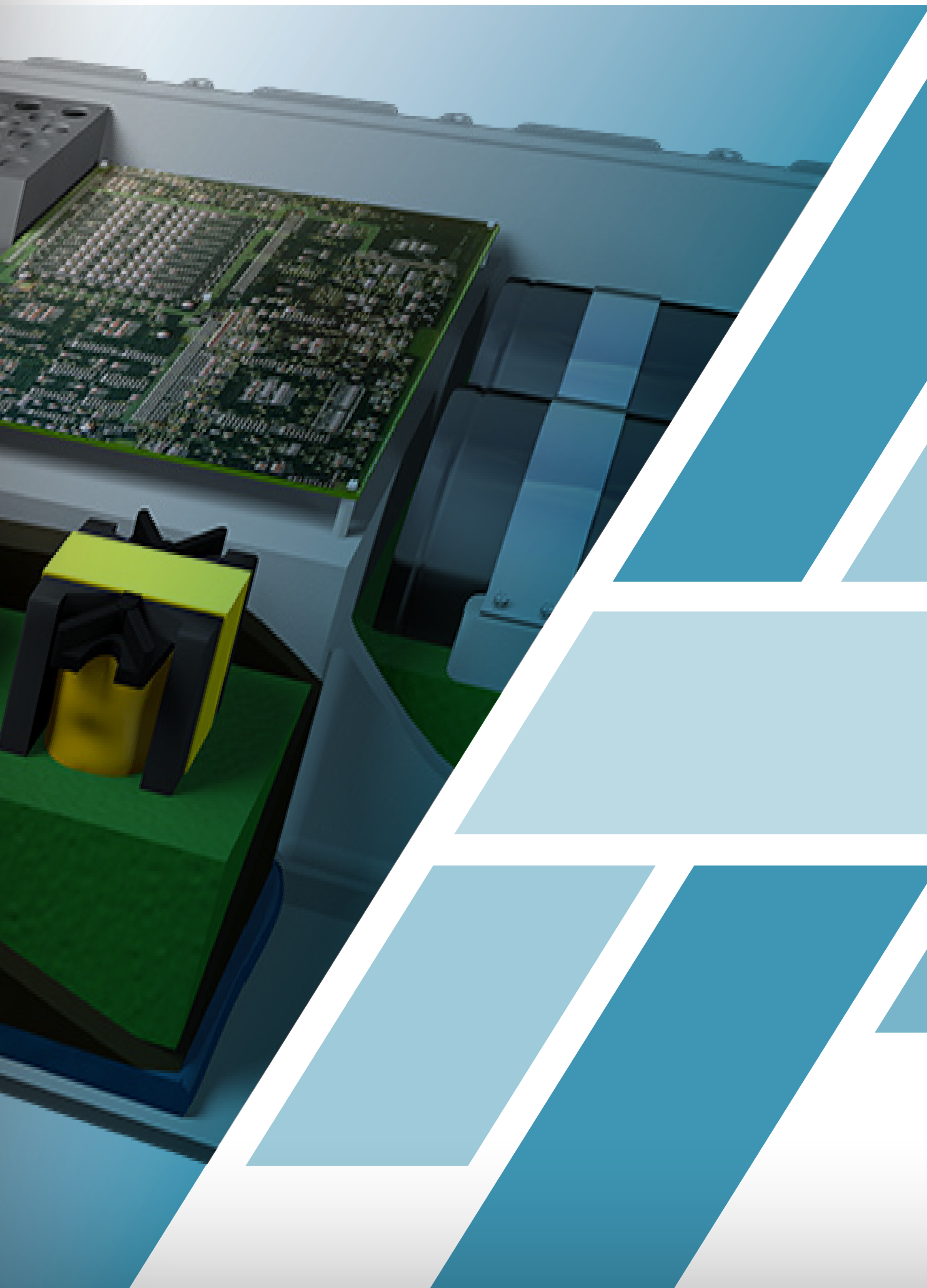
Advances in Flip Chip Underfill Technology for Lead-free Packaging

WHITE PAPER

LARRY WANG, PH.D. | LORD CORPORATION



LORD

Advances in Flip Chip Underfill Technology for Lead-free Packaging

ABSTRACT

Flip chip packaging is one of the fastest growing segments in the integrated circuit (IC) packaging industry due to its design advantages vs. wire bonding. However, flip chip packages also impose significant new demands on underfill encapsulation materials. Specifically, flip chip devices are moving towards smaller standoff gaps, finer bump pitches, and denser area array interconnects. Each of these trends contributes to making the underfilling process more difficult, and in some cases unworkable, for current underfill materials.

Separately, safety and health concerns along with regulatory limitations on anhydrides used in traditional underfills, also force material suppliers to explore different chemistries and technologies for underfill products. In all cases, the reliability requirements and standards on the packaged devices must not be compromised.

In the meantime, the worldwide initiative to switch from eutectic tin-lead solder to lead-free alloys makes the situation even worse due to the higher reflow temperatures and unfavorable characteristics of lead-free solders. Lead-containing solders have been employed as an interconnecting and surface coating material in many applications for decades. The two driving forces that affect the present and future requirements of solders for electronic and microelectronic applications are: first, the increased demands on the level of performance due to the increased density and complexity of circuitry; and second, concern about the toxicity and health hazards of lead. The second concern has led to government legislation and regulations that continue to affect the future of lead usage.

Extensive literature on lead-free solders has been published in the last decade. A growing area of interest is in lead-free solders for flip chip interconnects. Flip chip interconnections are the electrical and mechanical connections between the semiconductor integrated circuit and the package. These interconnects are formed on the periphery or in an area array on the active surface of a die. Flip chip interconnect bumps are smaller (on the order of 100 μm diameter) than other surface mount joints, and bump pitches are very fine (100-150 μm or below). The solder joints must withstand board-level reflow environments compatible with joining organic substrates that have a maximum reflow temperature of 260°C. The lead-free solder must meet these requirements and perform at, or above, the level of performance of the eutectic tin-lead solder alloy. Historically, the underfill has been carrying the burden to provide such needed protection of solder bumps (eutectic or lead-free). That is to say, all the challenges aforementioned are now effectively transferred onto underfill materials.

Aside from the situations mentioned above, integrated circuits are moving towards higher power density with increased constraint on device size and available space within a package. The resulting heat is becoming more intense and heat dissipation is often a critical consideration when designing a flip chip device. LORD Corporation is pioneering the development of thermally conductive underfills that conduct heat from the chip to the substrate. This is especially beneficial when flip chip devices have space limitations that exclude using conventional thermal interface materials applied to the top of the device.

This paper describes the key challenges in developing underfill technologies imposed by the package geometries (smaller gaps and denser interconnects) and performance requirements (faster flow, better reliability performance, and thermal conductivity). These new demands on underfill technology require the development of polymeric materials with improved chemistries and fillers with specially selected size, distribution, and morphology. In particular, the paper will cover the design, development and characterization of non-anhydride underfills with low viscosity, small particle size fillers, fast flow, and high reliability. These properties are essential in the underfill for encapsulation of small to large die with narrow standoff heights between the die and the substrate. Board-level reliability results using lead-free solder joints will also be discussed, including

thermal cycling, thermal shock, and humidity testing, along with confocal scanning acoustic microscopy (CSAM), scanning electronic microscopy (SEM), and x-ray images.

Current work has shown that the underfills presented here have excellent processing properties with fast flow, uniform flow fronts, and non-settling of filler particles. The assembled (cured) flip chip devices display uniform filler distribution, high adhesion, and excellent reliability passing 3000 cycles of air-to-air thermal cycling (AATC). CoolTherm™ ME-542 thermally conductive underfill and the improved version, CoolTherm ME-543, also show the expected lower Theta-JA temperature in flip chip devices compared to a conventional underfill, indicating the desired heat dissipation effect.

INTRODUCTION

The introduction of underfill encapsulation has given the flip chip solder interconnection an unprecedented mechanical integrity and a significant increase in solder fatigue resistance [1]. Today, the major trend in electronic products is to make them smaller, lighter, smarter, and thinner, with shorter electrical paths and faster signal processing. In addition, functionality is increasing while reliability requirements remain the same or higher in some cases. Of course, in addition to all these demands on flip chips, they must also be compatible with fast mass production techniques at a relatively low cost. One of the key technologies that is helping to make these goals possible is electronics packaging and assembly, especially low-cost flip chip technology. For high-speed microprocessors and ASICs, the complex integrated circuit (IC) designs require very high I/O count for package performance [2]. For these types of ICs and subsystems, area-array solder-bumped flip chip technology provides a viable solution since the flip chip offers obvious advantages over wire bonding. Compared to the face-up chip mounting configurations, flip chip provides the shortest possible leads, lowest inductance, highest frequency performance, highest packaging density, greatest number of I/Os, and the smallest device footprint.

Within the scope of electronics applications [3], solder serves two functions: first, as an electrical connection to complete the circuitry; and second, as the mechanical linkages to support system integrity. Solder interconnections can be formed in various configurations with a wide range of solder volumes, including through-hole solder joints, surface mount J-lead, passive chip termination joints and Ball Grid Arrays (BGA) solder bumps, by using various physical forms of solder. Therefore, to replace lead in solders, new solder alloys must possess the characteristics that are compatible with the current application techniques and equipment, and be able to remain stable and intact in the designated physical form under the common application conditions.

The fundamental material properties under study include:

- phase transition temperatures (liquids and solidus temperature) to be equivalent to lead-bearing counterparts
- suitable physical properties, specifically electrical and thermal conductivity, and coefficient of thermal expansion
- compatible metallurgical properties with the interfacial substrates of components and boards
- environmental shelf stability
- intrinsic wetting ability
- adequate mechanical properties including shear strength, creep resistance, isothermal fatigue resistance, thermo-mechanical fatigue resistance, and micro-structural stability.

EXPERIMENT METHODOLOGY

This section describes the methodology that is used to study the uncured and cured state properties of the underfill encapsulant. The uncured properties of an underfill encapsulant dictate its processing characteristics during flip chip assembly whereas the cured properties of the underfill determine its ultimate performance and the reliability of the flip chip device.

Uncured Properties of Underfills

Underfill viscosity is measured on a TA rheometer with constant shear rate at 25°C and at 90°C. Gel time is measured on a conventional Sunshine Gel Timer at 150°C.

The curing profile of the underfill is determined by differential scanning calorimetry (DSC) using a heating rate of 5°C/minute from 0°C to 300°C. The cure onset temperature and the enthalpy of reaction are determined from the DSC cure profile trace.

Underfill flow is measured using a parallel plate test assembly comprising of a glass slide over solder-masked FR-4 laminate separated by two metal shims of 50 μm thickness. The channel between two metal shims is 12.70 mm wide. Underfill is dispensed on one end to the pre-heated test assembly at 90°C, and the time is recorded when the underfill flow front travels a distance of 6.35 mm, 12.70 mm, and 25.40 mm, respectively.

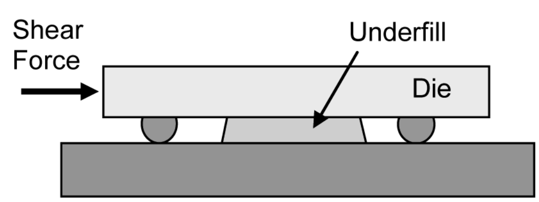


Figure 1: Diagram of die shear adhesion test assembly

Cured Properties of Underfills

The thermo-mechanical properties of underfills are determined using a thermo-mechanical analyzer (TMA) and a dynamic mechanical analyzer (DMA). The TMA is run from -50°C to 300°C at a heating rate of 5°C/minute. The coefficients of thermal expansion (CTE) below and above the glass transition temperature (Tg) are determined from the slope of the plot from -25°C to 0°C and from 225°C to 250°C, respectively. The glass transition temperature is determined as the intersection point of the two tangential lines on the TMA trace, one above and another below Tg. The DMA scan is performed using a cantilever fixture at a frequency of 1 Hz with a temperature range of 25°C to 300°C and a heating rate of 5°C/minute. The elastic modulus of the underfill is determined from the storage modulus curve at specified temperature. The peak of tangent delta (tan δ) curve characterizes the glass transition temperature of the cured polymer. A low stress curing condition of 120 minutes at 150°C is used to determine the above cured state properties of the polymer.

The thermal stability of the underfill is measured on a thermogravimetric analyzer (TGA) using a heating rate of 5°C/minute from 25°C to 700°C. The weight loss as a function of temperature is recorded in the graph and the temperature at 1% weight loss is reported. Thermal conductivity is measured by a laser flash method using a cured sample disc of 1 mm thickness.

The interfacial adhesion at the die-underfill interface is studied using two different die passivations – silicon nitride and polyimide. A bare FR-4 laminate, pre-baked for 24 hours at 125°C, is placed on the non-heated stage of an automatic dispensing system. Underfill dots are dispensed and the volume of the dots is controlled to achieve a dot diameter of 1.8 mm. Passivated silicon chips of 5 mm x 5 mm with peripheral bumps are placed over the dispensed dot by Assembleon placement equipment with a constant placement force of 300 grams. After curing in a box oven for 90 minutes at 150°C, the die shear adhesion is measured on a Dage 2400 tester.

The flip chip device reliability is determined by assembling a 5 mm x 5 mm, full-area-array bumped die with 317 I/Os on a high Tg FR-4 laminate as shown in Figure 2. Ten dies per laminate board comprise the test vehicle for this study.

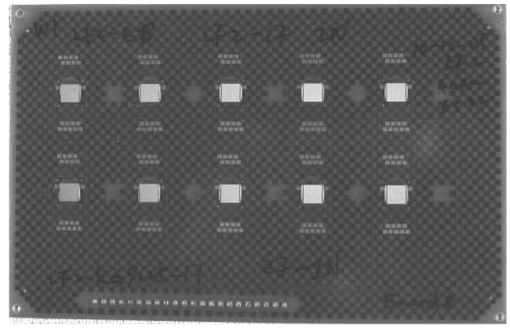


Figure 2: Flip chip reliability test vehicle, 5 mm x 5 mm chip with full-area-array, lead-free bumps

The solder bump metallurgy is a ternary lead-free alloy composition, 95.5Sn/3.8Ag/0.7Cu, commonly known as LF-2. Solder joint connections are achieved using a lead-free reflow profile that peaks at 260°C. The assembled flip chips are then underfilled using a dispense stage temperature of approximately 105°C; the substrate temperature being approximately 95°C. The underfill is cured in a box oven for 90 minutes at 150°C. The flip chip device is daisy-chained so that the electrical connectivity is monitored in-situ during the thermal cycling. The cycling condition is from -55°C to 125°C with a total cycle time of 90 minutes.

RESULTS AND EXPLANATIONS

Uncured Properties of Underfills

Table 1 summarizes the characteristic properties of the two underfills. The first observation to make is that the underfills are based on non-anhydride cure chemistry. Traditional underfills are based on catalyzed epoxy/anhydride chemistry. Due to the hygroscopic nature of the anhydrides, those underfills typically do not perform as well in JEDEC moisture sensitivity testing as the newer, non-anhydride cured underfills. Furthermore, for health and safety reasons, the European Union has limited the use of anhydrides. As a result, LORD has developed alternative chemistries in order to address these changes.

Table 1 also shows that the underfill viscosity is very low at 90°C, the typical temperature at which the underfilling process takes place. This low viscosity enables very fast flow under the die, and is essential for underfilling large and densely populated dies. The correct choice of filler type, particle size, and distribution ensures a homogenous distribution of filler particles in the resin matrix. This is shown in Figure 3, a CSAM image of cured underfill, and Figure 4, a cross-section view of the flip chip with cured underfill. The uniformity of the image indicates a uniform flow front without any density variations between the inorganic filler and the organic polymer phase. This is further confirmed in Figure 4, which shows the SEM micrographs of the underfill cross-section. The filler distribution is homogenous throughout the polymer phase between the die and the substrate.

Table 1: Characteristic properties of two underfills: conventional underfill (CoolTherm ME-541) and thermally conductive underfill (CoolTherm ME-542)

Property	ME-541	ME-542
Resin	Epoxy	Epoxy
Curing Agent	Amine	Amine
Filler	Silica	Ceramic
Filler Loading, weight %	~50	~50
Viscosity, Pa·s		
@ 25°C	33.0	20.0
@ 90°C	0.15	0.20
Flow, sec @ 90°C		
12.70 mm x 6.35 mm	6	6
12.70 mm x 12.70 mm	25	28
12.70 mm x 25.40 mm	97	105
Gel Time, min @ 150°C	3	3
Cure Condition	150°C 90 minutes	150°C 90 minutes
Cure Profile, DSC		
Onset, °C	116	120
Peak, °C	125	130
Enthalpy, J/g	253	260
Thermal Conductivity, W/m·K	0.3	0.8
TGA, °C @ 1% wt loss	364	338
Tg (by TMA), °C	145	138
CTE, ppm/°C, below Tg	31	35
CTE, ppm/°C, above Tg	100	110
Tg (by DMA), °C	149	167
Elastic Modulus, GPa @ 25°C	5.5	4.3
Elastic Modulus, GPa @ 250°C	0.44	0.40
Die Shear Strength, MPa	72	68

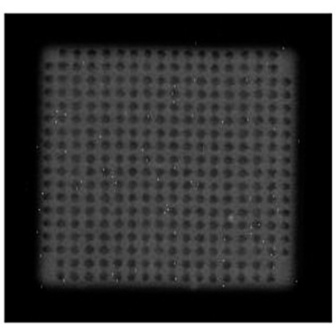


Figure 3: CSAM image of underfill viewed at the die-underfill interface, full-area-array lead-free bumps

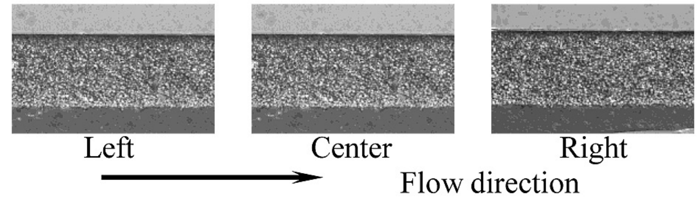


Figure 4: Particle distribution within the underfill cross-section of 5 mm x 5 mm flip chip assembly

The flow test, depicted in Figure 5, uses parallel plates at a 50 µm gap and shows a uniform flow front along the flow distance, progressively shown at 6.35 mm, 12.7 mm, and 25.4 mm.

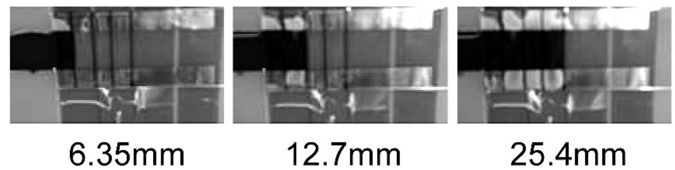


Figure 5: Flow front as underfill advances up to 25.4 mm under 50 µm gap at 90°C

The DSC cure profile of CoolTherm ME-541 underfill shows a cure onset temperature of 116°C, a peak exotherm temperature of 125°C, and an enthalpy of 253 J/g from the curing reaction as depicted in Figure 6.

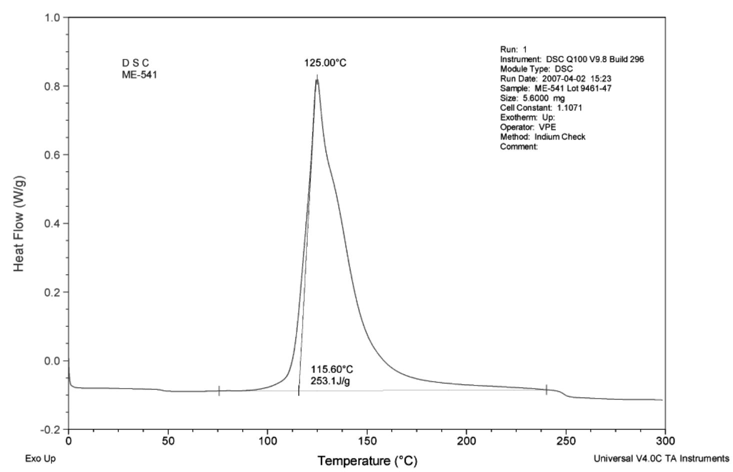


Figure 6: DSC thermogram for cure profile of underfill

The curing temperature of underfill is well above the application temperature for encapsulation so that premature curing of underfill does not occur. This curve also shows that most of the underfill curing has occurred by the time the temperature reaches 165°C.

Cured Properties of Underfills

Figure 7 depicts a TMA trace of the CoolTherm ME-542 thermally conductive underfill. It shows a glass transition temperature (Tg) of 138°C and a coefficient of thermal expansion (CTE) of 35 ppm/°C below Tg (Alpha 1). The moderate glass transition temperature maintains good dimensional stability of the IC package and the low CTE of underfill matches that of the lead-free interconnecting solder to minimize the thermo-mechanical stresses during temperature cycling.

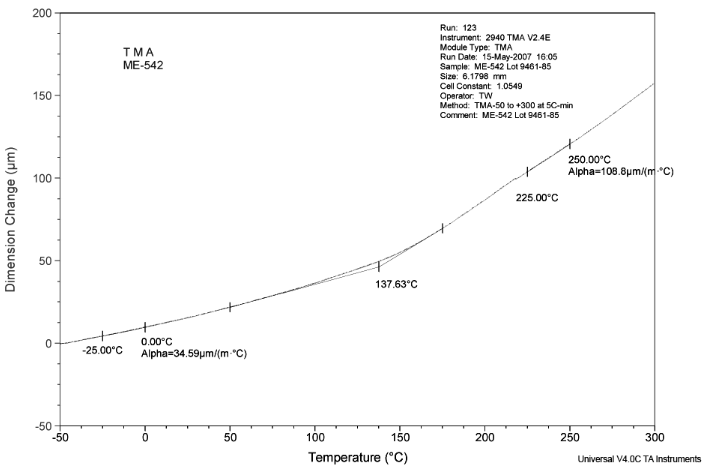


Figure 7: Thermal expansion coefficients and glass transition of CoolTherm ME-542 thermally conductive underfill

The thermo-mechanical properties of the CoolTherm ME-541 underfill are shown as an example in Figure 8. The elastic modulus below the glass transition provides mechanical coupling of the IC package. A modulus of 4-8 GPa is adequate for this function. The temperature dependence of the elastic modulus is shown in Figure 8 and indicates good stiffness and strength properties for this underfill. Mechanical energy, incurred at the temperature and frequency corresponding to the transition, will be absorbed by the material, then partially stored elastically and partially dissipated through internal microscopic friction. Tangent delta (tan δ), a measure of damping-related property of the material, is shown in the same graph. The temperature at the peak of the tan δ curve is reported as the glass transition temperature by DMA method. Accordingly, this underfill exhibits a glass transition temperature of 147°C.

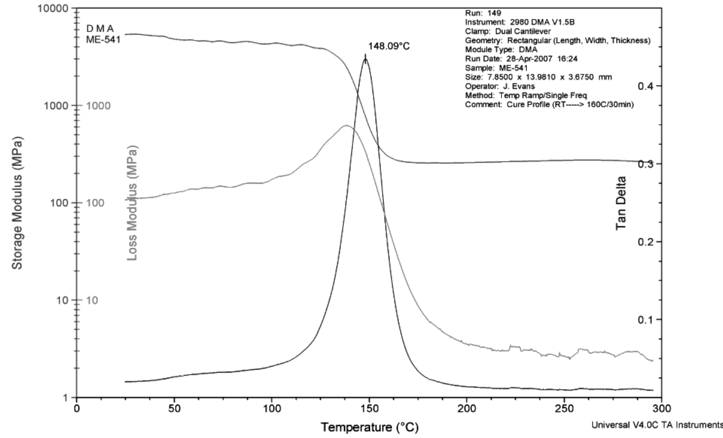


Figure 8: Temperature dependence of elastic modulus and glass transition of cured CoolTherm ME-541 underfill

The thermal stability of an underfill is studied from thermogravimetric analyses (TGA) of the cured underfill. Figure 9 is an example from CoolTherm ME-542 underfill, a thermally conductive underfill. It shows that the underfill exhibits a 1% weight loss at 338°C and a 5% weight loss at 398°C. In the flip chip processing of integrated circuits with lead-free interconnection, it is required that underfills have adequate thermal stability above 260°C as peak solder reflow temperatures in these processes are expected to reach high temperatures.

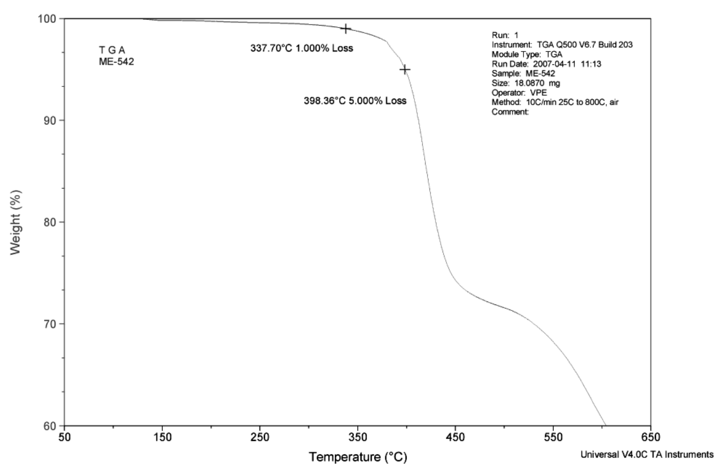


Figure 9: Thermal stability curve of CoolTherm ME-542 underfill from 50°C to 650°C showing temperature with 1% and 5% weight loss

Figure 10 depicts the die shear adhesion results of CoolTherm ME-541 underfill using silicon nitride and polyimide die passivation. The adhesion strength in MPa is plotted as a function of the number of thermal shock cycles for the two types of die passivation. Two observations can be made from this study. First, the adhesion strength is seen to decrease monotonically with the increasing number of thermal shock cycling. This is due to the effect of the repeated thermal shock in extremes of temperature (-55°C to 125°C) on the interfacial bonds at the die-underfill interface. The conclusion is that the strength of the adhesive bond at the die-underfill interface is dependent on the cycling conditions. Second, the die with polyimide passivation imparts better adhesion strength relative to the silicon-nitride die passivation. This is explained by the fact that the silicon-nitride passivated surface is hydrophilic whereas the polyimide surface is hydrophobic. The underfill surface is also hydrophobic in nature and, therefore, bonds better to the polyimide die passivation than the silicon-nitride passivation. The adhesion strength is adequate even after 1560 cycles and the underfill does not exhibit delamination from the die-underfill interface after 3000 thermal shock cycles as depicted in Figure 10.

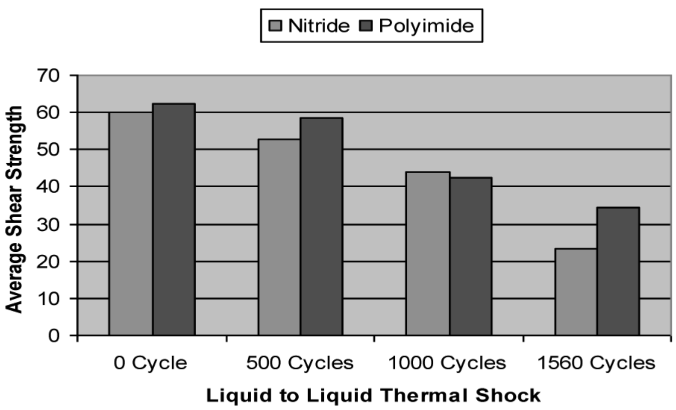


Figure 10: Die-underfill interfacial adhesion as a function of the number of thermal shock cycles

As shown earlier, Figure 2 depicts the test vehicle that is used for studying the reliability of the underfilled flip chip devices. The assembled dies are mounted onto a high Tg FR-4 organic substrate (Tg ~ 170°C) in a face-down (flip chip) configuration. This assembly is a flip-chip-on-laminate (FCOL). A line dispense pattern is used from one side and the fillets around the die can be seen after underfill flow and cure. The flip chip devices are daisy-chained and, therefore, the electrical connectivity of the devices can be monitored in-situ, i.e., during the thermal shock cycling. The interconnecting solder bumps comprise a ternary lead-free alloy LF2. A suitable no-clean, tacky solder flux is used to remove the oxide layers from the solder bumps to facilitate the bonding of the solder bumps to the solder pads on the substrate.

Underfill Application and Processing Study

Both underfills, CoolTherm ME-541 and ME-542, demonstrate good processing properties with easy dispense and fast flow into small gaps, and produce no abrasion or corrosion to the dispense equipment. Figure 11 shows the CSAM and x-ray images of the CoolTherm ME-541 underfill after curing. The featureless images indicate that the flow front of the underfill is even and homogenous, and there is no filler separation or segregation during underfill flow. This echoes the earlier results in Figure 4 that depict no signs of filler settling. Figure 12 shows the optical and x-ray images of a device underfilled by CoolTherm ME-542 thermally conductive underfill, again demonstrating the even flow and complete underfilling of the flip chip with good self-filleting and no voids.

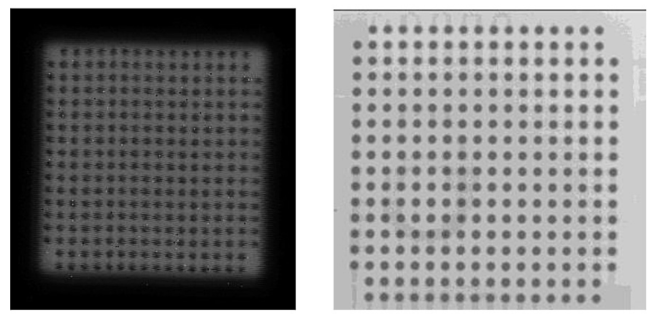


Figure 11: CSAM and X-ray images of the full-area-array flip chip with CoolTherm ME-541 underfill

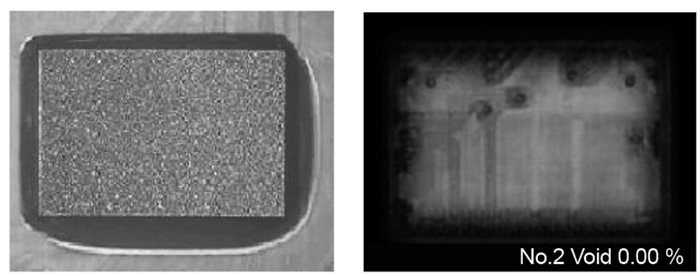


Figure 12: Optical and X-ray images of a flip chip device underfilled by CoolTherm ME-542 thermally conductive underfill

In addition to the ease of dispensing and flow, CoolTherm ME-542 underfill also offers the unique benefit of heat dissipation from the flip chip through the underfill layer. LORD is pioneering the development of the thermally conductive underfill that is usable as a capillary underfill. The bulk thermal conductivity measured on a laser flash is 0.8 W/m·K, doubling the value of a conventional silica-filled underfill. CoolTherm ME-542 is specially formulated to be benign for equipment, without abrasion and corrosion. It contains no harsh filler to scratch dispense equipment, nor does it have unstable materials that may decompose to release noxious chemicals. The electrically insulative fillers are selected so that settling does not occur during storage, application, and curing of the underfill.

Underfill Reliability in Flip Chip Devices

Figure 13 displays the Weibull distribution for the assembled flip chip devices shown in Figure 2, using CoolTherm ME-541 underfill. The results were reported after 4950 air-to-air thermal cycles from -55°C to 125°C. One curve represents 63Sn/37Pb eutectic solder alloy and the other curve is for lead-free LF2 alloy (959.5Sn/3.8Ag/0.7Cu). In-situ monitoring of the devices were performed and electrical failures were recorded as they occurred during the reliability studies. The first electrical failures for devices assembled with lead-free solder alloy is 2535 cycles, and the characteristic lifetime of the devices obtained from the Weibull plot is 4739 cycles.

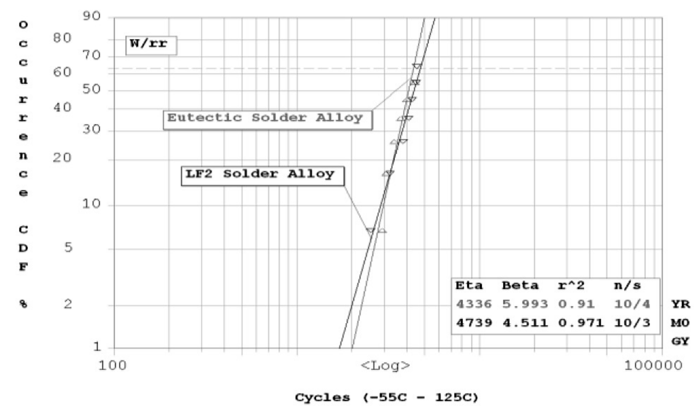


Figure 13: Weibull distribution for flip-chip-on-laminate using Sn/Pb solder alloy and lead-free LF2 solder alloy

A major electronic OEM and its CEM partners carried out the reliability test of CoolTherm ME-542 thermally conductive underfill. CoolTherm ME-542 underfill provided desirable thermal dissipation through the underfill layer as measured by the Theta-JA temperature. Additionally, CoolTherm ME-542 underfill exhibits excellent reliability results in this customer-specific flip chip device and customer-specified reliability tests. The underfill successfully passed, among many reliability measures, a thermal cycling test from –55°C to 125°C for 3000 cycles with zero failure out of 45 flip chip test devices. The inspections by CSAM, x-ray, cross-section, and flat-section of test devices after 3000 cycles confirmed that the underfill has provided sufficient protection to the lead-free solders, and there were no defects or signs of failure.

Next-Generation Thermally Conductive Underfill

LORD is keeping pace with the ever-evolving electronic industry, and maintains its leading edge in the thermally conductive underfill area. To facilitate faster heat removal from a more powerful flip chip, LORD has developed the next generation underfill with higher thermal conductivity. The new product, CoolTherm ME-543 underfill, is non-anhydride chemistry and offers the same benefits as early generation CoolTherm ME-542, but with higher thermal conductivity at 1.2 W/m·K. LORD Corporation's continuous research and development efforts makes it possible to achieve high conductivity while maintaining low viscosity. The key properties of CoolTherm ME-543 underfill are listed in Table 2.

Table 2: Characteristic properties of next generation thermally conductive underfill (CoolTherm ME-543)

Property	ME-543
Resin	Epoxy
Curing Agent	Amine
Filler	Ceramic
Filler Loading, weight %	60-70
Viscosity, Pa·s	
@ 25°C	21.0
@ 90°C	0.20
Flow, sec @ 90°C	
12.70 mm x 6.35 mm	8
12.70 mm x 12.70 mm	35
12.70 mm x 25.40 mm	116
Gel Time, min @ 150°C	4
Cure Condition	165°C 90 minutes
Cure Profile, DSC	
Onset, °C	118
Peak, °C	130
Enthalpy, J/g	172
Thermal Conductivity, W/mK	1.2
TGA, °C @ 1% wt loss	340
Tg (by TMA), °C	135
CTE, ppm/°C, below Tg	27
CTE, ppm/°C, above Tg	95

The lower viscosity facilitates the underfill flow, as indicated by the underfill flow test. The material readily fills into a small gap and advances to a half-inch in just 35 seconds. Experiments also demonstrated the even flow and non-settling properties. All of the above properties are essential for a process-friendly underfill. The material also keeps the similar physical properties that are important to achieve flip chip device reliability.

CONCLUSIONS

LORD has successfully developed new underfill materials with novel non-anhydride curing chemistry and unique properties. We have presented here the material properties, processing characteristics, and the reliability performance of these advanced flip chip underfill encapsulants for application in lead-free interconnection of flip chip devices. These underfills provide fast flow characteristics for small and large densely-populated die. This is from specially designed formulations based on non-anhydride cured epoxy, small filler particle size, and unique particle size distribution, which offer lower viscosity for fast flow. The results from the reliability studies indicate that for CoolTherm ME-541 underfill, in a flip-chip-on-laminate configuration, the first electrical failure occurs after 2500 cycles. No evidence of underfill delamination is seen after 3125 thermal shock cycles from -55°C to 125°C. For CoolTherm ME-542 thermally conductive underfill, the reliability performance in a customer-specific flip chip configuration has passed beyond the test duration of 3000 thermal cycles from -55°C to 125°C. It also provides reduction in thermal impedance of the package while incurring no mechanical or chemical damage to the dispense equipment.

We have demonstrated that all of these underfills from LORD have met the challenges of today's demanding microelectronics and lead-free packaging applications.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Professor Suhling and Professor Lall, from the NSF Center for Advanced Vehicle Electronics (CAVE) at Auburn University, for collaboration and valuable discussions.

REFERENCES

[1] Banks, R.D., Burnette, T.T., Cho, Y.C., Demarco, W.T., and Mawer, A.J., "The Effects of Solder Joint Voiding on Plastic Ball Grid Array Reliability," Proceedings of Surface Mount International, 1996, pp. 121-126.

[2] Mawer, A.J., Bolton, S.C., and Mammo, E., "Plastic BGA Solder Joint Reliability Considerations," Proceedings of Surface Mount International, San Jose, California, 1994, pp. 239-251.

[3] Hwang, J.S., Modern Solder Technology for Competitive Electronics Manufacturing, McGrawHill, (New York, 1996), pp 488.

CoolTherm and "Ask Us How" are trademarks of LORD Corporation or one of its subsidiaries.

LORD provides valuable expertise in adhesives and coatings, vibration and motion control, and magnetically responsive technologies. Our people work in collaboration with our customers to help them increase the value of their products. Innovative and responsive in an ever-changing marketplace, we are focused on providing solutions for our customers worldwide ... Ask Us How.

LORD Corporation
World Headquarters
111 Lord Drive
Cary, NC 27511-7923
USA

Customer Support Center (in United States & Canada)
+1 877 ASK LORD (275 5673)

www.lord.com

For a listing of our worldwide locations, visit LORD.com.

LORD
Ask Us How™