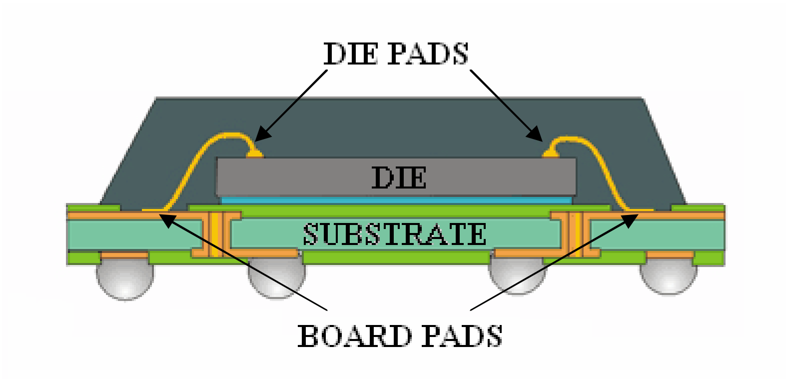


Figure 7 – Ball Grid Array Package

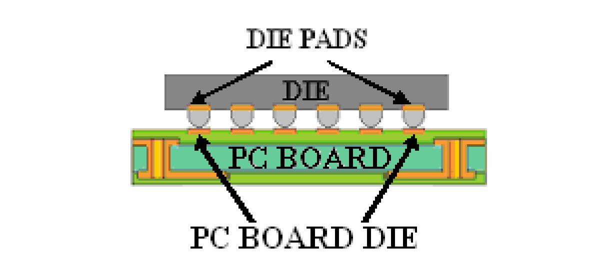


Figure 8 – Flip Chip Package

Braun et al. [27] [28] and Ding et al. [14] look into increasing the reliability of Flip Chip packages for high temperature applications by use of underfill encapsulates. The studies look at different underfill materials and how they interact with flip chip packages through thermal cycle testing on FR4 substrates. The study had test boards in an air-to-air chamber with temperatures from -55^{o}C to 150^{o}C and 175^{o}C. The results show that during thermal cycling, mismatches in CTE cause warpage to the package which causes stresses on the underfill's interface with the package and the package's interface with the solder balls. An illustration of these stresses is seen in Figure 9. The properties of the underfill materials change, more importantly the CTE increases when the temperatures start to reach the glass transition temperature (T_g). These changes in material properties cause failures in two different ways. Added thermal effects form intermetallics in the solder joints causing embrittlement and embrittlement of the underfill materials which causes weakening of the interconnections between the solder joints and package. Thermo-mechanical effects cause delamination of the underfill materials and further solder joint fatigue.

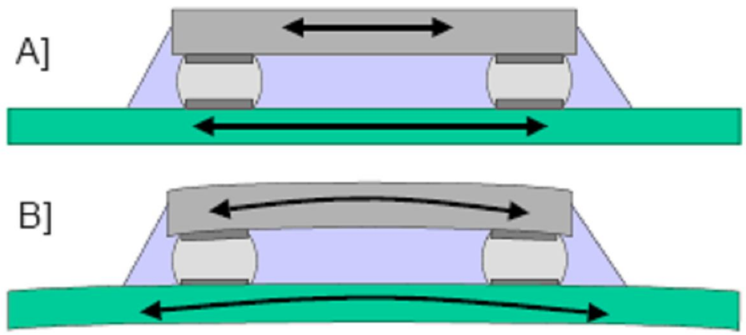


Figure 9 – Illustration of the effect of thermal mismatch of a Flip Chip package. A] shows the Flip Chip at room temperature without deformation; B] shows the warped Flip Chip at elevated temperatures.

The results from this test show that the adhesion properties of the underfill materials greatly affect the reliability of the packages. Complete adhesion to the package, solder balls, and PC board by the underfill material is needed in order to prevent delaminations or voids under the package which is one of the main causes for failures. Higher temperatures lead to increased delamination areas which also lead to higher thermal mismatches causing cracks in the solder balls. These delamination areas are generally seen where the highest stresses are seen, usually at the die corners. It was also reported that voids at solder balls causes a phenomenon where solder extrudes out into the voids due to thermal loads during thermal cycling. A diagram of how voids are created is seen in Figure 10. Also, the underfill materials CTE mismatch causes higher stresses in the z-direction than in non-underfilled applications adding to failure mechanisms on the solder joints. This work clearly shows that underfills increase the reliability of Flip Chip packages on FR4 substrates so that they can be used in harsh environment automotive applications.

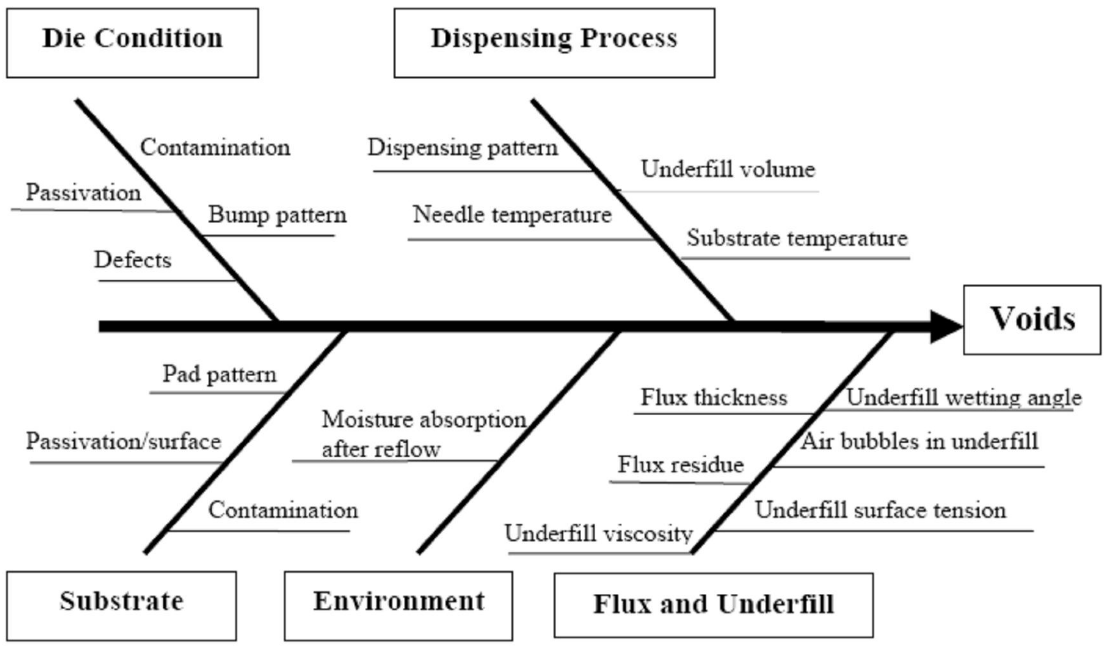


Figure 10 – Fishbone Diagram for Underfill Voids.

Babiarz et al. [17] also looks into the underfilling of Flip Chip packages and how it increases the overall reliability over non-underfilled packages. Board deflection being a key stress on components during thermal cycling is discussed, and an illustration of this is seen in Figure 11. The paper discusses how the underfill materials increase overall reliability and also looks into the dispensing techniques for underfills. Babiarz et al. [30] also discusses the process of underfilling Flip Chip packages in manufacturing in great detail which gives some insight on the extensiveness of the Flip Chip assembly process.

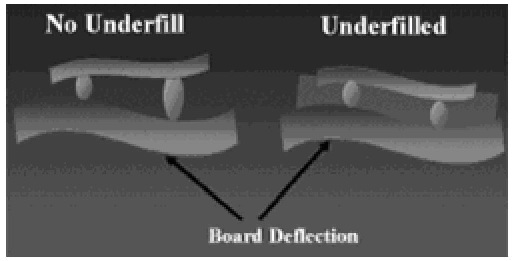


Figure 11 – Board Deflection Effect on Bump Strain.

Wong [29] in his article discusses the history of flip chip technology and also some of the negatives of flip chip technology. Flip Chip packages cannot be used without an underfill due to reliability issues. Other issues include the addition of the underfill process which also includes a curing process during manufacturing. An illustration of the underfilling process is shown in Figure 12.

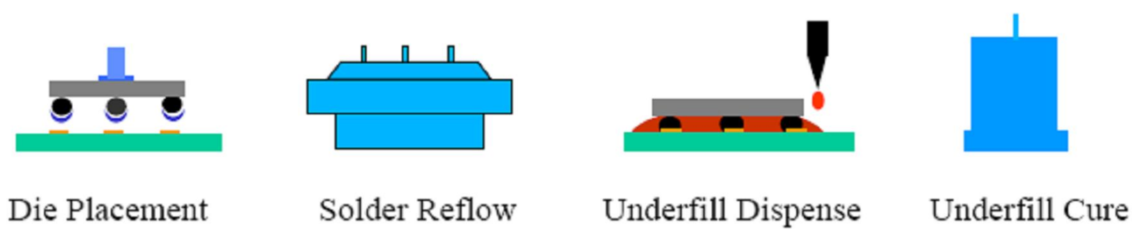


Figure 12 – Capillary Underfill Process Flow.

Schaefer [8] comprises testing and modeling of different underfill materials and characterizes the properties best suited for high reliability for multiple types of CSP and BGA packages, which are also a form of Flip Chip. Results showed that epoxy resins are the most suited for this application. Underfill materials with a low CTE or a CTE close to the substrate and solder's CTE, a reasonable or medium Elastic Modulus, and have good adhesion properties, increase the reliability of a broad range of components. These material properties usually yield a material with excellent sheer strength and good chemical resistance. The simulations performed of the underfill materials showed that hard underfill materials increase the overall reliability of the components by evenly distributing the stresses on the solder joints, however these tend to crack the chip and have higher delamination flaws. With stiffer underfill materials, the study recommends that the CTE and Elastic Modulus of the underfill material and the PC board substrate should be approximately the same. This creates a uniform mold around the solder joint which reduces the stresses on the solder joints. Soft underfill materials should have a CTE close to the solder being used so the compressive and tensile forces on the package are minimized during thermal cycling. This study also shows that cracks in the solder balls with stiffer underfill materials are usually seen where the PC board and the solder joints meet. Compressive forces in the solder joint and tensile stresses in the underfill material propagate cracks in the solder joint at the fore mentioned interactive point. Cracks in the underfill material due to the fore mentioned stresses at these areas also allow for solder penetration into the underfill material which can cause short circuits.

2.4 Overmold Material Research

Future testing with overmolded PC boards by CAVE, which will be discussed in a later chapter, will include wire bonded chip on board packages which will then be overmolded. Looking into overmold compounds used in electronic component packages, Gallo et al. [6] looks into different flame retardant molding compounds for high temperature applications for use in the automotive industry. The work looks into materials that will increase component reliability, especially plastic packages, up to a goal of 20,000 hours at 200^{o}C which is equivalent to 15 years and 900,000 miles for a truck. Testing was performed looking at different combinations of wire types, pad doping, and overmold materials. Results show that using metal oxides as flame retardants in overmolding compounds increases the overall reliability substantially over other molding materials when using Au wires, Al pads, and a metallic pad barrier. However, the reliability of wire bonded components is mostly dependent on the degradation rate of the Au/Al bond. These overmold materials are seen as the new future in overmold materials which could replace epoxy materials as the standard in the automotive industry.

Braun et al. [31] looks at the reliability of epoxy overmold materials when in interaction with “aggressive” fluids found in a car, such as transmission and brake fluids. Six different epoxy molding compounds were studied and analyzed before and after undergoing testing in the various substances. The paper also discusses the general makeup of epoxy compounds used. Most epoxies used in the automotive industry already have the epoxy resin and hardener already mixed with other additives added to increase overall performance. To increase T_g and decrease the CTE, SiO_2 is added. Adhesion promoters, colors, flame retardants, catalysts, and others are also added according to the specifications of the epoxy needed. The epoxies were chosen from standard materials used in encapsulation of BGAs, QFPs, and other packages of this nature. The results show that epoxy molding compounds are robust and the properties of the materials do not change drastically when in use in harsh environment conditions.

CHAPTER 3: APPLICATION

Automotive electronics are continuing to follow the trend of making smaller, lighter, more cost efficient, and with the ability to be placed in harsh environments. Current electronic designs due to reliability issues are placed within the passenger's compartment which requires long and often bulky wires and connectors. Because of wiring and weight, powertrain electronics have traditionally been placed under-the-hood near or on the engine, transmission, transfer case, and other places where high heat and other harsh environmental conditions are seen. Many of the places where these controllers are being placed have very little air flow for convection which requires PC board and controller module designs to maximize heat transfer using conduction. With requirements of greater content and higher power output on a smaller surface area increasing every day, this puts a larger strain on the PC board design to remain reliable in harsh environment applications.

Two applications are being looked at to use overmolding technology to redesign controller modules by Continental International. The first is their Transfer Case Control Unit (TCU) as seen in Figure 13 and the second is their Transmission Control Module (TCM) as shown by the illustration in Figure 17. (Note that any mention of Continental International in this publication is a specific reference to Continental International Automotive Electronics Division in Huntsville Alabama, and in no way is anything within this document to be construed as the opinion of Continental International or any of its subsidiaries.)

As the increase in the use of electronics in controlling critical systems within the engine, wires, wiring harnesses, sensors, actuators, and controller modules increased throughout the engine compartment. Nearly all of the early control modules were located in the passenger compartment due to the favorable environmental conditions on the electronic components and were connected to the various mechanical systems through lengthy wires and unreliable connectors. As harsh environment PC board and electronics technology advanced, many of these controller modules were placed within the engine compartment and even on or in the mechanical systems. Problems of cost and reliability have hindered this trend and have automotive manufacturers looking towards other alternatives.

Figure 13 – Continental Transfer Case Assembled Controller Module

Currently, the TCU is located under the dash board in the passenger compartment of the vehicle and is connected to sensors in and on the transfer case. The PC board, as seen in Figure 14, for the TCU uses only surface mount components with the exception of the connector which uses through-hole pins. The components used in this design include 20mm BGAs, various sized small outline transistors (SOTs), various sized quad flat packs (QFPs), transformers, transistors, and various sized ceramic chip resistors and capacitors. The board design also has components on both sides of the board requiring a double sided reflow which adds another step in the manufacturing process. Double sided reflow requires either another pass through the reflow oven or another reflow oven, thus increasing capital costs for the extra oven. In turn, this design increases the throughput of the controller module in the manufacturing process due to the double sided reflow. A clear conformal coat is also sprayed onto both sides of the PC board after component assembly which protects the components and the substrate surface from moisture. This adds yet another assembly process, calls for more capitol costs for an applicator machine to apply the conformal coat, and the cost of the conformal coat material.

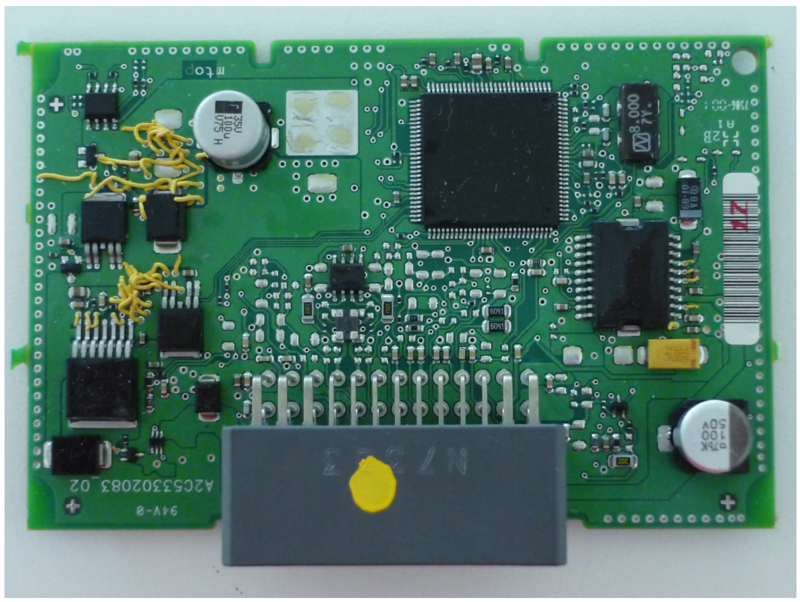


Figure 14 - Continental Transfer Case Controller Module PC Board

The PC board is attached to an aluminum backing using a thermal paste as seen in Figure 15 and Figure 16 below. The aluminum back plate has two ridges that are designed to attach to the back of the PC board where the most heat is generated. The thermal paste is applied at these ridges which connects the PC board to the aluminum back plate as well as aiding in heat dissipation. The PC board measures 108mm x 72mm x 1.75mm and aluminum back plate measures 114.25mm x 72.5mm x 1.6mm. A plastic housing is connected to the aluminum back plate using clips designed into the housing which is for protection from the environment. The completely assembled module measures 120mm x 78.5mm x 23.5mm and weighs approximately 1 lb.

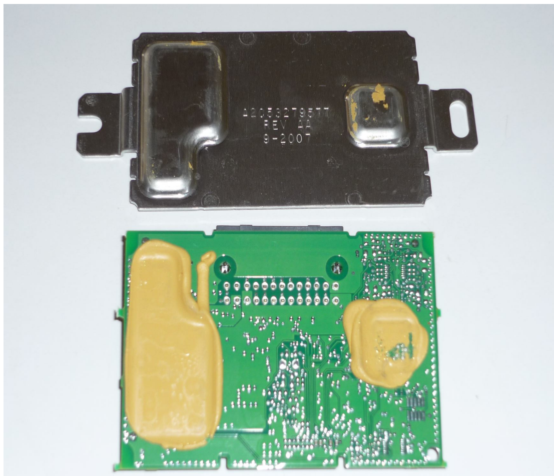


Figure 15 - Continental Transfer Case Controller Module Showing Thermal Adhesive Used to Attach PC Board to Aluminum Back Plane

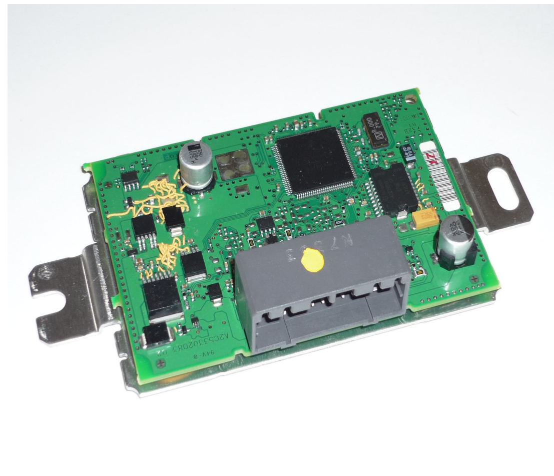


Figure 16 - Continental Transfer Case Controller Module PC Board Attached to Aluminum Metal Back Plane

The future of the TCU is to attach the PC board to a metal back plate and completely overmold the assembly using an overmold material reliable enough for harsh environment applications. The module could then be placed either closer or on the transfer case which would eliminate bulky wires and connectors inside the passenger compartment. Overmolding would eliminate the need of the plastic cover, the thermal adhesive, and the clear conformal coat thus eliminating parts, assembly machines, and assembly processes thus reducing costs. This would also eliminate the problem Continental is seeing of the plastic cover coming off in the field which introduces the PC board to the passenger compartment environment. Also, instead of using a separate connector, overmolding would be used to create the connector using the overmolding material which would eliminate the interconnection between the connector and the overmold, thus theoretically increasing connector reliability. However, using overmolding in this application is seen more of a business edge than a technology edge within the TCU market.

Another application of overmolding being used to increase reliability while decreasing costs is with Continental's Transmission Controller Module, as seen in Figure 17 below. This module connects directly to the side of the transmission and consists of a ceramic PC board which is connected by an adhesive to the bracket plate of the transmission controller module assembly. The PC board is then sealed from the environment by the use of a rubber seal and a cover which screws into the bracket plate creating a water tight seal. Area between the inside of the cover and the PC board is then filled with a silicon ballistic gel to further protect the PC board from the environment as well as aiding in vibration dampening on the components. This design only allows for direct conduction heat transfer from the PC board to the bracket plate, while the ballistic gel does offer minimal heat transfer capabilities. Also, the rubber seal creates a reliability hazard if the seal ever were to fail in the field. Theoretically, the reliability of the electrical components is greatly linked to the life of the rubber seal.

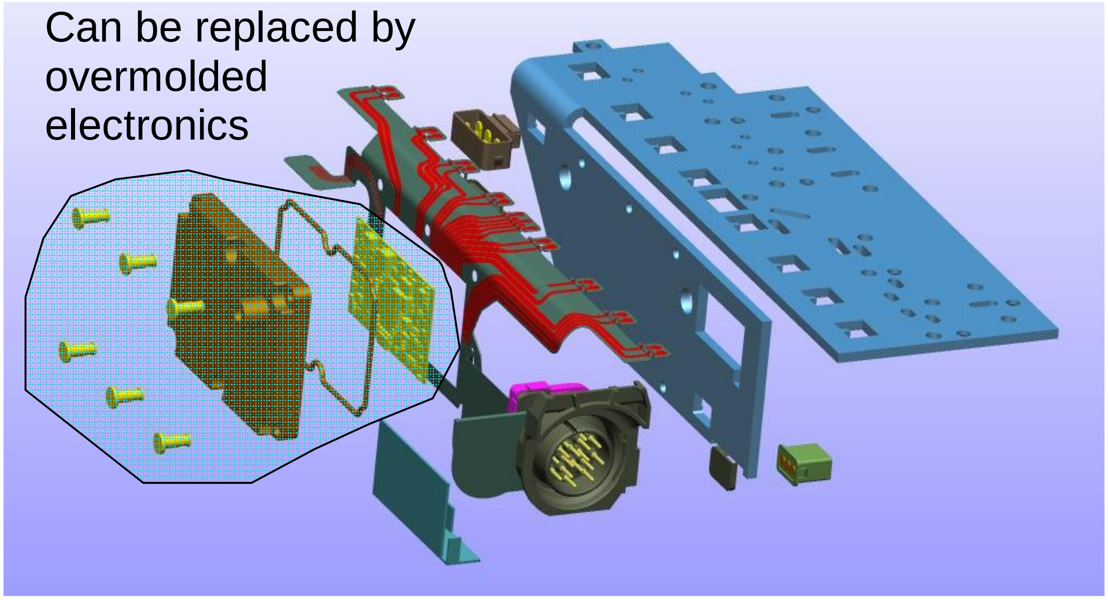


Figure 17 – Transmission Controller Module Assembly

The goal of using overmolding in this application is to replace the cover, screws, rubber seal, and PC board with a completely overmolded PC board on a cheaper substrate which would reduce costs by eliminating the cover and rubber seal. Also, the overmolding would also greatly reduce vibrations on the components while protecting them from the harsh environment. The reliability of the components would then not rely on the life of other outside components. Also, the overmolding would provide greater vibration dampening and conduction properties which would increase the life of the components and thus the transmission controller module.

CHAPTER 4: RESEARCH METHODOLOGY

The overmolding project was designed to better understand the reaction between overmolding materials and PC boards attached to an aluminum metal back plane in harsh environment applications. The testing will provide answers in how the overmolding materials flow under and over the parts. Also, this test will look at the adhesion properties of the overmolding materials through thermal cycling. The TV4 REV 1 test vehicle was designed using previous testing knowledge of connecting substrates on aluminum backing with PSA adhesive. The test will have FLEX and FR4 substrates attached to aluminum back planes with various overmolding materials used. The overmolding materials used are three epoxy materials and two thermoplastic polyamide, or "Hot Melt", materials. The results will give manufacturers a better understanding of the reliability increase of using overmolded PC boards and which overmold materials provide the greatest reliability. Testing of the overmold materials will be done in order to best understand the material properties of the overmold materials that provide the best reliability.

The test vehicle TV4 REV 1 was created to imitate an actual PC board which would be built in actual production lines and used in the automotive field. The test vehicle was designed for strictly testing purposes and will undergo laboratory testing which will best mimic real production unit harsh environment conditions. This test strictly places the test vehicles in air-to-air thermal cycling which bests imitates the thermal cycling effects seen on electronics in the under-the-hood environment of an automobile.

4.1 Test Board Design

The TV4 REV 1 test vehicle was used on two substrate materials, FR4 laminate PC board and flexible polyimide FLEX PC board. The dimensions of the substrates were chosen to be 88.95mm x 69.88 mm with the aluminum back plane dimension of 93.87mm x 74.85mm x 2.50mm. This board size was chosen by Henkel Corporation as a comfortable size for overmolding. The FR4 substrate is 0.70mm thick and the FLEX substrate is 0.30mm. The FR4 substrates have SnPb lead plating and the FLEX substrate has both SnPb and ImAg plating. The aluminum back plane was attached to the PC boards with PSA material. The component solder pads were solder masked defined with the copper traces located within the layers of the PC board.

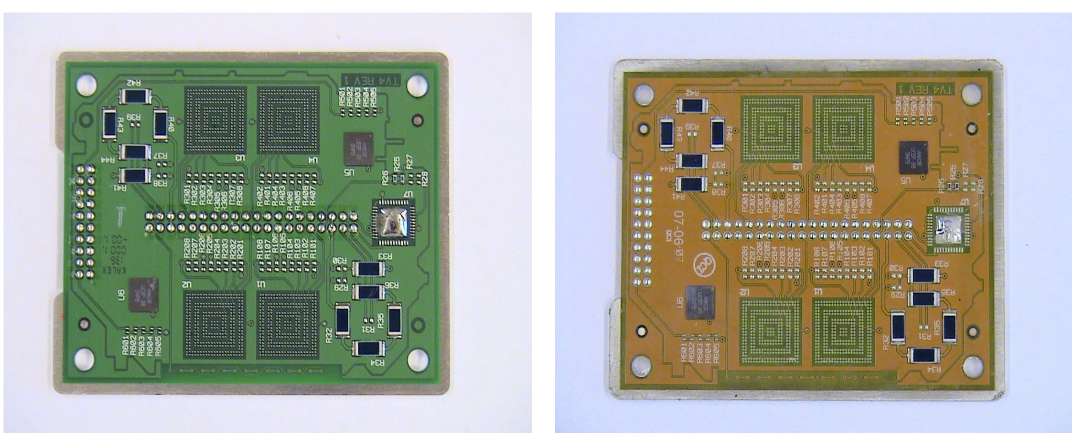


Figure 18 - Picture of populated FR4 and FLEX substrates on Aluminum back plane.

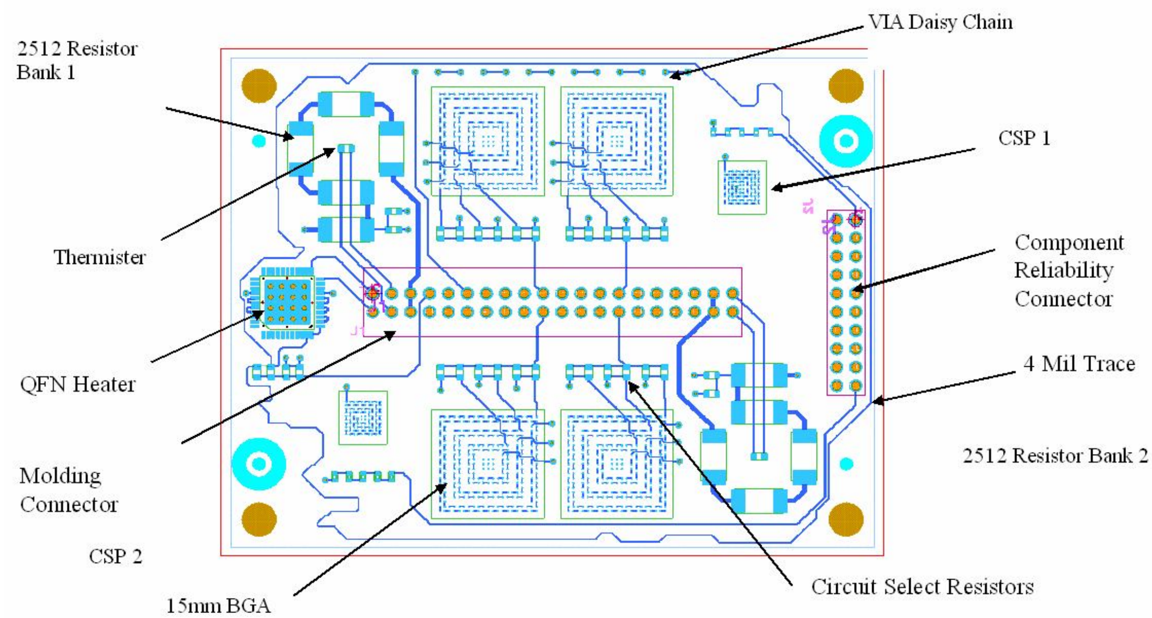


Figure 19 - Layout of TV4 REV 1

Each board has a common ground that is connected to each of the components and a trace connects them to through-hole wiring connections located both in the center of the board and on the side for electronic monitoring. One set of through-hole wiring connections is found in the center of the test board which was originally designed to have a through-hole connector molded as well and used for electronic monitoring. Since the test focus was to look at the reliability of the components and not the reliability of a connector, as the connector was not included in the building of this test vehicle. Furthermore, connectors often fail earlier than the electronic components in harsh environment applications. Functional traces are located on both the top and bottom of the substrate to mimic production units. Figure 18 above shows a picture of a populated PC board on aluminum with both FR4 and FLEX substrates attached which is how the boards were sent to Henkel Corporation to be overmolded. Figure 19 above shows the layout of the TV4 REV 1 traces, component pads, and component locations. Table 2 below shows the combinations of the substrate, plating, hot melt or epoxy, and thermal cycle testing temperatures combinations for the test boards used in this testing. Table 3 below shows the complete test matrix placed in thermal cycle testing.

Design	Board	Plating	Test
Hot Melt 1	FR4/Al	SnPb	-40C to +125C
Hot Melt 1	FLEX/Al	SnPb	-40C to +125C
Hot Melt 2	FR4/Al	SnPb	-40C to +125C
Hot Melt 2	FLEX/Al	ImAg	-40C to +125C
Epoxy 3	FR4/Al	SnPb	-40C to +125C & +150C
Epoxy 1	FR4/Al	SnPb	-40C to +125C & +150C
Epoxy 2	FLEX/Al	SnPb	-40C to +125C & +150C
Epoxy 1	Flex/AL	ImAg	-40C to +125C & +150C

Table 2 - Combinations of TV4 REV 1 Test Boards

Material	Board Type	No Primer in -40 - 125°C Thermal Cycling	Primer in -40 - 125°C Thermal Cycling	No Primer in -40 - 150°C Thermal Cycling
Hot Melt 1	FR4	14	0	0
Hot Melt 1	FLEX	8	0	0
Hot Melt 2	FR4	13	0	0
Hot Melt 2	FLEX	9	0	0
Epoxy 1	FR4	4	5	4
Epoxy 1	Flex	5	0	4
Epoxy 2	Flex	3	0	4
Epoxy 3	FR4	5	4	5

Table 3 - Number of TV4 REV 1 Test Board Combinations

The test vehicles were designed using solely surface mount components, specifically testing 2512 ceramic resistors and 7mm CSPs. Two other board design components were also monitored. The first is a four millimeter copper trace which runs around the perimeter of the PC board on the top layer of the substrate. The second board design component is a Through-Hole 0.25mm Diameter VIA Daisy Chain which runs along on side of the perimeter of the PC board. These were added to ensure the molding material does not crack small traces or vias. Table 4 gives the specifics of the surface mount components used on the TV4 REV1 test vehicles and Table 5 shows the number of components placed on each test board. The board was laid out for symmetry so board location would not be a factor with component reliability and the entire board surface was utilized to mimic a production unit.

Component Type	Body Size	Termination	Lead Count	Pitch	Solder Ball Layout	Pad Size
2512 Ceramic Resistor	6.3mm x 3.2mm x 0.71mm	SnPb	2	N/A	N/A	1.70mm x 3.10mm
CSP	7mm x 7mm x 1.75mm	SnPb	98	0.5mm	Full Array	0.25mm in Diameter

Table 4 - Components on TV4 REV 1

Component Type	Number of Components Per Test Board
2512 Ceramic Resistor	10
CSP	2
4mm Trace	1
VIA Daisy Chain	1

Table 5 – Number of Components per Test Board

The CSPs used in this test are actually large pitch and solder ball Flip Chip packages with a solder bumped silicon die which was then placed on the PC board. Amkor, the manufacture of the CSPs used in this test, calls this package a CSP package so this was the nomenclature given from the beginning of this test. Figure 20 shows an illustration of the CSP used in this test. The CSP package was chosen due to its low reliability expectations in Air-to-Air Thermal Cycle testing, and later analysis will show how the overmolding materials interacted with CSP components. More specifically, analysis will show how the molding material's adhesive properties bond with the CSP silicon die surface and the solder balls.

In non-overmolded or underfilled CSP or Flip Chip applications, the CTE mismatches are absorbed directly by the solder balls which results in failure from thermal fatigue after repeated cycling. Traditionally, solder ball failures occur directly beneath the silicon die corners. This study will determine if the overmolding materials disperses the stresses that would be placed on the solder balls of the CSP with the absence of an underfill/overmold material thus increasing the reliability of the CSP package.

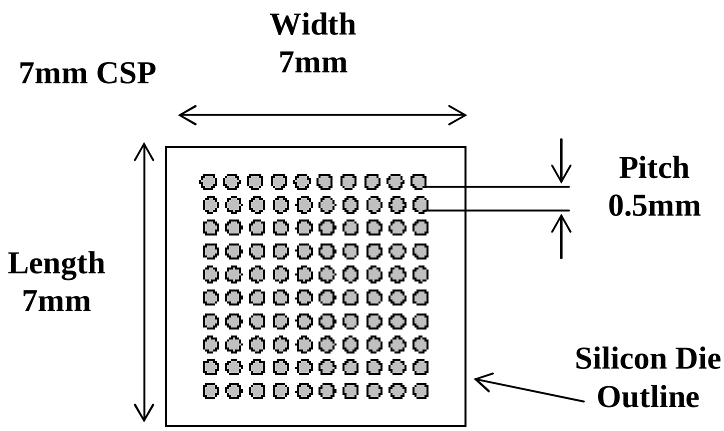


Figure 20 – CSP Illustration

2512 ceramic resistors were also used as a reliability reference due to their poor performance in harsh environment applications and previous harsh environment reliability accelerated life test data. Previous testing showed that 2512 ceramic resistors fail earlier than any other surface mount component when placed on FR4 substrate. Figure 21 and Figure 22 show the dimensions and components of the 2512 ceramic resister used in this test. As mentioned before with the CSP packages, the adhesion and flow properties of the molding materials will also be examined to see if voids were created in the overmolding process either underneath or around the edges of the 2512 resistors. The organization of the resistors into banks of five with four of them creating a square was to mimic the power output of a 16mm BGA when power was applied to the circuit. This design was for another test which looks into the delamination issues of the adhesive used to connect both FLEX and FR4 on aluminum back planes. This adhesive test was not included with the overmold testing and will be discussed in a later chapter.

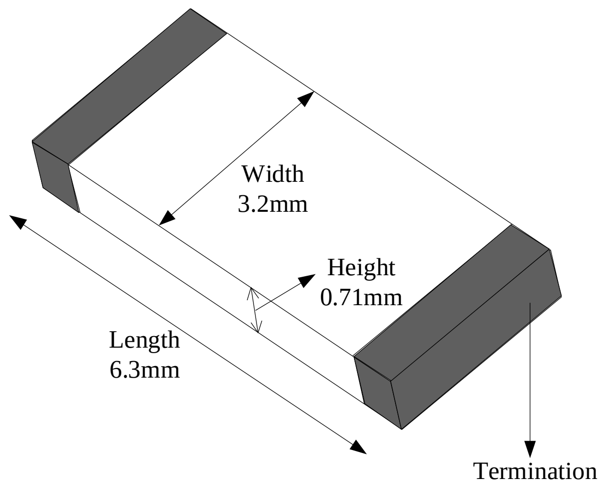


Figure 21 - 2512 Resistor Isometric View

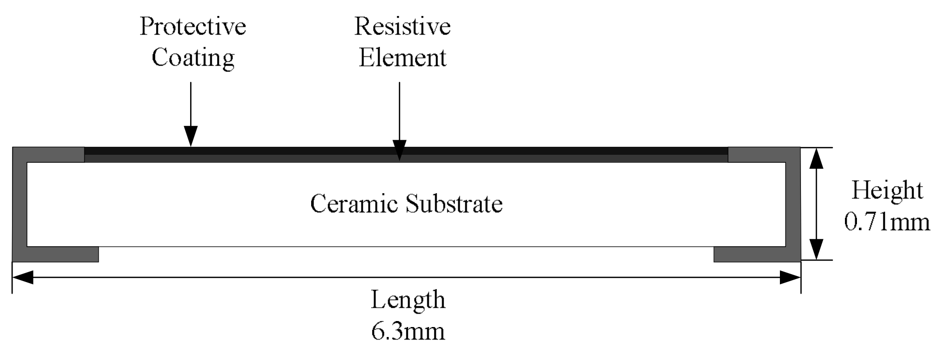


Figure 22 - 2512 Resistor Cross Section

Placing the resistors into banks of five yields more information than testing single resistors, which would increase the number of parts to be monitored significantly thus putting a strain on electronic monitoring equipment capabilities. However, this does yield less information than monitoring each of the five resistor banks separately. Since they are in series, when the first resistor fails it will create an open circuit, thus the ability for the electronic monitoring equipment to monitor the rest of the resistors in the circuit is rendered impossible. The other four resistors have to fail sometime after the first resistor failure, so they become censored data points. These censored data points are then assumed to fail along the same line with the predicted failure distribution. For this test, each board will have two true failure values and eight censored data points for the 2512 resistors. Each CSP was connected to a separate circuit for independent monitoring. However, due to an error in circuit layout within the PC board, the CSPs resistances were not able to be monitored in this test, but cross sections were still done on the packages to examine the overmolding affects on the CSPs during thermal cycle testing.

The theory behind choosing these two components is that solder joint failure is the main failure mechanism which is primarily caused by CTE mismatches. The difference in CTE values of the substrate, solder joints, and component materials cause stresses that create cracks to form in the solder joints of these two components. Also, the CSP package was chosen by Continental to evaluate the possibility of using this package in harsh environment applications with the use of overmolding in the automotive controller market.

As stated previously, placing a substrate on an aluminum back plane does decrease the reliability of components placed on the substrate. This test will determine if using overmolding materials will nullify or equally distribute the stresses caused by the CTE mismatches. Theoretically, the overmolding will distribute the CTE stress forces evenly throughout the PC board and components thus the heat sink back plane would provide adequate heat dissipation without decreasing reliability, which was the original theory behind attaching a metal back plane to a PC board.

4.2 Test Board Manufacturing Process

The TV4 REV 1 test board FR4 substrates were manufactured by Kalex and the FLEX substrates were manufactured by Sheldahl. Both manufacturers placed the substrates on the aluminum back planes before sending the unpopulated boards to Continental. The boards were then plasma cleaned to ensure contaminate free surfaces. The boards were then populated using a MPM Screen Printer, Universal GSM placement machine, and a Rehm Thermal Oven for reflow.

The first step in the fabrication process was to apply the 63Sn-37Pb Kester Easy Profile 256 solder paste onto the PC board using the MPM Screen Printer. Once this was done, the board was then inserted into the Universal GSM placement machine where the components were then placed onto the board. The Universal GSM placement machine picked the electronic components from a matrix tray feeder for the CSPs and a "tape and reel" feeder for the 2512 resistors. The board was then feed into the Rehm Thermal Oven which turns the solder paste to liquid solder and then bakes liquid solder until it turns into solid solder joints. The reflow profile recommended by Kester and used for these test boards is seen in Figure 23. Next, the boards are then inspected for defects before being packaged and sent to Henkel for overmolding. Figure 18 shows FR4 and FLEX substrate populated test boards which were sent to Henkel.

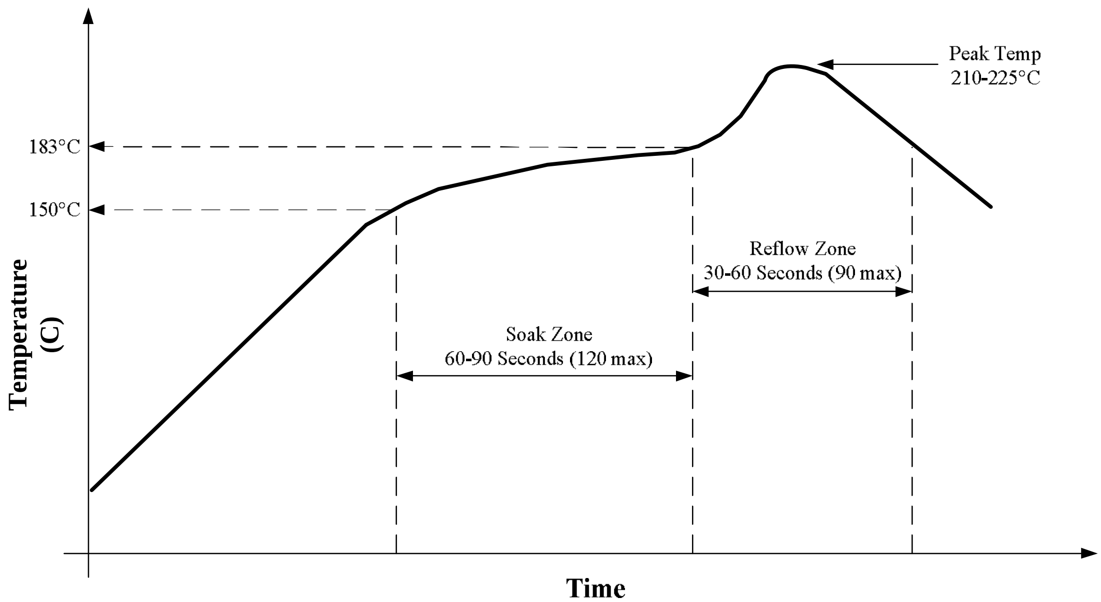


Figure 23 - Kester's Suggested SnPb Reflow Profile

Once Henkel received the test boards, the boards were plasma cleaned again to remove any surface contaminants. Each board was then placed into a designed mold for these test boards and the molding materials were then injected into the mold. This molding technique requires the molding materials to be at a pressurized liquid state. The molding material is then injected under high pressure into the mold. The mold is then cooled so the overmolding materials become a solid. The molding material properties for injecting molding used by Henkel are seen in Table 6 and Table 7. Once all the boards were molded, they were packaged and sent to CAVE for testing. Figure 24 and Figure 25 show an epoxy overmolded test board. Figure 26 and Figure 27 show a hot melt overmolded test board.

Material	Mold Temp (^oC)	T_g (^oC)	Softening Point (^oC)	Performance Temperature (^oC)
Hot Melt 1	**225 – 235**	**-40**	**182 – 194**	**-40 – 150**
Hot Melt 2	**200 – 240**	**-36**	**170 – 180**	**-40 – 125**

Table 6 - Hot Melt Material Properties

Material	Board type	Mold Temp	Transfer Pressure, psi	Preheat, °C
Epoxy 1	**FR4**	**150°C**	**1000**	**80-100**
Epoxy 1	**Flex**	**150°C**	**1000**	**80-100**
Epoxy 2	**Flex**	**130°C**	**1000**	**80-100**
Epoxy 3	**FR4**	**150°C**	**1000**	**80-100**

Table 7 - Epoxy Manufacturing Settings

Figure 24 – Bottom View of Epoxy Overmolded Test Vehicle

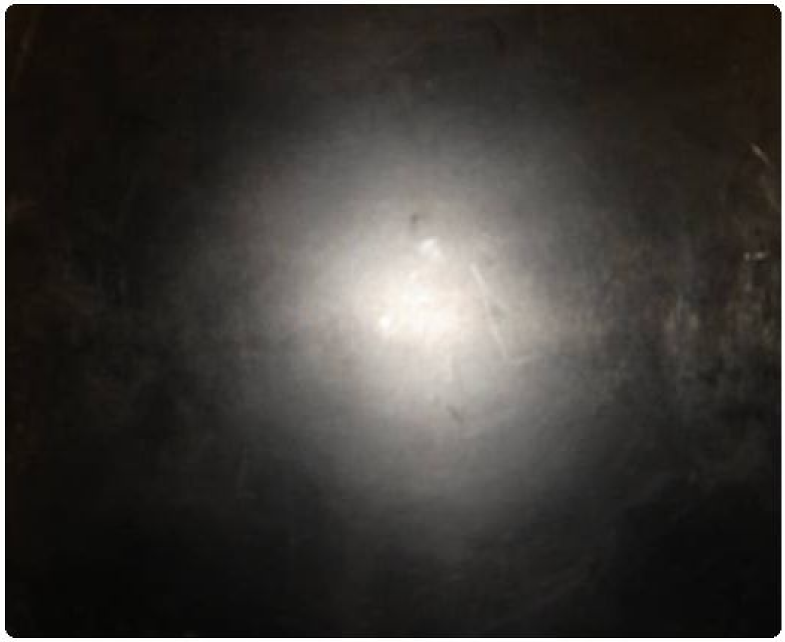


Figure 25 – Top View of Epoxy Overmolded Test Vehicle

Figure 26 – Bottom View of Hot Melt Overmolded Test Vehicle

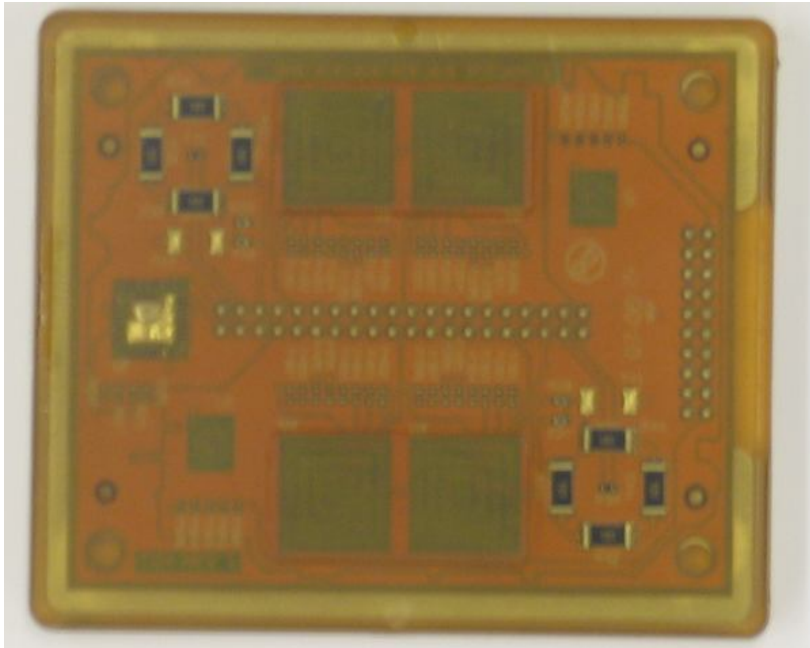


Figure 27 – Top View of Epoxy Overmolded Test Vehicle

4.3 Testing Description

This test places the test boards in Air-to-Air thermal cycle testing which is a form of Accelerated Life Testing (ALT). ALT simulates the stresses caused by environmental conditions seen by electronic components over a normal operating lifetime. By overstressing the components with thermal or mechanical stresses, the failure mechanisms and reliability can be studied in a smaller time frame. This allows for quicker testing and analysis which lowers the cost of research and development and allows for a quicker time to market for electronic components. The TV4 REV 1 test boards used thermal ALT since under-the-hood electronic failures are usually caused by cyclic and static thermal stresses.

Thermal cycle testing has become the standard for testing the reliability of harsh environment automotive electronics. A depiction of the stress-strain hysteresis curve for a solder joint under thermal cycle testing is seen in Figure 28. An illustration of a typical Air-to-Air thermal cycle profile is seen in Figure 29. Shear stresses are created on the solder joints during the heating and cooling portion of a thermal cycle. The shear stress is then relieved and strain is produced during the dwell times due to creep. Plastic deformation of the solder joints starts to occur as the number of cycles increases which decreases the solder joint's ability to alleviate the shear stress. Once the plastic deformation becomes too significant, the shear stresses start to cause fatigue on the solder joints which leads to cracks in the solder joint, thus causing electronic circuit failures.

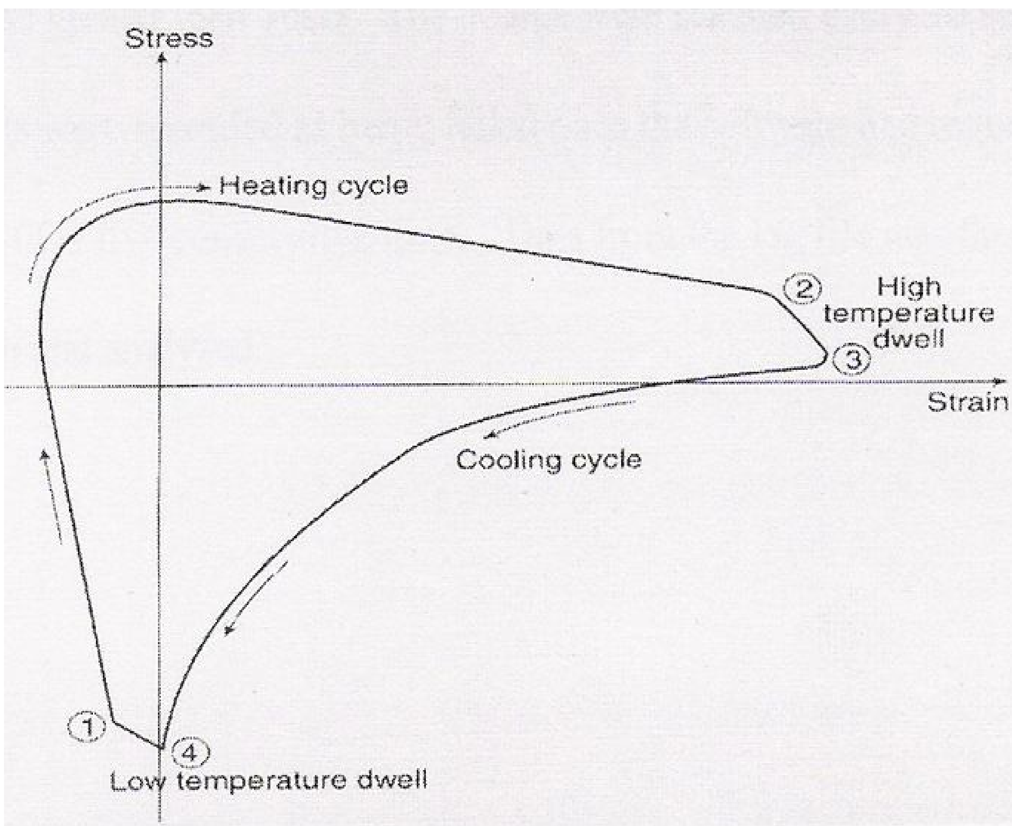


Figure 28 – Stress-Strain Hysteresis Curve (EPIH)

The thermal cycling of these test vehicles will be different than non-overmolded boards in cycling time and temperatures. The thermal cycle chamber temperature profile is close to the PC board temperature profile with non-overmolded circuit boards. However, with overmolded boards this is not the case. The temperature of the chamber and the temperature of the board will not be equivalent due to the thermal mass that the overmold material adds to the circuit boards. Most non-overmolded PC board thermal cycle testing done by CAVE have had profiles of close to 90 minutes or 120 minutes as the standards according to the abilities of the thermal cycle chambers used and the dwell times are usually fifteen minutes. The thermal cycle profile for this test was based on the PC board temperature. The board temperature was determined by the use of thermistors that were placed on a few overmolded test boards for chamber profiling purposes. In order to profile the board temperature, this meant that the chamber profile is significantly longer than the traditionally used 90 or 120 minute profiles. The chamber temperatures will be higher and lower than the testing temperatures so the PC boards will quickly get to the required temperatures. Also, the dwell times are longer in order to get the PC boards to the required temperature due to the increased thermal mass of the overmolding material and aluminum back plane.

For this testing, two chambers were used since two different tests were run. One chamber has a board profile of -40^{o}C to 125^{o}C (125^{o}C Chamber) with fifteen minute dwell times. This chamber had the hot melt overmolded boards and the 125^{o}C epoxy overmolded boards, as seen in Table 3 above. The second chamber has a board profile of -40^{o}C to 150^{o}C (150^{o}C Chamber) with fifteen minute dwell times. This chamber had the 150^{o}C epoxy overmolded boards, as seen in Table 3 above also. The profile for the

125°C Chamber is seen in Figure 29 and Figure 30. The profile for the 150°C Chamber is seen in Figure 31 and Figure 32.

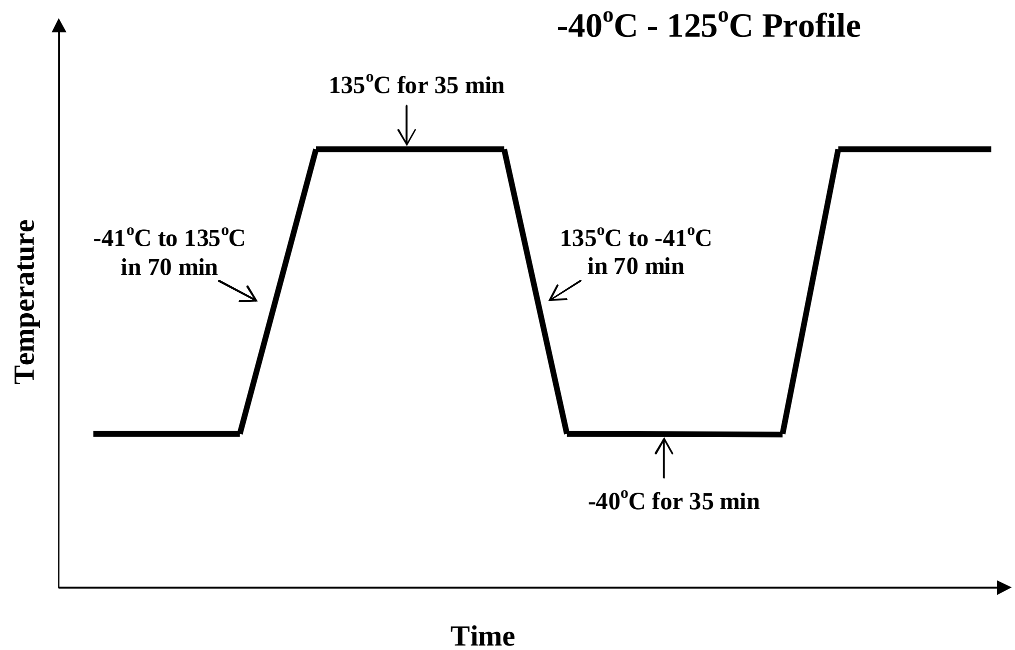


Figure 29 - -40°C – 125°C Air-to-Air Thermal Cycle Profile Illustration

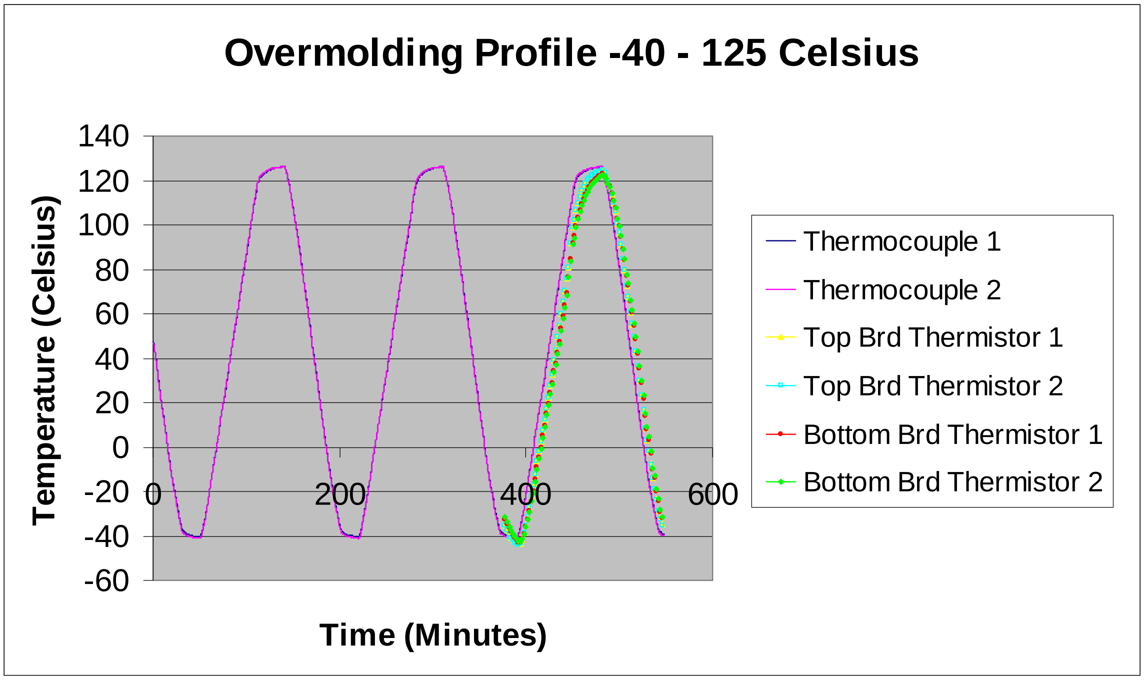


Figure 30 - -40°C – 125°C Air-to-Air Thermal Cycle Profile

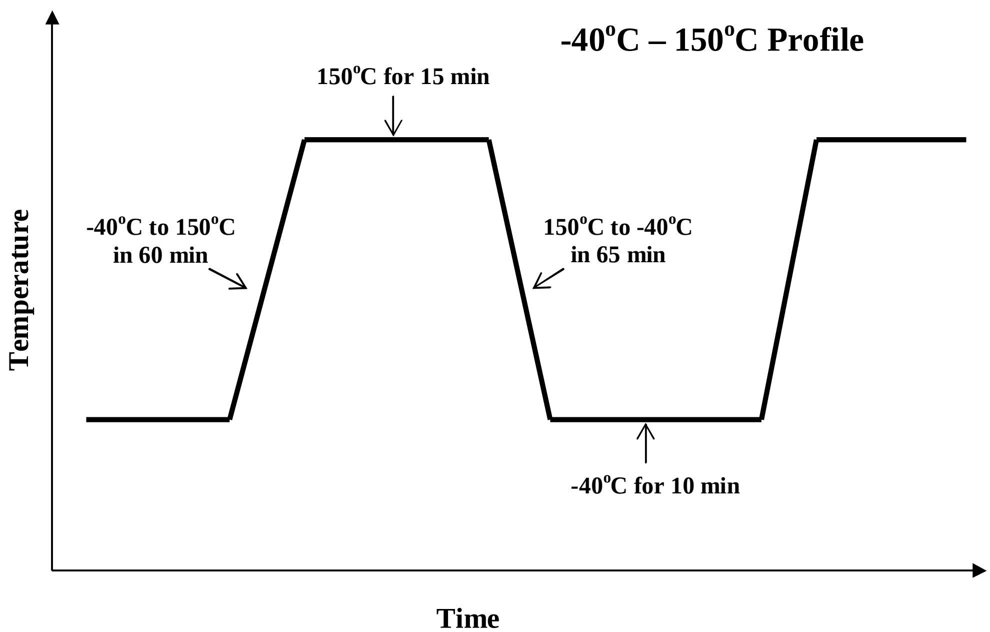


Figure 31 - -40°C – 150°C Air-to-Air Thermal Cycle Profile Illustration

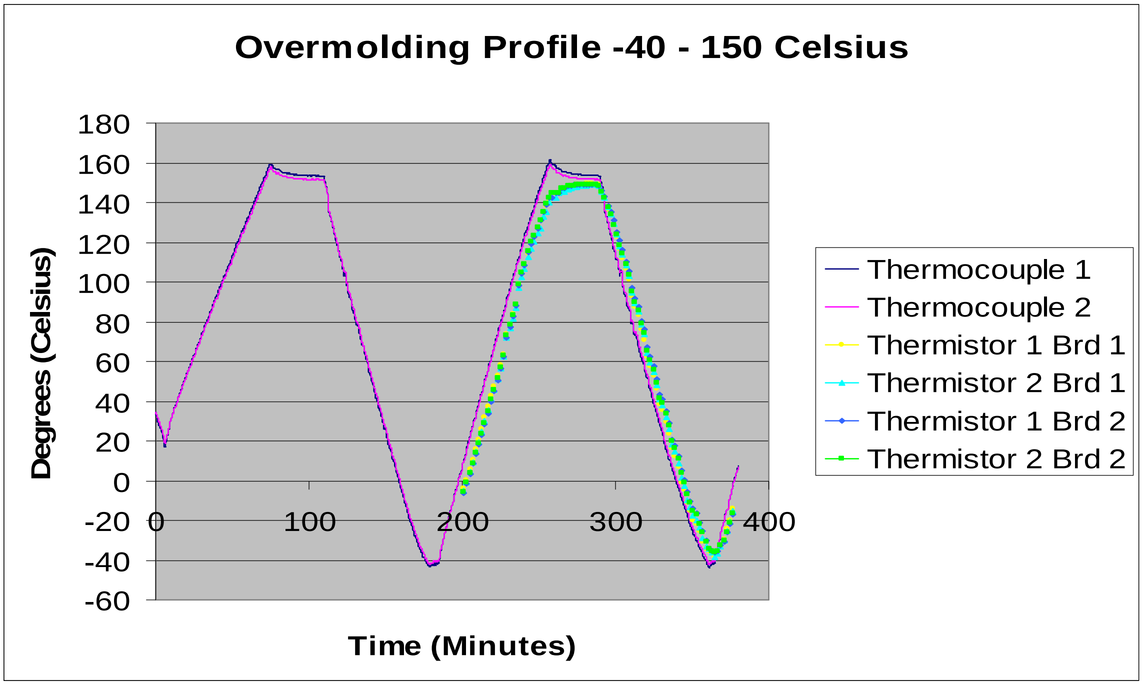


Figure 32 - -40°C – 150°C Air-to-Air Thermal Cycle Profile

Both the 125°C Chamber and 150°C Chamber are Thermotron S8 environmental chambers. The 125°C Chamber had a cycle with duration of 200 minutes with a 70 minute ramp up and ramp down time, 35 minute dwell time at 135°C, and 25 minute dwell time at -41°C. This chamber profile has a higher temperature and cycle time due to the increased thermal mass of the test boards along with the high number of test boards within the chamber. The thermal mass of the test boards required a longer profile in order to get the PC boards to the required temperatures and allow the PC board to dwell at -40°C and 125°C for the required 15 minutes. The 150°C Chamber had a cycle with duration of 150 minutes with a 60 minute ramp up time, 65 minute ramp down time, 15 minute dwell time at 150°C, and 10 minute dwell time at -40°C. The chamber temperature and PC board temperature for this chamber are nearly the same due to fewer test boards being tested at 150^{o}C. However, the cycle time was still required to be longer than 120 minutes due to the increased mass of the test boards due to the overmolding and aluminum back plane.

For this testing, the proprietary MarkDano [32] electronic monitoring system created by CAVE was used to monitor the resistance values of the components on the overmolding test boards. The two 2512 resistor banks, CSP packages, 4mm copper trace, and VIA daisy chain were all wired to connector boards, and the test boards were then placed in vertical racks within their respective thermal cycle chambers. The wires connecting the test boards and the connector cards run through an access hole in the chambers. The MarkDano monitoring system consists of a Keithley 2000 highly accurate digital multimeter and a Keithley 7002 Switch System. The failure resistance value was set to 15Ωs which means that any resistance value greater than 15Ωs is considered a failure. The components are scanned approximately every two minutes and a component was considered to have failed if the recorded resistance value was greater than 15Ωs five consecutive times. Failures were written to a log file and all failures were checked through out testing to ensure the components did fail instead of an element of the monitoring system. The process of checking for true failures is seen in Appendix B. The data from the log file will be analyzed at a later date when a greater percentage of failures have occurred. This will be discussed in the next chapter.

CHAPTER 5: ANALYSIS AND RESULTS

The material property testing for the overmolding materials and the substrates were conducted to get a better understanding of the CTE mismatches seen within the test boards. The material property testing was conducted and the results will be discussed below. The hot melt materials were not able to be tested due to test setup issues. For the tension/torsion testing, the hot melt materials were too soft to provide consistent, accurate, or significant test data. Also, the CTE values for the hot melt materials could not be determined due to the soft properties of the material. Therefore, the material properties provided in the tables below are from Henkel's data sheets on the materials.

Air-to-Air thermal cycling was conducted for this test along with material property testing for the different overmolding materials and the different substrates. The thermal cycling for both the 125^{o}C Chamber and 150^{o}C Chamber are still continuing to be run and monitored. Initial problems with the CSP packages due to board layout issues permitted electronic monitoring of the resistance values to determine when failures occurred. Failure data for the 2512 resistors is still being collected for this test as thermal cycling continues. Test boards of each type were pulled at 1200 cycles for both the 125^{o}C and 150^{o}C tests and cross sectioned to look at the interaction of the overmolding with the substrate, components, and solder joints. The analysis of the cross sections is discussed later in this chapter. The method for creating cross sections is found in Appendix A.

5.1 Overmold Material Properties Testing

Three different tests were completed on the overmolding and substrate materials to determine mechanical properties. The first was a Tension/Torsion test on the epoxy samples which provided stress versus strain curves for each epoxy at different temperatures and elastic modulus versus temperature curves for each epoxy. The second test was a TMA test to determine the CTE values for the different epoxies. The third test was a thermo-mechanical strain gage test which provided CTE values in the X and Y directions for the different substrates attached to the aluminum back plane.

5.1.1 Epoxy Tension/Torsion Testing

For this part of this study, a microscale tension/torsion thermo-mechanical test system from Wisdom technology, Inc. was used to load the epoxy test samples, as seen in Figure 33. This test placed a load on the epoxy test sample and a stress/strain curve and elastic modulus was calculated at certain temperatures. The system used a resistance heater environmental chamber to get the test sample temperature from 25^{o}C to 150^{o}C in increments of 25^{o}C. The computer system controlled the actuators to provide a uniaxial displacement with resolution of 0.1 microns. The computer system also measured the force on and the displacement of the test samples. Using the measured force and displacement, the axial stress and strain are calculated using the formulas below.

$$\sigma = F / A \qquad\qquad \varepsilon = \Delta L / L = \delta / L$$

In the formulas above σ is the uniaxial stress, ε is the uniaxial strain, F is the measured force, A is the original cross-sectional area, L is the specimen gage length (initial length between the machine grips), and δ is the measured displacement of the grips.

Figure 33 – Wisdom Technology, Inc. Microscale Tension/Torsion Thermo-Mechanical Test System

The results of this testing are seen in Figure 34 through Figure 39 and Table 8. Epoxy 1 is an electronic grade overmolding material which has been used for circuit board protection in previous applications. The epoxy was designed for high volume molding of tantalum capacitors, to provide premium moldability, and to have a fast cycle time. This is considered the best epoxy for this application out of the three epoxies tested. The stress/strain curves, seen in Figure 34, for the temperatures ranging from 25°C to 150°C were in close proximity to each other with a range from approximately 10 MPa to 6 MPa at the highest strain value tested. The stress values were low and consistent for Epoxy 1 therefore this material will have near consistent properties through the testing temperature range. The elastic modulus curve has a low negative slope throughout the temperature range and ranges from 14.85 GPa to 9.25 GPa, as seen in Table 8 and in Figure 35. With both the stress and elastic modulus varying slightly throughout the temperature range tested, Epoxy 1 is shown to have stable mechanical properties. This stability should provide good protection and create minimal stresses on the solder joints on the Epoxy 1 overmolded test boards during thermal cycle testing.

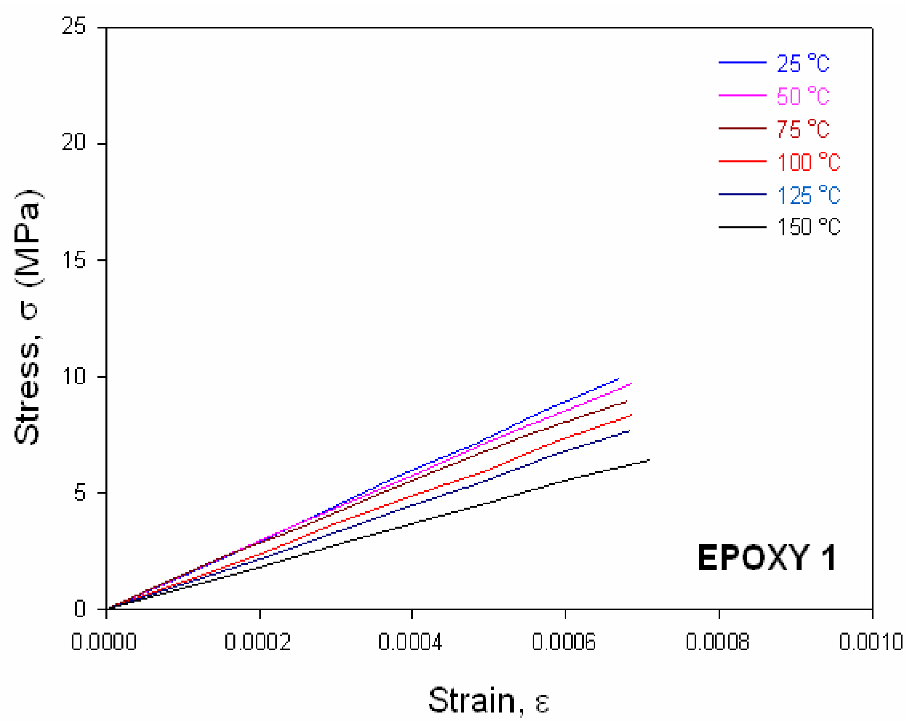


Figure 34 – Epoxy 1 Stress versus Strain Graph

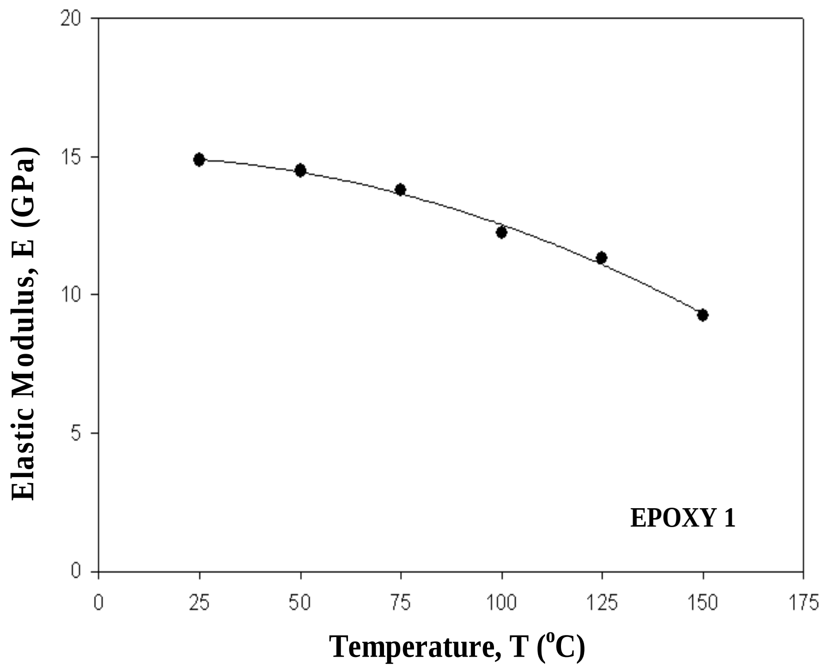


Figure 35 – Epoxy 1 Elastic Modulus versus Temperature Graph

Epoxy 2 is an environmental friendly green electronic grade molding material that comes in a powder form which can be molded at low temperatures to prevent damage to the flex boards. As like Epoxy 1, it was designed for high volume molding of tantalum capacitors, to provide premium moldability, and to have a fast cycle time. This is the midlevel epoxy of the three epoxies tested. The stress/strain curves, seen in Figure 36, for the temperatures ranging from 25°C to 125°C were in close proximity to each other with a range from approximately 14 MPa to 9 MPa at the highest strain value tested. At 150°C the stress dropped 6 MPa showing that the properties of Epoxy 2 change slightly at higher temperatures. The elastic modulus curve has a low negative slope throughout the temperature range of 25°C to 125°C with a range from 15.36 GPa to 10.53 GPa, as seen in Table 8 and in Figure 37. The slope decreases drastically from 125°C to 150°C changing from 10.53 GPa to 7.16 GPa again showing that the properties of Epoxy 2 change slightly at higher temperatures. With both the stress and elastic modulus varying slightly throughout the temperature range of 25°C to 125°C, Epoxy 2 is shown to have stable mechanical properties up to approximately 125°C. This stability should provide good protection and create minimal stresses on the solder joints on the Epoxy 2 overmolded test boards in the 125°C Chamber thermal cycling test but reliability will decrease in the 150°C Chamber thermal cycle testing. The reliability of Epoxy 2 overmolded test boards will be slightly lower than Epoxy 1 overmolded test boards.

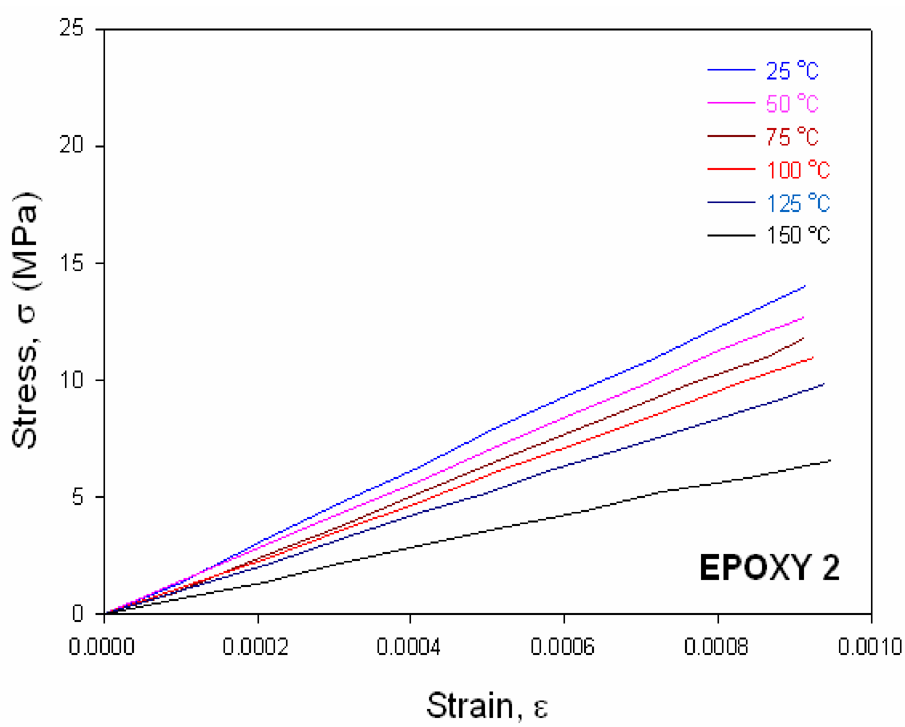


Figure 36 – Epoxy 2 Stress versus Strain Graph

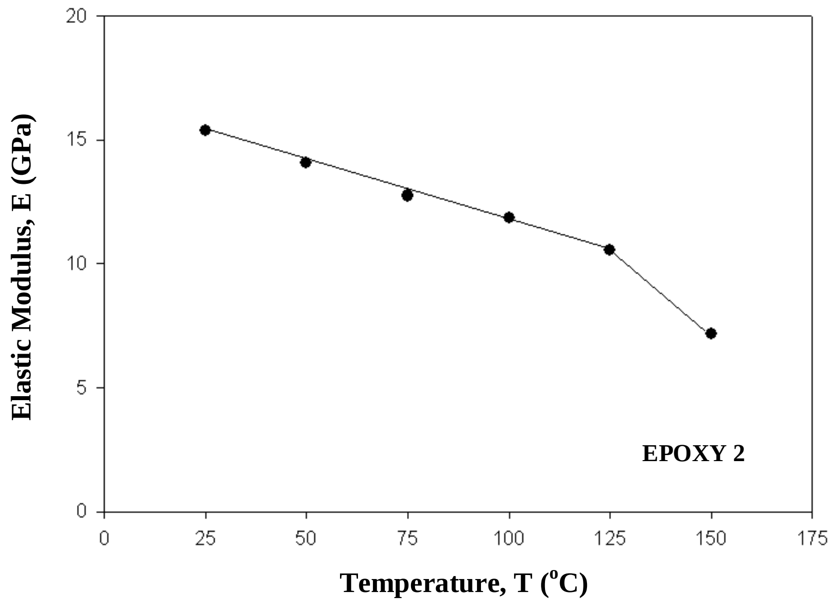


Figure 37 – Epoxy 2 Elastic Modulus versus Temperature Graph

Epoxy 3 is a soft flowing structural material that was chosen to provide protection for the board and its components. The epoxy is designed for use in high volume overmolding of automotive sensors and is fiber re-enforced to provide additional strength. This epoxy is the lowest grade overmolding material out of the three epoxy materials tested. The stress/strain curves, seen in Figure 38, for the temperatures ranging from 25^{o}C to 100^{o}C were in close proximity to each other with a range from approximately 9 MPa to 6 MPa at the highest strain value tested. At 125^{o}C the stress dropped to 3 MPa approximately and it continues to decrease at 150^{o}C showing that the properties of Epoxy 2 change significantly at higher temperatures. The elastic modulus curve has a decreasing negative slope throughout the temperature range of 25^{o}C to 150^{o}C with a range from 13.20 GPa to 0.53 GPa, as seen in Table 8 and in Figure 39. With this decreasing slow as temperature increases shows that the properties of Epoxy 3 change significantly at higher temperatures. With both the stress and elastic modulus varying dramatically throughout the temperature range of 25°C to 150°C, Epoxy 3 would have the most benefits at lower temperature ranges where protection from the environment is the main function. The instability of this overmold material will create high stresses on the solder joints on the Epoxy 3 overmolded test boards in the 125°C and 150oC Chamber thermal cycling test which will decrease reliability relative to Epoxy 1 and Epoxy 2 overmolded test boards.

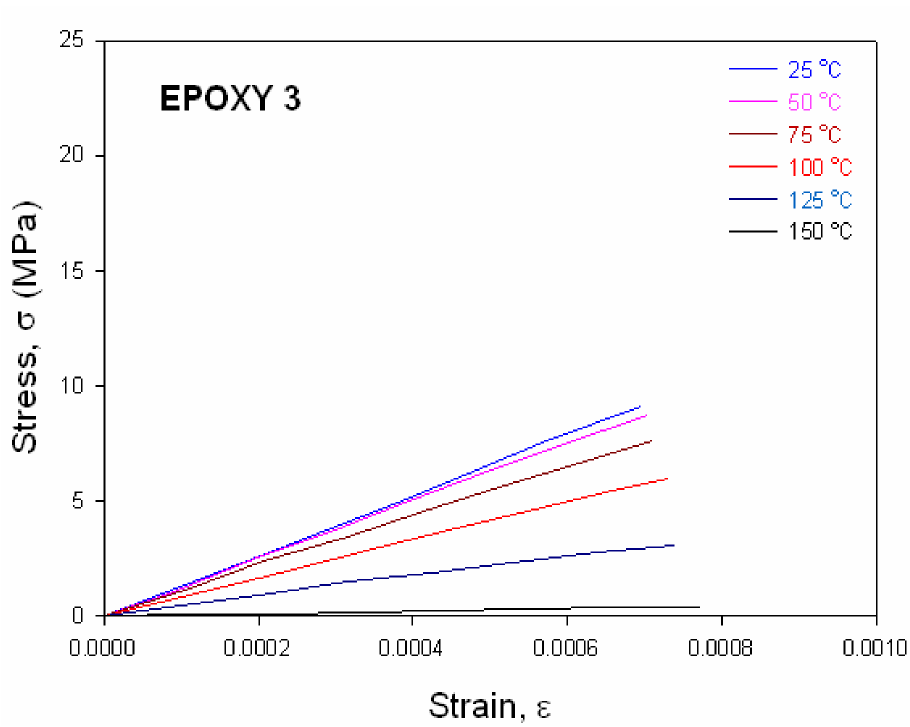


Figure 38 – Epoxy 3 Stress versus Strain Graph

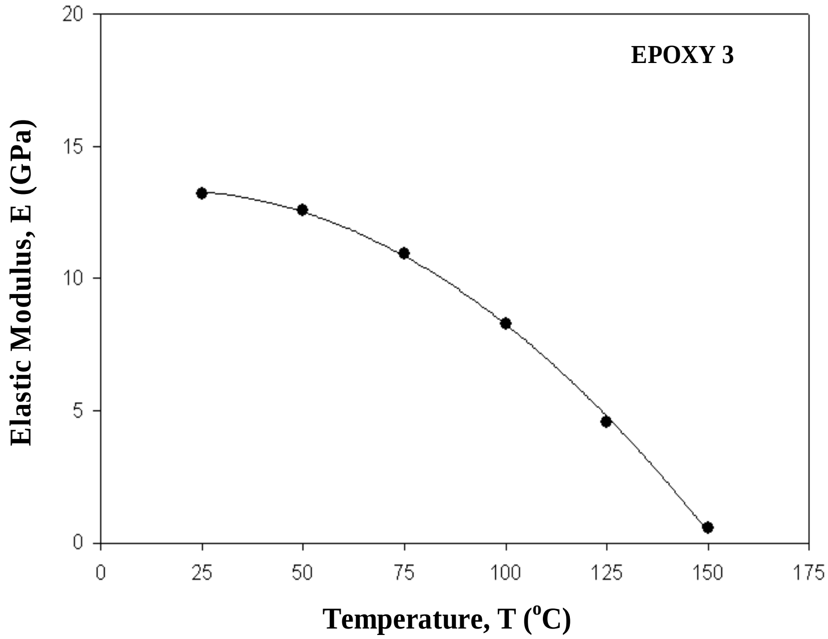


Figure 39 – Epoxy 3 Elastic Modulus versus Temperature Graph

	25°C	50°C	75°C	100°C	125°C	150°C
Epoxy 1 E (GPa)	14.85	14.47	13.76	12.23	11.29	9.25
Epoxy 2 E (GPa)	15.36	14.04	12.73	11.85	10.53	7.16
Epoxy 3 E (GPa)	13.20	12.55	10.94	8.26	4.55	0.53

Table 8 – Epoxy Elastic Modulus at Certain Temperatures

5.1.2 Epoxy CTE Z Direction Testing

Thermo-mechanical analysis (TMA) was used in this part of the test to determine the CTE and Glass Transition Temperature (T_g) of the epoxy overmolding materials and the substrates. As mentioned previously, the substrate materials were too thin for the TMA test setup. Therefore, the CTE and T_g values for the exact substrates used in this test are not included. However, testing was done on the substrates attached to the aluminum metal back plane to see if the CTE value could be determined. The values and graphs of the epoxies and the substrates attached to the aluminum back plane are included below.

This test used a Dupont Instruments 942 Thermo-Mechanical Analyzer to determine the CTE and T_g values, as shown in Figure 40. The TMA setup uses a glass rod with a thermocouple inside the rod which is placed vertically on top of the sample. Using a small resistance heater, the sample is heated and the heat causes the sample to expand. A sensor in the machine reads the height difference of the glass rod at the different temperatures and a computer system calculates the CTE values. The CTE values are calculated finding the curve of the displacement of the rod versus temperature graph produced for each sample. The test samples were tested from 25^{o}C to 200^{o}C and the results are shown below. All T_g values given by this test are approximate values due to human error in choosing the transition point of the Alpha 1 slope and the Alpha 2 slope.

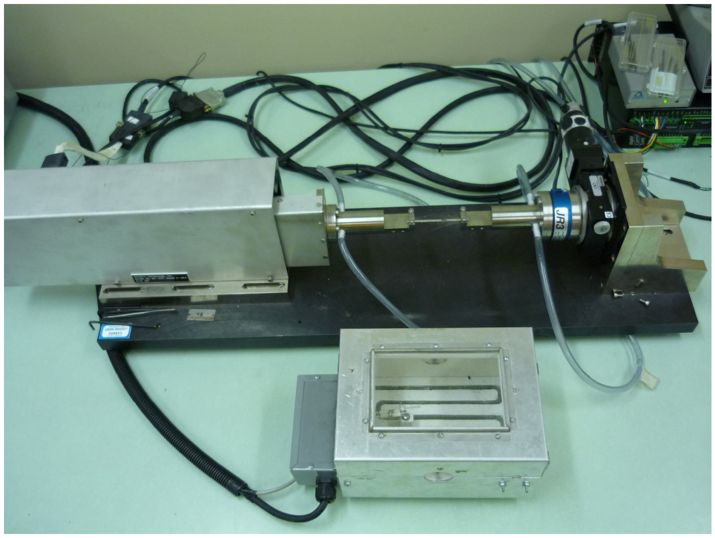


Figure 40 – Dupont Instruments 942 Thermo-Mechanical Analyzer Test Setup

The TMA result for Epoxy 1 is shown in Figure 41 which shows a smooth displacement curve with an Alpha 1 CTE value of 20.15 ppm/^oC, an Alpha 2 CTE value of 50.75 ppm/^oC, and a T_g value of 169.06 ^oC. There were three tests performed on Epoxy 1 and all three results are shown in Appendix C. This graph was chosen due its values being near the average for the three test results. The Alpha 1 and T_g values are near the values given by the Henkel material data sheets for the epoxies provided in Table 9. These results show that Epoxy 1 has a CTE value close to that of FR4 substrates on aluminum which is approximately 20 ppm/^oC and is close to SnPb solder which is near 24 ppm/^oC. Epoxy 1 should provide good stress dispersion and protection of the solder joints due to its CTE similarities with the substrate and solder joints. Also, the higher T_g allows for this epoxy to be used at the high temperature of 150 ^oC without the CTE value and overall material properties deteriorating. This test data strengthens the theory of the reliability performance of Epoxy 1 discussed in the previous section.

Material	Flow, in	Tg, °C	Alpha 1, ppm/°C	Alpha 2, ppm/°C
Epoxy 1	25	170	19	67
Epoxy 2	30	168	21	70
Epoxy 3	55	145	32	75

Table 9 - Epoxy Material Properties

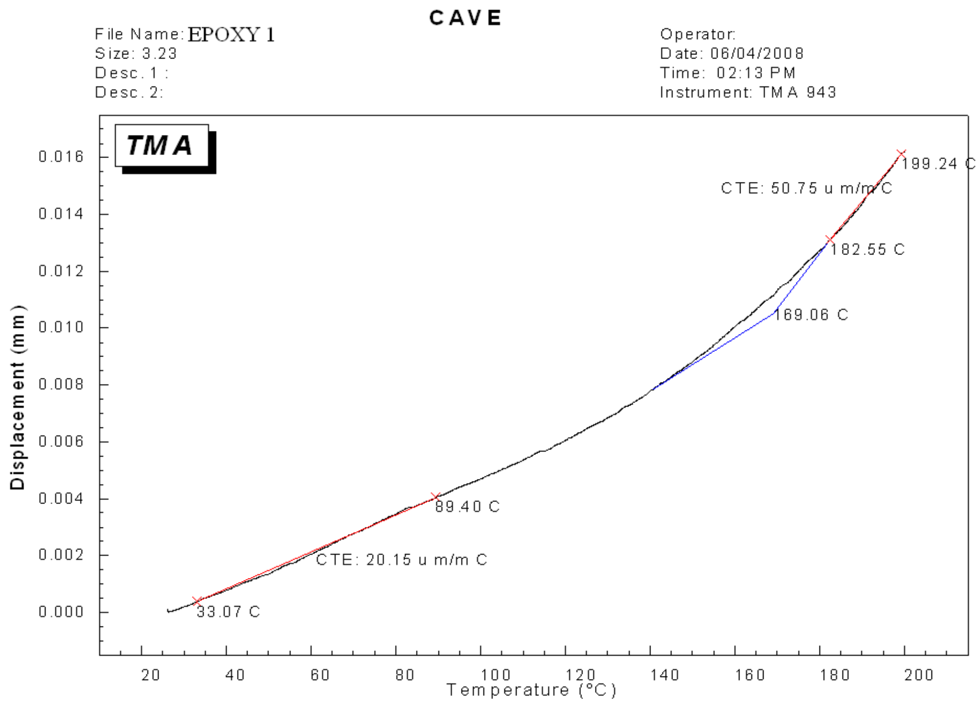


Figure 41 – Epoxy 1 TMA Graph Showing CTE and T_g Measurements

The test result for Epoxy 2 is shown in Figure 42 which shows a smooth displacement curve with an Alpha 1 CTE value of 20.62 ppm/°C, an Alpha 2 CTE value of 60.45 ppm/°C, and a T_g value of 168.26 °C. There were three tests completed on Epoxy 2 and all three results are shown in Appendix C. This graph was chosen due its values being near the average for the three test results. The Alpha 1 and T_g values again are near the values given by the Henkel material data sheets for the epoxies provided in Table 9. As with Epoxy 1, this epoxy should provide good stress dispersion and protection of the solder joints due to its CTE similarities with the substrate and solder joints. Also, the higher T_g allows for this epoxy to be used at the high temperature of 150°C without the CTE value and overall material properties deteriorating. However, at higher temperatures this epoxy's material properties would deteriorate faster than Epoxy 1, thus decreasing the reliability of the test boards slightly. Again, this test data strengthens the theory of the reliability performance of Epoxy 2 discussed in the previous section.

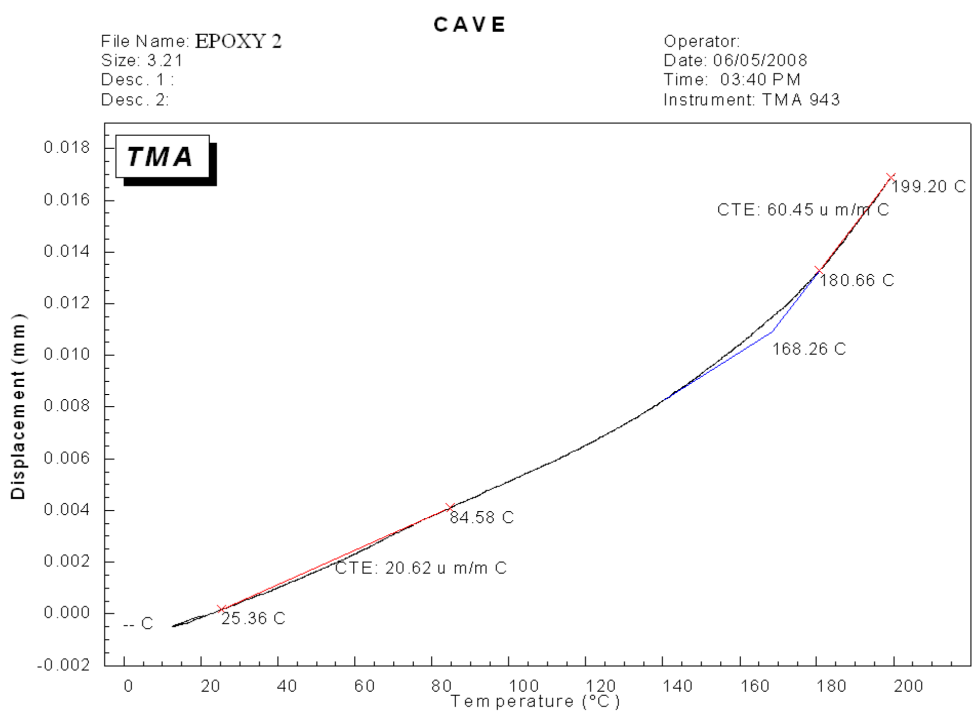


Figure 42 – Epoxy 2 TMA Graph Showing CTE and T_g Measurements

The test result for Epoxy 3 is shown in Figure 43 which shows an irregular displacement curve with an Alpha 1 CTE value of 33.28 ppm/^{o}C, an Alpha 2 CTE value of 87.13 ppm/^{o}C, and a T_g value of 148.04 ^{o}C. There were four tests completed on Epoxy 1 and all three results are shown in Appendix C. This graph was chosen due its values being near the average for the four test results. The Alpha 1 and T_g values again are near the values given by the Henkel material data sheets for the epoxies provided in Table 9. This epoxy has a slightly higher CTE value from ambient to 100 ^{o}C, which due to CTE mismatches, could cause greater stresses to be seen on the solder joints and the component. This could cause increased voiding, delamination, or stress fractures to occur. The CTE of the epoxy increases after 100 ^{o}C to a value of 90.76 ppm/^{o}C until it reaches the T_g. The graph shows the epoxy having two T_g temperatures points. This material property change for Epoxy 3 was also seen around 100 ^{o}C in the previous section which provides further proof that this curve is an accurate description of Epoxy 3 throughout the tested temperature range. As stated in the previous section, T_g value allows for this epoxy to be used at the temperature below 100 ^{o}C without the CTE value and overall material properties deteriorating. However, at temperatures above 100 ^{o}C, this epoxy's material properties would deteriorate faster than Epoxy 1 and 2, thus decreasing the reliability of the test boards significantly. Again, this test data strengthens the theory of the reliability performance of Epoxy 3 discussed in the previous section.

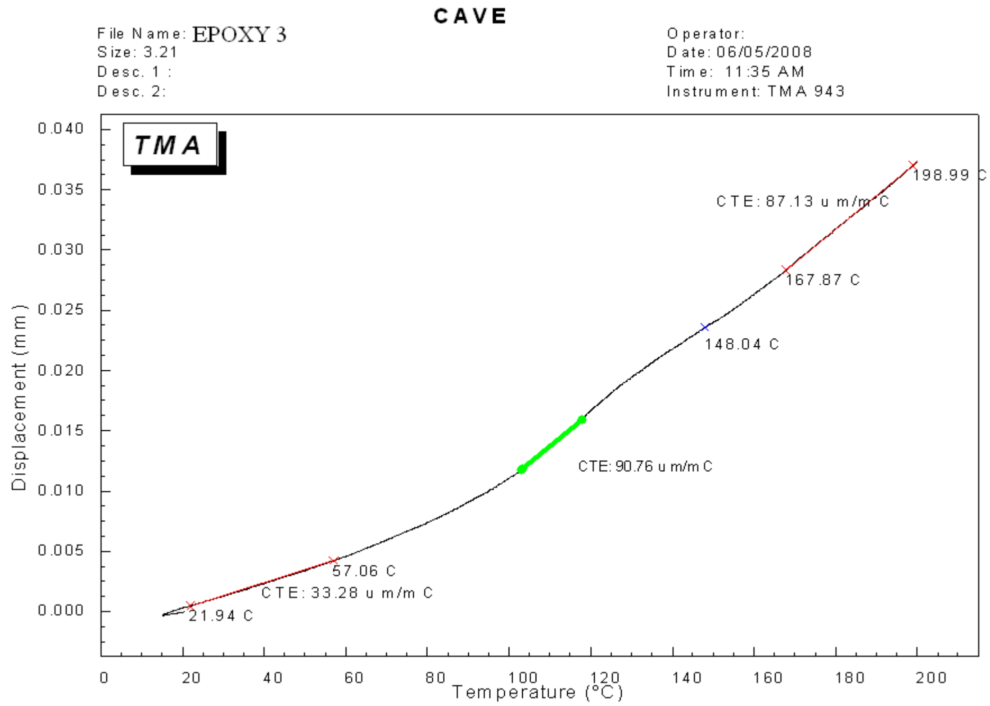


Figure 43 – Epoxy 3 TMA Graph Showing CTE and T_g Measurements

The result for FR4 on the aluminum back plane attached is shown in Figure 44 which shows a smooth displacement curve with an Alpha 1 CTE value of 58.71 ppm/^{o}C. Due to the linearity of the displacement curve, a true T_g or Alpha 2 values could not be determined. There were three tests performed on FR4 on the aluminum back plane and all three results are shown in Appendix C. This graph was chosen due its values being near the average for the three test results. This test provides a general CTE measurement of the FR4 substrate attached to the aluminum back plane with PSA. The CTE value is significantly higher than the epoxy materials shown above, but this is looking at the thermal expansion in the Z direction only. Thus the readings take into account the CTE values of the aluminum, PSA, and FR4 substrate. This high CTE value in the Z direction of the substrates could put strain on the overmold materials since the molding material is attached to the substrate and the aluminum. However, the stresses that could be caused by this would be around the perimeter of the board near the bond of the molding material to the aluminum and the substrate. This could cause voids, delamination, or cracking of the overmold material at these interaction points which could introduce the board to the environment. Thus reliability could be influenced if this possible problem were to be seen. Future testing would need to look into this possible issue.

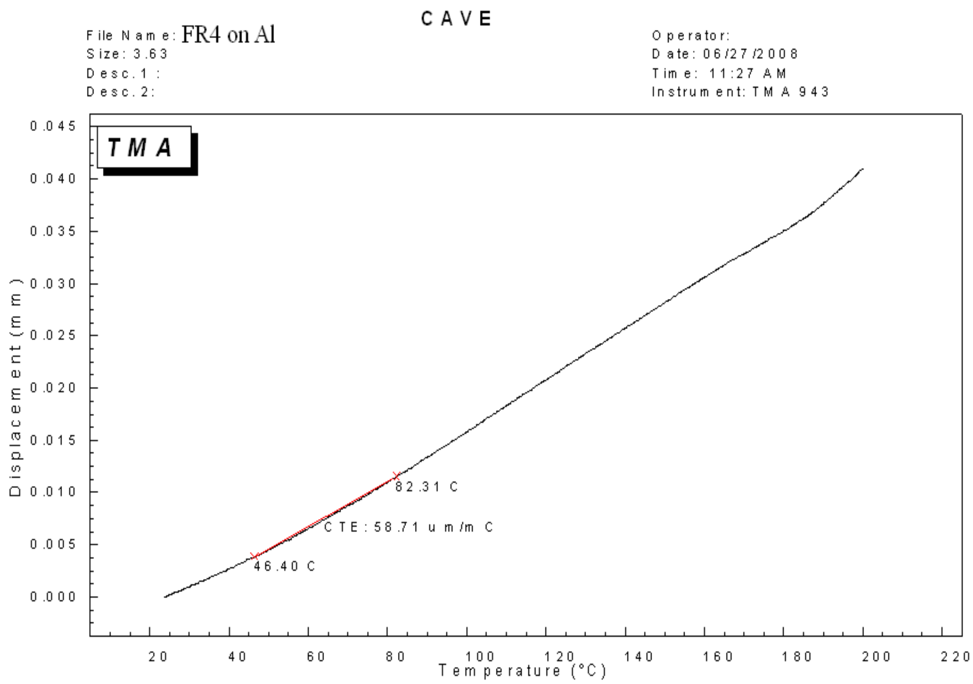


Figure 44 – FR4 on Al TMA Graph Showing CTE Measurement

The result for FLEX on the aluminum back plane attached is shown in Figure 45 which shows a smooth displacement curve with an Alpha 1 CTE value of 68.46 ppm/^{o}C. Due to the linearity of the displacement curve, a true T_g or Alpha 2 values could not be determined. There were two tests performed on FLEX on the aluminum back plane and both results are shown in Appendix C. This graph was chosen due its curve being the smoothest between the two tests performed. This test provides a general CTE measurement of the FLEX substrate attached to the aluminum back plane with PSA. The CTE value is significantly higher than the epoxy materials shown above and is slightly higher than the FR4 above. Again, this is looking at the thermal expansion in the Z direction only, so the readings take into account the CTE values of the aluminum, PSA, and FLEX substrate. This high CTE value could cause the same problems as the FR4 substrate could as mention previously. Future testing would need to look into this possible issue.

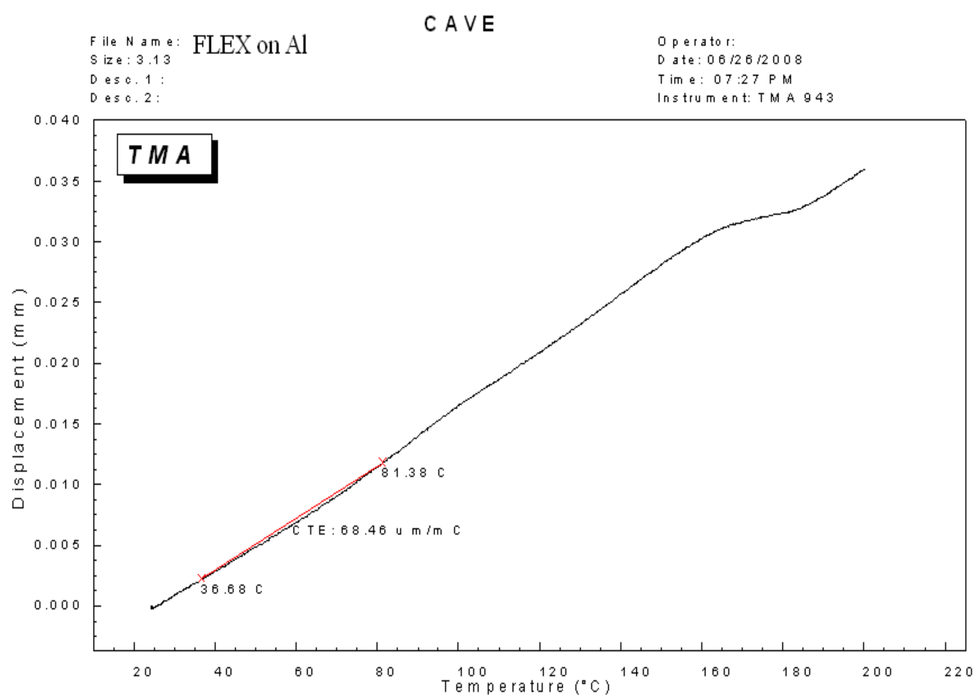


Figure 45 – FLEX on Al TMA Graph Showing CTE Measurement

5.1.3 Substrate CTE X and Y Direction Testing

To determine the CTE in the X and Y directions, testing using strain gages was used. Samples of FR4 and FLEX substrates attached to an aluminum back plane were made and strain gages were attached in both the X and Y directions. A computer software system takes the strain gage measurements and uses the formula below to determine the CTE in the X and Y directions for the different substrate combinations tested.

$$\varepsilon = (\alpha SiN - \alpha Si)\Delta T$$

The variable αSi is a known value and the strain gauge reading gives the ε value. The CTE of the sample is αSiN which is solved for using the software system. Measurements will be taken at increments of ten degrees Celsius to find the average CTE value across the temperature range of $25^{o}C$ to $115^{o}C$. The strain versus temperature graphs for the two substrate combinations are shown in Appendix D. The CTE measurements for the two substrate combinations are shown in Table 10.

	CTE (ppm/^{o}C)	
Substrate	**X**	**Y**
.031" FR4 With Aluminum	17.356	19.362
.015" FLEX With Aluminum	17.349	19.683
FR4 No Aluminum	13 - 15	
FLEX No Aluminum	14 - 17	

Table 10 – Substrate Combinations for X and Y CTE Measurements

The values of the bare FR4 and FLEX are included as reference and were determined from previous works done at CAVE. The CTE measurements for both the X and Y directions do not differ significantly which will not affect the reliability of the surface mounted components according to their orientation. The values for the substrates on aluminum are not significantly different so the reliability performance of the two substrates should be very similar. The CTE values of the substrates on the aluminum are slightly higher than the bare substrate values. This is due to the aluminum having a value of 23 ppm/^{o}C and with the two being attached, the CTE will be slightly higher than bare substrate. This also proves why substrates attached to aluminum have lower component reliability than bare substrates. This test setup had been verified for accuracy and repeatability previous to being used in this study. The graphs for each of the tests show smooth curves and show good repeatability thus verifying the test technique further. CTE testing was not done with the overmolded substrates on the aluminum back plane due to the CTE of the overmolding materials being the same in the X, Y, and Z directions and CTE measurements were already done on the overmolding materials.

5.1.4 Hot Melt Material Property Conclusions

The two hot melt overmold materials provided by Henkel are thermoplastic polyamides designed to provide good adhesion to various substrates. They are designed to require low processing pressure due to low viscosity and provide a moisture and environmental seal. They were also designed to provide a good balance of low and high temperature performance in different applications. The material properties of the two hot melt materials are provided in Table 11.

Material	Performance Temperature (^{o}C)	Softening Point Temperature (^{o}C)	Molding Temperature (^{o}C)	% Elongation
Hot Melt 1	-40 to 150	182 – 192	225 – 225	600
Hot Melt 2	-40 to 125	170 – 180	200 – 240	400

Table 11 - Hot Melt Material Properties

The adhesion properties of the hot melt materials to the substrate materials after manufacturing are poor compared to the expectations explained on the material data sheets. Both materials show multiple and often times large areas of delamination from the substrate and component surfaces before being placed into thermal cycle testing. Figure 46 and Figure 47 show delaminations of the hot melt materials to the test boards before thermal cycle testing. These delaminations provide pockets for heat to get trapped in during thermal cycling instead of providing direct conduction from the substrate or component to the atmosphere. These “heat pockets” cause the temperature of the substrate or component to be higher than the surrounding area which causes mismatches in CTE. The mismatches cause failure mechanisms to appear quicker within component solder joints. They also cause the delaminated areas to grow which allows for other contaminants to reach the board surface if the delaminations grow to the test board surface. The overmolding materials also absorb some stresses placed on the components induced by thermal cycling thus increasing reliability. They also delay crack propagation once the crack has formed by holding the component against the solder pad. Both of the abovementioned events only occur when the overmolding materials are directly contacted to the component.

Figure 46 - Hot Melt 2 Test Board on FR4 Substrate Showing Delamination before Thermal Cycle Testing

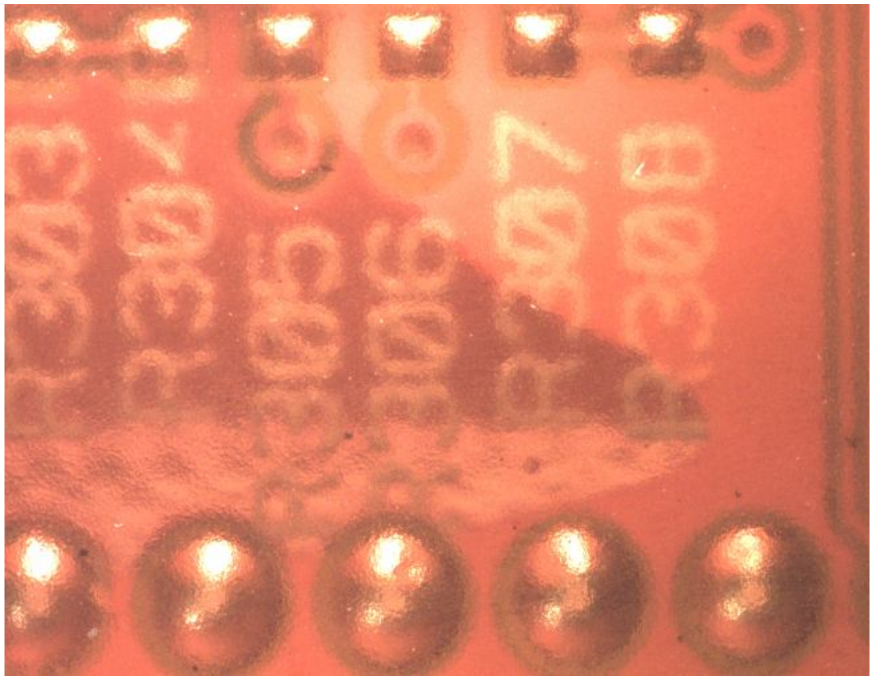


Figure 47 - Hot Melt 1 Test Board on FLEX Substrate Showing Delamination before Thermal Cycle Testing

The hot melt materials were chosen to see if they could withstand a harsh environment under thermal cycling for future applications. However, these materials showed poor properties for uses as overmold materials in the testing environment. Figure 48 shows the cross-section of a 2512 resistor on a hot melt test board before thermal cycling. Both of the hot melt materials are firm, not easily penetrable with a tip of a ball point pen, are amber in color, and are nearly transparent before thermal cycling. However, the physical and material properties of the materials both change in both color and texture before 400 thermal cycles. The materials become softer, are easily penetrable with a tip of a ball point pen, turn a brownish red color, and become nearly opaque. Figure 49 shows a hot melt test board that has been through 1200 thermal cycles from -

40°C to 125°C. The hot melt materials in both pictures below are above the white ceramic center of the 2512 resistor.

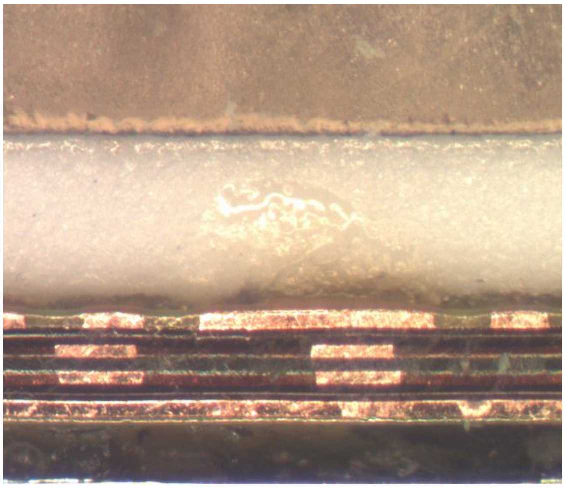


Figure 48 - Hot Melt Test Board 0 Cycles

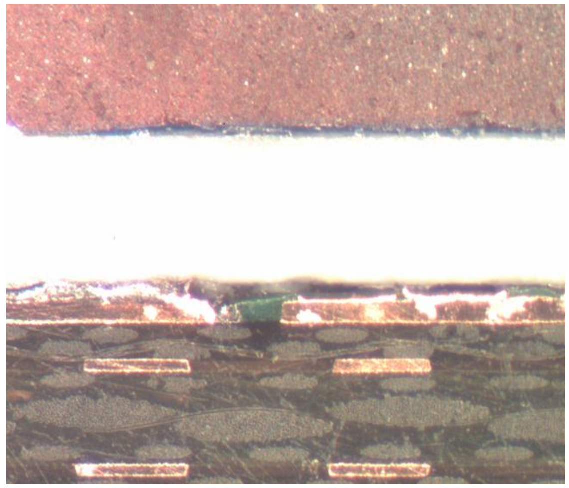


Figure 49 - Hot Melt Test Board 1200 Cycles

During the hot side of the thermal cycle testing the hot melt material temperatures start to reach their softening point temperatures as seen in Table 11. The hot melt materials then soften to the point where they become tacky and attach to the fixture they are placed in. Once the overmold is then cooled, the overmold has attached itself to the fixture and during the cold side of the thermal cycle the overmold material starts to crack at the interaction of the fixture and the overmold material due to CTE mismatches between the two materials. After this cycle of events occurs numerous times, the cracks in the overmold surface start to propagate across the board until the overmolding attached to the fixture eventually becomes completely detached from the test board, as seen in Figure 50. Also during this time, the CTE mismatches and deterioration in adhesion properties of the hot melt materials causes further delamination to start occurring at the substrate and component surfaces. The delamination occurs at a slower pace however than the overmold surface cracking since the board surface temperature is lower than the overmolding surface temperature.

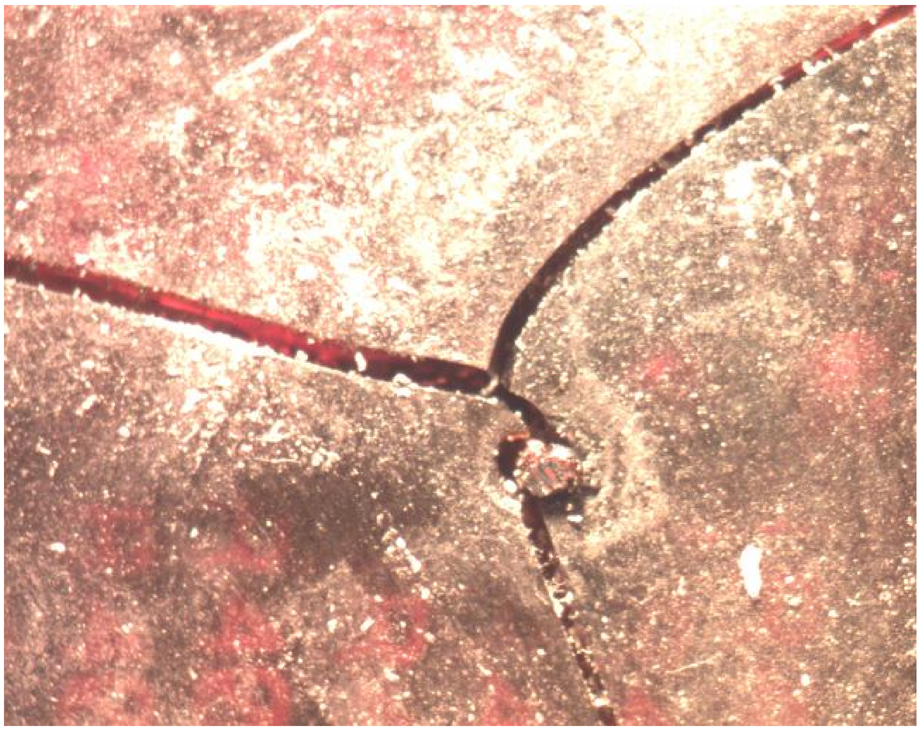


Figure 50 - Hot Melt 2 Test Board Showing Cracks in the Hot Melt Material, 1200 Cycles

Both of these failures of the hot melt overmolding materials cause the test boards to be subjected to the environment with very little protection both thermally and physically. These failures cause the components to have a failure rate close to non-overmolded boards on aluminum back planes. Although failures of the overmolding materials for both of the hot melt materials, one material is better than the other and the material properties prove this. Hot Melt 1 overmold material has performed better up to the current point in testing, 1545 thermal cycles, than Hot Melt 2 due to its higher performance temperature rating and higher softening point temperature as seen in Table 11 above. With a higher softening point, Hot Melt 1 does not become as tacky as Hot Melt 2 and does not stick to the fixture as easily. There are far fewer Hot Melt 1 test boards that have had parts of the overmolding to break off due to the aforementioned phenomenon. Looking at the boards at the current thermal cycle count and the material properties provided, Hot Melt 1 test boards should have better reliability than the Hot Melt 2 boards but will not be near the reliability of any of the epoxy test boards. Reliability data will be compiled at a later date which will show the failure rates of the hot melt test board components since the testing is still on going and the percentage of component failures is below 50% at a current thermal cycle count of 1545 cycles. This data will be compared to both non-overmolded boards on aluminum back planes and the epoxy overmolded test boards' reliability data to determine the effectiveness on reliability of the hot melt overmolding materials.

5.1.5 Epoxy Material Property Conclusions

The three epoxy overmold materials provided by Henkel are resin epoxies designed to provide good adhesion to various substrates. They provide a moisture and environmental seal and are designed to provide excellent low and high temperature performance in different applications. The material properties provided by the material data sheets from Henkel of the three epoxy materials are provided in Table 12.

Material	Flow, in	Tg, ^{o}C	Alpha 1, ppm/^{o}C	Alpha 2, ppm/^{o}C
Epoxy 1	**25**	**170**	**19**	**67**
Epoxy 2	**30**	**168**	**21**	**70**
Epoxy 3	**55**	**145**	**32**	**75**

Table 12 - Epoxy Material Properties

These epoxy materials were designed for high temperature harsh environment applications with CTE and T_g values close to FR4 and FLEX substrates. Epoxy overmolding materials provide good adhesion to the substrate surface and components which is important for heat and stress dispersion. The matches in CTE values will reduce the thermal stresses the components will see during thermal cycling, will dampen vibrations on the components, and provide physical protection from the environment.

As stated in a previous section, the T_g values for Epoxy 1 and Epoxy 2, shown in Table 12 above, are above 150^{o}C and should provide excellent reliability in the thermal cycle testing at both 125^{o}C and 150^{o}C thermal cycle testing. Epoxy 3 is slightly below 150^{o}C and reliability of the components on the test boards should be lower than the other two epoxy overmolding materials due to this property. However, Epoxy 3 should provide slightly lower if not equal reliability performance in the 125^{o}C thermal cycle testing.

For Epoxy 1 and Epoxy 2 overmold materials, the CTE values closely resemble the CTE values of the substrate materials in both the X and Y directions, as seen in Table 13. As stated previously, maximum reliability should be seen with these two epoxies throughout testing. Epoxy 3 has a higher CTE value than both the X and Y CTE values for the substrates. This CTE mismatch will cause stresses on the adhesion bonds between the overmold and the substrates and the overmold and the components. These stresses will cause cracks to form at both the board surface causing delamination, eventually leading to air pockets forming and thermal degradation of the module to increase. As for the stresses placed on the solder joints of the components due to the CTE mismatches, the affect may cause significant loss in component reliability, or the overmolding will evenly distribute the stresses throughout the component and solder joints thus having a minimum affect on component reliability. How the epoxy overmolding materials interact with solder joint reliability will be looked at in a later section of this chapter.

SUBSTRATE	CTE IN X DIRECTION AVERAGE (ppm/^{o}C)	CTE IN Y DIRECTION AVERAGE (ppm/^{o}C)
.031” FR4 With Aluminum	17.356	19.362
.015” FLEX With Aluminum	17.349	19.683
FR4 No Aluminum	13 - 15	
FLEX No Aluminum	14 - 17	
SUBSTRATE	CTE IN Z DIRECTION (ppm/^{o}C)	
FR4 With Aluminum	58.71	
FLEX With Aluminum	68.46	
OVERMOLD MATERIAL	CTE (ppm/^{o}C)	
Epoxy 1	20.15	
Epoxy 2	20.62	
Epoxy 3	33.28	

Table 13 – Substrate and Epoxy Material CTE Measurements

Testing on the CTE values of the substrate materials attached to an aluminum back plane was done and the results were discussed in a previous section of this chapter.

Future testing was suggested for determining the affects of the CTE mismatches of the substrates in the Z direction and the overmolding materials. The high CTE value in the Z direction of the substrates could put strain on the overmold materials since the molding material is attached to the substrate and the aluminum. These stresses would first be seen where the overmolding material adheres to the aluminum back plane edge as seen in Figure 51. The stresses could cause voids, delamination, or cracking of the overmold material at these interaction points which could introduce the board to the environment.

Figure 51 - Bottom View of Epoxy Overmolded Test Board

This adhesion point of the overmolding materials to the aluminum back plane edge was looked on the boards which had been taken from both the 125^{o}C and 150^{o}C thermal cycle testing after 1200 thermal cycles to be cross sectioned for analysis. Crack images of every test board combination of epoxy overmolded test boards can be seen in Appendix E. All of the test boards from the 125°C thermal cycle test showed cracks along the back plane edge, as seen in Figure 52, with the exception of the Epoxy 1 overmolding material and FLEX substrate, as seen in Figure 53.

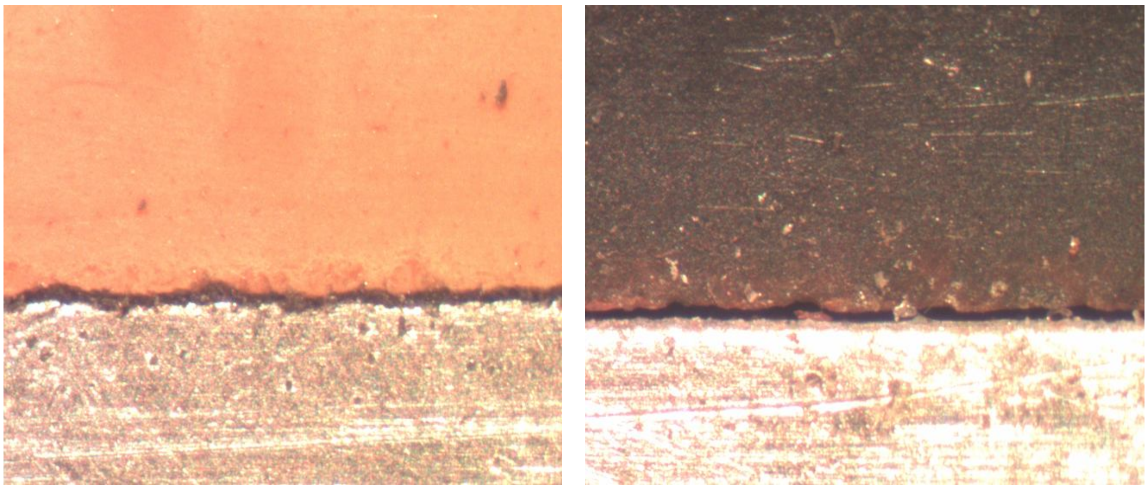


Figure 52 - Epoxy Overmold Delamination from Aluminum Back Plane Edge from 125°C Thermal Cycle Test, 1200 Cycles

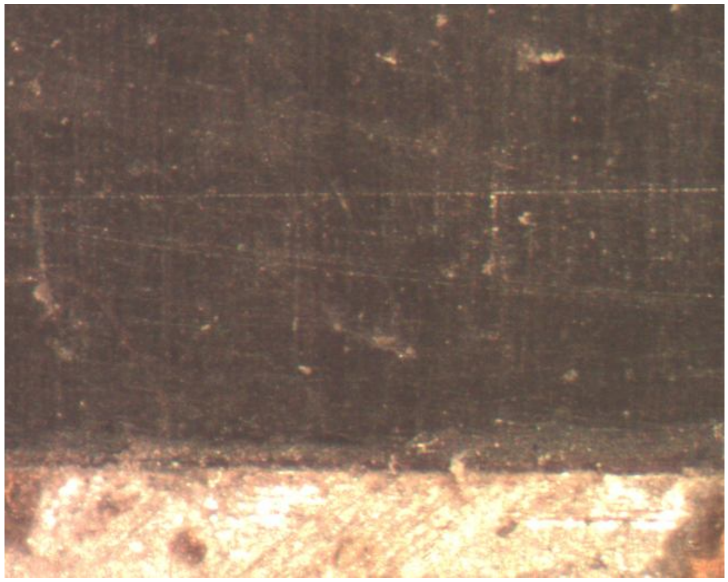


Figure 53 - Epoxy 1 Overmold on FLEX Substrate Showing Good Adhesion to Aluminum from 125^{o}C Thermal Cycle Test, 1200 Cycles

Images from the 150^{o}C thermal cycle test boards of the aluminum back plane edges were nearly identical to the 125^{o}C thermal cycle test boards, as seen in Figure 54. Epoxy 1 overmolding material on FLEX substrate showed no cracks along the edge of the aluminum back plane, as seen in Figure 55, which was also seen with the 125^{o}C test boards. The depth of the cracks was not determined since cross sectioning would possibly damage the adhesion between the epoxy overmolding material and the aluminum back plane edge. However, the existence of these cracks does pose an issue in the overmolded module design process. This crack could allow for direct access for air or liquids to the PC board which could degrade the PSA adhesion to the PC board and aluminum back plane and could decrease the reliability of components' solder joints due to increased CTE mismatches.

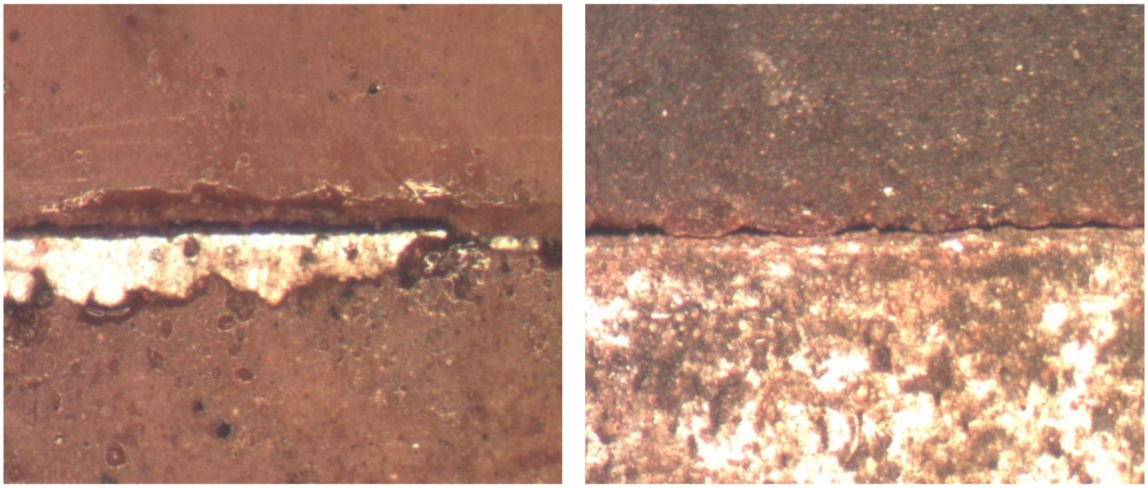


Figure 54 - Epoxy Overmold Delamination from Aluminum Back Plane Edge from 150^{o}C Thermal Cycle Test, 1200 Cycles

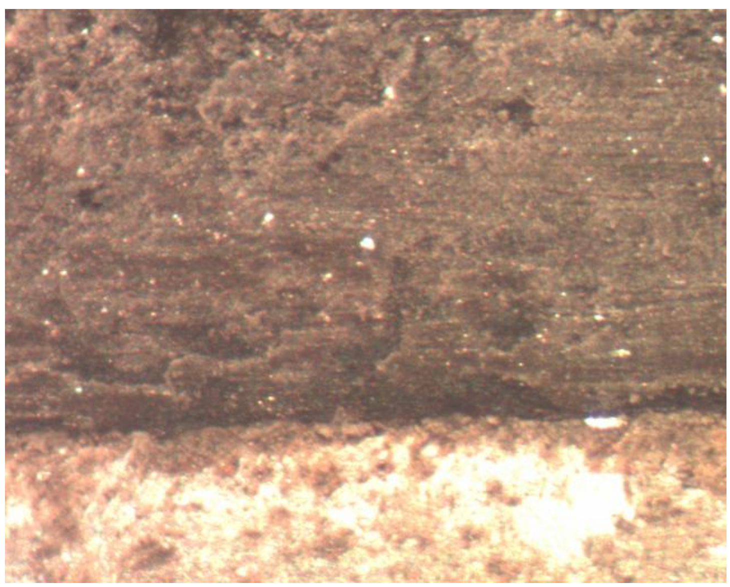
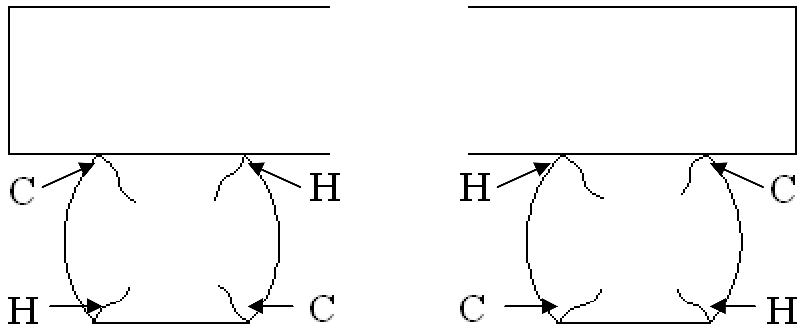


Figure 55 - Epoxy 1 Overmold on FLEX Substrate Showing Good Adhesion to Aluminum from 150^{o}C Thermal Cycle Test, 1200 Cycles

As seen in the figures above, Epoxy 1 overmolding material on FLEX substrate seems to be a solution to this issue for both the 125^{o}C and 150^{o}C thermal cycle tests. This is probably due to the special expansion and contraction characteristics of the FLEX substrate and the good adhesion properties of Epoxy 1. The expansion and contraction of the substrate would absorb some or all of the thermal stresses which would be placed on the aluminum back plane edges. Other design changes would need to be made to eliminate this issue. One solution would be to completely overmold the entire PC board, PSA, and aluminum back plane assembly so no edge would exist where cracks could occur. Further studies would need to be performed in this area to determine the optimal design for correcting this issue.

5.2 Component Failure Analysis

A test board of each combination type was taken from the thermal cycle test and samples of the components were cross-sectioned for failure analysis and overmolding interactions with the components. The cross-sections allowed for failure mechanisms to be determined for both the 2512 resistors and the CSP package. Both the hot melt test boards and the epoxy test boards were cross sectioned for analysis. The results are discussed below. Figure 56, Figure 57, and Figure 58 give schematics of the failure mechanisms often seen on a solder joint of a CSP or Flip Chip package [1]. Cross-section analysis will allow for characterization of the failures seen at the solder joints for the CSP packages on the different test boards.



H = Hot Side of Thermal Cycle Crack
C = Cold Side of Thermal Cycle Crack

Figure 56 - CSP Solder Ball Crack Locations

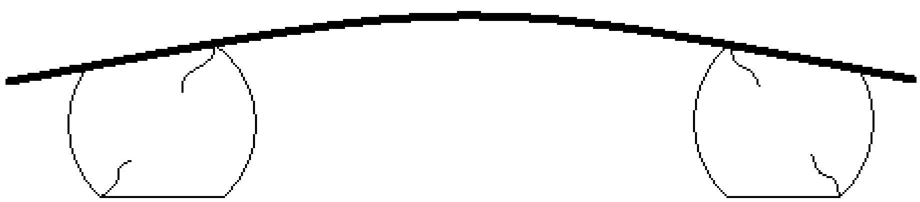


Figure 57 - CSP Thermal Cycle Hot Side Crack Locations

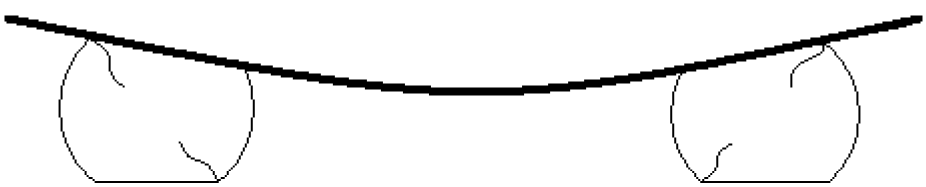


Figure 58 - CSP Thermal Cycle Cold Side Crack Locations

Cross-sections were also completed on the 2512 ceramic resistors to determine the failure mechanisms. Figure 59 gives a representation of the solder failure mechanisms often seen on a solder joint of a ceramic resistor. Cross-section analysis will allow for characterization of the failures seen at the solder joints for the resistors on the different test boards.

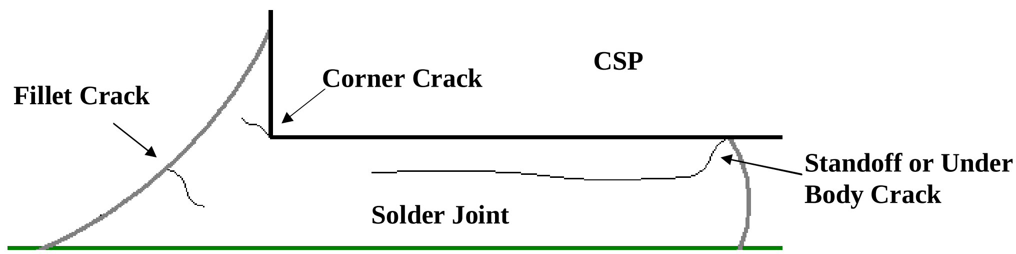


Figure 59 - Resistor Solder Joint Crack Locations

5.2.1 Hot Melt Test Boards Failure Analysis

During the thermal cycle testing process, test boards of each type were taken from the -40^{o}C to 125^{o}C thermal cycle tests after 1200 thermal cycles had been completed. Cross sections were completed on the test boards of each substrate and hot melt overmolding combination to determine the failure mechanisms on the CSP and 2512 ceramic resistors.

The majority of the failures seen on the 2512 resistors on the Hot Melt test boards were voids in the solder joints and cracks that started at inner edge of the resistor's solder terminal, propagating between the resistor pad and the board pad toward the outside of the solder joint as seen in Figure 60 and Figure 61. As thermal cycling increases in number, the properties of the overmolding materials change. Mainly, the CTE increases when the temperatures start to reach and also exceeds the T_g. The material property changes add more heat to the solder joint thus causing intermetallics in the solder joints to form. This then causes embrittlement in the solder joints as well as in the overmolding material which also puts added stresses on the solder joints. Thermo-mechanical effects cause delamination of the overmolding materials and further solder joint fatigue [14].

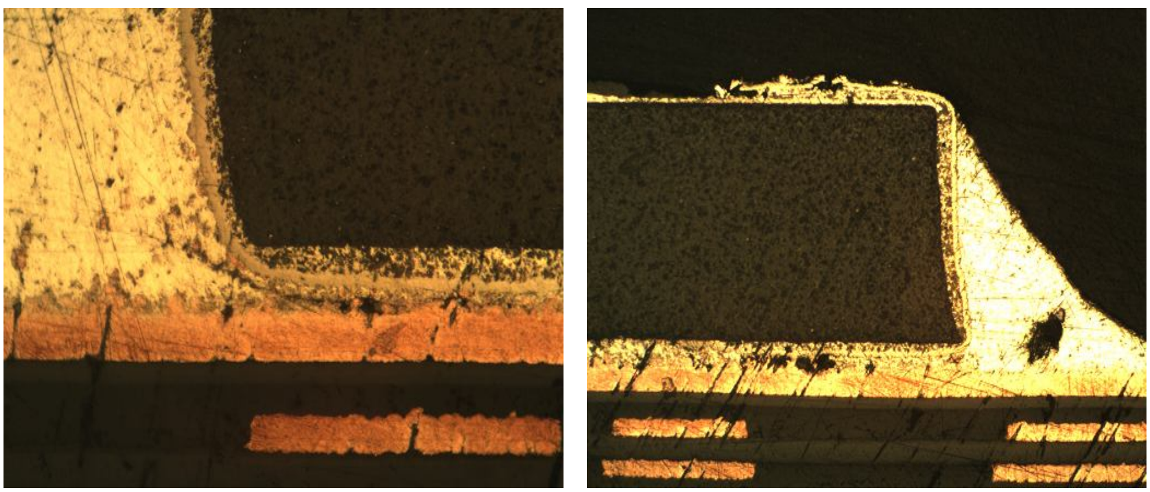


Figure 60 - Hot Melt 1 2512 Resistor Failure Mechanisms, 1200 Cycles

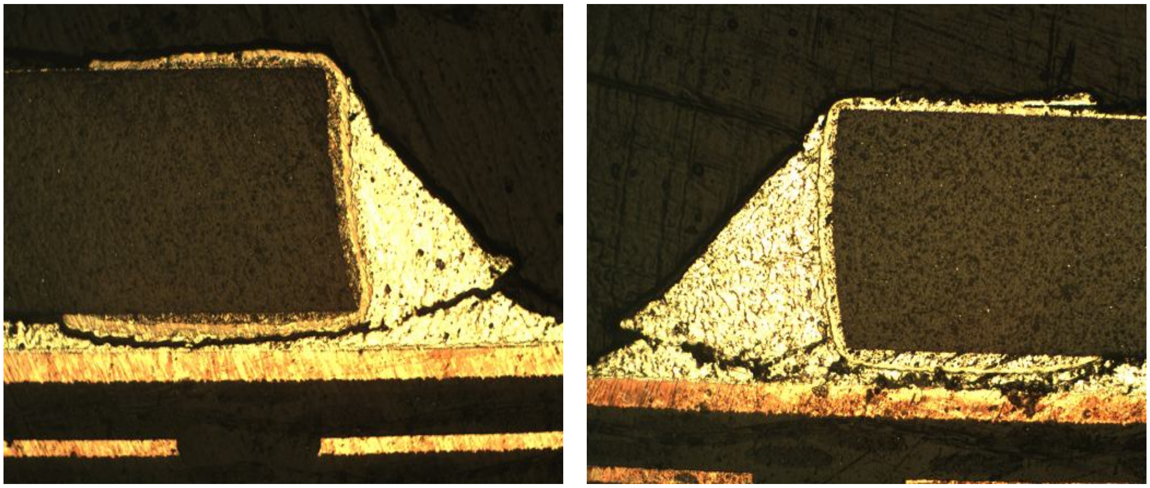


Figure 61 - Hot Melt 2 2512 Resistor Failure Mechanisms, 1200 Cycles

The adhesion properties of the overmolding materials have a great affect on the reliability of the 2512 resistors. Full adhesion to the resistor both on top and underneath the resistor is needed to prevent voids or delaminations under the packages from occurring which lead to failures. Most of these delamination areas or voids are seen near the solder pads. At higher temperatures, there is an increase in delamination due to CTE mismatches which generally lead to bigger voids forming near the solder pads where the stress is the greatest. As seen in Ding's [14] study of underfilling flip chip packages, the phenomenon of solder extruding into voids found in the overmolding material was also seen in this study. These extrusions are due to the solder joint being placed under thermal load along with the CTE mismatches in the Z direction of the substrate attached to the aluminum backplane and the overmolding material during thermal cycling cause the solder to extrude out into the voids at the solder joints.

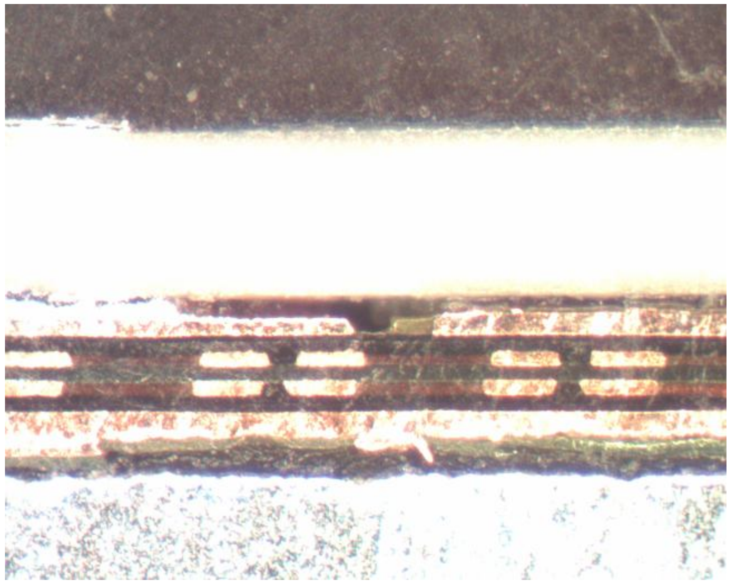


Figure 62 - Void Under 2512 Resistor at Solder Pad on Hot Melt 1 Test Board, 1200 Cycles

Voids under the resistor banks in the hot melt overmolding materials are seen mostly near the beginning of the solder pad under the resistor's solder terminals, as seen in Figure 62 above. These voids were seen in nearly all the resistors cross sectioned with solder extrusions into the voids at the solder pads seen as well. These extrusions, as seen in Figure 63 below, allow cracks to easily form at the edges of the solder joint where the solder is the thinnest and thus less likely to handle the thermal stresses it sees. These cracks then start to propagate along solder pads. Also, since five resistors were in series, it is not necessarily known if the partial cracks or voids seen in the cross sections are the cause of the failures or early indications of future electrical connection failures.

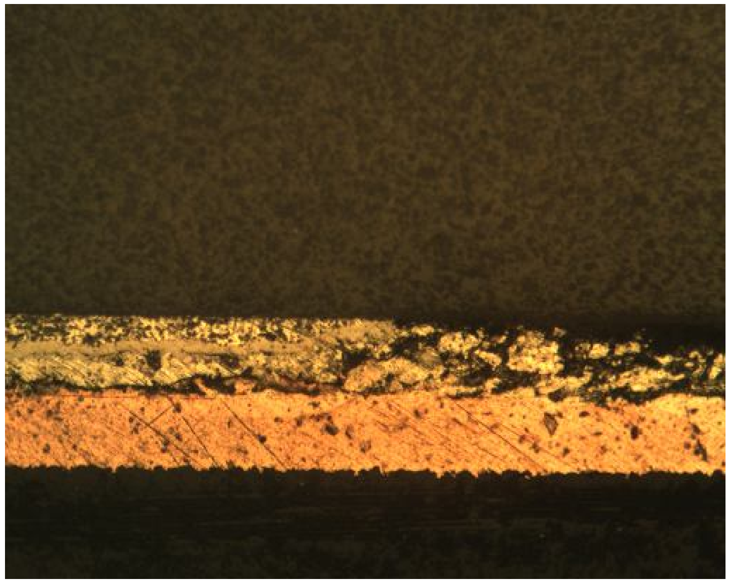


Figure 63 - Solder Extrusion into Void under a 2512 Resistor, 1200 Cycles

The CSP packages showed similar failures as the 2512 resistor banks for the Hot Melt test boards. As seen in Figure 64, the CTE mismatches between the overmolding material and the CSP cause the adhesion between the two to fail, either cracking or breaking of the edges of the CSP or delaminating from the CSP. These failures in the adhesion occur both on top of and underneath the CSP packages on both the Hot Melt test materials. The failures underneath the CSP cause voids or delamination areas near the solder balls and the solder extrusion phenomenon is seen with the solder balls of the CSP as well. These extrusions into voids are found at the solder ball pad connection both at the CSP and the PC board. The voids at the CSP are caused mainly by the cracking of the CSP edges as explained previously, and the voids at the PC board are due to the solder mask creating a void at the edges of the solder pads.

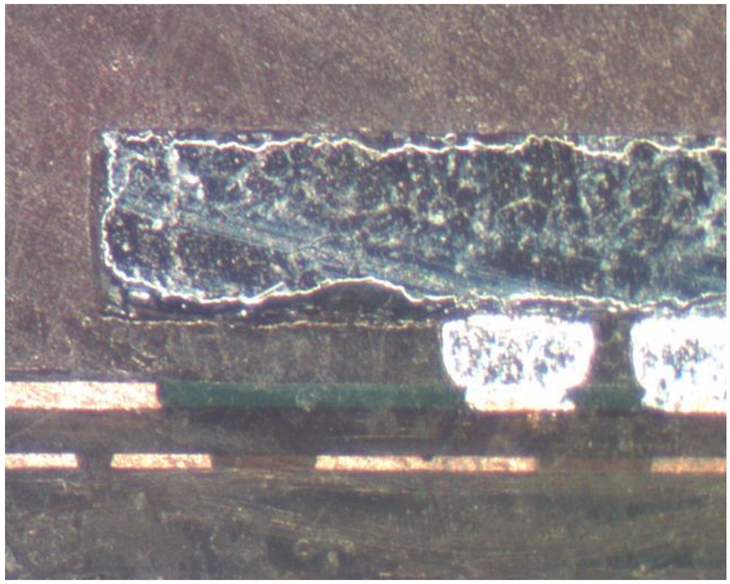


Figure 64 - CSP Cracking on Hot Melt Test Board, 1200 Cycles

Solder extrusions are the main failure mechanism for the solder balls of the CSP packages. Figure 65 and Figure 66 shows the solder joint failures for the Hot Melt 1 and Hot Melt 2 CSP packages, respectively. Both hot melt materials have solder extrusions into voids and the solder crack propagates along the top of the solder ball near the solder pad of the CSP. The solder extrusions cause the solder joints to become weak near the void due to increased embrittlement of the solder, and the thermal stresses form cracks at these solder extrusions near the CSP. Therefore, the solder failures are mainly due to CTE mismatches between the solder joint and the CSP, but no one failure mechanism can be singled out as the main cause of the failures in both the CSP packages and the 2512 resistors.

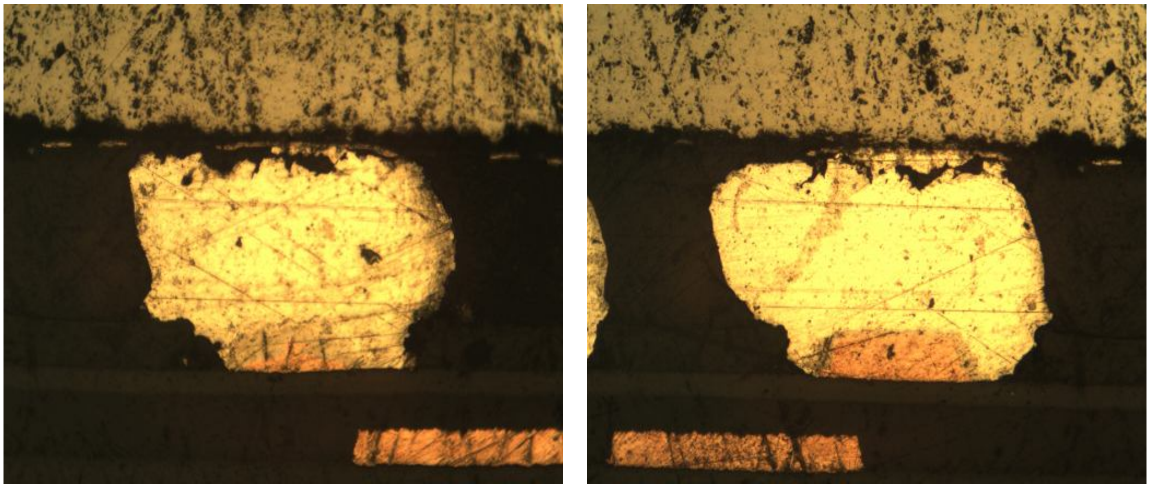


Figure 65 – Hot Melt 1 CSP Solder Ball Failures, 1200 Cycles

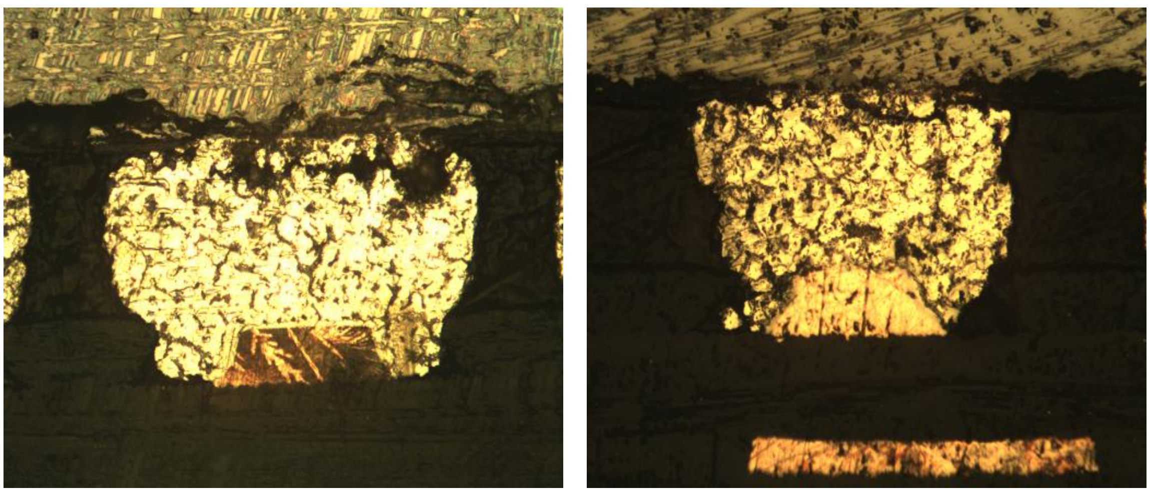


Figure 66 – Hot Melt 2 CSP Solder Ball Failures, 1200 Cycles

The cross section analysis illustrated the theory that Hot Melt 1 test boards would have a higher reliability than the Hot Melt 2 boards due mainly to the higher softening point temperature and higher performance temperature. However, the CSP cross sections show no reliability difference between the two hot melt overmolding materials. In conclusion for the Hot Melt overmolding materials, the early failures of the components and the failure mechanisms of the components confirm that these Hot Melt overmolding materials are not suitable for harsh environment applications where high temperature cycling is involved. More images of the cross sections done on the hot melt test board components are found in Appendix F. The reliability data of the 2512 resistors is shown in a Weibull plot in Appendix H which also shows that these two materials do not provide a reliability increase and have the nearly the same failure trends.

5.2.2 Epoxy Test Boards Failure Analysis

During the thermal cycle testing process, test boards of each type were taken from the -40^{o}C to 125^{o}C and -40^{o}C to 150^{o}C thermal cycle tests after 1200 thermal cycles were completed. Cross sections were performed on the test boards of each substrate and epoxy overmolding combination to determine the failure mechanisms on the CSP and 2512 ceramic resistors.

5.2.2.1 -40^{o}C to 125^{o}C Thermal Cycle Test Boards

No solder joint failures for the 2512 resistors were seen in any of the -40^{o}C to 125^{o}C thermal cycle test. All three epoxies showed good adhesion of the overmolding to the resistor was seen both on top and underneath the resistors on both FLEX and FR4 substrates. Few voids were seen underneath the resistor near the solder pads, as seen in Figure 67, but no solder extrusions were seen into the voids. The epoxy materials showed good underfilling beneath the resistor banks with few exceptions which were due to board surface variations.

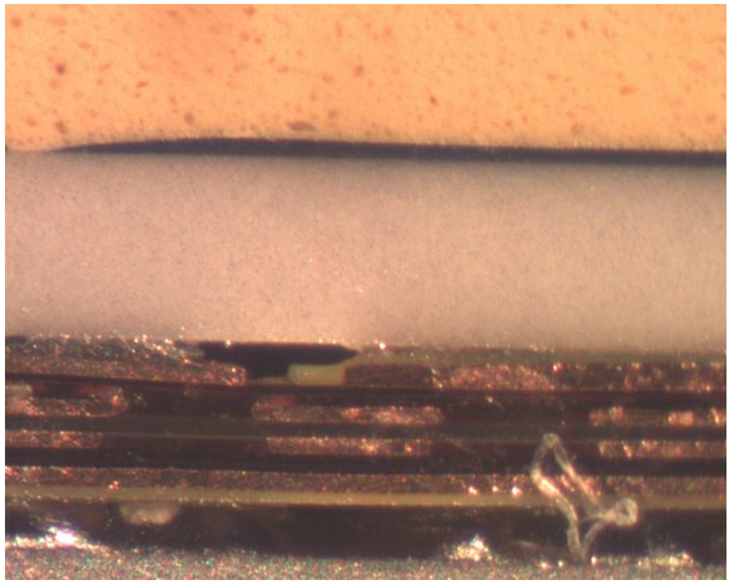


Figure 67 - Epoxy 2 Test Board on FLEX 2512 Resistor Void, 1200 Cycles

The CSP packages showed no failures for the Epoxy 1 and Epoxy 2 test boards on both FLEX and FR4 substrates. The CSP packages had good underfilling between the solder balls with few voids seen. If voids were present, solder extrusions into the voids were not seen which is seen in Figure 68. This leads to the conclusion that the Epoxy 1 and Epoxy 2 overmolding materials provide adequate stress relief on the solder balls in all directions, even overcoming the large CTE mismatch in the Z direction of the overmolding material and the substrate attached to the aluminum back plane as discussed in a previous section. Also, very little destruction to the CSP surface is seen in the cross sections as well for the two epoxy overmolding material test boards as was seen in the hot melt test board CSP packages. This strengthens the previous statement of epoxy overmolding materials providing excellent overall protection to the PC board and the components.

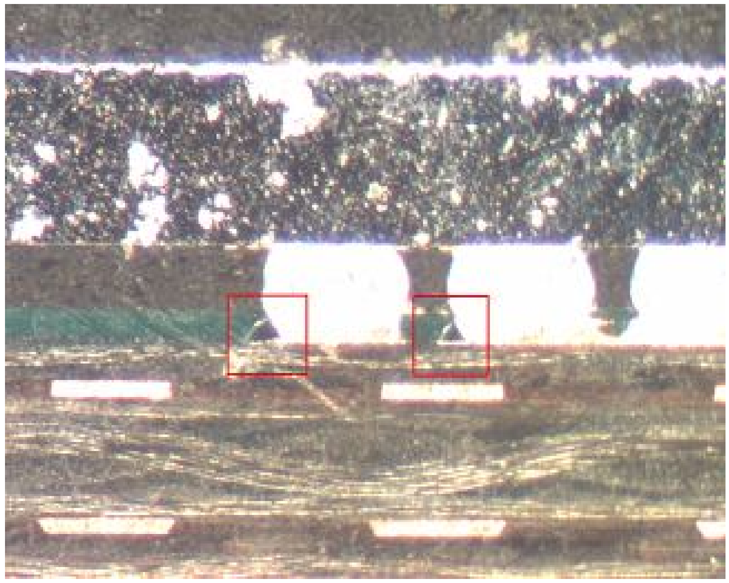


Figure 68 - Epoxy 1 Test Board Showing Voids at Solder Ball Pads with no Solder Extrusion, 1200 Cycles

Epoxy 3 test boards showed significant failures with the CSP packages. Very few voids were seen around or in between the solder balls and any solder extrusions into voids were very small. However, cracks were seen across the top and the bottom of the solder balls both on the outside and inside rows of the package, as seen in Figure 69. These failures are caused by thermal stresses being placed on the solder balls due to CTE mismatches between the solder balls, overmolding material, substrate, and CSP. Due to the low T_g of Epoxy 3, the CTE of the epoxy approximately triples in value from 33 ppm/^{o}C to 90 ppm/^{o}C above 100^{o}C as discussed in a previous section. This drastic increase in CTE at high temperatures, as seen in Figure 43 above, puts extra stress on the solder balls of the CSP causing stress fractures at the high stress areas of the solder balls.

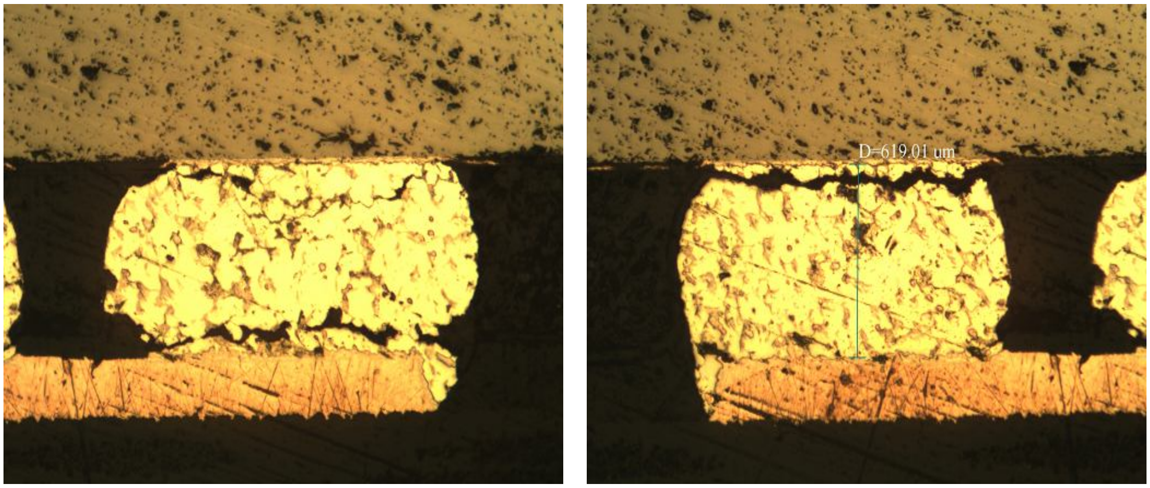


Figure 69 - Epoxy 3 CSP Solder Ball Cross Sections showing Solder Joint Failures, 1200 Cycles

The cross section analysis proved the theory that Epoxy 1 and Epoxy 2 test boards would have a higher reliability than the Epoxy 3 test boards due to the lower CTE and the higher T_g values. The cross sections for the 2512 ceramic resistors show no reliability difference between the three epoxy overmolding materials. However, Epoxy 3 does not provide adequate reliability for the CSP or Flip Chip packages. In conclusion for the epoxy overmolding materials at -40°C to 125°C thermal cycle testing, Epoxy 1 and Epoxy 2 provide excellent protection and increase reliability of the components in harsh environment applications within the temperature range -40°C to 125°C. Epoxy 3 provides adequate protection and increases reliability of the 2512 ceramic resistors, but should not be used for CSP or Flip Chip components in harsh environment applications.

5.2.2.2 -40°C to 150°C Thermal Cycle Test Boards

No complete solder joint failures for the 2512 resistors were seen in of the -40°C to 150°C thermal cycle test. All three epoxies showed good adhesion of the overmolding to the resistor was seen both on top and underneath the resistors on both FLEX and FR4 substrates. Few voids were seen underneath the resistor near the solder pads, as seen in Figure 70, but no solder extrusions were seen into the voids. The epoxy materials showed good underfilling beneath the resistor banks with few exceptions which were due to board surface variations. Any failures seen were in the beginning stages of crack propagation as seen in Figure 71. These failures seen were cracks connecting small voids found in the solder joints. Whether these voids in the solder joints were a manufacturing flaw or caused by the high temperature thermal cycling is unknown.

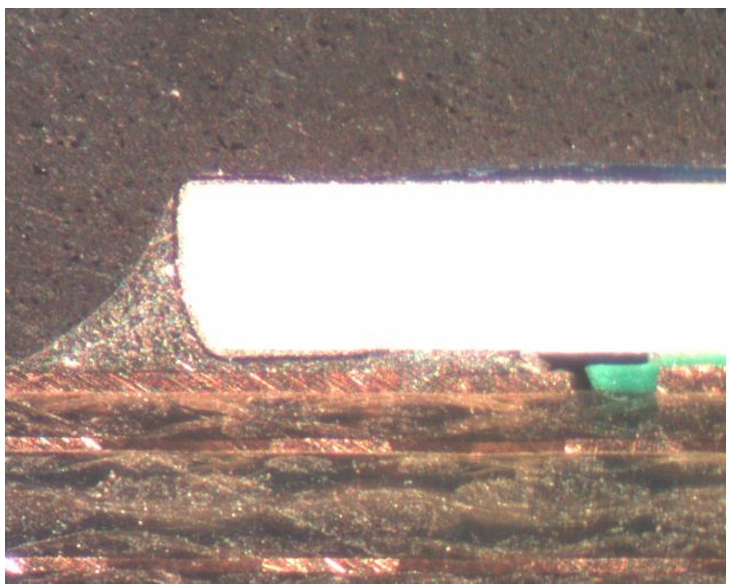


Figure 70 - Epoxy Test Board on FR4 2512 Resistor Void, 1200 Cycles

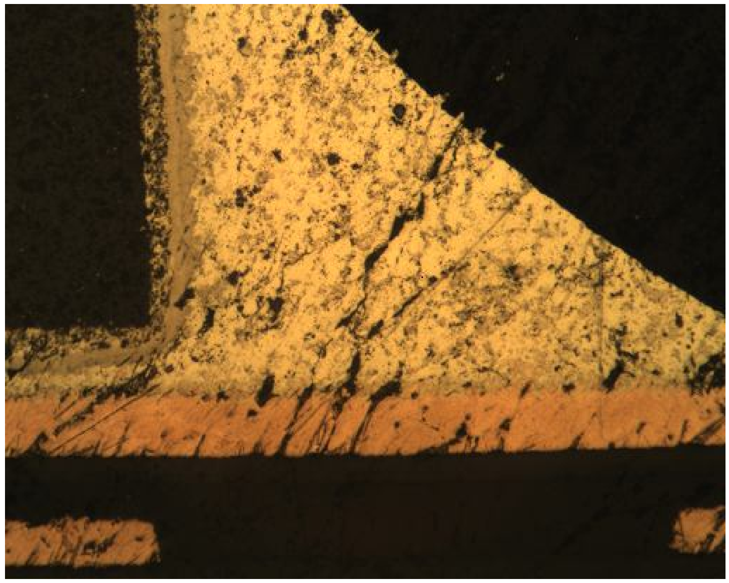


Figure 71 - Epoxy Test Board on FR4 Substrate Solder Joint Crack, 1200 Cycles

The CSP packages showed the initial stages of failures for all three epoxies on both substrates. The CSP packages had good underfilling between the solder balls with few voids seen. Similar to the Hot Melt test boards, the CTE mismatches between the CSP and the epoxy overmolding materials caused slight delamination and cracking of the edge of the CSP, as seen in Figure 72. Unlike in the 125^{o}C test, the higher temperature causes the CTE to increase for the overmolding materials which then places more stress on the adhesion between the CSP and the epoxies. This causes the delamination and cracking at the CSP surface.

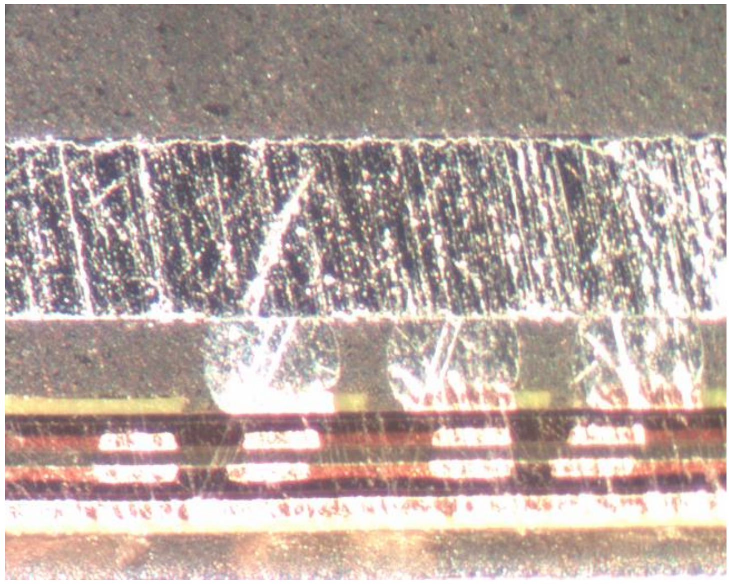


Figure 72 - Epoxy Test Board Showing CSP Surface Cracking, 1200 Cycles

The solder extrusion into overmolding voids was also seen in the cross sections of the CSP packages on the 150^{o}C test boards. The cracks of the solder joints for all three epoxies were due to solder extrusions and increased thermal stresses due to increased CTE mismatches at higher temperatures. All three epoxies nearly triple their CTE values near 150^{o}C. This accounts for the cracks seen in the 150^{o}C test boards compared to the 125^{o}C test boards. All the cracks however originated from the voids or extrusions. Also, seen were cracks connecting small solder ball voids and whether the voids are due to the high temperature thermal cycling or not is again unknown. The solder ball cracks for the different combinations in the 150^{o}C test are shown in Figure 73 through Figure 76.

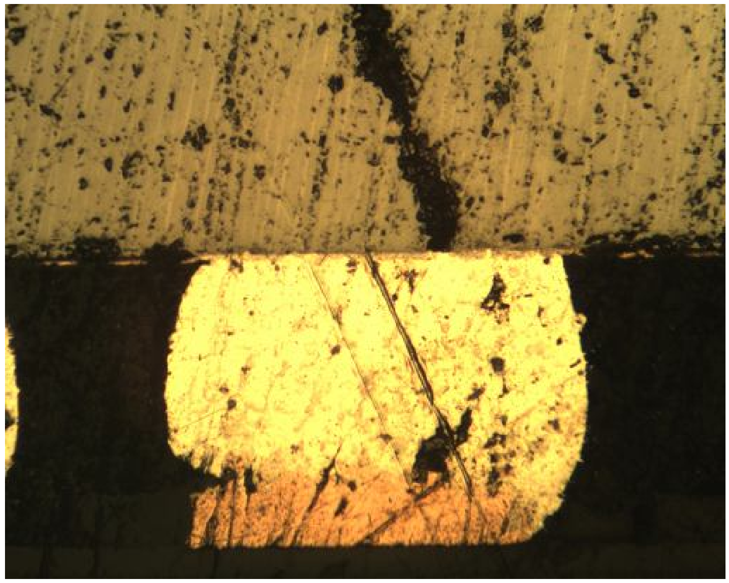


Figure 73 – Epoxy 1 on FLEX Substrate Solder Ball Crack, 1200 Cycles

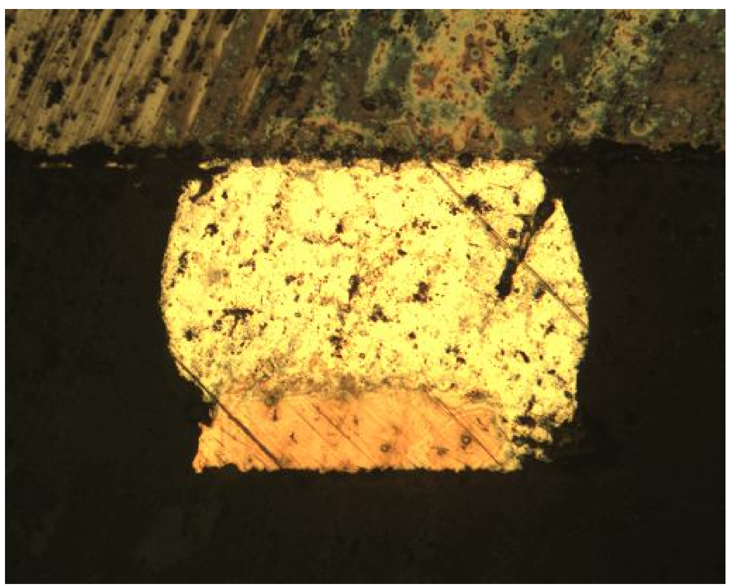


Figure 74 – Epoxy 1 on FR4 Substrate Solder Ball Crack and Solder Extrusion into Void, 1200 Cycles

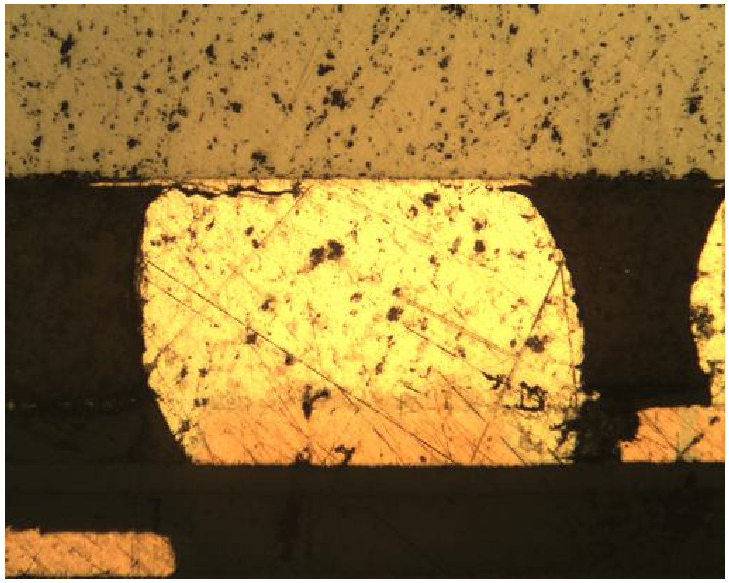


Figure 75 – Epoxy 2 on FLEX Substrate Solder Ball Crack and Solder Extrusion into Void, 1200 Cycles

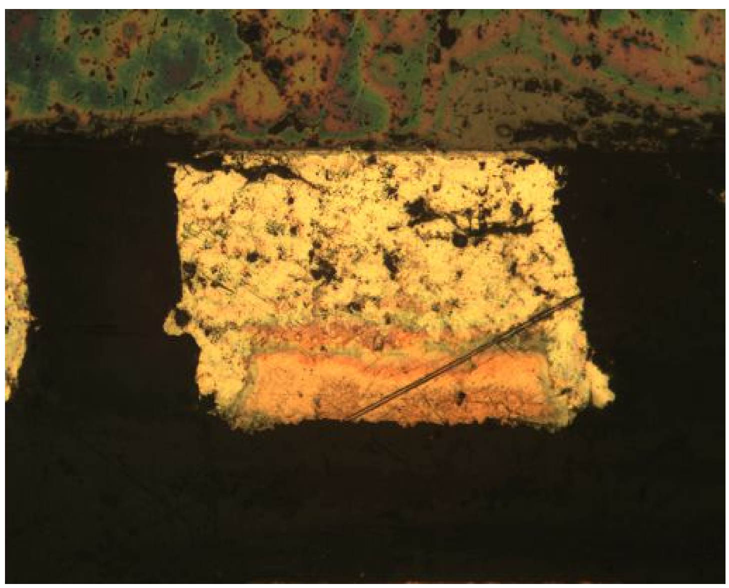


Figure 76 – Epoxy 3 on FR4 Substrate Solder Ball Crack, 1200 Cycles

Two things are drastically different on the Epoxy 2 and Epoxy 3 test boards than were seen in the 125^{o}C test mentioned above. First for the Epoxy 2 test boards, the epoxy was seen to crack at the edge of the CSP package. This crack, seen in Figure 77, is due to CTE mismatches between the CSP and the epoxy which is increased at the high temperature of the 150°C thermal cycle testing. Secondly, Epoxy 2 test boards show the overmolding material delaminating from the substrate surface, as seen in Figure 78. This allows for cracks to start forming in the solder balls of the Epoxy 2 test boards, unlike in the 125°C test, due to CTE mismatches in the Z direction between the substrate attached to the aluminum back plane and the overmolding material. Once detached from the substrate, the epoxy can no longer protect the solder joint from the thermal stresses caused by this CTE difference.

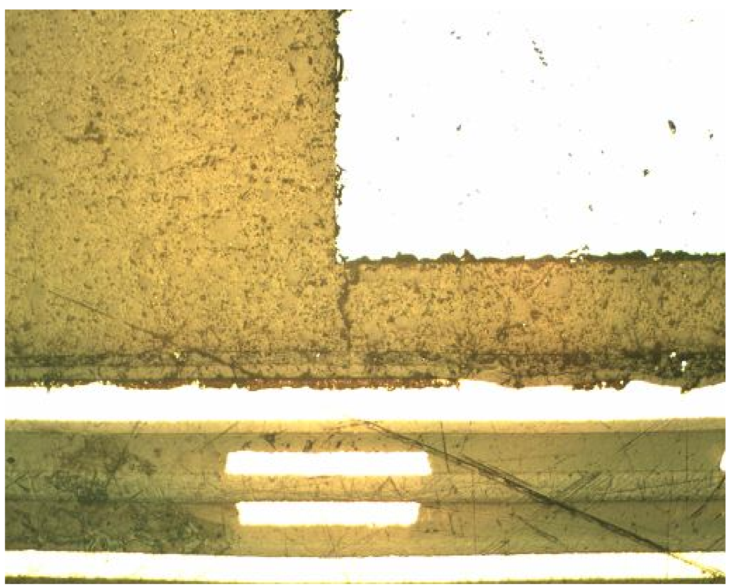


Figure 77 – Epoxy 2 on FLEX Substrate Showing Overmolding Crack at CSP Edge, 1200 Cycles

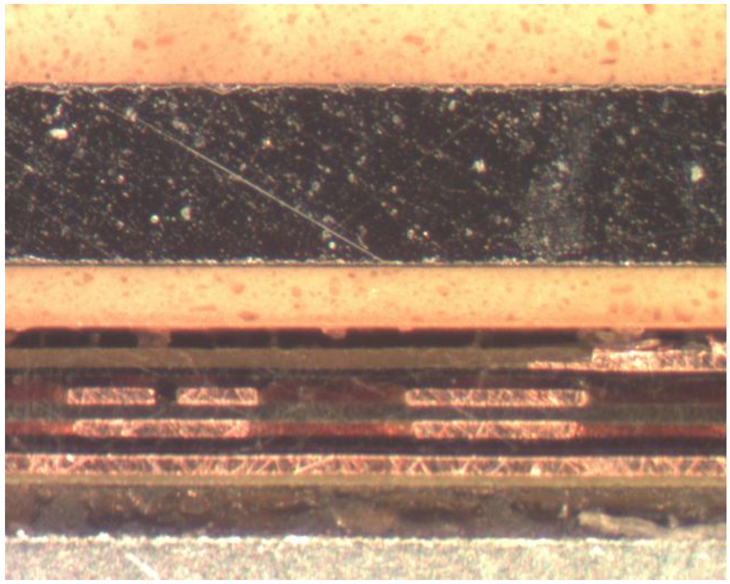


Figure 78 – Epoxy 2 on FLEX Substrate Delamination of Overmold from the Substrate, 1200 Cycles

For the Epoxy 3 test boards, no complete solder joint failures were seen in the Epoxy 3 150^{o}C test boards compared to multiple being seen in the 125^{o}C test boards. There were definite signs of solder extrusions and cracks forming within the solder joints so failure is imminent within the packages, but the failure of the components seemed to have been slowed down due to the delamination of the overmolding from the substrates. Further studies would need to be done in order to understand why this phenomenon is happening.

The cross section analysis shows that the three epoxy overmold materials are not well suited to be used as overmolding materials for Flip Chip applications where the temperature reaches 150^{o}C. However, for 2512 resistors the epoxy overmolding materials seemed to have increased the reliability even at the increased temperature range. In conclusion for the epoxy overmolding materials at -40^{o}C to 150^{o}C thermal cycle testing, the three epoxies provide adequate protection and increases reliability of the 2512 ceramic resistors, but should not be used for CSP or Flip Chip components in harsh environment applications. More images of the cross sections done on the epoxy test board components are found in Appendix G.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

6.1 Future Work

This research was performed to investigate the subject of completely overmolding a fully populated PC board to be used in harsh environment applications. The work has broadened the knowledge of this area along with raising more questions and providing better ideas for future works in this area. The information from these works can be directly applied to the future design area of overmolding electronic components. There are two tests that are either being completed now or are in the beginning stages of design. The first is looking into the thermal reliability of the adhesive used to attach the substrate to the metal back plane. The second is the second stage of this overmolded PC board study.

The first study, which is currently being run, looks at the thermal reliability of different adhesive materials attaching FLEX and FR4 substrates to aluminum metal back planes. The system uses a test fixture which the substrates attached to an aluminum back plane are securely fastened to make a water proof seal on the bottom of the aluminum plate. A thermocouple attached to fixture measures the temperature of the aluminum back plane directly below a bank of four 2512 100 ohm resistors. The resistors are arranged in a square and when power is applied to the circuit will produce heat emulating a BGA package. A thermistor is in the middle of the four resistors directly above the thermocouple. A computer system then runs different power amounts through the circuit and measures the thermistor and thermocouple temperatures. The software measures and records the difference in temperature between the thermocouple and thermistor. The test boards are then placed in thermal cycle testing for a certain number of cycles until pulled and the temperatures measured again. The test is looking for delamination of the adhesive due to thermal stresses applied during thermal cycling. This study will help determine the best adhesive to use in future applications where a metal back plane is used.

The second work is the second phase of this overmolding PC board research. The next phase uses only epoxy overmolding materials on both FR4 and Stablcor FR4 substrates included in the test matrix. Stablcor materials when placed in substrates have been shown to significantly increase component reliability by lowering the CTE of the substrate thus increasing the thermal performance of the PC board. The test will use two different board layouts, two different adhesives to attach the substrate to the aluminum back plane, three different epoxy overmolding materials, and two different solders. One board layout will have Flip Chip packages, 2512 ceramic resistors, 1218 ceramic resistors, 1206 ceramic resistors, and 1206 ceramic capacitors. The second board layout will contain some Chip-on-Board (CoB) packages, 2512 ceramic resistors, 1218 ceramic resistors, 1206 ceramic resistors, and 1206 ceramic capacitors. Also, an underfill material will be dispensed under the Flip Chip packages before being overmolded on certain test boards, and a glob top material will be dispensed on the CoB packages before being overmolded on certain test boards. The test will look at the reliability of the components while being test in Air-to-Air thermal shock testing. This research along with the follow of the study presented in this document will provide adequate knowledge in looking into the future of overmolded PC board technology.

6.2 Conclusions

This thesis concentrated on the reliability affects of overmolding a populated PC board attached to an aluminum back plane. Two Hot Melt and three Epoxy overmolding materials were used on FLEX and FR4 substrates. Each board had two 7mm CSP packages and two, five 2512 ceramic resistors in series resistor banks. Two different tests were setup due to the high temperature of the Air-to-Air thermal cycle testing. The -40^{o}C to 125^{o}C test had both the Hot Melt and Epoxy materials in the test matrix. The second test had temperatures of -40^{o}C to 150^{o}C and included only the epoxy overmolded test boards. The profiles of the thermal cycle chambers were setup up to have the substrate and components to the desired temperature ranges with fifteen minute dwells on the hot and cold sides of the thermal cycles in both tests. Material property testing was done on the epoxy overmolding materials and the substrates to determine the CTE, T_g, Stress versus Strain curves for different temperatures, and elastic modulus values. Test boards of each combination were also taken out at 1200 thermal cycles in both tests to be cross sectioned and analyzed.

The following was concluded from the material property testing: (1) the Hot Melt overmolding materials are not suitable for harsh environment applications due to low softening point temperature, (2) Epoxy 1 and Epoxy 2 should provide excellent protection and increase the reliability of both the CSP and 2512 ceramic resistor components in the -40^{o}C to 125^{o}C thermal cycle test and Epoxy 3 will not significantly increase reliability compared to the other two epoxies due to the significant deterioration of material properties after 100^{o}C, (3) all three epoxies will not provide adequate protection or significantly increase reliability in the -40^{o}C to 150^{o}C thermal cycle testing due to significant increase in CTE values near 150^{o}C, (4) CTE mismatches in the Z direction between the substrates attached to an aluminum metal back plane are highly significant and should cause immense thermal stresses to be placed on the components and overmolding material adhesion to the aluminum back plane.

The following was concluded from the -40^{o}C to 125^{o}C thermal cycle testing: (1) the Hot Melt overmolding materials are not suitable for harsh environment applications due to rapid deterioration and destruction of the overmolding materials, (2) Epoxy 1 and Epoxy 2 provide excellent protection and increase the reliability of both the CSP and 2512 ceramic resistor components, (3) Epoxy 3 increases the reliability of the 2512 resistors but the CSP shows significant failures after 1200 thermal cycles, (4) thermal stresses cause solder to extrude into voids at solder joints which quicken the creation of solder joint cracks.

The following was concluded from the -40^{o}C to 150^{o}C thermal cycle testing: (1) all three epoxies will not provide adequate protection or significantly increase reliability in the -40^{o}C to 150^{o}C thermal cycle testing for Flip Chip packages, (2) the significant changes in CTE values of the overmolding materials increases the thermal stresses placed on the Flip Chip packages thus decreasing reliability, (3) thermal stresses cause solder to extrude into voids at solder joints which quicken the creation of solder joint cracks.

The overall reliability benefits of overmolding electronic PC boards will be looked into in the follow up testing done of this first phase of this research work.

However, valuable information about how the overmolding interacts with the components and substrates will give light to future designs to use overmolding technology in the automotive industry.

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APPENDIX A: Cross Section Procedure

Step I: Underfill the Electronic Package

1. Retrieve the underfill and allow 30 minutes for the underfill to thaw out.
2. Retrieve a hot plate and heat it to 110ºC. For accuracy, use a thermocouple to ensure that the hot plate is 110ºC.
3. Place the board on the hotplate.
4. Using a suitable syringe tip, dispense the underfill on the sides of the desired electronic component.
5. Bake the board at 165ºC for 20-25 minutes.

Step II: Coating the Plastic Holders

1. Retrieve the red/blue plastic holders.
2. Retrieve the silicone release agent (Buehler Release Agent).
3. Apply the silicone agent liberally to the inside of the plastic holders.
4. Let the silicone agent dry (5 minutes), and then reapply.
5. Label all of the holders so that each cross section can be easily identified.

Step III: Cutting the Electronic Package

1. Using a fine tipped permanent marker, mark the area of interest of the electronic package.
2. The Isomet 1000 wet saw is used to make the cuts.
3. If the coolant is clean, continue, otherwise replace solution:
    a. 1 part coolant with 9 parts water (ratio 1:9).
    b. Cover the bottom of the saw with 3/8" of the solution.
4. Dress the cutting blade at 250 rpm - 2 passes.
5. Develop a cutting scheme for the electronic package.
6. Cutting speed at ~ 200 rpm.
7. Cut "proud" of the electronic package.
8. When finished, empty and replace the solution.

Step IV: Pouring Epoxy Resin

1. Retrieve the Sampl-Klips.
2. Put these clips on all of the samples.
3. With the use of tweezers, put the area of interest down (flush) in the holder.
4. Using the appropriate ratio, mix the epoxy resin & hardener in a Dixie cup.
5. Mix the resin and hardener by scooping with a tongue depressor from the bottom while tipping the cup at the angle. The mixture should turn clear when completely mixed.
6. Lay down aluminum for all of the plastic holders to be placed on.

7. Pour the epoxy on the sample. Start the pouring directly on the samples. The mold is completed when the epoxy resin completely covers the sample.
8. Allow 24 hours at room temperature for hardening.

Step V: Polishing Part 1

1. While the sample is still in the mold, etch onto the top of the mold the details of the sample so that they can be distinguished.
2. Push the sample out of the plastic holder
3. The surface grinder/polisher is the Ecomet 6.
4. Turn the main water valve on.
5. Take the metal clamp off of the wheel and put on the 250 grit paper.
6. Once the paper is secured on the wheel, turn on the water and make sure the stream of water hits the middle of the wheel.
7. Turn the wheel On ➔ 150 – 200 rpm.
8. Wet the sample.
9. With moderate pressure, place the sample on the spinning wheel. Move the sample back & forth for 3-5 seconds. Lift the sample up, rotate 90º, and place it back on the spinning wheel. (~3 minutes)
10. When the solder ball/termination is noticeable, switch to the 750 grit paper and apply the same routine a mentioned before. (~3 minutes)
11. Put the 1,200 grit paper on the polisher and apply the same routine. (~3 minutes)

Step VI: Polishing Part 2 – Masterprep

1. Replace the 1,200 grit paper and replace it with a magnetic black cover (Chemomet).
2. Turn the water on to dampen the black cover.
3. Shake the white masterprep solution.
4. Wet the sample.
5. Turn the wheel on ➔ 200 rpm.
6. While the wheel is spinning add a couple drops of the masterprep solution every 5-6 seconds.
7. With moderate pressure, place the sample on the spinning wheel. Move the sample back & forth for 3-5 seconds. Lift the sample up, rotate 90º, and place it back on the spinning wheel.
8. To check the progress, clean the sample and look under the microscope. The scratches in the sample should be disappeared and everything should be clear.
9. This process takes approximately 5-7 minutes.
10. When finished, turn the water off and squeegee the solvent out. To dry the black surface, increase the wheel speed to 300 rpm and let it spin for 5 minutes.

Wash off and dry the samples with compressed air.

APPENDIX B: How to Check Component Failures

Use a multimeters to probe out the part on the PC board using the designated wire holes on the board. Also, probe out the Connector board using the soldered together Ground pins and appropriate Channel # pin found on the back side of the Connector board. You should get the same reading when probing out the PC board and the Connector board.

A. If the part probes out high on both the PC board and Connector board. Go to STEP 2.

B. If the part probes out normal on both the PC board and the Connector board but MarkDano outputs the resistance of the part above the resistance level set in the failure file. Go to STEP 3.

C. If both the PC board and the Connector Board read "0", go to STEP 4.

D. If the part probes out okay on the PC board and not on the Connector board. Replace the foot (the metal crimped part that connects into the plastic connectors which are then connected to the Connector boards).

E. Probe out both the PC board and Connector board again. If no change occurs, go to STEP 4.C.

F. If the part probes out okay on the Connector board and not on the PC board. Resolder the wire for the part on the PC board. Probe out both the PC board and Connector board again. If no change occurs, go to STEP 5.

2. If the part probes out high.

   A. Resolder the wire and replace the foot for the part.

   B. Probe out the part again on both the PC board and the Connector board. If it still probes out high in both places then it's a failure. Document the failure in the appropriate log file.

   C. If the PC board reads normal and the Connector board still reads high, go to STEP 4.C. and treat it like it's an open circuit.

   D. If the Connector board reads normal and the PC board still reads high, resolder the wire. Probe out both the PC board and Connector board again. If both probe out normal, reset the failure value count to zero for the part. If no change occurs, go to STEP 5 and treat it like it's an open circuit.

3. If the part probes out normal but MarkDano reads the resistance level above the resistance level set in the failure file.

   (This will occur sometimes if the part has actually failed. The failure will show back up when the cycle reaches the hot side.)

   A. Resolder the wire and replace the foot for the part and reset failure value count for that part to zero.

   B. If the part shows back up as a failure again within 10-20 cycles of resetting the failure value count, then it's a failure. Document the failure in the appropriate log file.

4. If the part probes out as "0" on the multimeters, meaning that there is an open circuit.

   A. Resolder the wire and replace the foot for the part.

   B. Probe out the PC board and the Connector board again to see if a reading is seen on the multimeters. If both the PC board and Connector board probe out normal, reset the failure value count to zero for the part.

   C. If a reading is seen on the PC Board and not the Connector board, probe out the wire for the part from the PC board to the Connector board to see if the wire needs to be replaced. If wire is bad, replace wire. Then probe out the PC board and the Connector board again to see if there are any changes. If they both probe out normal, reset the failure value count to zero for the part. If the do not probe out normal, go to STEP 4.C.I.

I. If the wire is okay, replace the Connector board. Then probe out the PC board and Connector board again. If they probe out normal, then reset failure value counts to zero for the part. If no change, go to STEP 4.C.II.

II. If the Connector board still reads "0", replace the ribbon cable. Then probe out the PC board and Connector board again. If they probe out normal, then reset failure value counts to zero for the part. If still no change is seen, it's a failure. Document the failure in the appropriate log file.

D. If a reading is seen on the Connector board and not the PC board, resolder the wire for the part. If both PC board and the Connector board probe out normal, reset the failure value count to zero for the part. If no change occurs, go to STEP 5.

E. If PC board and Connector board probe out as “0” still, replace the Connector board. If both PC board and the Connector board probe out normal, reset the failure value count to zero for the part. If they still probe out “0”, replace the Ribbon Cable. If both PC board and the Connector board probe out normal, reset the failure value count to zero for the part. If both are still reading “0”, it’s a failure. Document the failure in the appropriate log file.

5. If the Connector board probes out normal and the PC board probes out to be “0”.

A. Make sure the wire for the part is connected to the correct Channel # on the Connector board. If there is a mix up in the wiring on the Connector board, reset the failure value counts for the parts which were not correctly connected to the Connector board. Then go to STEP 2.

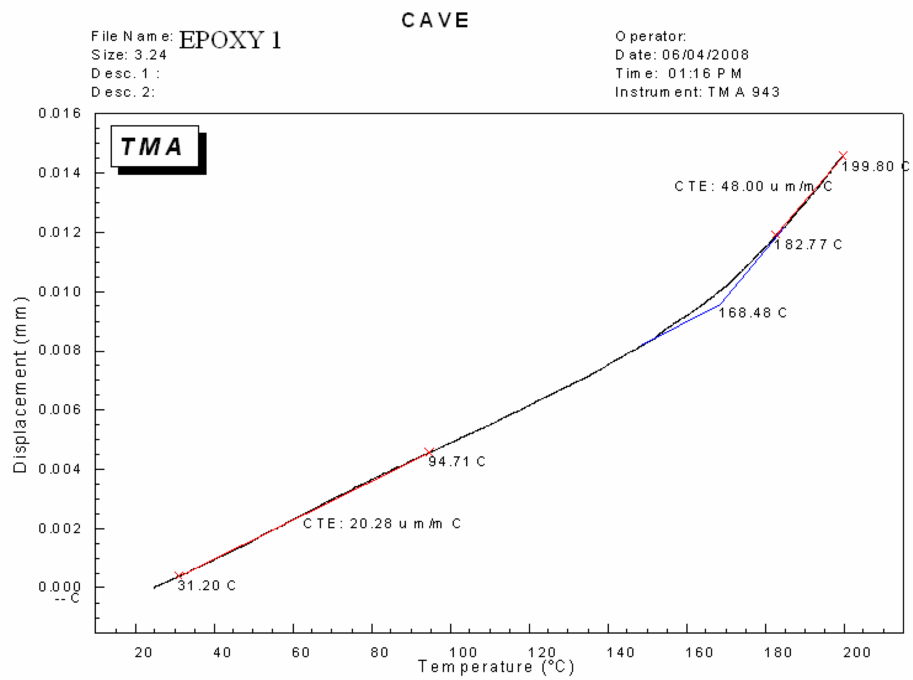
B. If wires are connected correctly on the Connector board, resolder the wire. Probe out the PC board and the Connector board. If they probe out normal, reset failure value counts to zero for the part.

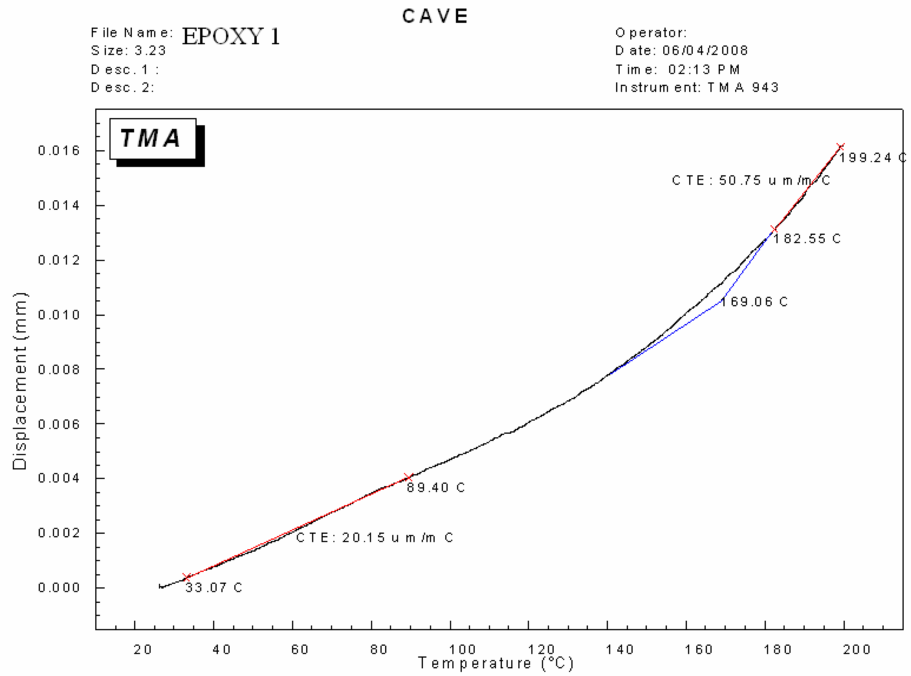
C. If no change occurs, make sure the probes are connected correctly to the multimeters and that the multimeters has good batteries. Probe both the PC board and Connector board again. If they probe out normal, reset failure value counts to zero for the part.

D. If you still can not probe out the part on the PC board but you still can probe it out on the Connector board and MarkDano is giving you a reading that is not an open circuit, start at STEP 2 again. You have done something wrong.

APPENDIX C: Epoxy and Substrate TMA Test Results

EPOXY 1





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CTE: 50.75 um/m C
182.55 C
169.06 C
89.40 C
CTE: 20.15 um/m C
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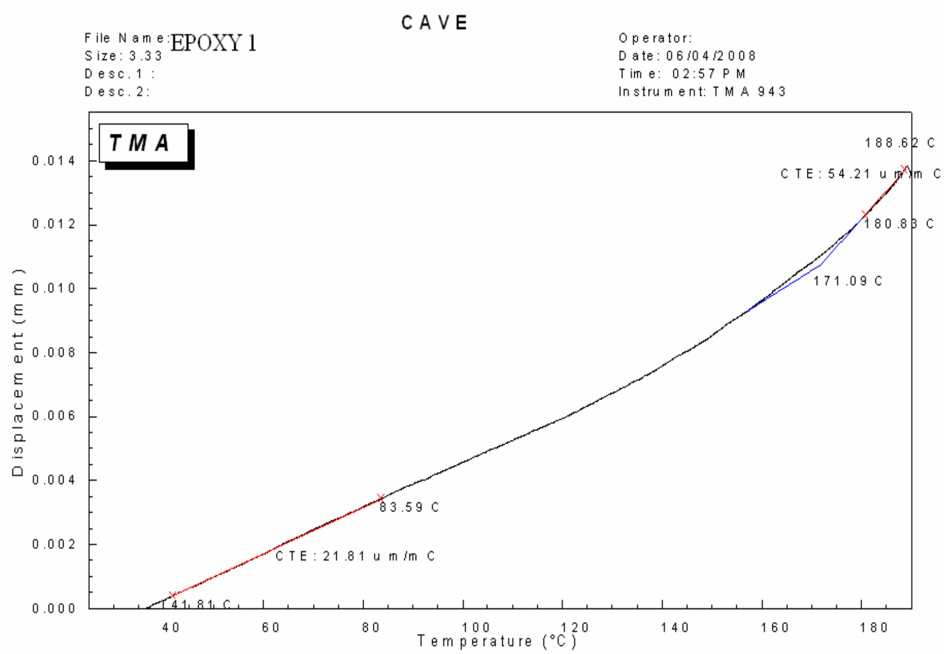
Displacement (mm)
Temperature (°C)



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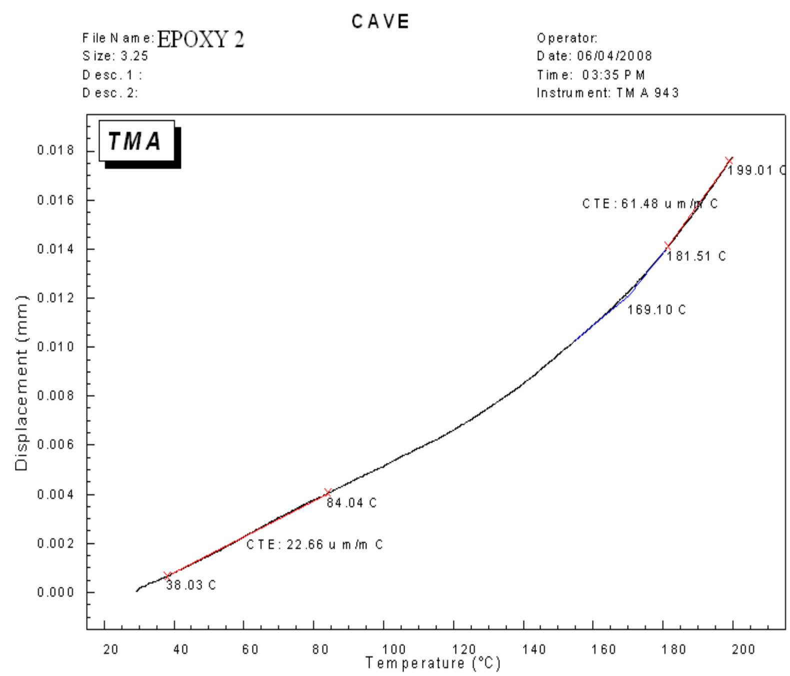
Temperature (°C)

EPOXY 2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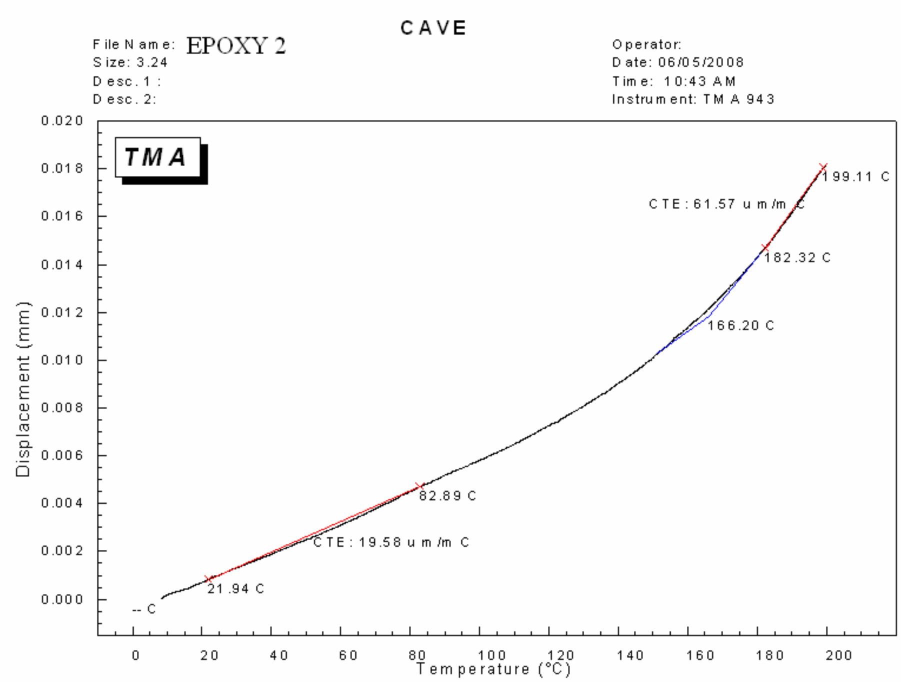
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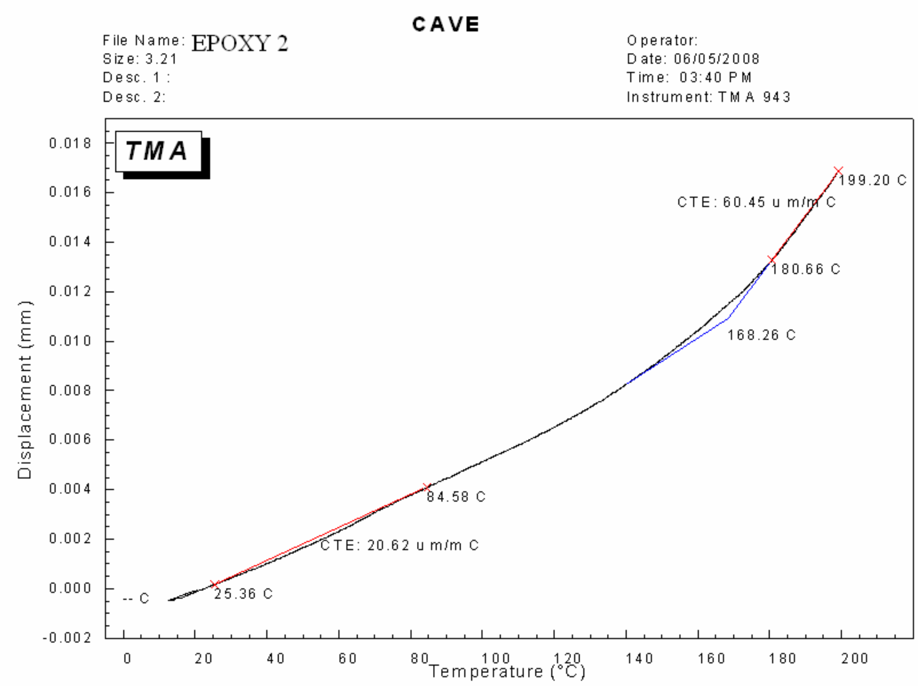
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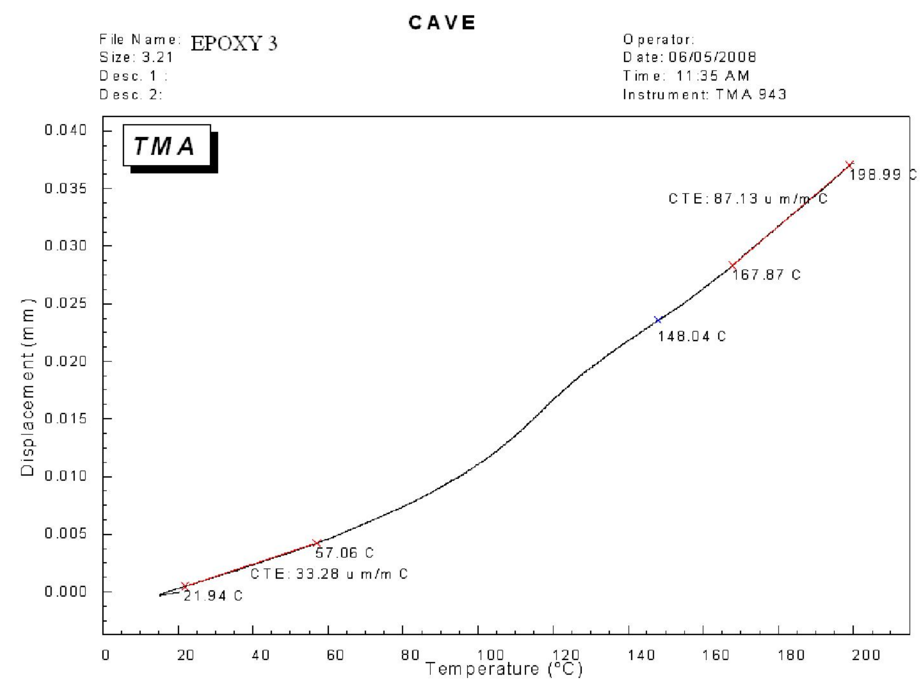
Temperature (°C)

EPOXY 3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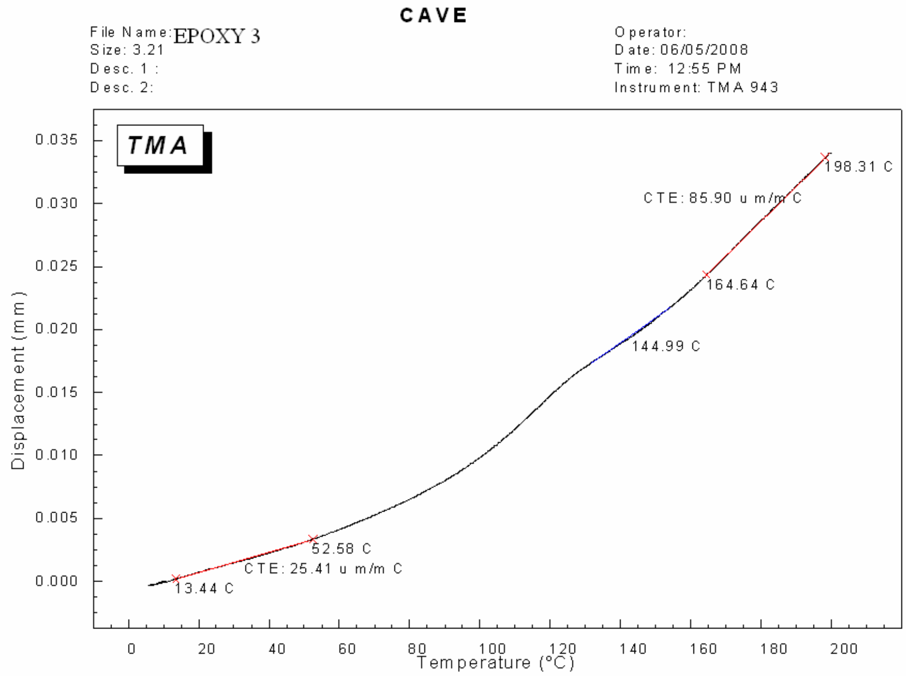
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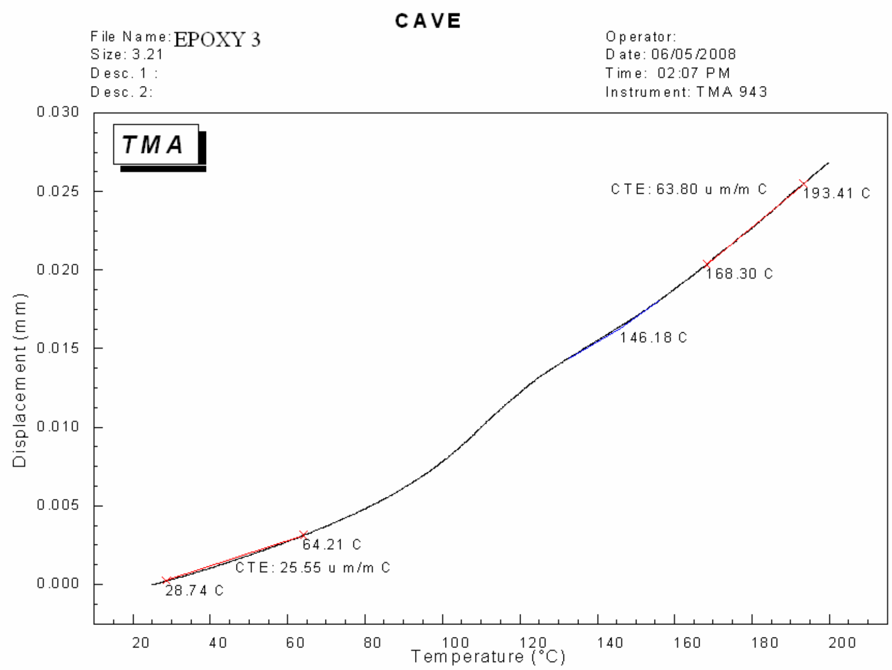
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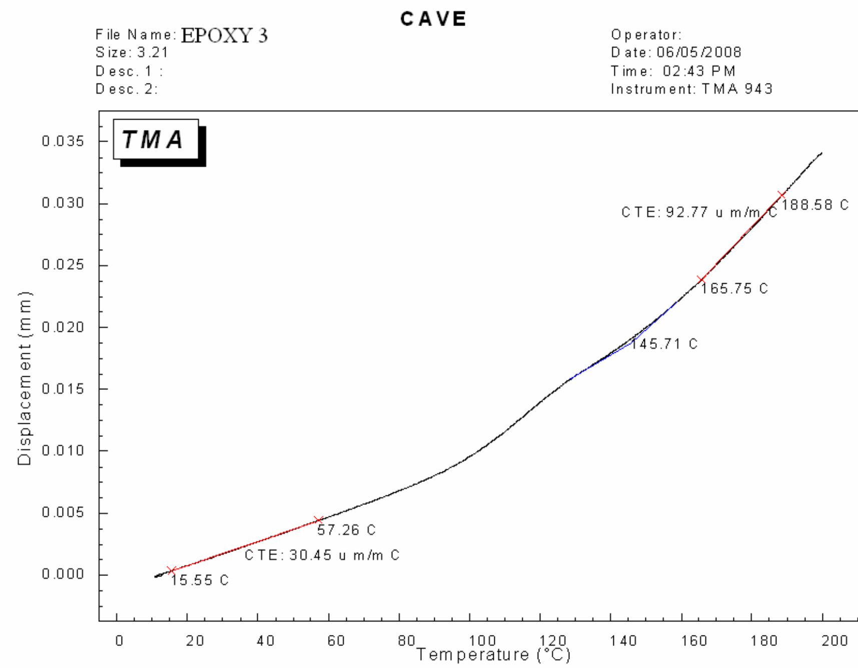

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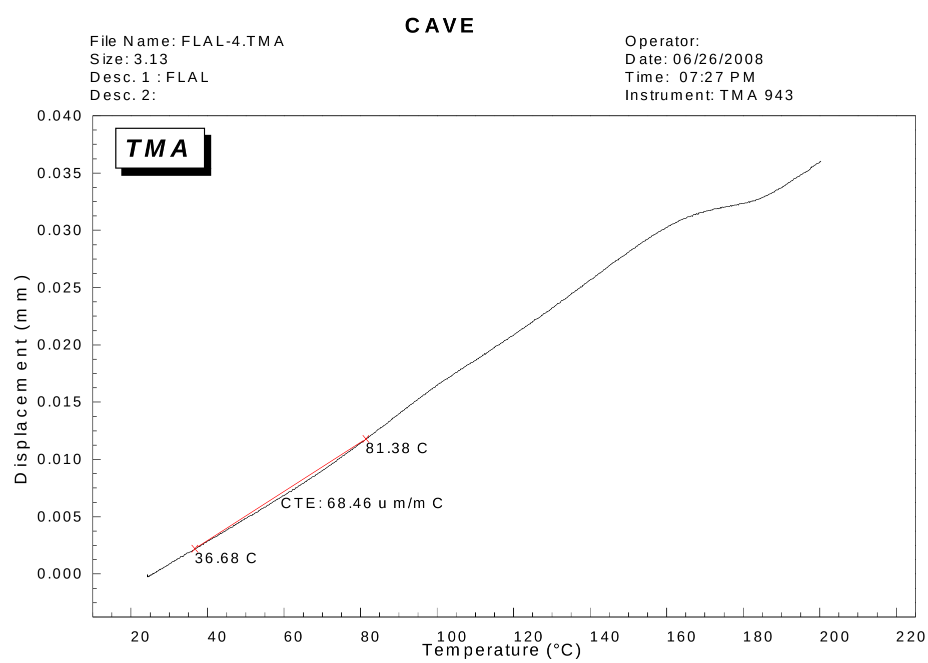

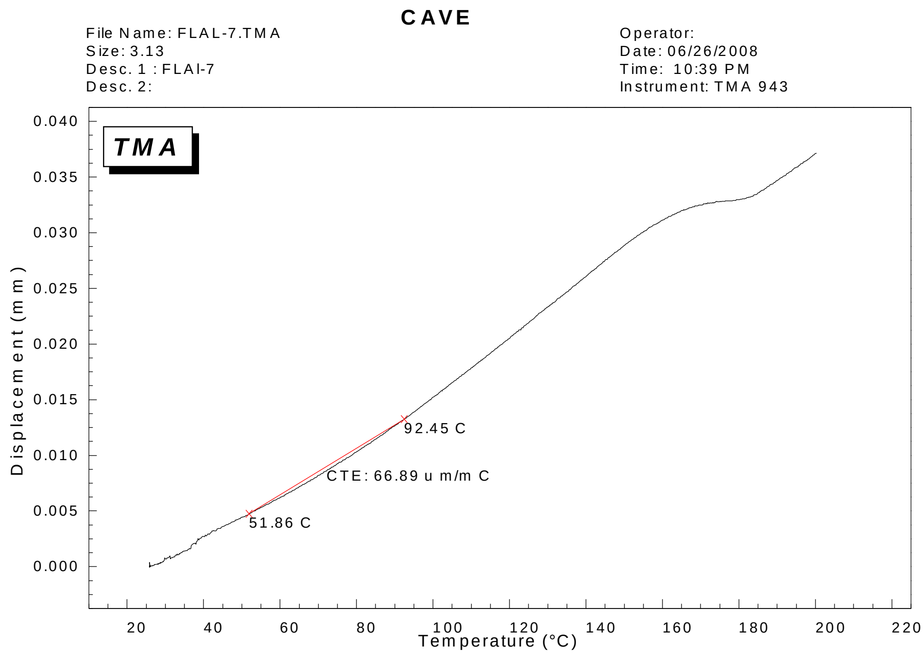

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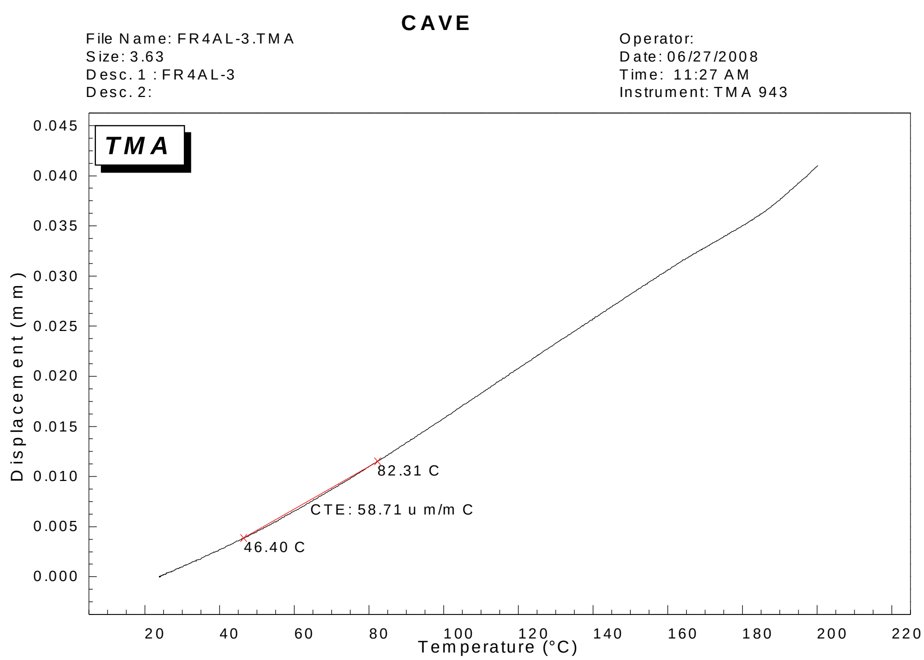

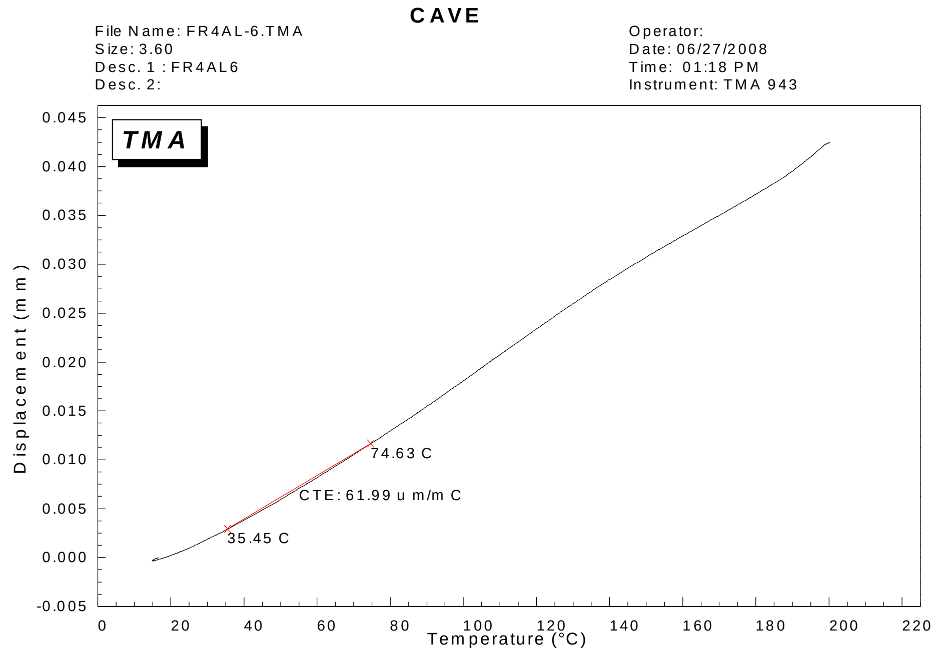
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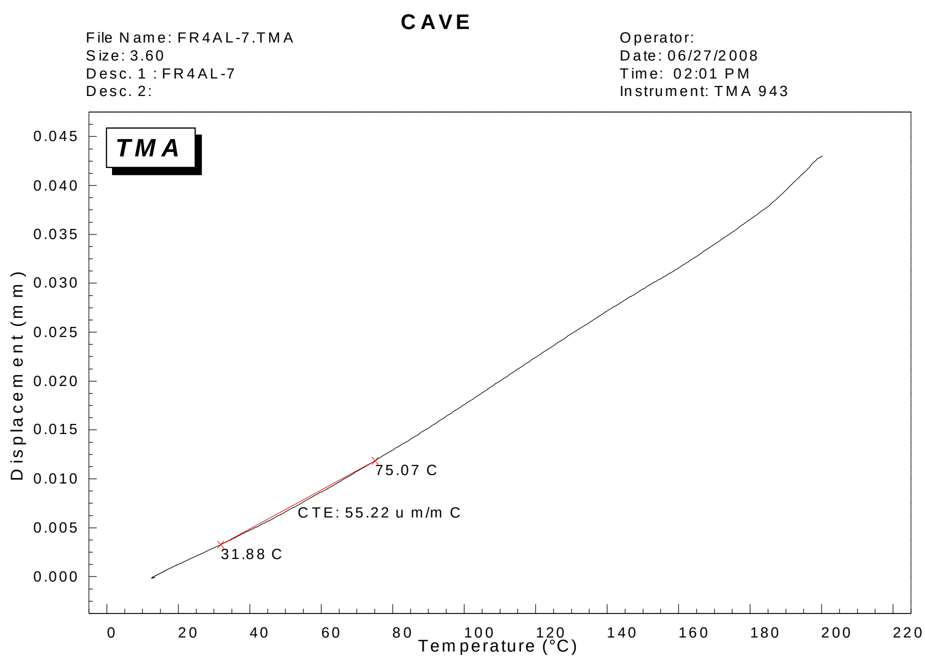
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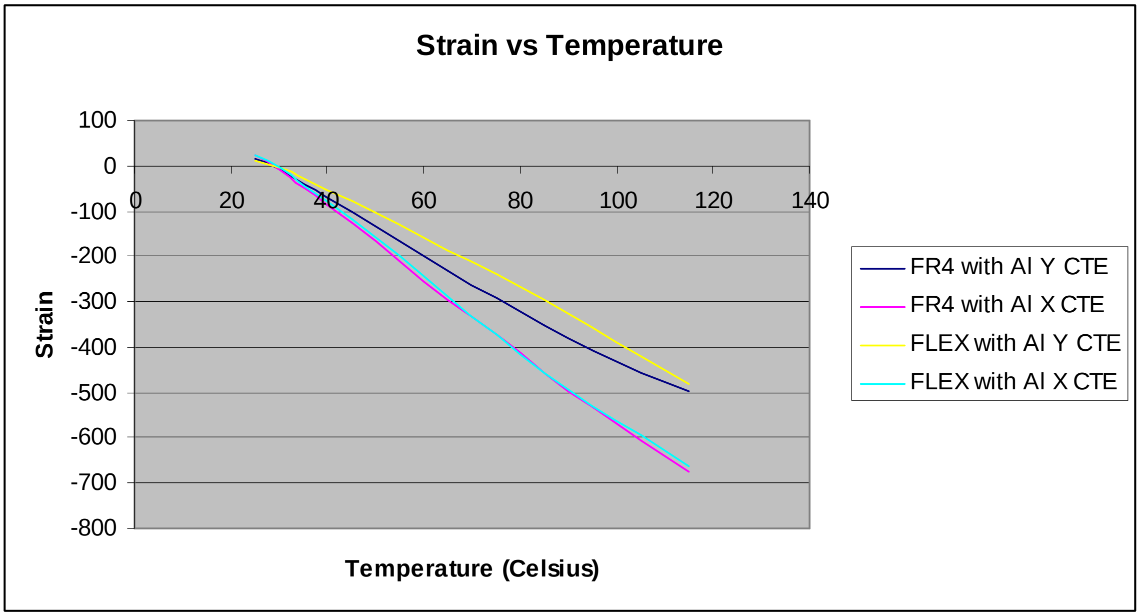
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
20
40
60
80
100
120
140
160
180
200
220

APPENDIX D: Strain versus Temperature Graphs from the Strain Gage CTE Testing



APPENDIX E: Epoxy Test Board Images of Cracks at Aluminum Edge after 1200 Cycles

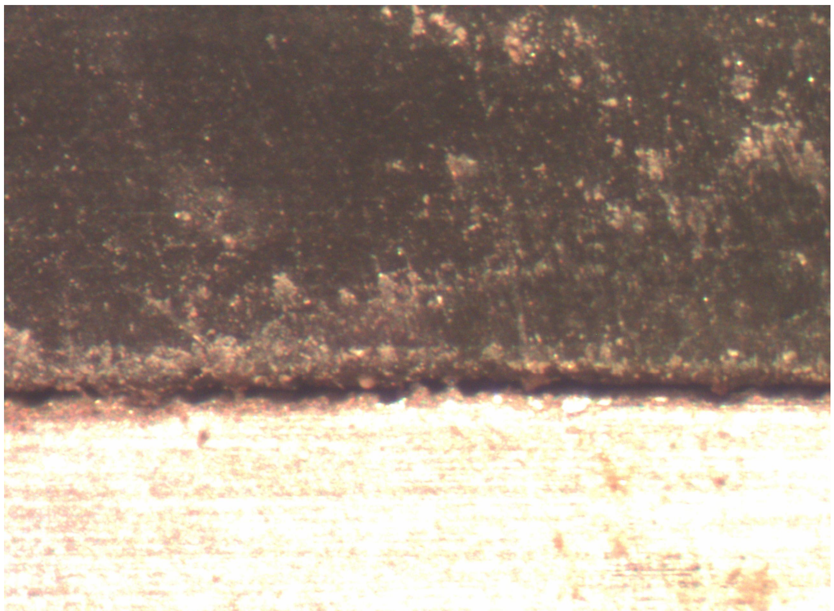


Figure A1: 125°C Epoxy 1 on FR4 Test Board Aluminum Edge Crack

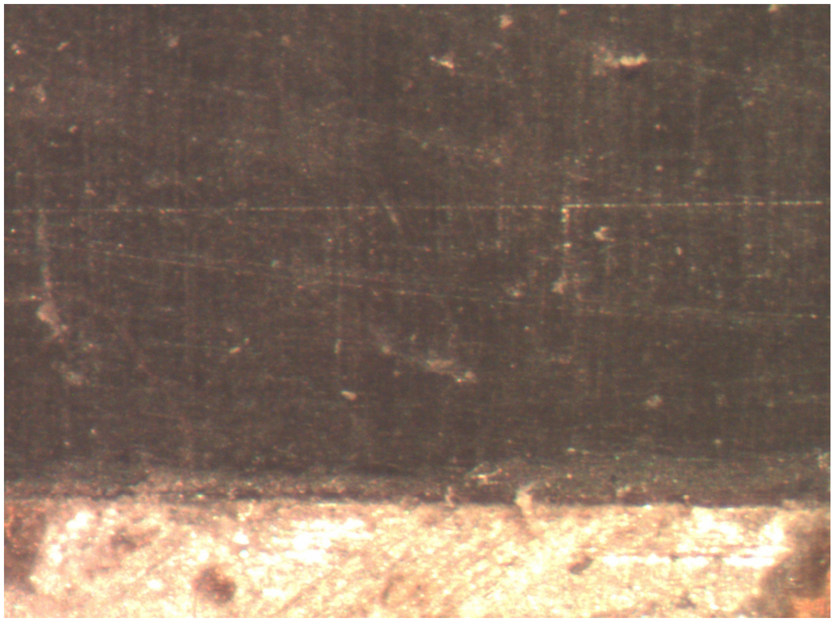


Figure A2: 125^{o}C Epoxy 1 on FLEX Test Board Showing Good Adhesion to Aluminum

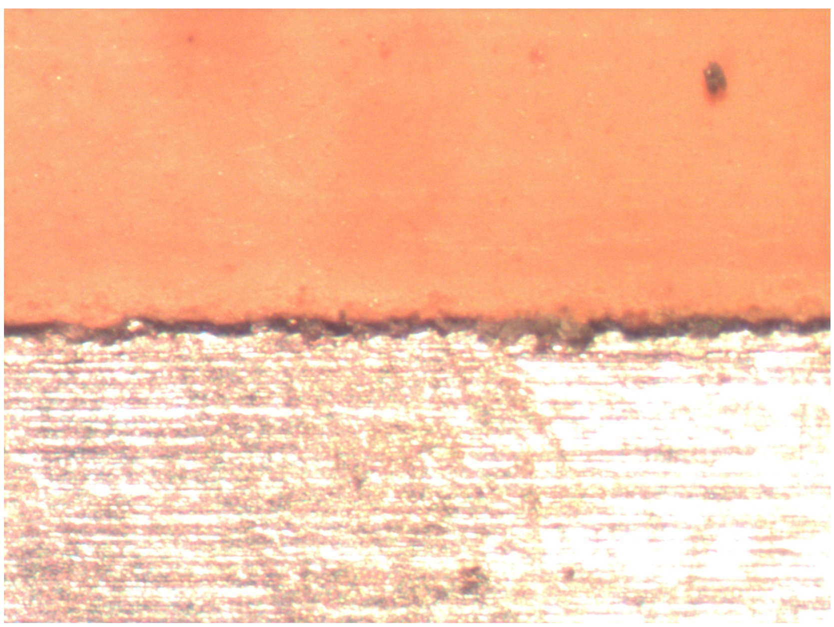


Figure A3: 125^{o}C Epoxy 2 on FLEX Test Board Aluminum Edge Crack

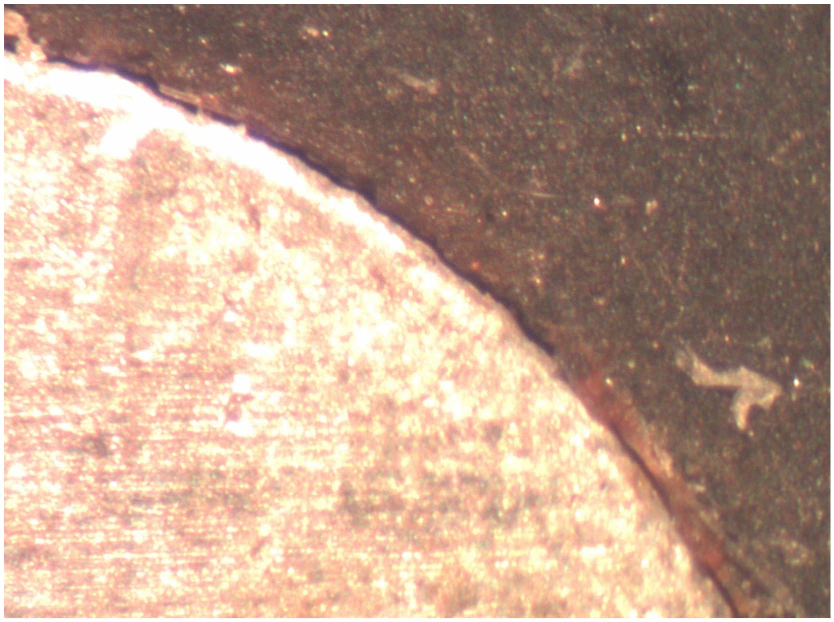


Figure A4: 125^{o}C Epoxy 3 on FR4 Test Board Aluminum Edge Crack

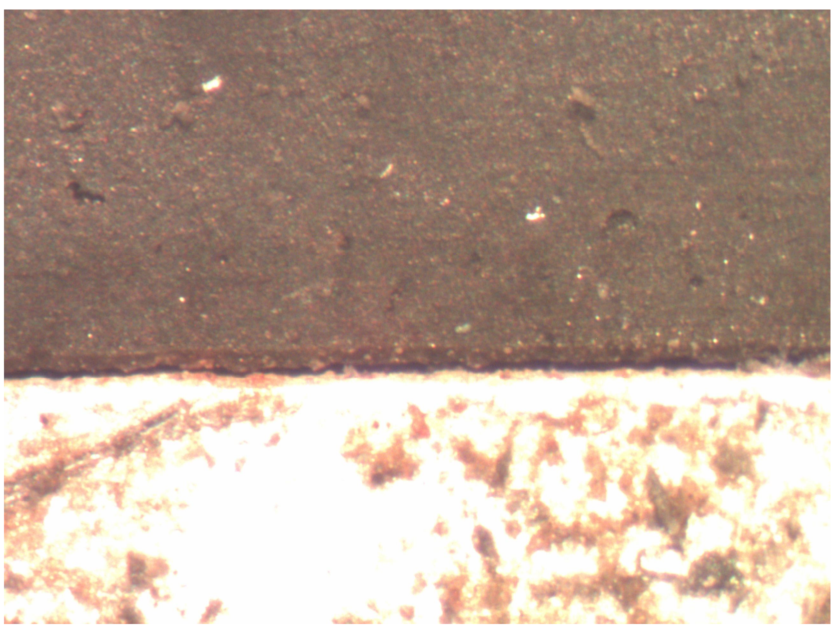


Figure A5: 150^{o}C Epoxy 1 on FR4 Test Board Aluminum Edge Crack

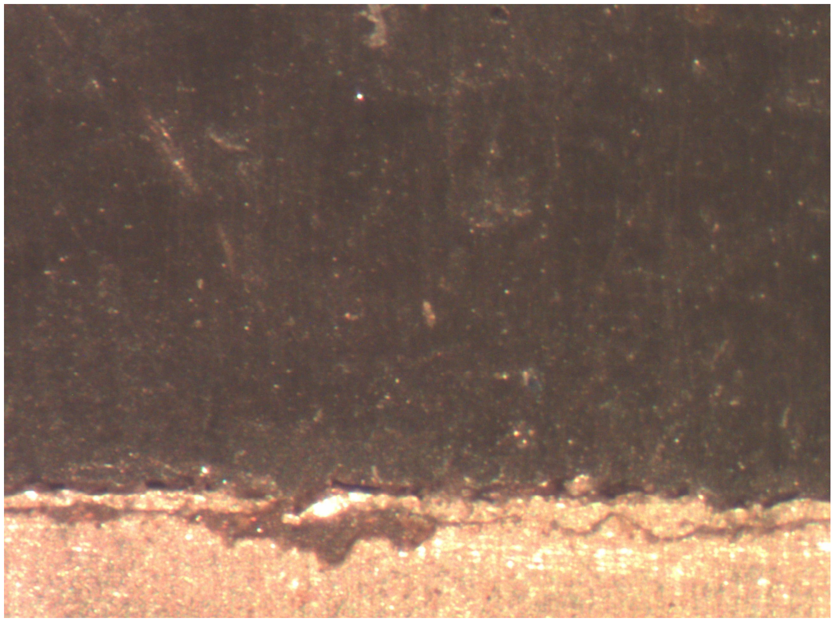


Figure A6: 150^{o}C Epoxy 1 on FLEX Test Board Showing Good Adhesion to Aluminum Edge

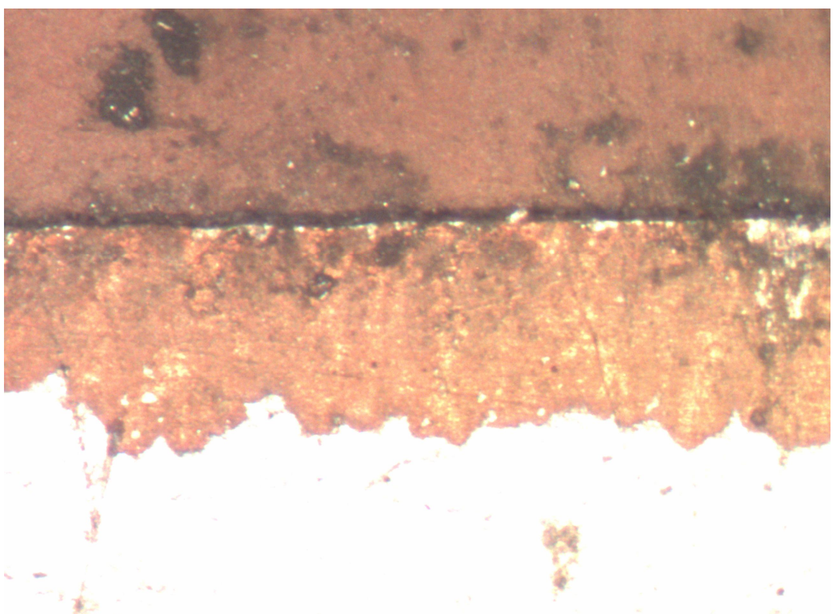


Figure A7: 150^{o}C Epoxy 2 on FLEX Test Board Aluminum Edge Crack

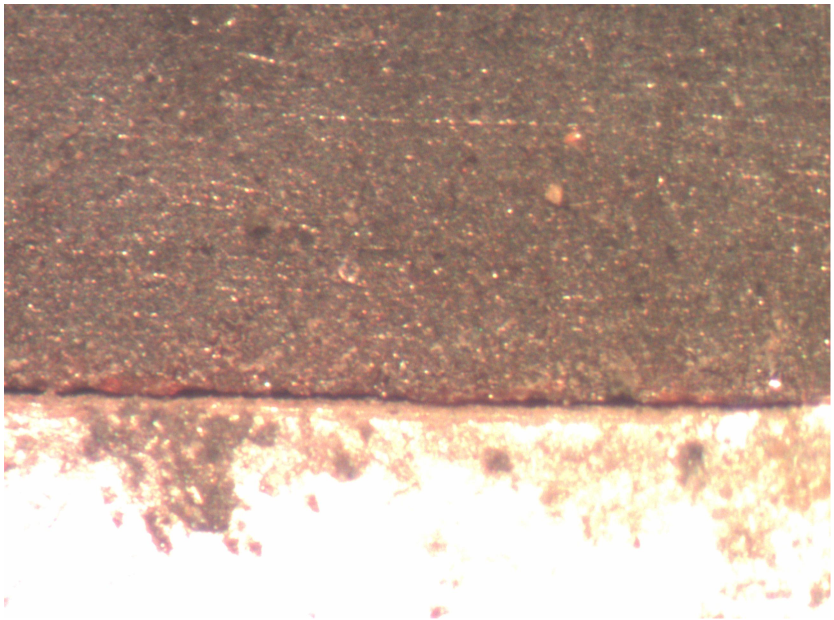


Figure A8: 150^{o}C Epoxy 3 on FR4 Test Board Aluminum Edge Crack

APPENDIX F: Hot Melt Test Board Cross Section Images after 1200 Cycles

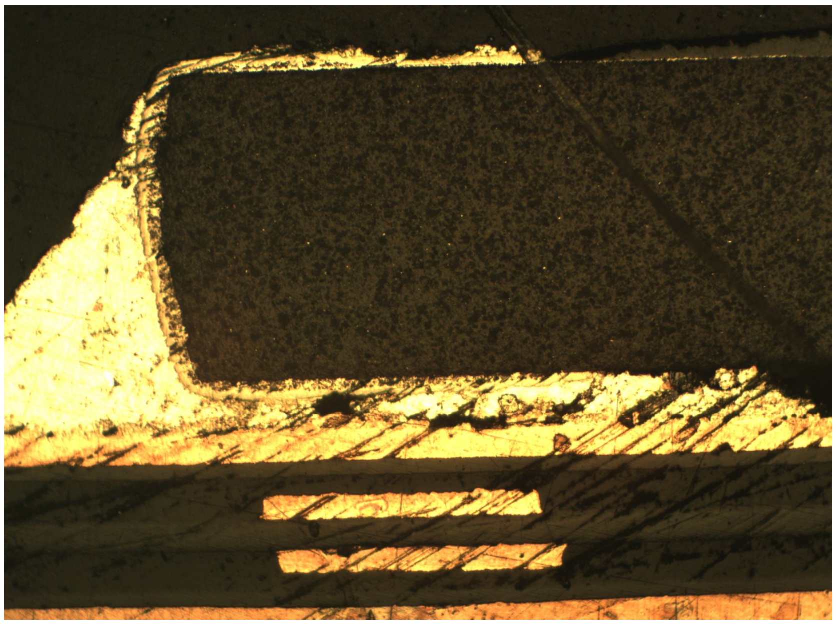


Figure A9: Hot Melt 1 on FR4 Test Board 2512 Resistor Image

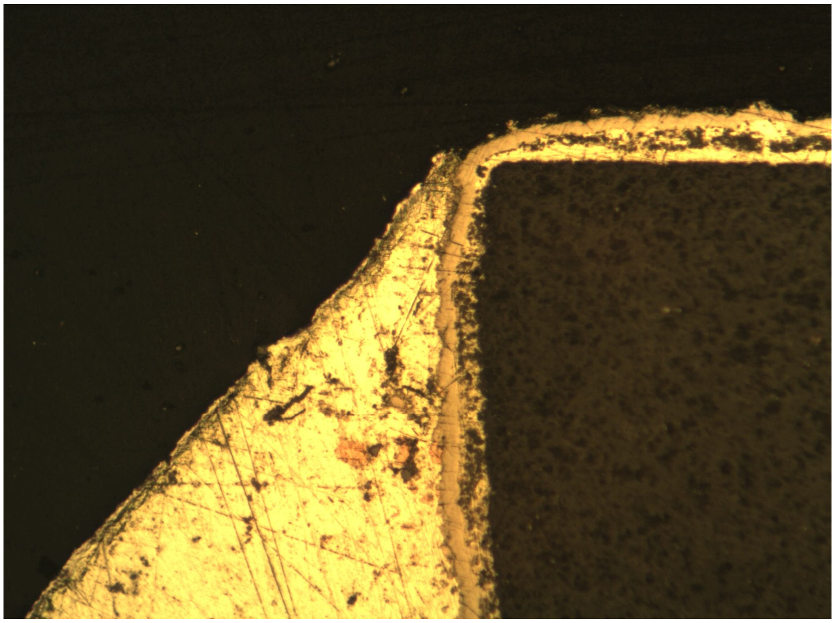


Figure A10: Hot Melt 1 on FR4 Test Board 2512 Resistor Image

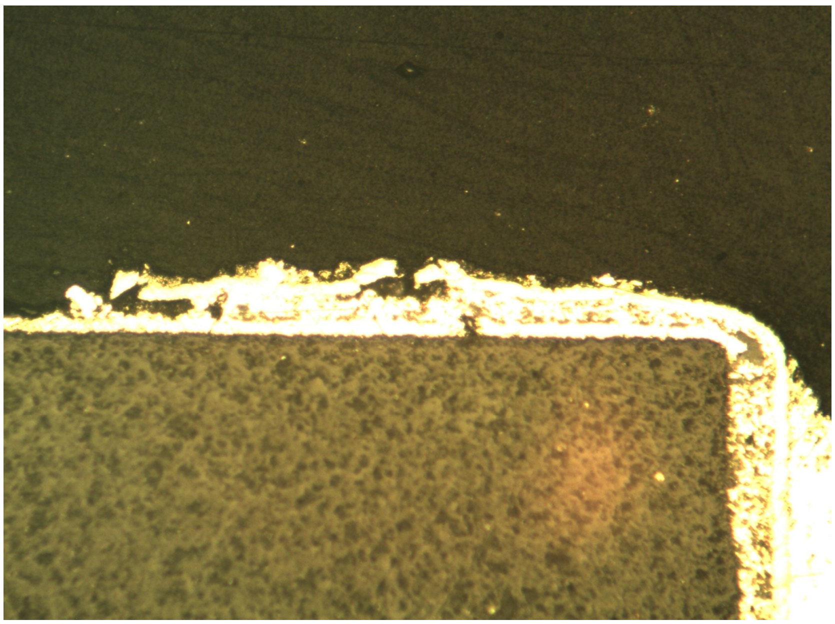


Figure A11: Hot Melt 1 on FR4 Test Board 2512 Resistor Image

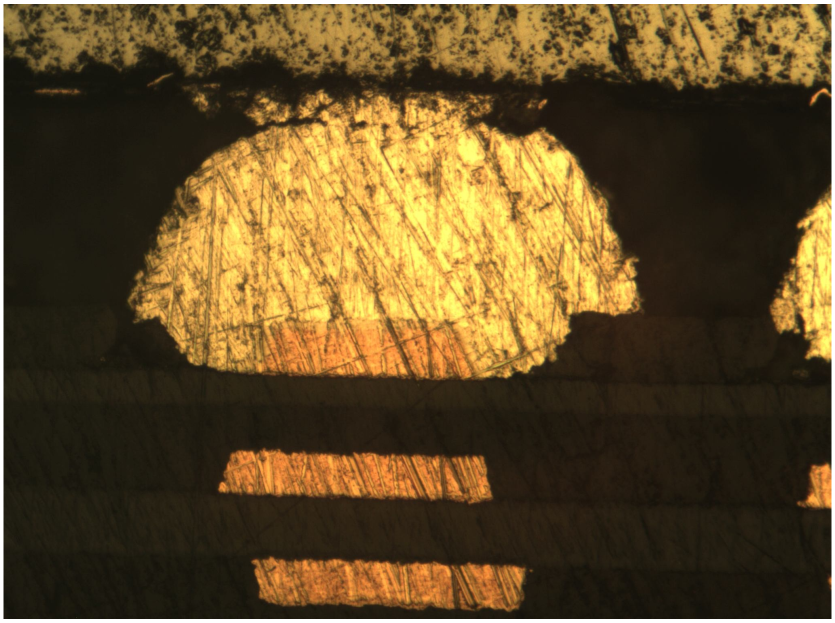


Figure A12: Hot Melt 1 on FR4 Test Board CSP Image

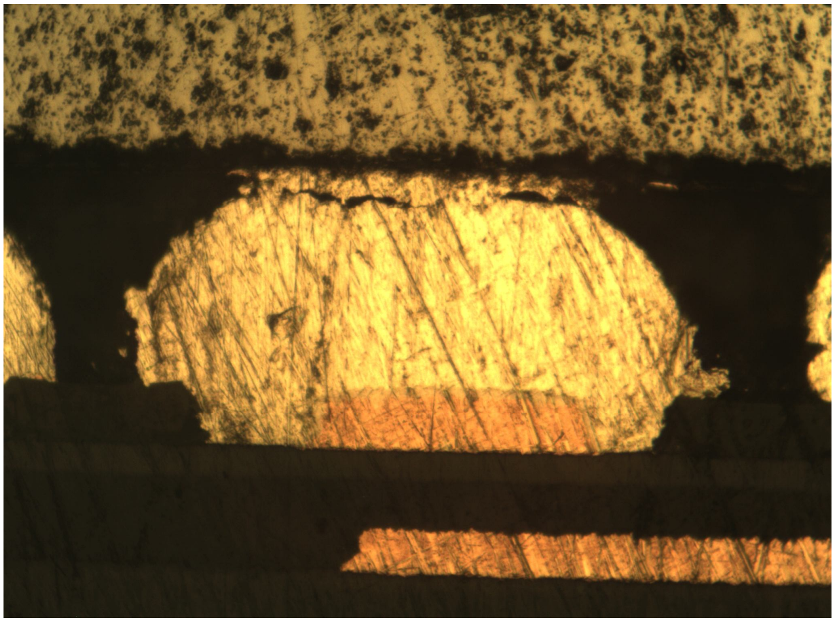


Figure A13: Hot Melt 1 on FR4 Test Board CSP Image

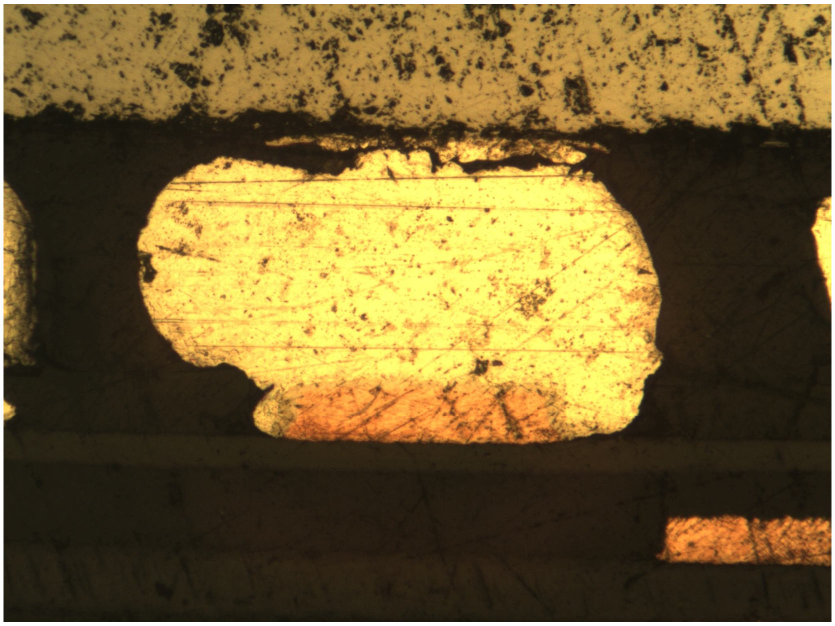


Figure A14: Hot Melt 1 on FR4 Test Board CSP Image

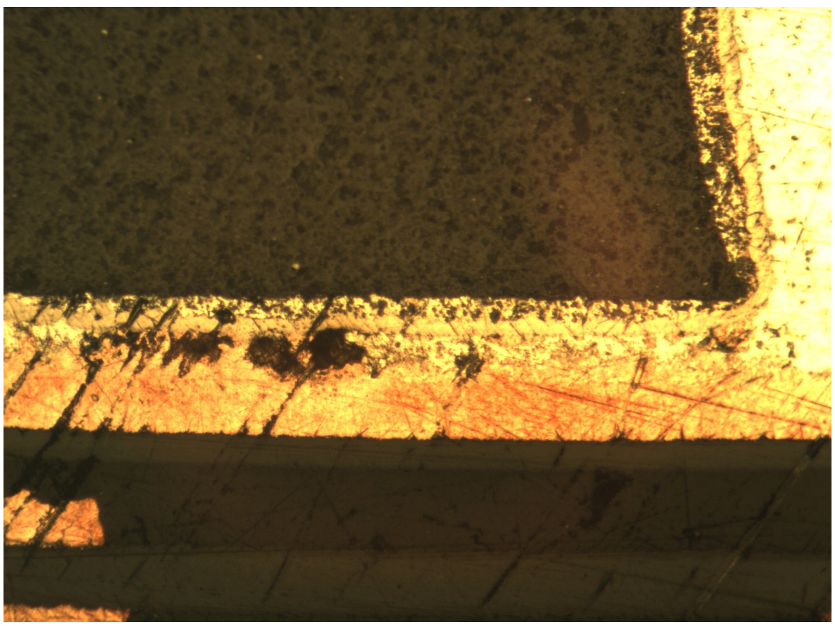


Figure A15: Hot Melt 1 on FLEX Test Board 2512 Resistor Image

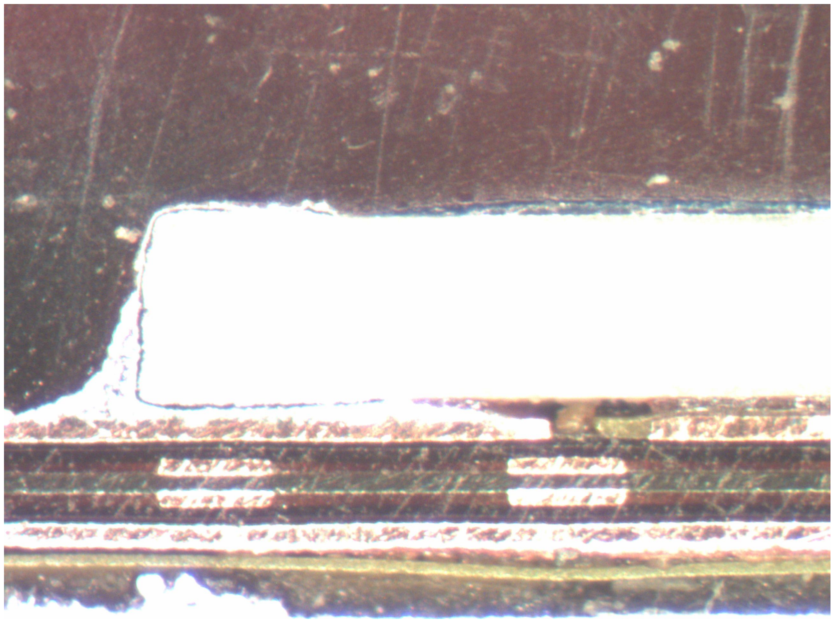


Figure A16: Hot Melt 1 on FLEX Test Board 2512 Resistor Image

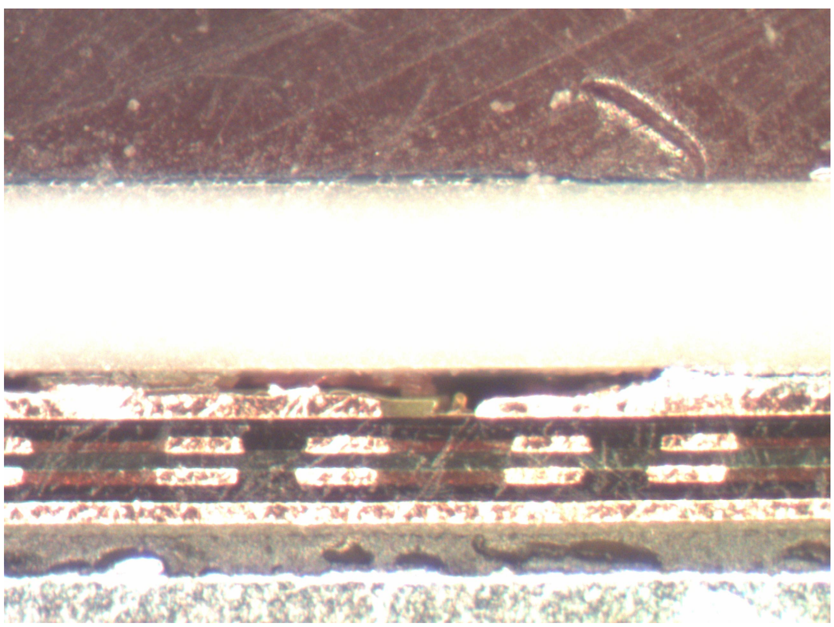


Figure A17: Hot Melt 1 on FLEX Test Board 2512 Resistor Image

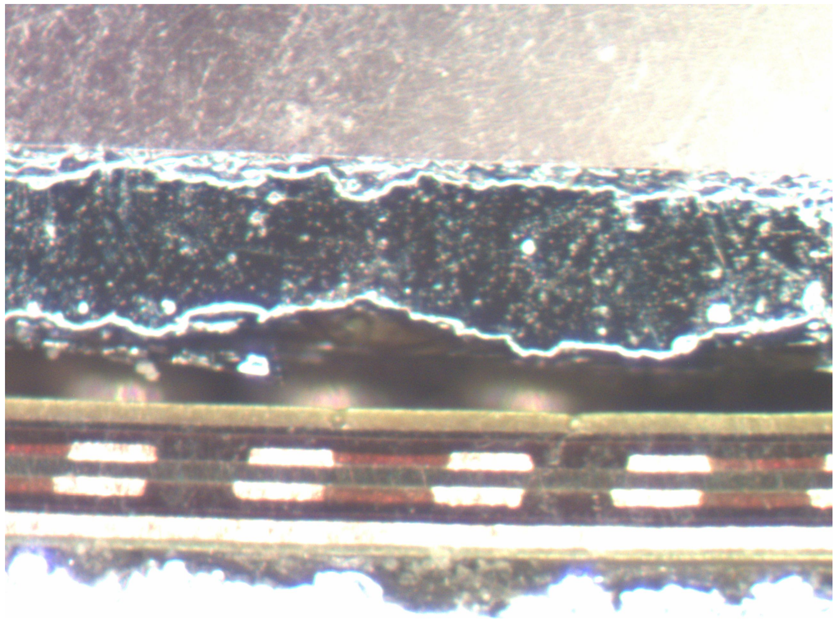


Figure A18: Hot Melt 1 on FLEX Test Board CSP Image

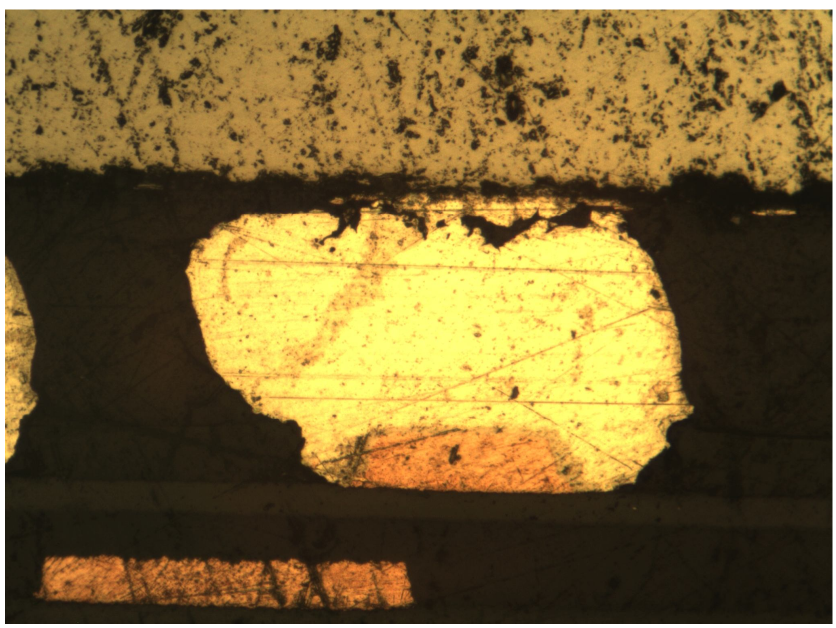


Figure A19: Hot Melt 1 on FLEX Test Board CSP Image

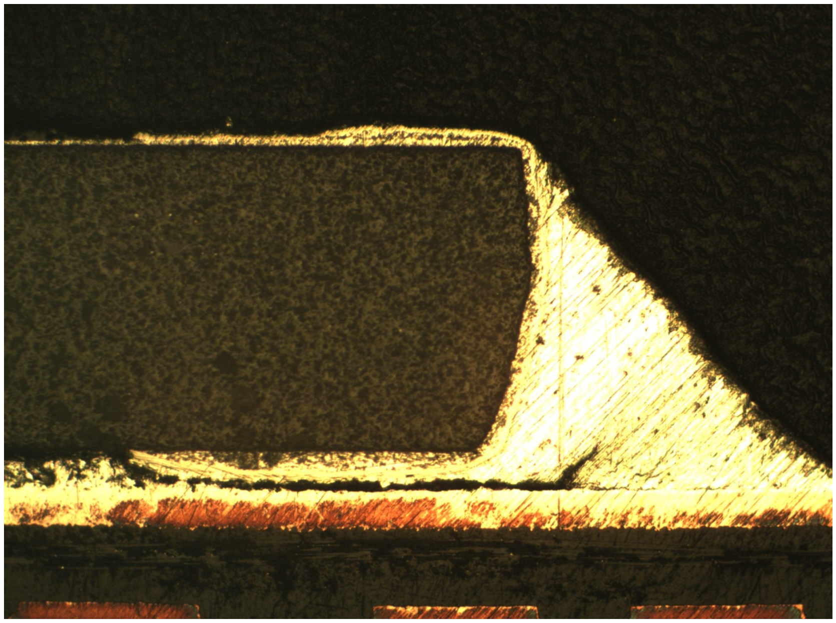


Figure A20: Hot Melt 2 on FR4 Test Board 2512 Resistor Image

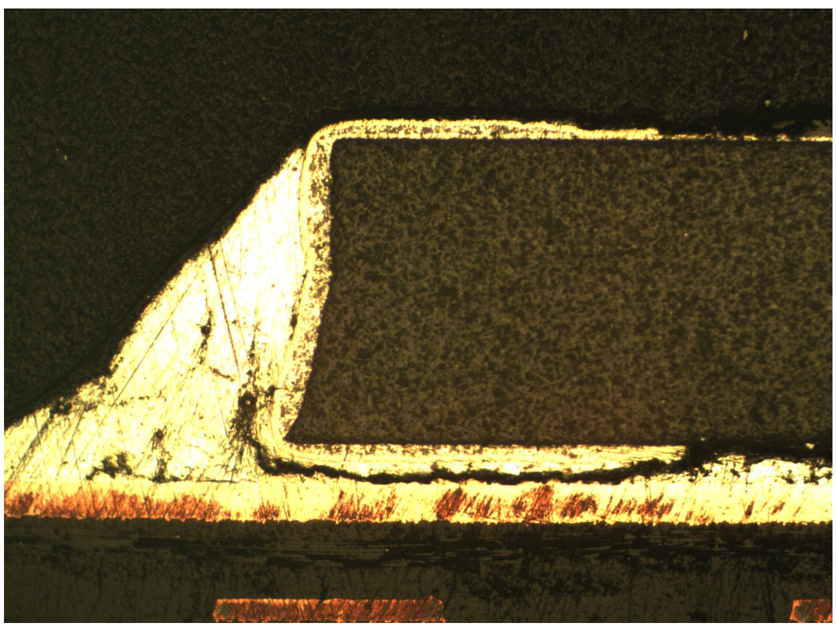


Figure A21: Hot Melt 2 on FR4 Test Board 2512 Resistor Image

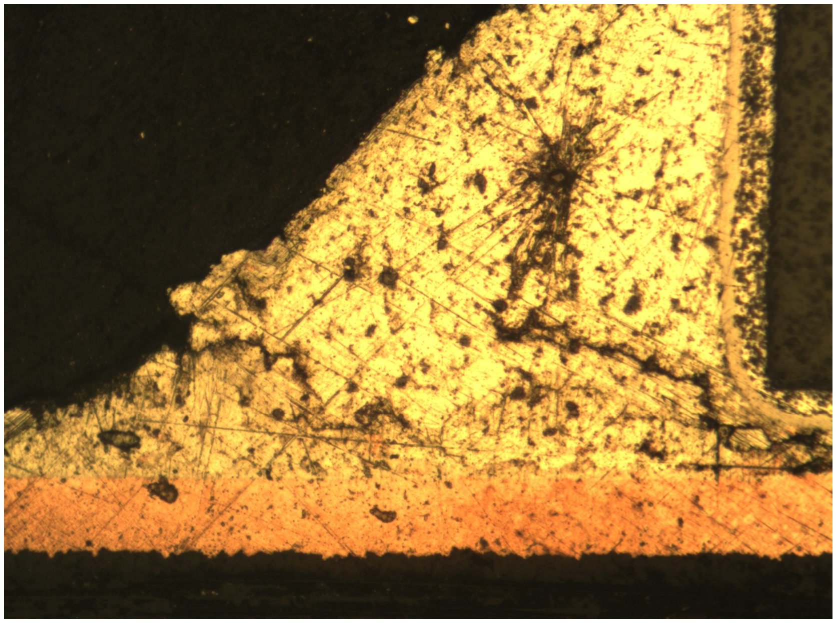


Figure A22: Hot Melt 2 on FR4 Test Board 2512 Resistor Image

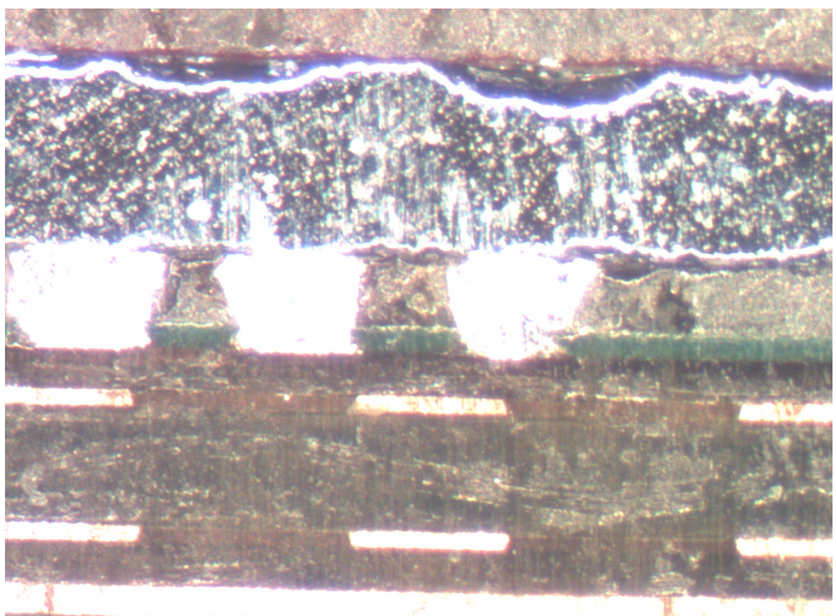


Figure A23: Hot Melt 2 on FR4 Test Board CSP Image

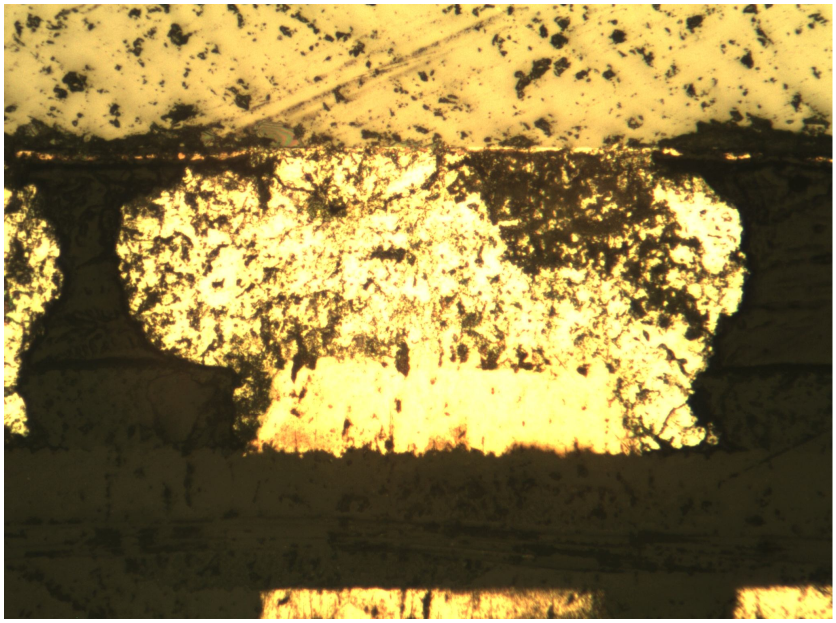


Figure A24: Hot Melt 2 on FR4 Test Board CSP Image

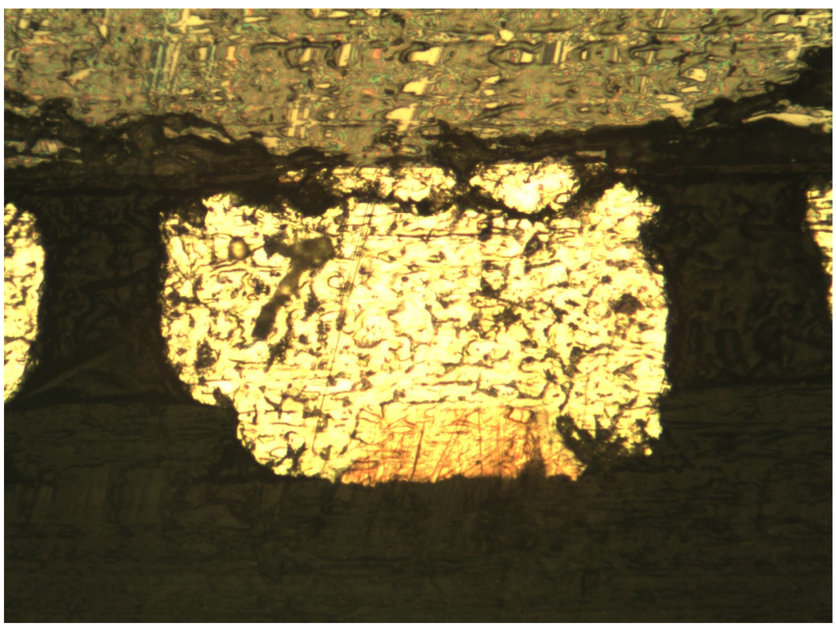


Figure A25: Hot Melt 2 on FR4 Test Board CSP Image

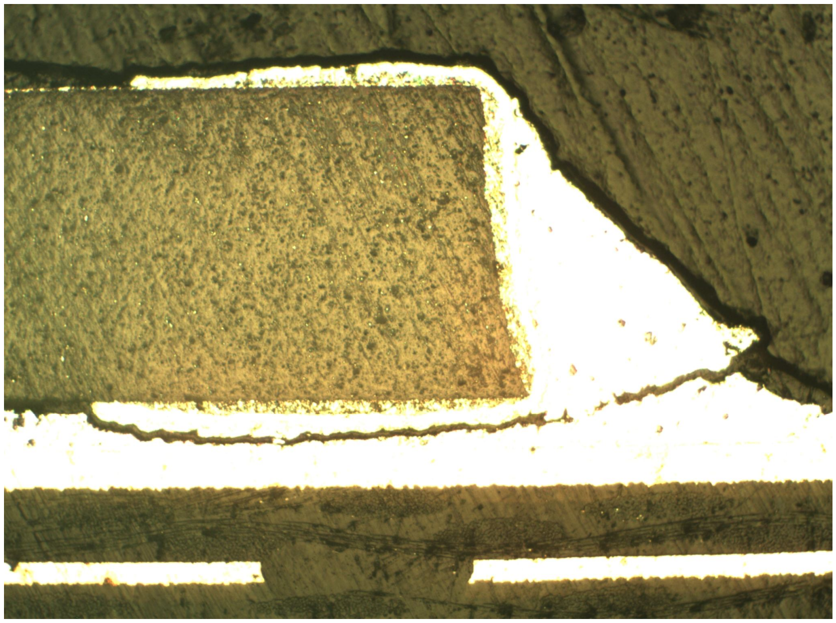


Figure A26: Hot Melt 2 on FLEX Test Board 2512 Resistor Image

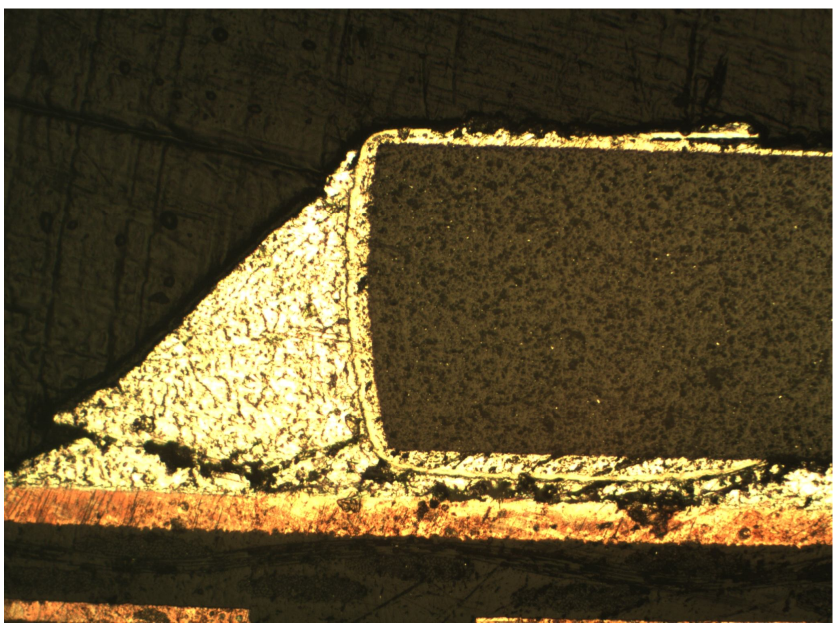


Figure A27: Hot Melt 2 on FLEX Test Board 2512 Resistor Image

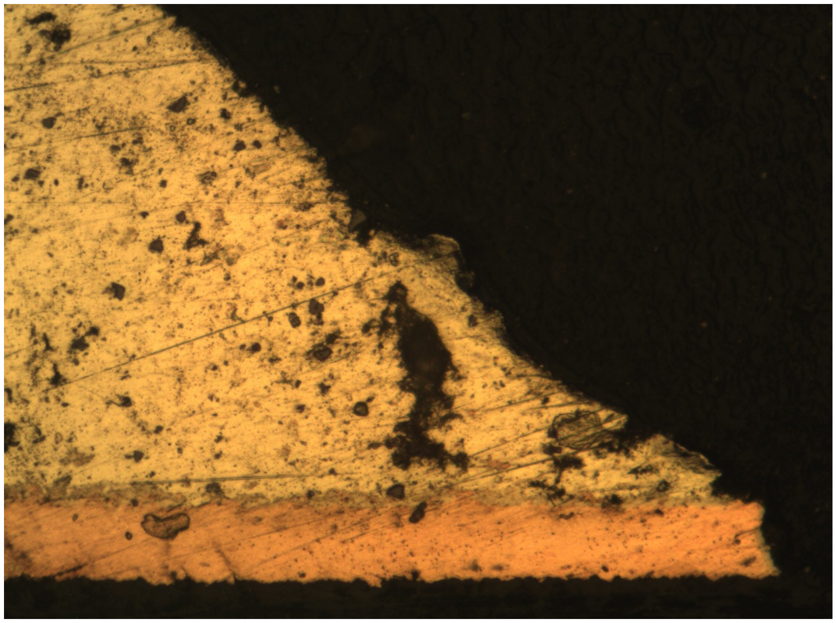


Figure A28: Hot Melt 2 on FLEX Test Board 2512 Resistor Image

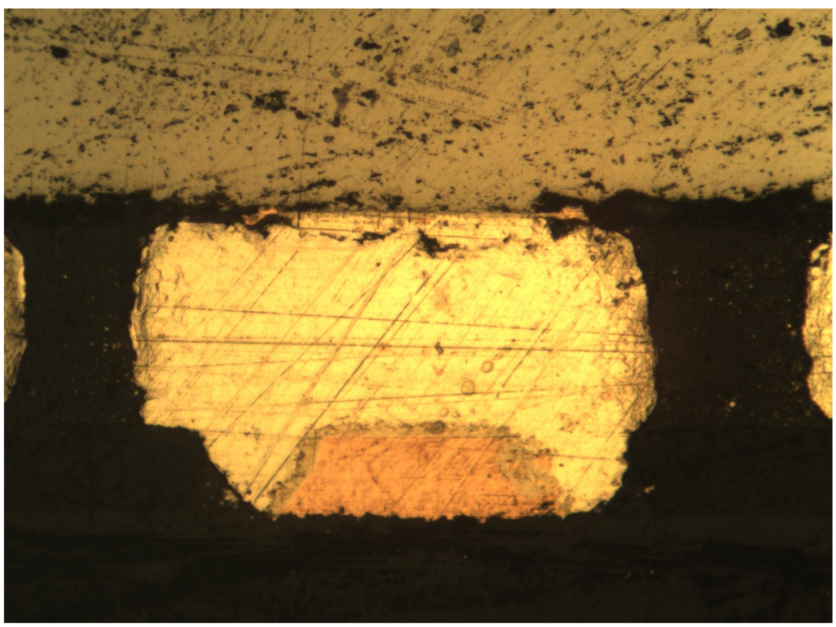


Figure A29: Hot Melt 2 on FLEX Test Board CSP Image

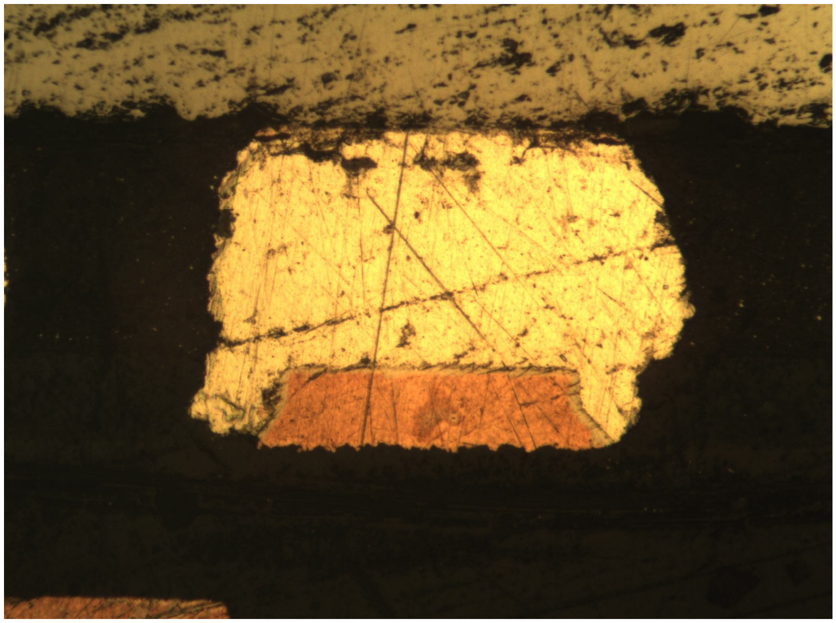


Figure A30: Hot Melt 2 on FLEX Test Board CSP Image

APPENDIX G: Epoxy Test Board Cross Section Images after 1200 Cycles

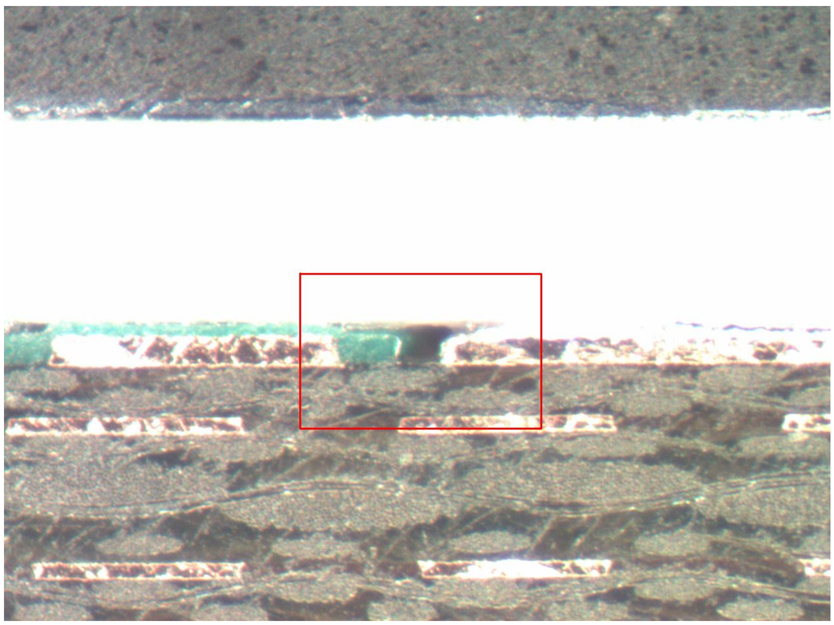


Figure A31: 125°C Epoxy 1 on FR4 Test Board 2512 Resistor Image

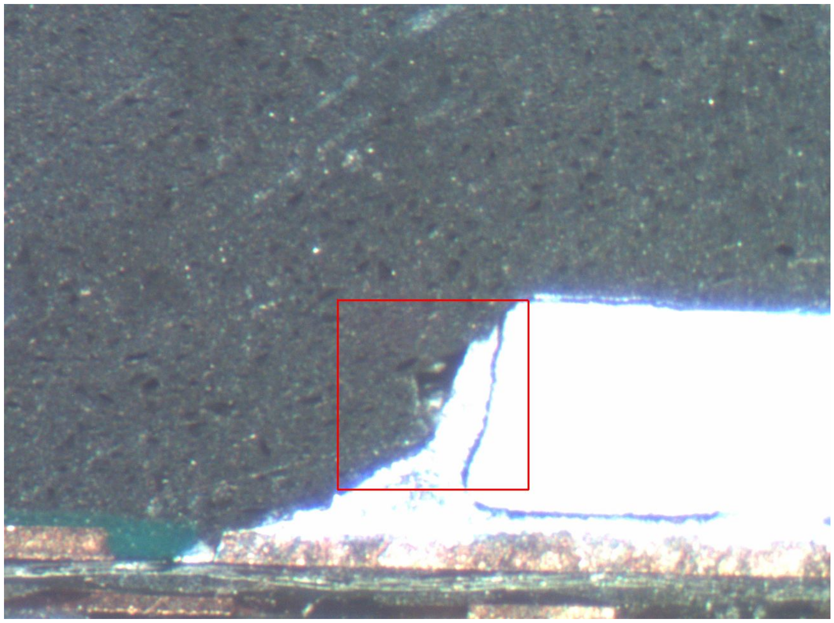


Figure A32: 125^{o}C Epoxy 1 on FR4 Test Board 2512 Resistor Image

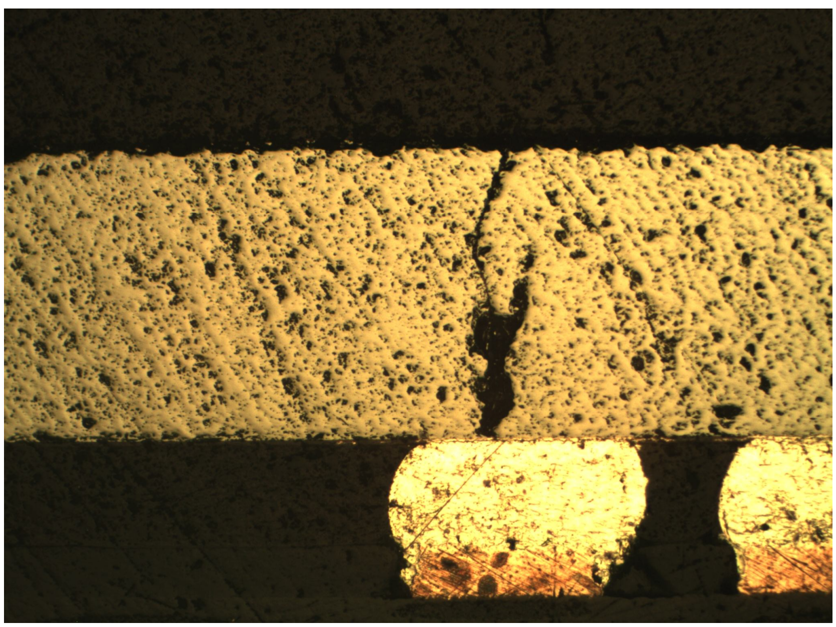


Figure A33: 125^{o}C Epoxy 1 on FR4 Test Board CSP Image

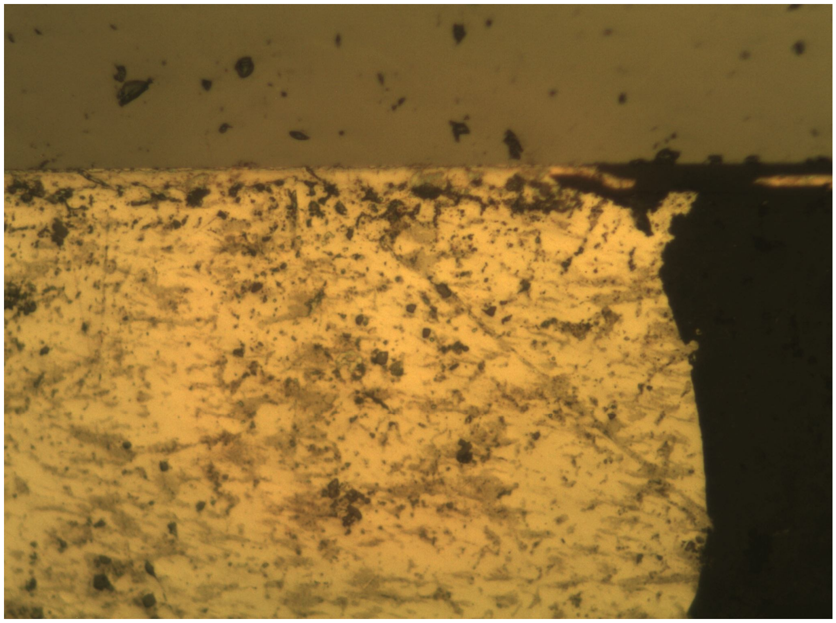


Figure A34: 125^{o}C Epoxy 1 on FR4 Test Board CSP Image

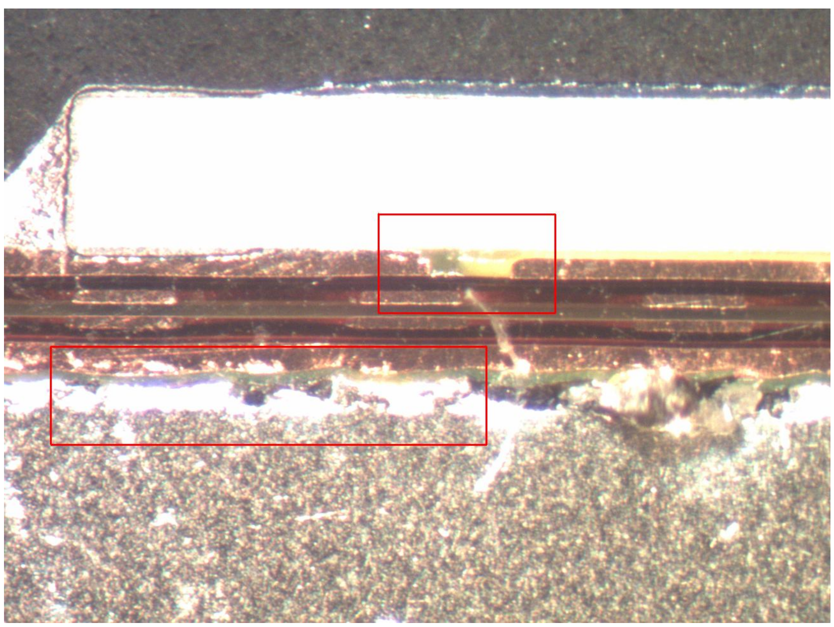


Figure A35: 125^{o}C Epoxy 1 on FLEX Test Board 2512 Resistor Image

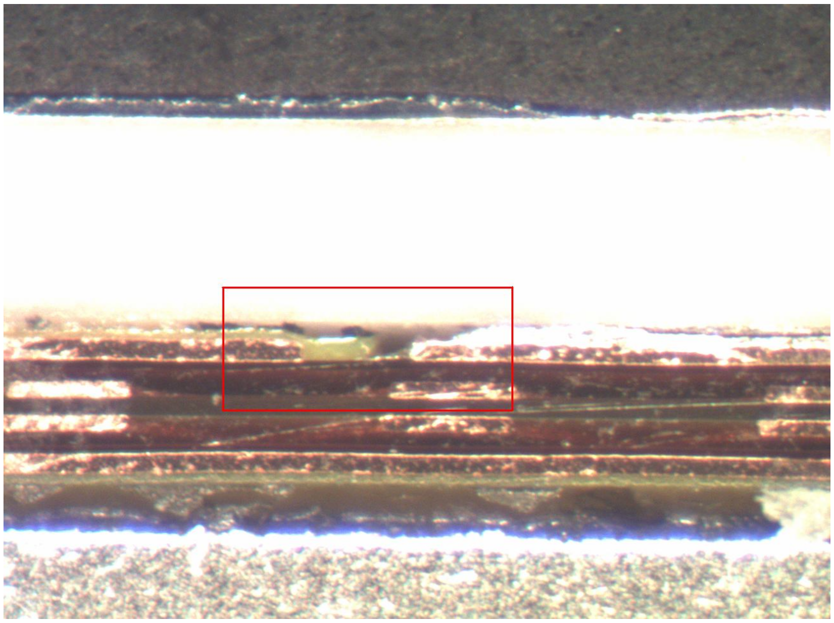


Figure A36: 125°C Epoxy 1 on FLEX Test Board 2512 Resistor Image

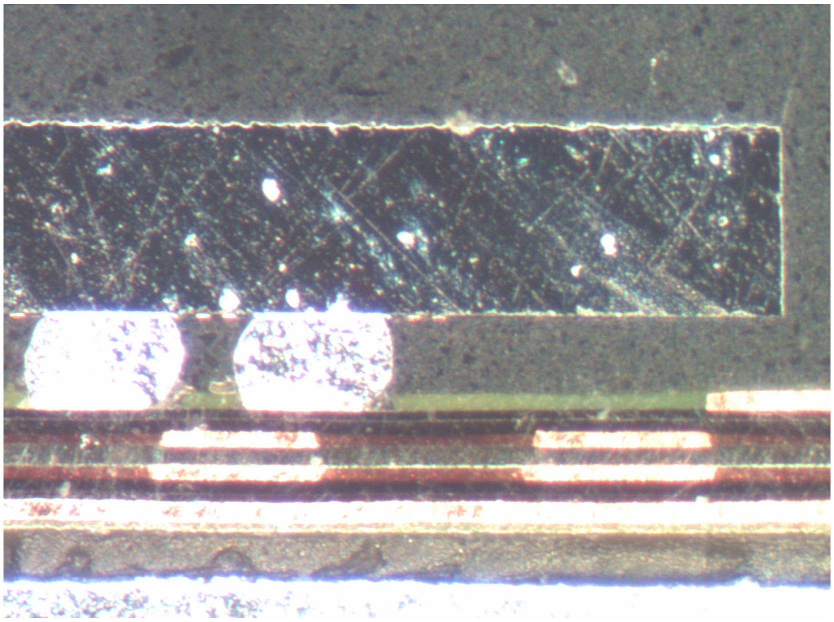


Figure A37: 125°C Epoxy 1 on FLEX Test Board CSP Image

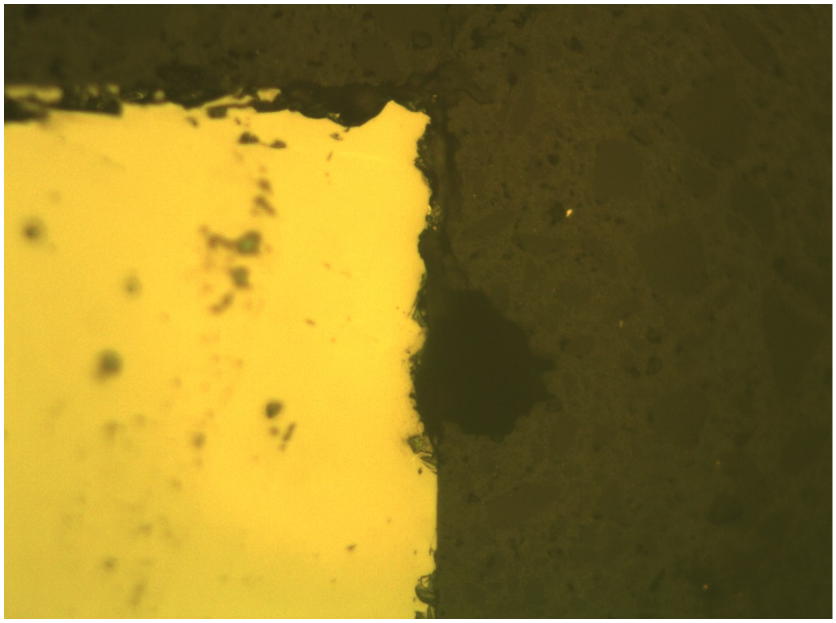


Figure A38: 125^{o}C Epoxy 1 on FLEX Test Board CSP Image

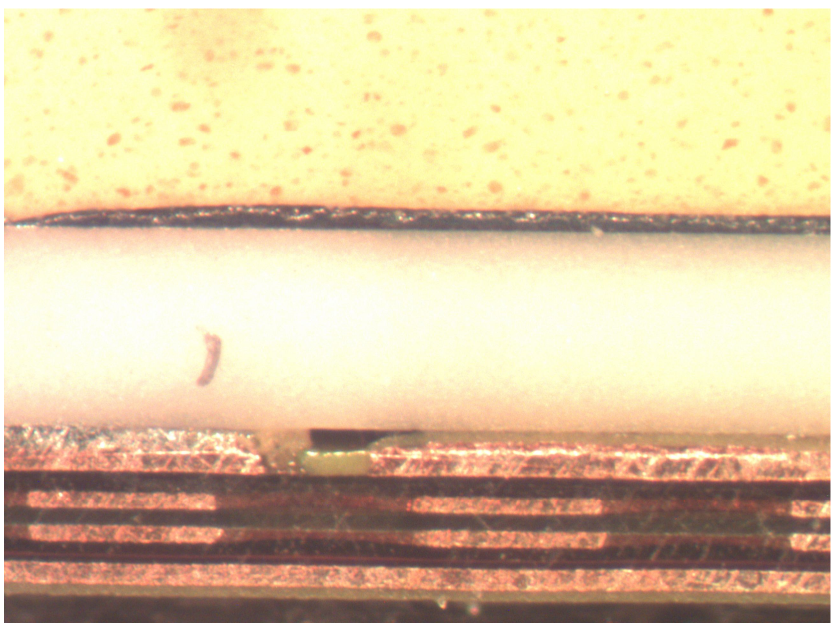


Figure A39: 125^{o}C Epoxy 2 on FLEX Test Board 2512 Resistor Image

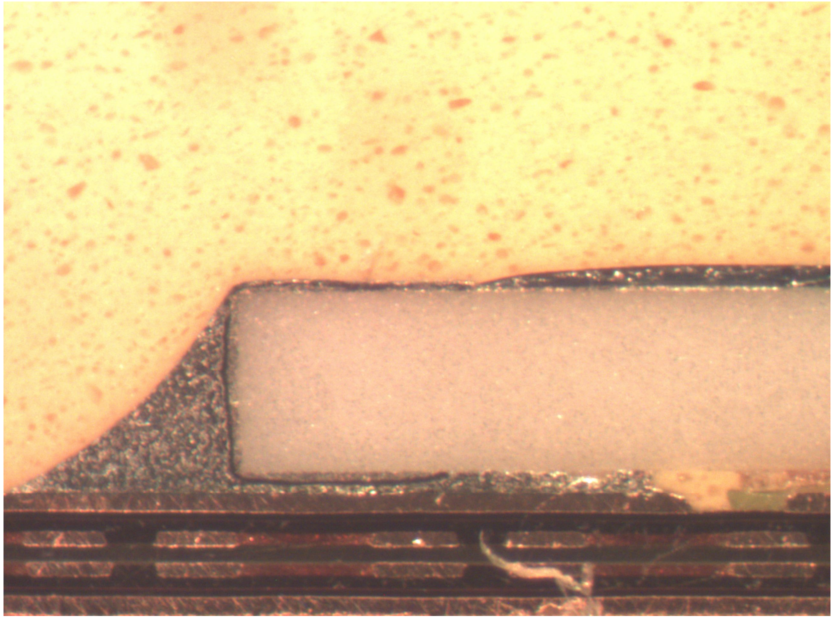


Figure A40: 125^{o}C Epoxy 2 on FLEX Test Board 2512 Resistor Image

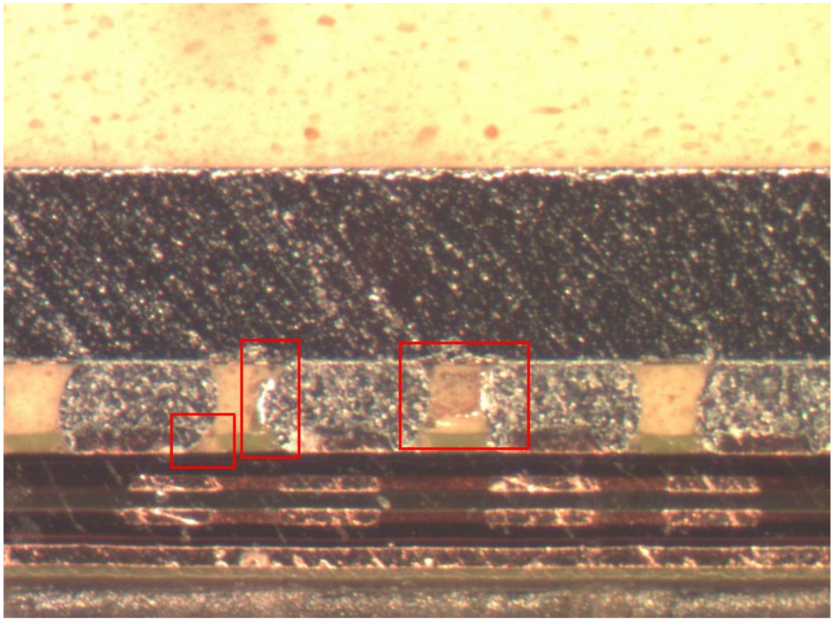


Figure A41: 125^{o}C Epoxy 2 on FLEX Test Board CSP Image

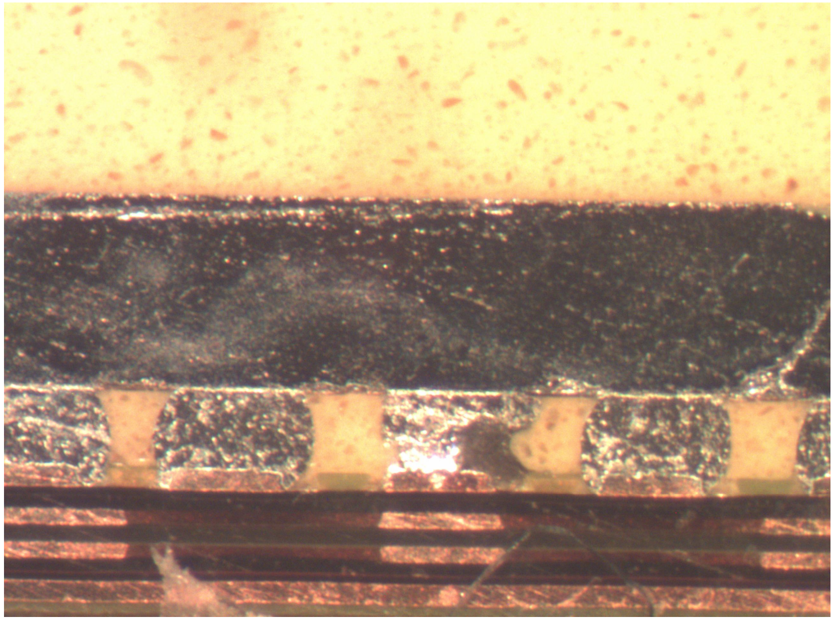


Figure A42: 125^{o}C Epoxy 2 on FLEX Test Board CSP Image

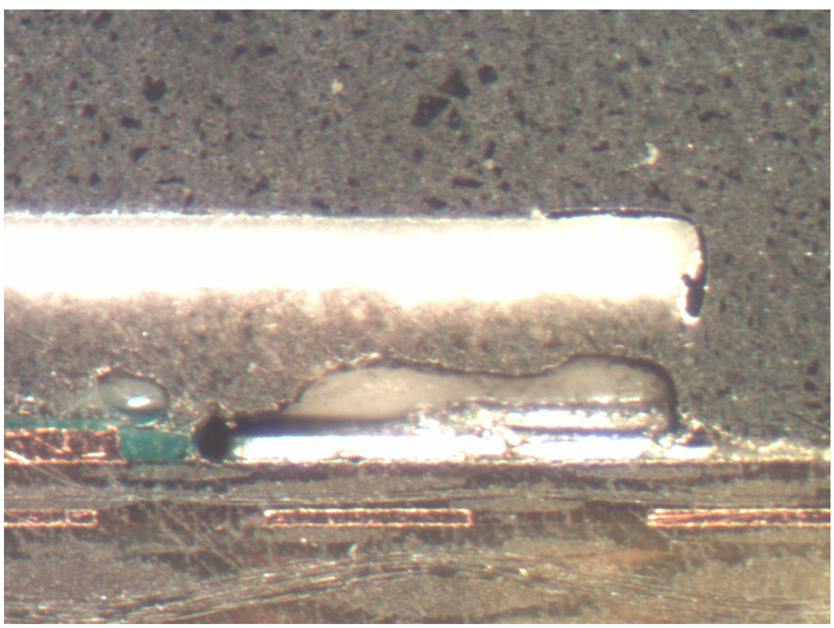


Figure A43: 125^{o}C Epoxy 3 on FR4 Test Board 2512 Resistor Image

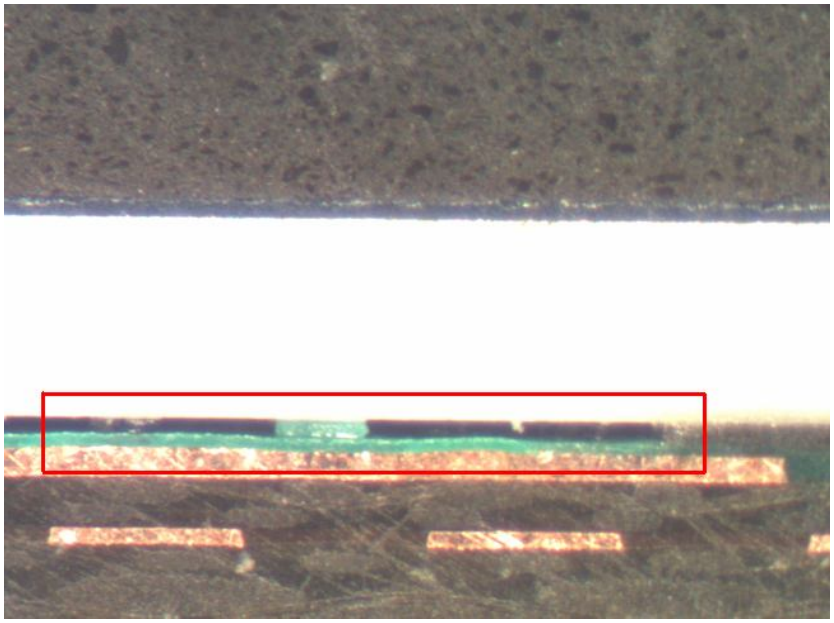


Figure A44: 125°C Epoxy 3 on FR4 Test Board 2512 Resistor Image

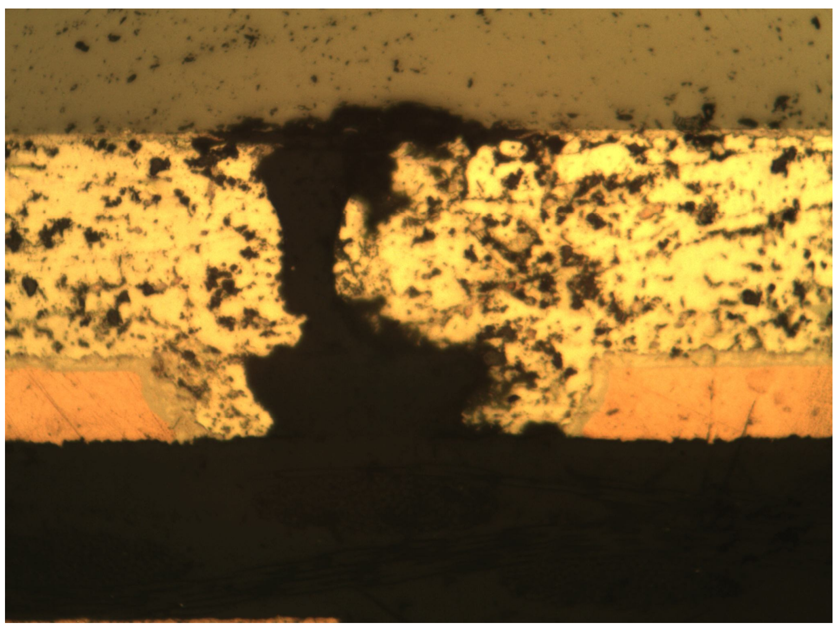


Figure A45: 125°C Epoxy 3 on FR4 Test Board CSP Image

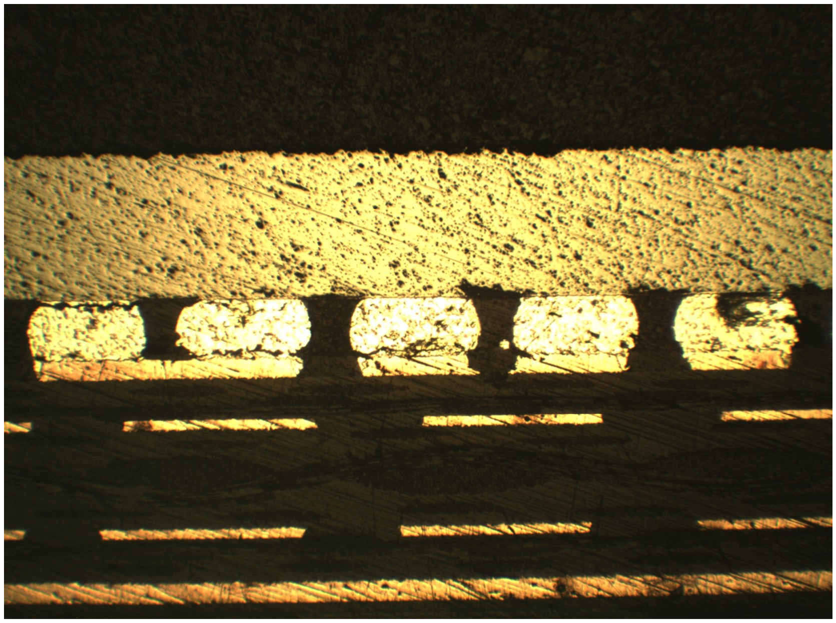


Figure A46: 125^{o}C Epoxy 3 on FR4 Test Board CSP Image

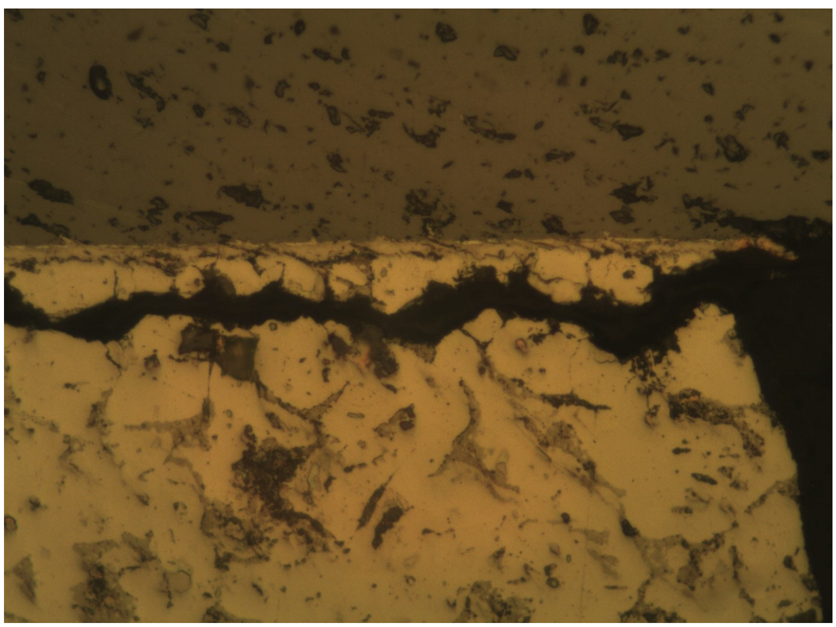


Figure A47: 125^{o}C Epoxy 3 on FR4 Test Board CSP Image

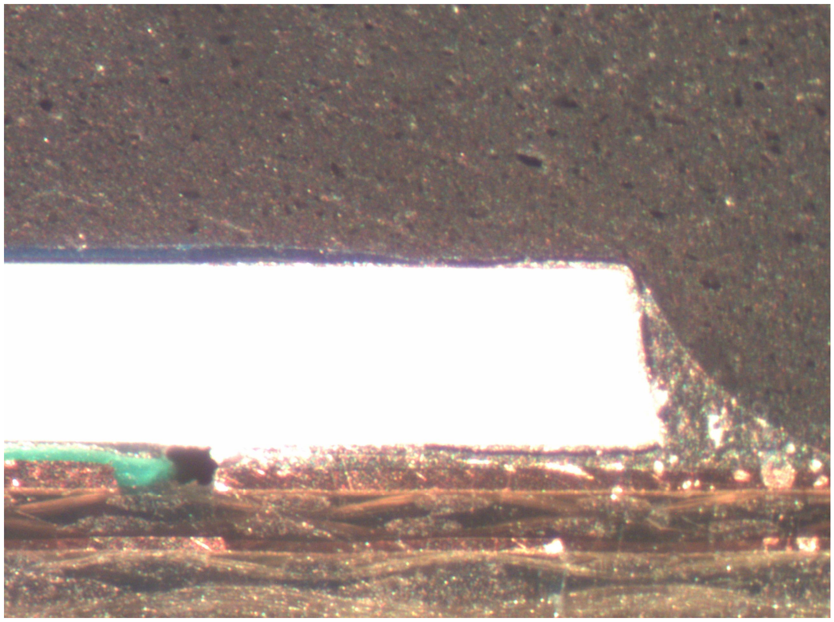


Figure A48: 150^{o}C Epoxy 1 on FR4 Test Board 2512 Resistor Image

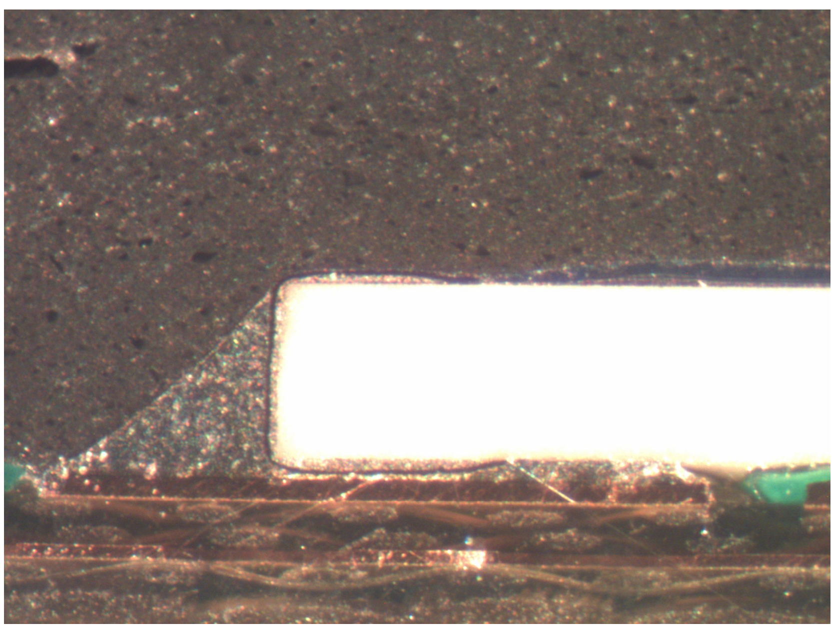


Figure A49: 150^{o}C Epoxy 1 on FR4 Test Board 2512 Resistor Image

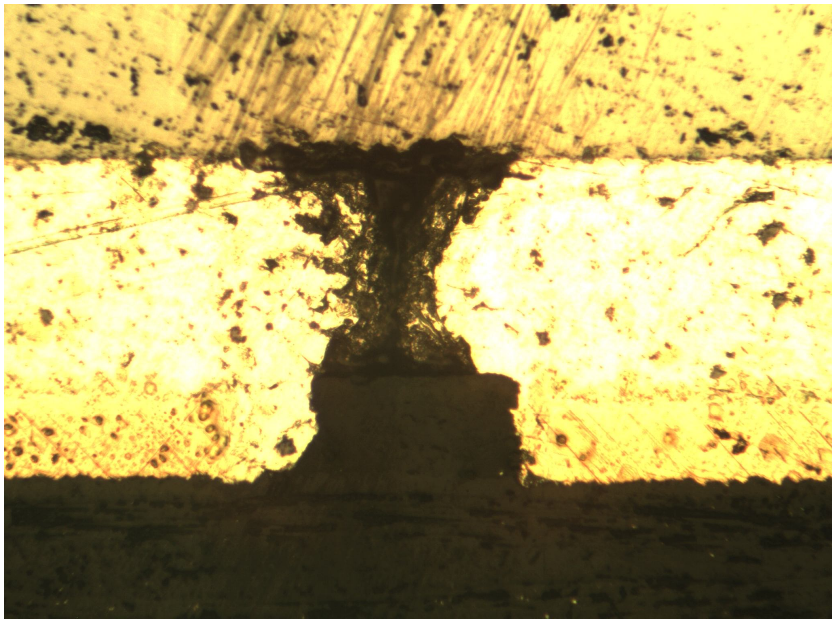


Figure A50: 150^{o}C Epoxy 1 on FR4 Test Board CSP Image

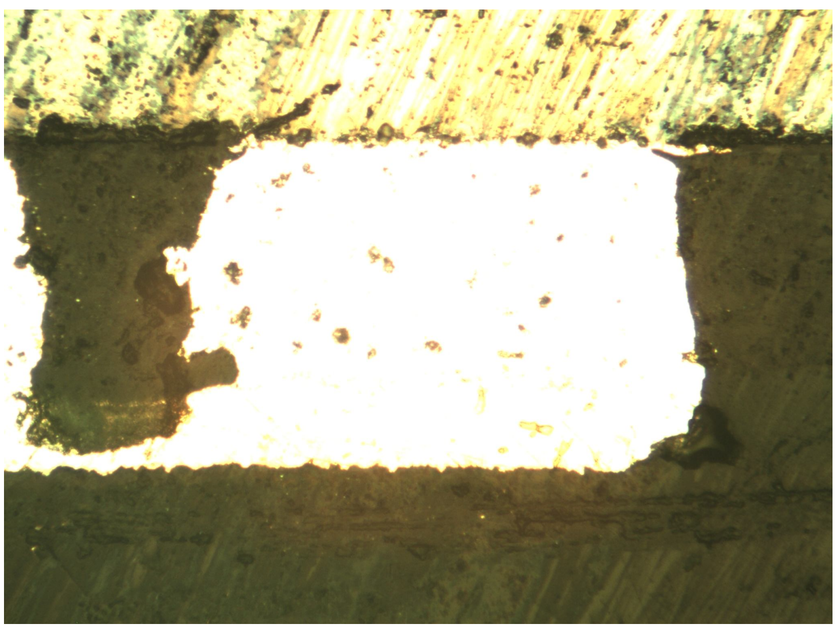


Figure A51: 150^{o}C Epoxy 1 on FR4 Test Board CSP Image

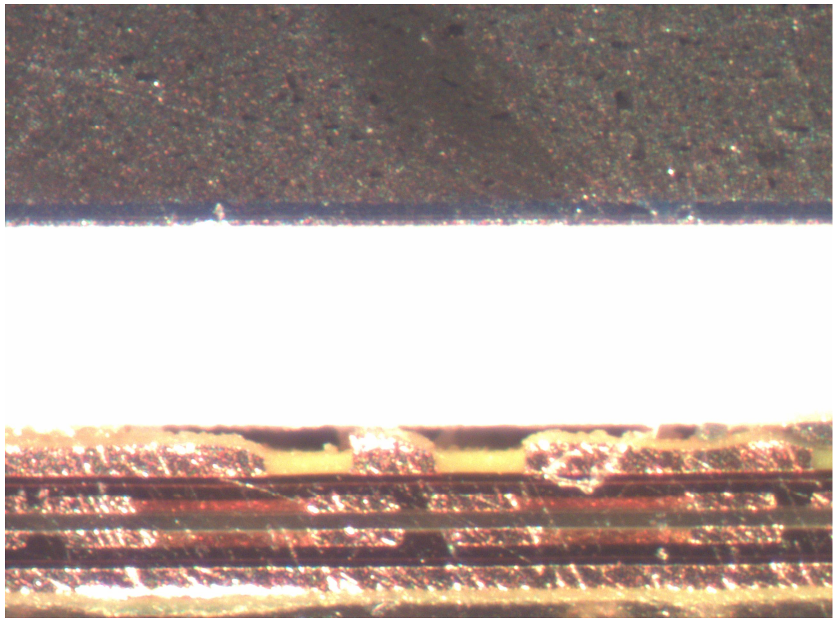


Figure A52: 150^{o}C Epoxy 1 on FLEX Test Board 2512 Resistor Image

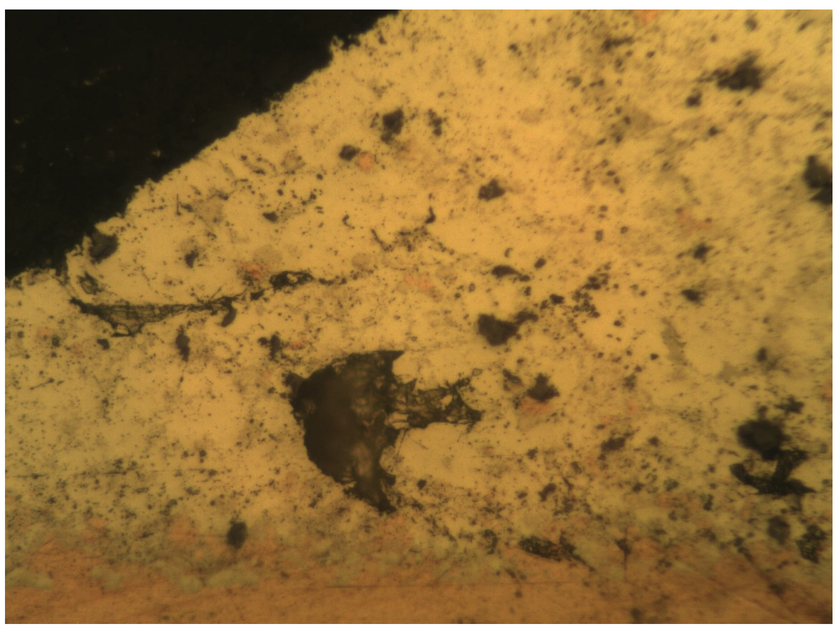


Figure A53: 150^{o}C Epoxy 1 on FLEX Test Board 2512 Resistor Image

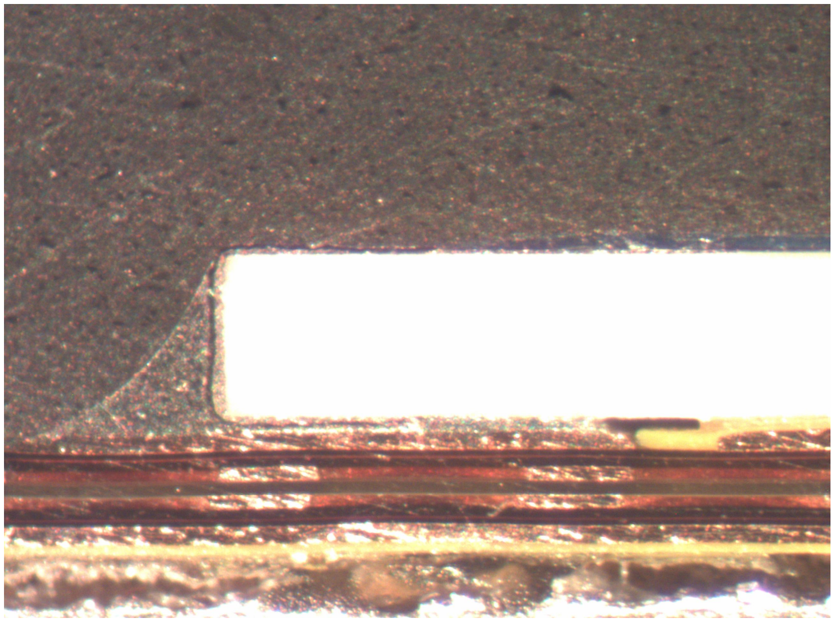


Figure A54: 150^{o}C Epoxy 1 on FLEX Test Board 2512 Resistor Image

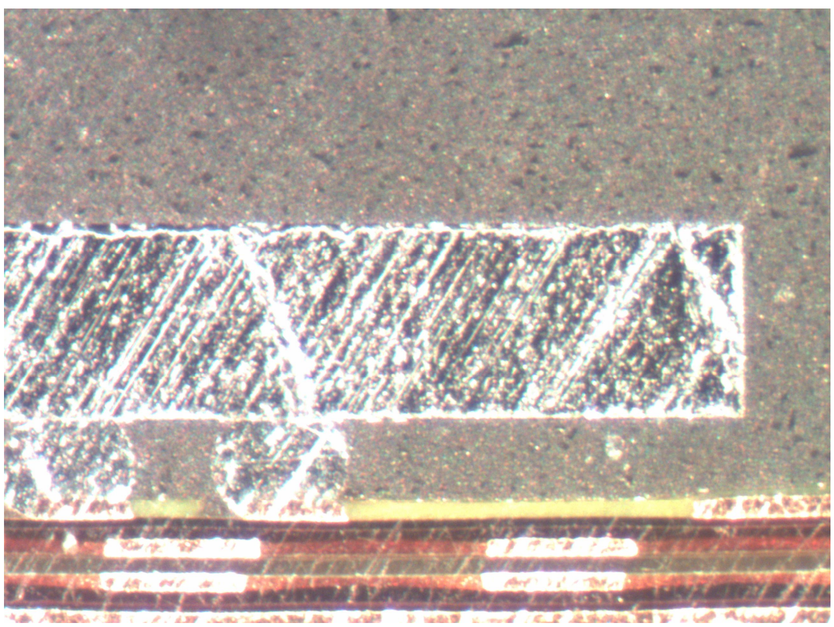


Figure A55: 150^{o}C Epoxy 1 on FLEX Test Board CSP Image

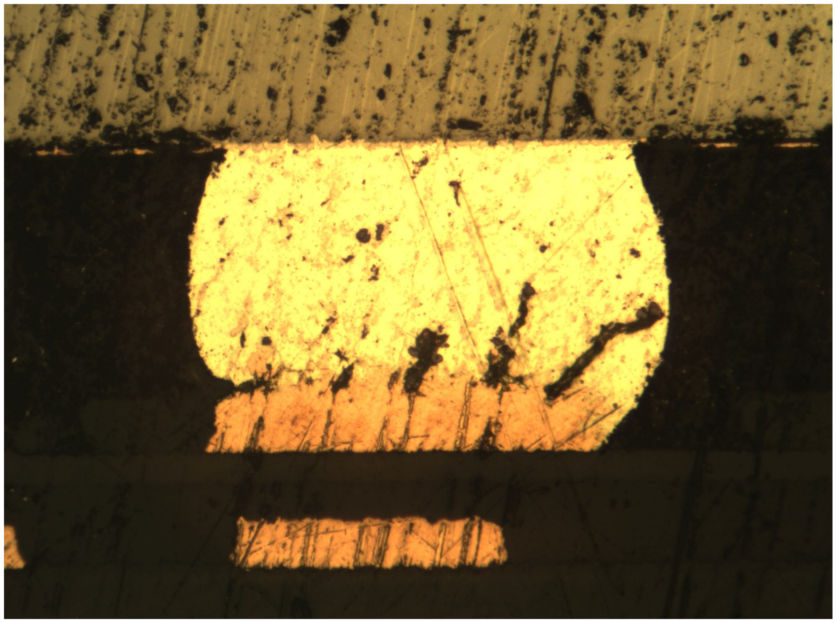


Figure A56: 150^{o}C Epoxy 1 on FLEX Test Board CSP Image

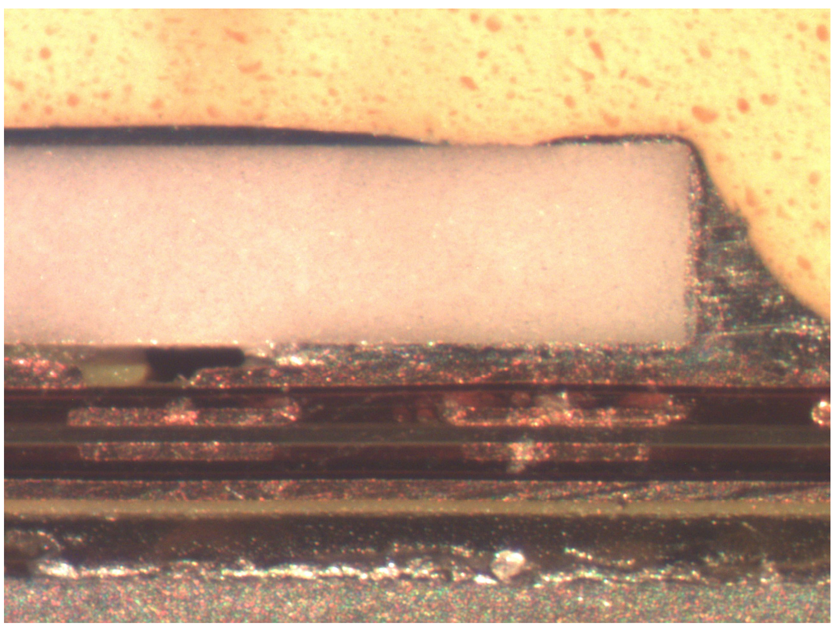


Figure A57: 150^{o}C Epoxy 2 on FLEX Test Board 2512 Resistor Image

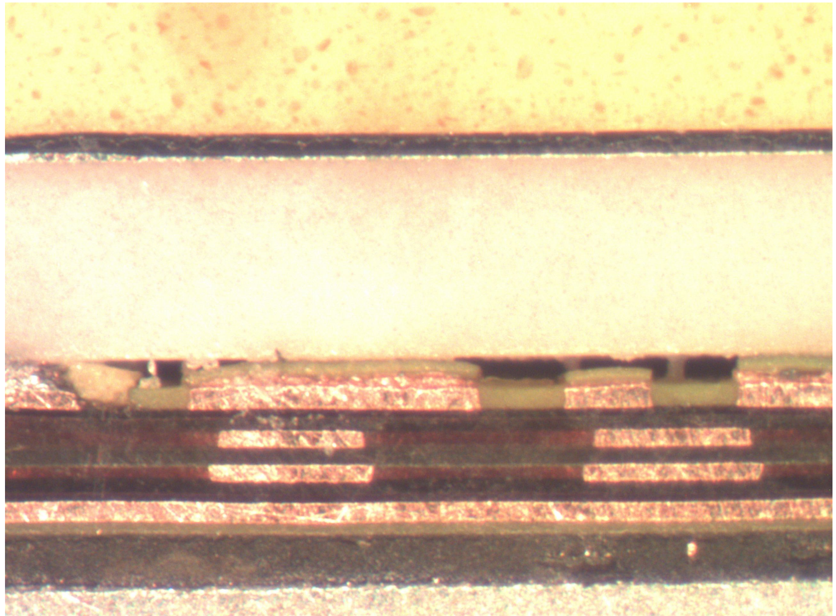


Figure A58: 150^{o}C Epoxy 2 on FLEX Test Board 2512 Resistor Image

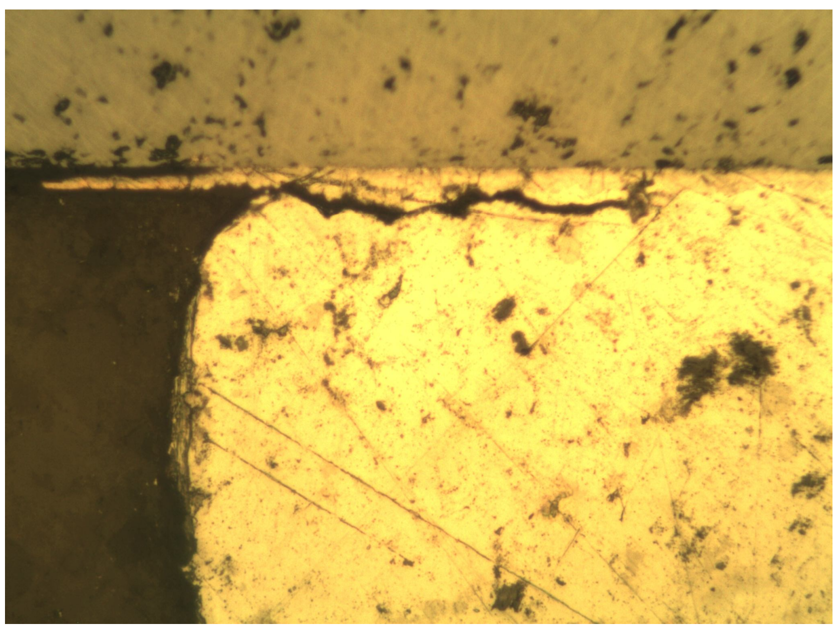


Figure A59: 150^{o}C Epoxy 2 on FLEX Test Board CSP Image

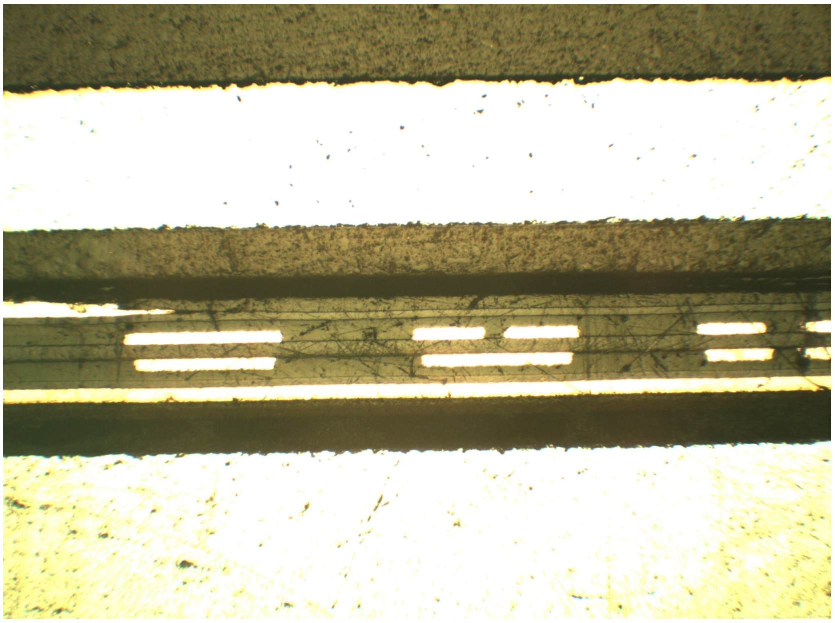


Figure A60: 150^{o}C Epoxy 2 on FLEX Test Board CSP Image

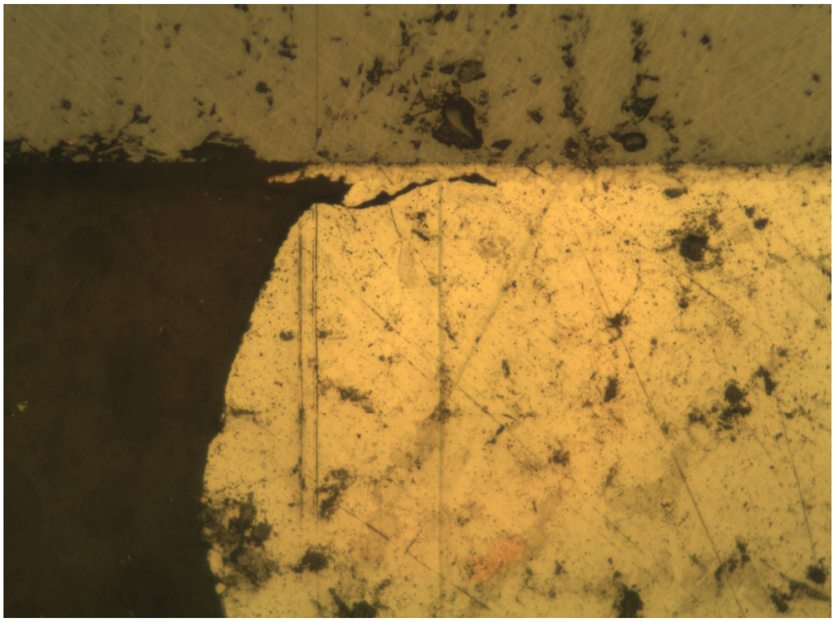


Figure A61: 150^{o}C Epoxy 2 on FLEX Test Board CSP Image

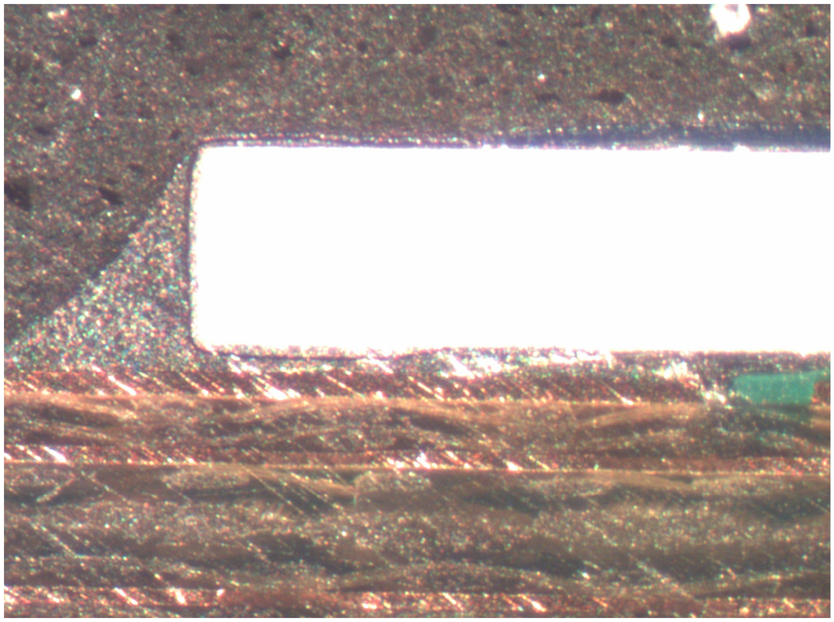


Figure A62: 150^{o}C Epoxy 3 on FR4 Test Board 2512 Resistor Image

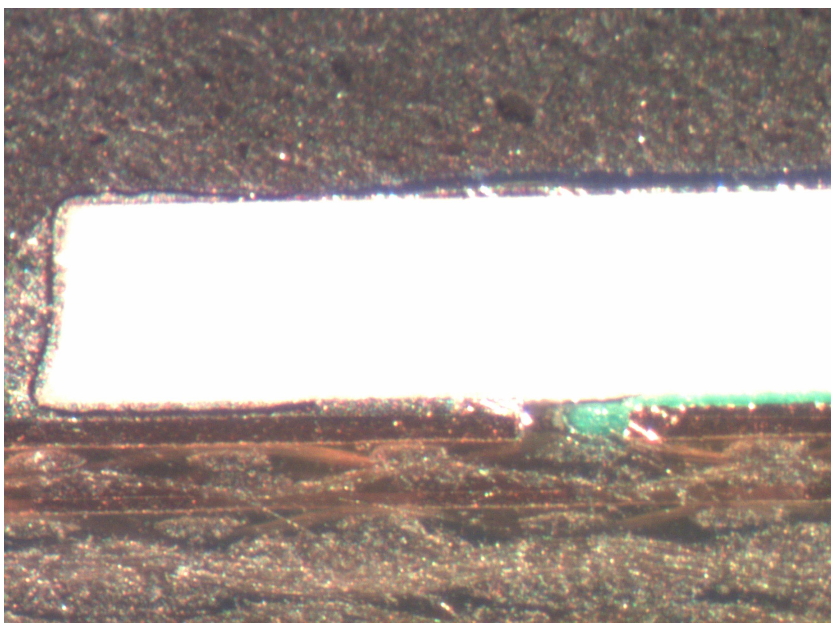


Figure A63: 150^{o}C Epoxy 3 on FR4 Test Board 2512 Resistor Image

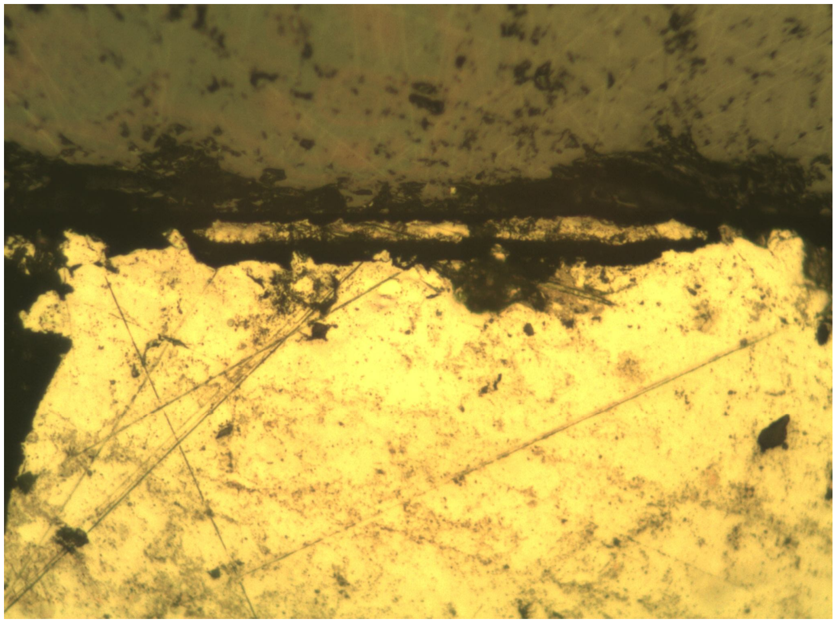


Figure A64: 150^{o}C Epoxy 3 on FR4 Test Board CSP Image

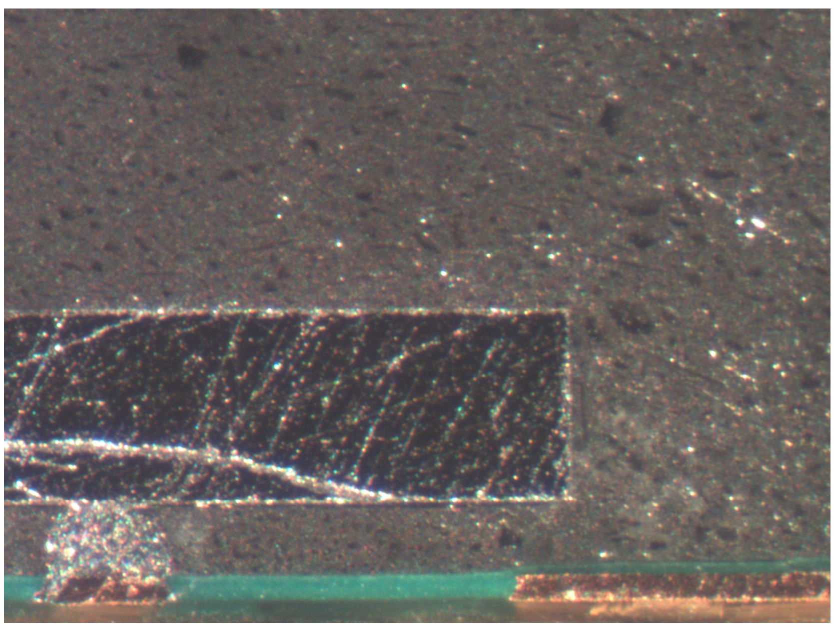


Figure A65: 150^{o}C Epoxy 3 on FR4 Test Board CSP Image

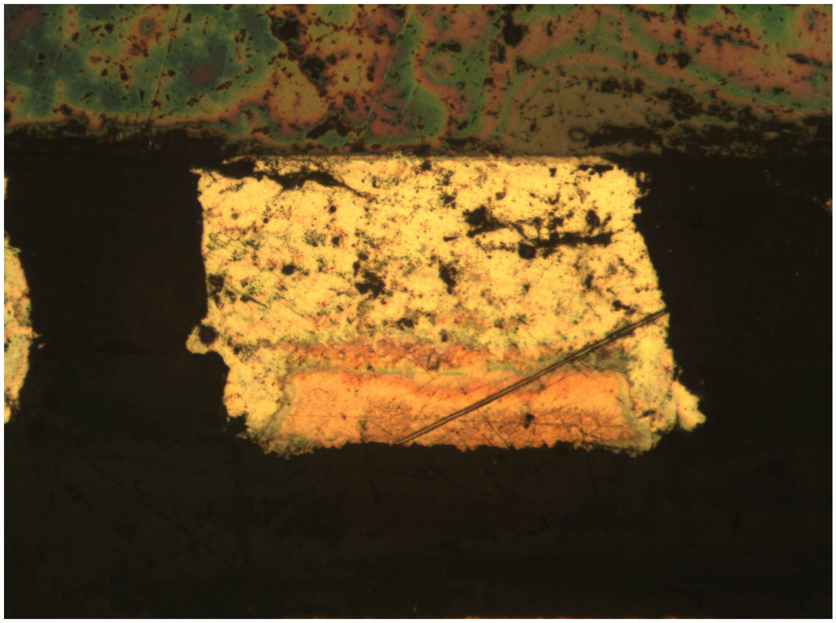


Figure A66: 150^{o}C Epoxy 3 on FR4 Test Board CSP Image

APPENDIX H: Hot Melt 2512 Reliability Data