Evaluation of Overmolded Electronic Assembly Packaging Using Thermoset and Thermoplastic Molding

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INTRODUCTION

Plastics have been used extensively in electronics packaging for the past half-century. Thermoset epoxies have a long history as being one of the most robust materials for packaging electronic components. In 1963, the first DIP (Dual-In-Line) IC package began high volume production. The huge growth in the electronics industry also brought about growth in the plastic industry because thermoset epoxy compounds were the primary material used for packaging most integrated circuits.

With advances in IC package miniaturization, primarily due to flip-chip and micro-BGA packaging, it has become possible to overmold the entire circuit board assembly into one large SiP (System-In-Package) package using thermoset transfer molding. Thermoset materials have been used in the electronics industry for many decades because of their superior properties which make them an excellent choice to overmold the PCB assembly.

Thermoplastic materials are also being used to encapsulate PCB assemblies. This technology was developed in Europe during the early 1990s initially for the automotive industry. It is now being used in the telecommunications, computer, and medical industries and is basically a low pressure injection molding process utilizing hot melt polyamide resins to allow encapsulation and sealing of electronic devices. The low pressure molding process falls between the standard injection molding process and a traditional potting process. Although the material properties of most hot melt thermoplastics are not as attractive as the thermosets, a thriving market exists for thermoplastic low pressure molding of PCB assemblies.

This report provides background information on the subject of using thermoplastic and thermoset overmold technology to form electronic enclosures for a wide variety of electronic assemblies. A comparison of thermoset and thermoplastic overmold technology was examined. The manufacturing assembly process, manufacturing equipment, reliability, and thermal management are among the attributes that will be compared. The overmolding packaging technique offers a potential cost effective solution for many applications in the automotive environment over traditional electronic encasement methods.

CONCEPT DESCRIPTION

Traditional product encasement methods consist of a circuit board assembly located between two metal case halves that are held together with screws (clam-shell design). A peripheral gasket is generally applied between the case halves to seal the unit from moisture. Heat sinking the IC components is usually accomplished by contact to a heat rail attached to the circuit board or by direct contact to the product case. Assembly of these types of product packages can be quite cumbersome due to monotonous tasks such as driving screws, applying seal gaskets, and attaching spring clips to heat rails. Figure 1 shows an exploded picture of an aluminum die-cast clam-shell type design of a typical electronic engine controller.

The electronic content of automobiles is projected to increase partially due to controllers located in severe environments such as the engine compartment, inside the transmission, and on the brake caliper. These electronic controllers experience high ambient temperatures and high vibration levels. Circuit board support is limited in traditional metal cased enclosures. Therefore, component to board solder interconnections may be susceptible to cracking due to excessive PCB flexure resulting in a vibration-induced electrical failure. Continued silicon integration will generate higher power densities, and will lead to increased device temperatures, and potentially decreased reliability. New packaging solutions may be necessary to address these constraints while also meeting the ever growing cost pressures from global competition.

The overmold electronic packaging concept consists of a populated PCB assembly that can be adhesively bonded to a metal backplate and then overmolded to form the electronic enclosure. This technique offers many benefits, including a more streamlined manufacturing process, increased reliability, increased durability and superior thermal management. Figure 2 shows an exploded view of this concept and Figure 3 shows a drawing of a typical thermoset overmolded engine controller.

The thermal conductivity of plastic mold compounds are relatively low (< 0.7 W/m°K). Therefore, an integral heat sink (metal backplate) can be insert-molded with the PCB assembly for high-power applications. Flip-chips and other surface mount components that require additional heat sinking are bonded to the metal pedestals in the backplate with thermally conductive compounds. Using this concept, flip-chip thermal management is improved by nearly 100 times compared to a flip-chip in still air. Since the mold compound is 20 times more thermally conductive than air, the overall package heat dissipation is also significantly improved.

With the use of innovative packaging techniques, and recent advances in thermoset and thermoplastic materials, overmolding technology can be practically used to form a plastic package that encapsulates the entire product electronic assembly. The application of flip-chip and micro-BGA packages has enabled the form factor of the automotive electronic controller to be reduced by as much as 75%. With this reduction in package size, it becomes economically feasible to overmold the entire circuit board assembly and address the new challenges associated with the severe environments.

Figure 1

Figure 2

Figure 3

THERMOSET MATERIAL PROPERTIES

Thermoset molding is a very mature technology. Over the years the material properties have been optimized for packaging integrated circuits for the electronics industry. Retention of electrical, mechanical, thermal, and chemical properties at elevated temperatures makes them a great choice for packaging electronic components. Thermoset epoxies are highly filled, possess low shrinkage, and have a low susceptibility to stress formation. They have good adhesion to most materials, high tensile and vibration strength, high heat resistance, and high chemical attack resistance. These properties make thermoset epoxy an excellent material to overmold PCB assemblies.

Even with the excellent properties stated above, some improvements in thermoset epoxy material were necessary so that a relatively large assembly could be overmolded. Lower viscosity resins with optimum gelation times were required so that the large cavity could fill prior to gelation. Materials that obtain a glass-transition temperature (Tg) which exceeds the maximum operating temperature of greater than 150°C are a good candidates. Due to the relatively large size of the overmolded package, a material with low shrinkage is an absolute necessity. The material properties must be carefully chosen so that an optimized manufacturing process and reliable product can be developed.

When overmolding an entire electronic assembly, several dissimilar materials are encountered. The material properties of the PCB, metal backplate, silicon ICs, and other surface mount components have to be taken into account. The coefficient of thermal expansion (CTE) is chosen so that it closely matches that of the other components of the assembly to prevent inadvertent thermal cycle-related interactions. Choosing the correct thermoset material is an enabler to produce a

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product that exceeds current reliability and durability levels.

THERMOPLASTIC MATERIAL PROPERTIES

While thermosets have been used in the electronics industry for many decades, the thermoplastic "hot melt" resins have only recently been seen as a material to encapsulate electronic assemblies. Many of the applications currently in production in the auto industry are located in relatively benign environments such as the passenger compartment. Figure 4 shows an electronic module designed for thermoplastic molding which demonstrates insert molding the connector wire harness.

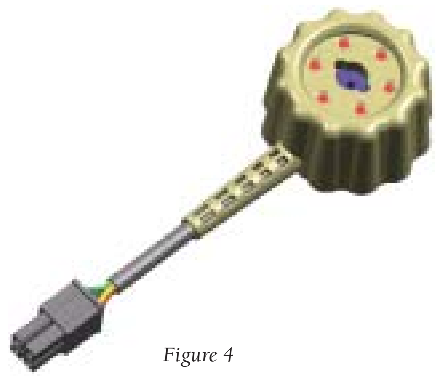

Figure 4

The polyamide and polyolefin resins have much different material properties from the thermoset plastics. The most significant differences being the CTE, modulus, and Tg. The "hot melt" thermoplastics generally have a CTE in the range 200 to 300 ppm/°C with a Tg in the neighborhood of -40°C. Since the CTE is much higher than that of the thermosets, one would expect the material to be very damaging to the solder joints of the components mounted to the PCB. But the material also has a very low modulus. This tends to somewhat counteract the large rate of expansion of the material during temperature excursions and helps to prevent over-stressing the component solder joints. Also, in the case of thermoplastics, since the Tg of the material is -40°C, the product operating environment is generally above the Tg. But with thermosets, the product operates below the Tg of the material (+150°C). In either case, large changes in the material properties of the plastic (primarily CTE) do not occur within the product's operating temperature range.

Thermoplastic materials offer the advantage of being reworkable, and hence the molded module can potentially be repaired. Thermoset materials are not reworkable and defective units must be scraped. Thermoplastic materials are also more environmentally friendly with no hazardous fumes and are non-flammable without additional additives. They generally provide excellent adhesion to most materials that are within an electronic assembly. Since they do not contain any filler materials, their properties are nearly impossible to "tweak" which makes material optimization for various packaging configurations difficult. The thermal conductivity is also inferior to that of the thermoset materials. Chart 1 shows a comparison of some of the more important properties of both materials.

	Viscosity (Pa)	CTE	Tg (°C)	Tensile Modulus (psi)	Specific Gravity	Thermal Conductivity
Thermoplastic (polyamide)	25 to 50	100 to 300	-32 to -52	3200	0.98	0.15
Thermoset (filled epoxy)	10 to 50	8 to 28	150 to 200	28,000	2.00	0.7

Chart 1

MOLDING PROCESS & EQUIPMENT - Thermoset Transfer Molding

Transfer molding has been around for many decades. It is generally a fast and consistent manufacturing technique that results in high quality parts at high yield and high throughput. This relatively simple process can be highly automated, which makes it a great choice for a lean manufacturing line.

The mold cavity is typically made out of hardened tool steel to prevent wear from the high molding pressures and abrasive filler particles in the mold compound. This results in higher tooling costs and longer delivery times. The transfer molding presses can also get relatively expensive. The cost of a standard manual press begins at about $100K US, while a fully automatic press can cost more than $750K US. A microwave heater is also necessary in a manual operation to pre-heat the compound pellets, which also adds cost to the manufacturing line. High production volumes are necessary to offset the equipment costs of the thermoset molding process.

Due to the relatively low strength of most solders at elevated temperatures, the molding temperature and pressures are set lower than used in traditional IC package molding to prevent damage to the solder joints during the molding process. The thermoset material properties and mold press settings are all interrelated. Once a design is finalized and a material set is chosen, the process window can be set wide enough to result in a robust manufacturing process.

A huge advantage is realized when the flip-chips or BGAs are underfilled simultaneously during the overmolding process with the thermoset compound. The manufacturing process can be simplified by using this one-step process. Underfill-dispense machines and long conveyer furnaces can be removed from the manufacturing floor resulting in cost savings. When underfilling during the molding process, all devices are underfilled and cured in less than 3 minutes. Finally, several other manual assembly steps related to encasing the module can be removed from the manufacturing process by over molding the product in plastic.

MOLDING PROCESS & EQUIPMENT - Thermoplastic Low-Pressure Injection Molding

Traditional injection molding has also been around for quite some time, but the low-pressure "hot melt" injection molding machines and processes are relatively new. They are much more cost effective than a transfer molding press and have a smaller foot-print thus taking up less floor-space on the manufacturing line. Manufacturing equipment costs can be 2 to 5 times lower for the low pressure thermoplastic process. Shorter cycle times are possible with the low-pressure molding process because the material immediately "cures" (solidifies as it cools). In thermoset molding the resin takes time to cross-link, and sometimes a post mold cure at elevated temperature is necessary to obtain the desired material properties.

Since the thermoplastic molding process is done at lower pressures than the transfer molding, the cost of the mold cavity is lower, and can be made out of aluminum instead of hardened tool steel. This saves money and time when tooling up a product enclosure. The material process does not require venting because no hazardous fumes are involved. Since the material is injected with low pressures, insert molding wiring cables, product connectors, grommets, etc. are a possibility. The chart below shows a comparison of the typical manufacturing process parameters and manufacturing equipment for both thermoset and thermoplastic materials.

Item	Thermoplastic	Thermoset
Material pre-heat temp	130°C - 240°C	85°C - 125°C
Molding temperature	30°C - 50°C	155°C - 175°C
Injection pressure	15psi - 450psi	300psi - 850psi
Clamping force	1 ton	75 - 120 tons
Mold press cost	38K - 88K	120K - 750K
Pre-Heater cost	Included in press	~ 20K
Mold cavity cost	5K	40K - 60K
Mold cavity material	Aluminum	Tool Steel

Chart 2

COMPONENT SOLDER JOINT RELIABILITY STUDY

Test boards consisting of various daisy-chained surface mounted components (IC packages and zero-ohm chip resistors) were soldered to a FR-4 laminate circuit board using eutectic SnPb solder. Three groups were then placed on temperature cycle testing: overmolded with thermoset; overmolded with thermoplastic; and not overmolded (control group). The samples were subjected to two thermal cycle profiles: underhood (-40°C to 150°C) and passenger compartment (-40°C to +85°C). Therefore the reliability of six distinct test cells was measured. Interconnect life data was obtained by monitoring electrical continuity of the solder joints of the daisy-chained components during temperature cycling. The units were cycled for 3000 hours (1hr/cycle).

Cycle	-40 to +85		
Device	Thermoplastic	Thermoset	Control
289 LBGA			
0603 RES			
0402 RES			
168 BGA	Fail		Fail
SOT 23-6L			
0805 RES			
54 TSOP			
44 QFPN			
48 FBGA	Fail		
68 VFQFN			
64 LQFP			

Cycle	-40 to +150		
Device	Thermoplastic	Thermoset	Control
289 LBGA	Fail		
0603 RES			
0402 RES			
168 BGA	Fail		Fail
SOT 23-6L			
0805 RES			
54 TSOP	Fail		Fail
44 QFPN	Fail		
48 FBGA	Fail		Fail
68 VFQFN	Fail		
64 LQFP	Fail		

Tables 1 and 2

Results of the reliability tests are shown in Tables 1 and 2. The cells shown as "fail" indicate that the test-cell had failures prior to 1000 cycles and/or a MTTF less than 2000 cycles. Inspection of the summarized data shows that the thermoset parts had no failures on both temperature profiles. The thermoset molded parts even out-performed the control group (unmolded PCB). The thermoplastic parts had numerous failures on the 150°C cycle. Failures were also seen on the BGA parts in the thermoplastic group at the +85°C temperature profile. This data indicates that the "hot melt" thermoplastic material that was tested is not suitable in environments where the maximum operating temperature is in the 125°C to 150°C temperature range.

End-of-life analysis was performed on several of the test samples. Figures 5-7 show a cross-sectional view of the microstructure of solder bumps from the 168 BGA package test cells. The solder joint of the thermoset molded part in Figure 5 shows little to no solder degradation after 3000 cycles. However, cracks were found in the solder joints of parts that had not been molded after only 2000 cycles as shown in Figure 6. A large crack with displaced solder is seen in Figure 7 on the part that was molded with thermoplastic compound. A separation such as this is indicative of a large mechanical overstress applied to the solder joint. It appears that the expansion of the thermoplastic compound trapped beneath the BGA package (CTE= 280 ppm/°C) created a large stress that was transmitted to the solder balls. The repeated stress that occurred during the temperature excursions eventually cracked the solder balls. The absence of solder grain growth indicates that the stress was relieved and the crack occurred very early in the temperature cycle test. In fact, this group had a MTTF of less than 500 hours. This implies that BGA and flip-chip devices may require some type of underfill prior to overmolding with thermoplastic compound.

Figures 8-10 show the microstructure of the 54 TSOP packages. Examination of Figure 8 shows the solder joint of the TSOP that was overmolded with thermoset compound again had very little degradation, while the part that was not molded (control group shown in Figure 9) displays a large crack resulting in an electrical failure. The solder structure of the TSOP device from the thermoplastic test cell shows some grain coarsening in the heel of the solder fillet (see Figure 10). The lead frame of the TSOP package is made from an Alloy 42 material which typically fails earlier than devices with copper lead frames due to a larger local CTE mismatch between the device lead and the PCB.

The interconnect life of BGAs, QFN, QFP, and other surface mount components has been shown to increase when encapsulated with thermoset compound. Much in the way underfill protects the solder joints of flip chips, the epoxy resin protects all of the components' solder joints from the stresses created between the CTE mismatch of the component itself and the PCB. This encapsulation technique results in increased module life at higher temperatures which enables their use in harsh environments. If material properties of the system components are carefully chosen, product reliability can increase by nearly two times.

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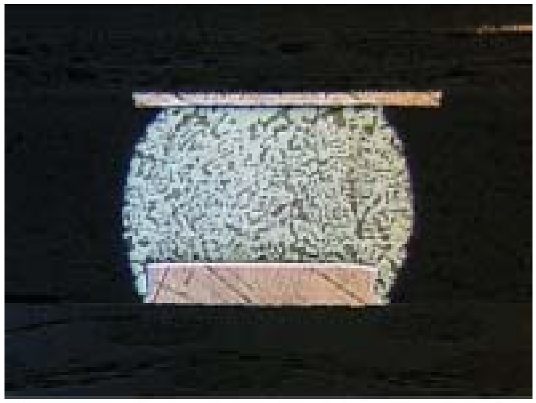

Figure 5

Figure 6

Figure 7

Figure 8

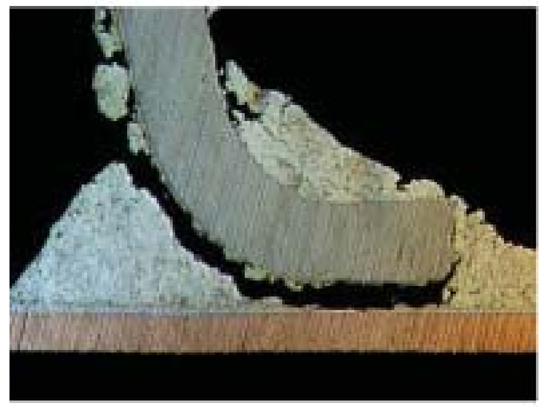

Figure 9

Figure 10

SUMMARY

The manufacturing process, equipment, and product reliability were compared when using thermoset and thermoplastic overmolding technology to form the product electronic enclosure. There are advantages to using each of these technologies. The encapsulation technology that one chooses depends on a variety of factors. Manufacturability, product operating environment, thermal management, product connection system and of course the total system cost should be evaluated when making the decision to use overmold technology as a product packaging choice. Unique product requirements, such as harsh operating environment, or protection from product espionage, can also steer the product in this technology direction.

Even though the reliability performance of modules manufactured with thermoplastic materials is not as great as thermoset, they still have their place in the overmolding technology space. In fact, the thermoplastics offer manufacturing cost advantages over the thermoset molding process and can be considered for products in benign environments.

With proper design and material selection and the use of new plastic mold compounds, an overmolded electronic product enclosure can be formed resulting in a cost improvement over traditional electronic packaging designs. The technology also offers other benefits such as improvements in reliability, thermal management, and manufacturability. Overmold technology can be an attractive choice for product encasement and should be a part of engineers' packaging portfolios.