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Electronic Components for High-g Hardened Packaging

by Morris S. Berman

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14. ABSTRACT A survey of packaging technology applicable to high-g environments is presented. Specifics of the artillery gun launch environment are discussed. The advantages and disadvantages of various external techniques including underfill and potting are also discussed. Discussion of the impact of the manufacturing process and resulting defects is included. Some key failure mechanisms are also identified.					
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Contents

List of Figures	v
1. Description of Technology	1
1.1 Encapsulation	2
1.2 Underfill	2
1.3 Load Path Management.....	3
1.4 Component Selection	3
2. Advantages of Technology	3
2.1 Encapsulation	3
2.2 Underfill	4
2.3 Load Path Management.....	5
2.4 Component Selection	5
3. Market Size and Opportunities	5
4. Critical Hurdles to Development of Acceptance	6
4.1 Encapsulation	6
4.2 Underfill	7
4.3 Load Path Management.....	7
4.4 Component Selection	8
5. Manufacturing Process and Material Selection	8
5.1 Encapsulation	8
5.2 Underfill	9
5.3 Load Path Management.....	9
6. Manufacturing Defects	10
6.1 Encapsulation	10
6.2 Underfill	11
6.3 Load Path Management.....	11
6.4 Component Selection	11

7. Key Failure Mechanisms	11
8. Failure Models for Key Mechanisms	12
9. Screening Tests	13
9.1 Potting and Underfill	13
9.2 Component Selection	13
10. References	14
Distribution List	17

List of Figures

Figure 1. Tank cannon launch acceleration.	1
Figure 2. Typical drop test acceleration profile (3).	2
Figure 3. Underfill effectiveness for drop tests (8).....	4

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1. Description of Technology

This report discusses the issues surrounding electronics exposed to a high acceleration or “high-g” environment. Two of these environments are discussed in depth: consumer electronics and artillery munitions subjected to the gun launch environment. Several Army programs require complex electronics to survive the gun launch environment. The other environment comprises mainly dropped and mishandled consumer electronics devices.

Although these environments appear to be very different, they subject the internal electronics to high accelerations and high frequencies. A gun-launched projectile can be subjected to acceleration magnitudes of 30,000 g’s (from a tank cannon) quasi-static, followed by high frequency excitation as great as 5,000 g’s (12, 1). A typical waveform for a tank cannon launch is shown in figure 1. Artillery projectiles are subjected to a similar acceleration profile, with a duration of approximately 10 ms and a peak of 15,000 g’s. Dropped consumer electronic devices can be subjected to accelerations from 400 g’s to 4,000 g’s (2, 3). A typical drop acceleration profile appears in figure 2.

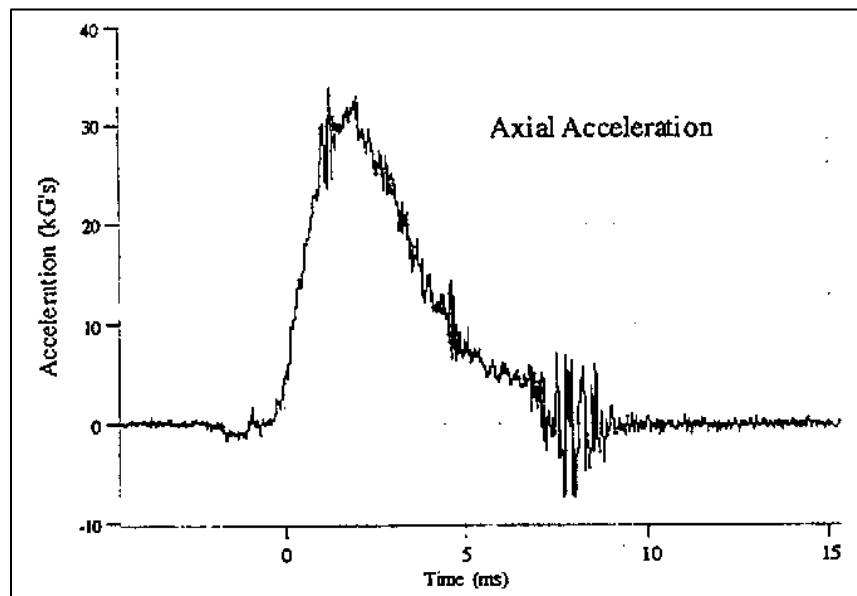


Figure 1. Tank cannon launch acceleration.

In order for these devices to continue operating after being subjected to these high accelerations, a variety of techniques can be employed. These techniques include encapsulation, underfill, load path management, and careful component selection. The first three techniques seek to control the loads to which the components are subjected. The last technique seeks to identify specific components or classes of packages most likely to survive a given load.

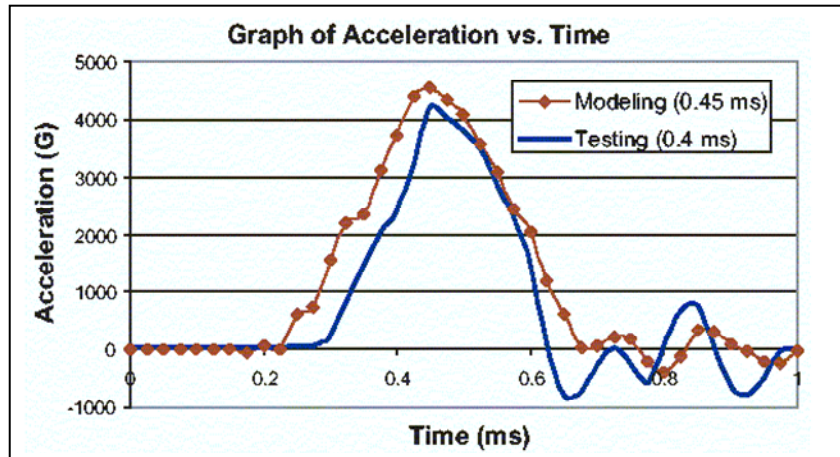


Figure 2. Typical drop test acceleration profile (3).

1.1 Encapsulation

The circuitry is placed into a cavity and then filled with a “potting” material. These materials can take a variety of forms (5, 6). They can be filled or unfilled thermosetting epoxy resins. The encapsulation material can also be a foaming material (such as Stycast¹). Its principal purpose is to provide structural support to the components embedded within it.

A secondary function served by encapsulation is to provide a damping mechanism. The potting materials currently employed have a significantly higher damping property than the traditional materials in which they reside. As a result, these materials tend to absorb and dissipate the mechanical energy imparted to them.

1.2 Underfill

Underfill materials are usually filled epoxy composites that are placed beneath flip chip or ball grid array (BGA) packages to fill the area surrounding the solder joints (7). Underfill has also been successfully used on chip scale packages (CSPs) to increase their reliability (8).

CSPs primarily employ two types of underfill. Capillary underfill is applied after the solder reflow process has been completed. These underfills have a low viscosity which allows them to flow under the CSP via capillary action. A heat process is then used to cure the material.

Fluxing underfill combines the solder flux functionality with the underfill functionality. The underfill is placed in the center of the CSP’s destination on the printed wiring board (PWB). The “pick-and-place” machine then places the component. The fluxing underfill is then drawn to the CSP’s perimeter upon placement by pressure exerted by the pick-and-place machine. During solder reflow, the fluxing underfill provides flux to the soldering process. The reflow provides the initial cure to the underfill which often undergoes a subsequent post-cure heat cycle.

¹Styecast is a registered trademark of Emerson and Cumings, Inc.

1.3 Load Path Management

This is a broad category of techniques ranging from isolation to design of the outer casing of the electronic package. PWB flexure is a primary cause of electronic product failures (9).

Therefore, the product should be designed so that impacts or shocks to the exposed portions of the product result in minimal deformation of the internal PWBs. Careful material choice and design of the connection between external surfaces and the internal PWB supports are used for this failure mitigation technique.

If certain components of a particular design are susceptible to shock and vibration damage, a shock and vibration isolator may be used to minimize the probability of damage. Isolators may use active, passive, or semi-active techniques as well as a variety of materials. They mitigate the propagation of shock and vibration from one boundary to another.

1.4 Component Selection

The electrical function of major classes of electronic components results in an interchangeability for a component with a given function and set of electrical characteristics. However, the different materials comprising the components as well as the factory and lot of manufacture can have a significant impact on the component's reliability in the shock environment. Supply chain management is critical to ensure that components continue to meet the required specifications, whether those specifications are guaranteed by the manufacturer or measured by the user.

As a result, careful consideration of the mechanical characteristics for a given component must be included in its choice. An electronic component vendor is often providing a component that meets or exceeds its electrical specification. Rarely does an electronic component vendor guarantee the component's mechanical performance. It is incumbent upon the system integrator to test critical components to ensure that they meet required performance levels at the design phase as well as throughout the device's lifetime. Previous gun launched munitions programs have suffered reliability losses when a vendor's processes change and mechanical performance is negatively impacted.

2. Advantages of Technology

2.1 Encapsulation

The U.S. Army has been using potting compounds in gun-launched munitions to ensure the survival of critical fuze components (10) since 1950. More recently, potting compounds have been employed extensively in the development electronic module assembly (EMA) of the sense and destroy armor (SADARM) submunition (11) as well as an in-house-developed launch environment characterization data acquisition unit (6).

Encapsulation materials can be added to almost any electronic design. In most cases, the addition of potting material increases the robustness of the design. There is a wide variety of potting materials to choose from, ranging from room temperature vulcanizing rubber to urethanes to lightweight structural foams. Potting materials come in a wide range of strengths and coefficients of thermal expansion (CTEs), thus enabling them to be matched to most applications. A side benefit of potting for shock reliability is that these assemblies are also environmentally protected by the encapsulation. Several potting materials are designed to break down when a particular solvent is applied. This reaction enables the removal of the potting material and subsequent re-working of the assembly.

2.2 Underfill

Underfill has been used extensively with the flip chip attachment method. As a result, manufacturers have significant experience with the required process steps. In a flip chip application the primary purpose of the underfill is to enable load sharing with the solder. The loads result from different CTEs between the die and the substrate. The underfill provides a physical constraint to the solder which further increases the reliability of the component attach. As the underfill cures, it also shrinks, resulting in the solder being compressed between the die and the substrate.

Liu et al. (8) investigated the effectiveness of several different underfills for the purpose of increasing the robustness of CSPs in a drop test environment. Their results are shown in figure 3. Regardless of the specific underfill technology employed, a significant increase in the number of drops that a CSP survives was noted. The significant decrease in failure frequency of the subject component under shock testing is the main advantage of this technology.

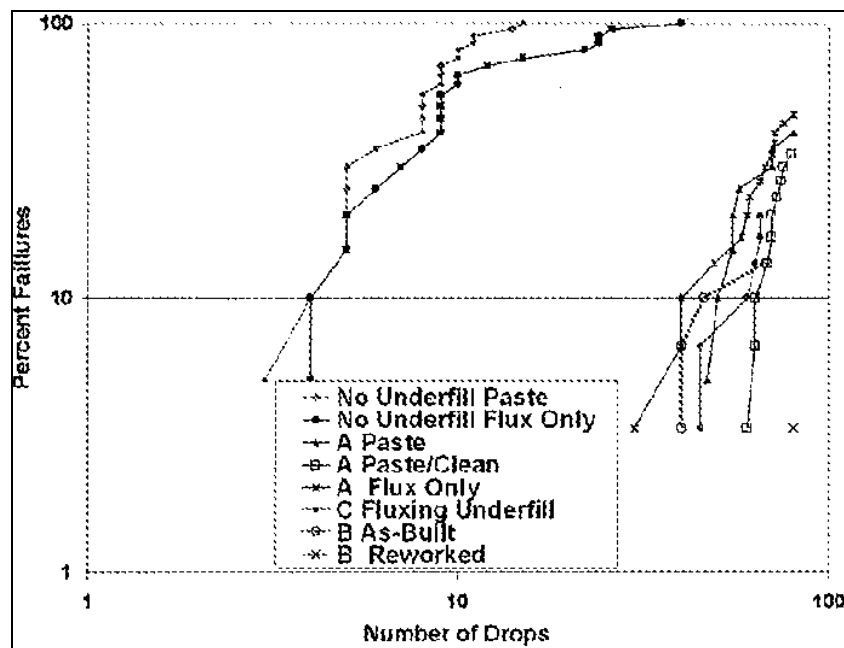


Figure 3. Underfill effectiveness for drop tests (8).

2.3 Load Path Management

Careful design of the load path from the external shell of an electronic product to the internal electronic packages is a critical element of any product's design. However, it requires consideration from the earliest inception of the product's design. Incorporation of design features that mitigate the adverse effects of high-g shocks to the critical components of a product can be a low cost option when done early in the design process. However, modifying basic elements of a mature device design that did not consider high-g loading can be expensive and can significantly reduce the effectiveness of any mitigation technique.

2.4 Component Selection

A basic understanding of the shock response of any particular packaging technology plays a critical role in the selection of a packaging technology to be used for a particular function. Careful choice of the proper package increases the reliability of the product and decreases the cost of future modifications resulting from a poor initial choice.

3. Market Size and Opportunities

The market size and opportunities for the design of high-g electronic devices are increasing. The military's continued reliance on electronics and consumers' expectations that their PDAs and cellular phones will continue to work after being dropped are driving designers to consider high-g environments in a variety of products.

The Army awarded the engineering and manufacturing development (EMD) phase for SADARM to Aerojet Corporation in 1986. A program reaches this phase of development when the Army is convinced that the technologies that it comprises are deemed mature. Five years later in 1991, a qualification test indicated that the overall reliability of SADARM was 16%, and 39 root causes of failure were identified. In 1993, the Army initiated another series of test flights after having resolved all 39 known root failure causes. This test series was discontinued before its scheduled conclusion because of significant reliability issues (20).

After another study, a combined Army-contractor team concluded that SADARM could succeed technically but that significant program changes would be necessary. They also concluded that the root causes of failure were still unknown in many cases. Of critical importance was the failure of 17% of the munitions to self-destruct upon impact. This poor performance poses a significant hazard in the tactical environment (20).

The military's increasing reliance on smart munitions mandates that larger quantities of more complex electronics will be expected to survive the gun launch environment. The unacceptable performance resulting from poor design decisions ultimately led to the cancellation of the

SADARM program. Over the life of the program, the estimated total cost of development went from \$365 million to \$1.1 billion dollars and the unit cost of a submunition increased from \$11,000 to \$36,000 (20).

The SADARM program is indicative of a gun launched munitions program that did not give proper consideration to the design details necessary to survive the high-g environment. The Army and Navy are continuing to develop “smart” gun-launched projectiles. Each of these development efforts represents a potential multi-billion dollar market for technologies that enable reliability in a high-g environment.

Consumer electronic devices represent a more subtle market. As technology has become more ubiquitous, consumers have also expected it to become less fragile. In order to meet that expectation, manufacturers are becoming more adept at “hardening” their products to survive rough handling by the consumer. Product hardening is often a post-design exercise and does not receive due consideration in a product’s initial design.

Competition in the consumer product sector of industry is fierce. As the technical capabilities of a given product at a particular price point coalesce, the consumers begin to evaluate product reliability as a critical issue in their purchase decision. Therefore, the ability of a company to incorporate high-g hardening into their designs at minimal costs in time and money can provide them with a significant advantage in the marketplace. This marketplace advantage is not secured with a single product. It is the culmination of a company’s commitment to design goals and priorities that results in a reputation for producing highly reliable products. A reputation for quality, reliable products also increases their market share.

4. Critical Hurdles to Development of Acceptance

4.1 Encapsulation

The gun launched munitions community clearly understands that specialized technologies and procedures are necessary to ensure the reliability of components. The fuzing community has been using potting materials since 1950 to ensure the survival of electronic and electro-mechanical components. Given the state of the technology and the mass of the components, potting was the only viable means to ensure survival through the gun launch process in 1950. As fuze technology progressed, the use of potting to harden fuze components continued.

When the Army began considering smart projectiles, the electronic assemblies required to survive gun launch became significantly more complex and expensive. Although potting is still an effective means to harden components, it has several drawbacks. The CTE of the components in a potted assembly is a critical issue that requires careful attention. If the thermo-mechanical properties of the potting are poorly chosen, temperature changes will result in failure of the

electronic assembly. Military components are expected to have a shelf life of 20 years and operate in environments from -45 °F to 145 °F. It is very difficult to formulate potting compounds that retain their mechanical properties for that duration over that range of temperature.

The cost of the components incorporated into a smart projectile is a significant portion of its cost. As a result, rework of a failed or marginal part is preferred over disposal of the entire projectile or electronic assembly. Unfortunately, it is extremely difficult to remove a component from a potted assembly. Soluble potting compounds ease the removal process but significantly limit the choice of potting materials. The inability to rework components eliminates encapsulation as a preferred hardening solution. However, it is still employed as an option of last resort.

4.2 Underfill

Underfill of components has been used extensively to increase the reliability of flip chip and BGA devices. Research has shown that underfill greatly decreases a component's susceptibility to failure under bending loads. Until recently, underfilling components also precluded their rework. Recently, Loctite² developed a reworkable underfill (8). When heated in a reflow oven, this underfill breaks down, allowing the component to be removed and replaced.

In the gun hardening community, g-hardening is more important than cost. The consumer products community is less likely to use underfilling as a hardening technique because of the increased labor and inability to rework those components. Cost, not g-hardening, is a more critical consideration in the consumer products industry. Consumers are more apt to choose a cellular based on a \$20.00 cost difference than on its ability to survive 12 drops instead of 3. As reworkable underfill technology matures, it can be employed with minimal cost impact. This development will remove a significant barrier to more extensive use of underfill in the commercial sector.

4.3 Load Path Management

Similar differences separate the commercial and munitions sectors when we consider the use of load path management techniques. Essentially, the user of this technique requires a heavy investment in modeling and understanding of how shock loads are transmitted through a product. The munitions community has made extensive use of modeling for the design of the primary load-bearing structures. With the introduction of smart projectiles, modeling is being used to design the electronic components and their support structures. Experiences, such as the SADARM's cancellation because of unreliability, are providing impetus to the projectile community to more carefully consider the structural dynamic aspects of projectile-borne electronics. Advances in computational structural dynamics are enabling more complex and realistic models which can be used to drive design decisions.

²Loctite is a registered trademark of Henkel Technologies.

The consumer electronics industry is driven more by cost and time to market than by reliability. The goal is to design new products and produce them cheaply while keeping them “reliable enough.” As a result, external structural designs have focused more on ergonomics and style issues rather than on decreasing the shock loads experienced by their internal electronic components. Recent projects at Computer-Aided Life Cycle Engineering (CALCE), University of Maryland at College Park, by Vargehese et al. (21) and Barker et al. (22) as well as Ong, Shim, Chai, and Lim (2), have begun to look at the shock transmission from an electronic product’s outer shell to its printed wiring assemblies and components. The funding of this work is indicative of the industry beginning to accept these design aspects as important elements of their designs.

4.4 Component Selection

Experiences in the SADARM program indicated that component survival is sensitive to subtle design differences that may not be a part of their specification. The gun hardening community has realized the importance of these design differences and carefully chooses its components on the basis of mechanical design as well as electronic function. In some cases, components with identical functionality are provided from a specific supplier to ensure their survival. In one instance of hardening a commercial off-the-shelf (COTS) device to the gun environment, an oscillator from one vendor was substituted for an electrically equivalent oscillator from another vendor. In another case, a COTS supplier was requested to provide a specially modified component that enabled its survival in the gun launch environment.

Cost considerations preclude the consumer electronics industry from specifying process changes in commodity parts. Helmhold, Blattau, and Hillman (23) have begun a project at CALCE to qualify commodity capacitors for given design and application environments. The impetus for this work comes from increasing reliance on discrete capacitors and the realization that they are a significant contributor to electronic product failures. In addition, three of the major capacitor vendors are relocating their manufacturing facilities to China and there is a concern that subtle process changes will probably occur. The funding of this project at CALCE is indicative of industry realizing that although the electronic function of commodity components may be identical, subtleties in their construction can result in critical structural dynamic differences.

5. Manufacturing Process and Material Selection

5.1 Encapsulation

As previously stated, potting materials can be obtained in a wide variety of configurations and a wide range of physical parameters. When selecting which potting material to use for a specific application, one needs to consider a variety of factors.

The CTE of the potting material must be compatible with the items being encapsulated as well as the structure containing the assembly. The strength of the chosen material must be capable of providing the desired level of support. However, the potting must not excessively mass load the components that are being protected (6).

Most potting materials undergo some form of manufacturing processing to be cured. The curing process is usually a heat process. Other components must be compatible with the required cure temperature. In addition to the curing process, the components in contact with the potting material must be chemically compatible.

5.2 Underfill

The performance of capillary and fluxing underfills was examined (8). Most production processes currently use capillary underfill. With this type of underfilling technique, the material is applied after the components have been placed onto the PWB and soldered into place. The area to be underfilled must be clear of excess solder flux as well as moisture to maximize the effectiveness of the underfill. These two requirements add more processing steps to the manufacturing process before underfill placement. After these additional steps are complete, the underfill can be placed around the perimeter of the package where it is drawn underneath the component and cured.

Fluxing underfill is placed before chip placement and eliminates the need for solder paste and flux. Solder balls provide an obstacle around which voids can form as the underfill is squeezed out to the edges of the CSP. The placement parameters and reflow profile must be adjusted to minimize the formation of flaws.

Different choices of underfill material exist for each class. Both flux-only and solder-paste assembly processes are used for the capillary type underfill. The results (8) indicate that any underfill material choice improves the probability of the CSP surviving a high acceleration event.

A thermally reworkable underfill is also available. This underfill falls into the capillary action class of underfills. The advantage of this underfill is that rework of the component is enabled. Upon heating of the component to solder reflow temperatures, the underfill breaks down and loses its adhesive properties (8). The component can then be lifted from the board and cleaned.

5.3 Load Path Management

Extensive modeling of the SADARM projectile at various levels was initiated in an attempt to understand the interaction of various structures in the transmission of loads into electronic components. The entire SADARM projectile and gun system was modeled by Wilkerson et al. (24). This model characterized the load path from the gun tube to the major structural elements of the SADARM projectile. Results from this model were used by Berman et al. (11) in the development of a detailed model of the EMA. These structural models enabled a detailed understanding of how launch loads impact the critical electronic components. These models

were executed in various configurations to help us understand the detailed interactions between potting material, underfill, and encapsulation. This understanding led to material and processing changes which improved the reliability of the EMA. Detailed structural dynamic modeling continues to be a critical tool in the selection of materials and assessing the impact of processing techniques on Excalibur, the Army's current smart projectile.

Although the use of potting compounds is diminishing, Quesenberry (5) has characterized potting compounds using mixtures of hollow and solid glass bead filler material. Relationships were developed for determining the material's CTE and density as a function of the ratio of hollow to solid fill material. An intended use for this material is to minimize the weight of necessary potting material while maintaining a compatible CTE and strength for designs that require encapsulation.

The consumer products industry has yet to embrace modeling as a critical technology in an overall load path management methodology. Ong, Shim, Chai, and Lim have performed experimental investigations to understand the difference in PCB mechanical response to drop tests when mounted in a device or on a fixture outside a device (2). They determined that the mechanical response of the PCB differs significantly, depending on whether it was bare or installed. The differences were the result of interactions with other components and the boundary conditions imparted by the PCB support mechanism.

Varghese et al. have a research program at CALCE to examine the dynamic behavior of plastics under impact loading (21). This research program enables the development of a material model that can be used for the exterior case of electronic devices. Once this methodology is developed, it can be used to quantify the effect of processing variables on the plastic's properties as well as to quantify the difference between various plastics.

Shi, Wang, Pang, and Zhang have developed a methodology to characterize underfill materials as a function of temperature and strain rate in support of finite element modeling (7). The variation of material properties as a function of strain rate is an important parameter in modeling components subjected to impact events. These two material characterization efforts enable designers to quantify the impact of different material choices on the load path to a component.

6. Manufacturing Defects

6.1 Encapsulation

The manufacturing defects associated with encapsulation fall into two categories. Voids can form in the potting material and the potting can fail to adhere to the cavity walls or components. Void formation can be controlled if we carefully monitor the curing process and minimize the

probability of contamination. Careful cleaning of components and cavity surfaces is the key to ensuring adherence of the potting.

6.2 Underfill

The basis for manufacturing defects for both types of underfill primarily lies in contamination of the area to be underfilled. Flux residue is a significant concern for the capillary type underfill. Excess flux can preclude the underfill from touching all areas beneath the component by interfering with the capillary action and thus the underfill flow. Before the underfill is applied, the component and PWB must be free of moisture. Moisture that seeps in from the board or adheres to the solder ball is another contaminant that will interfere with the underfill flow. Both of these defects result in voids in the underfill that decrease its efficiency. In some cases, fill is added to the epoxies to obtain a CTE match with other components. In this case, the fill material can interfere with the flow of the underfill beneath the component.

The fluxing underfill is not subject to contamination by flux or voids resulting from flow time. However, the placing parameters of the component become critical. As the component is placed on the board, void can be trapped by the solder ball array. As the size of the balls increases, the probability for trapped voids also increases (8).

6.3 Load Path Management

Once a validated model of the structure of interest has been developed, it can be exercised for a variety of conditions. Various structural elements can be “damaged” to simulate manufacturing defects. The result of these defects on the structural response of the electronic components can then easily be quantified.

6.4 Component Selection

One element of selecting components is the consistency of their response to shock loads. Lower quality components with significant manufacturing defects should manifest this property in their characterization tests. The designer is then able to choose components from a manufacturer that is capable of consistently delivering high quality components.

7. Key Failure Mechanisms

Reliability of electronic packages has traditionally focused on thermal and thermo-mechanical issues. Although the consideration of high acceleration loads touches upon some of the same basic physics, the causes of the loads resulting from high-g loads are different. Thermo-mechanical loads and shock loads induce strain differentials between the PWB and the

component. The strain difference is one of the key mechanisms for electronics subjected to high accelerations.

Bending of the PWB is the primary mechanism through which a high-g environment imparts strain into an electronic device (8, 13 through 17). As package-to-PWB interconnections have moved from leaded to solder ball attaches, the compliance between the board and component has decreased. Shetty et al. (13) investigating the bending loads necessary to impart failure in CSP packages, and Barker (15) is investigating the bending loads necessary to impart failure to plastic ball grid array (PBGA), capacitors, and other common packages. Varghese and Dasgupta (9) identify cracking at the intermetallic layer of solder balls as a result of bending stress.

The second key failure mechanism for high-g devices is simply a result of the acceleration to which they are subjected. In a high-g environment, all materials and parts in a device are subjected to a body force equal to the product of mass and acceleration. For commercial applications, the inertia is relatively small. However, as a device is subjected to accelerations of 5,000 to 30,000 times the acceleration of gravity, the force that the internal and external support structures must support becomes significant. D'Amico (12) notes that a key to survival of the gun launch process is to minimize component mass. In one gun launched munitions program, a particular component had to be specially procured with aluminum wire bonds since gold wire bonds were too weak to survive gun launch. The reduction of mass also results in the reduction of bending moments, thus minimizing one of the primary failure mechanisms.

8. Failure Models for Key Mechanisms

Tropea, Mellal, and Botsis (18) have examined in detail the failure properties of solder balls at the intermetallic layer. The actual solder ball failure results from complex interactions between the intermetallics. In some cases, the tin-lead interfaces break up and become surrounded by microcracks. Long cracks can form along the copper-tin interface. Cracks also tend to form along boundaries between different grain structures (18). Understanding the micromechanical damage is crucial in developing a physics-based failure model.

Underfill is a critical component for low-compliance packaging attachment schemes. Shi, Wang, and Pickering (19) have developed a characterization method for understanding failures in filled epoxy films. Linear elastic fracture mechanics were used to describe and predict grown crack tips in the epoxy material (19).

Barker has taken a macroscopic approach to developing a failure model. A failure model for capacitors has been developed which depends on knowledge of the strain values of the PWB at the base of the capacitor solder fillets. A failure model applicable to PBGAs is in the

development process. Recent experimentation has indicated that low cycle fatigue may be a critical factor in the development of a failure model (15).

9. Screening Tests

9.1 Encapsulation and Underfill

In order to ensure the highest consistency and thus reliability in the high-g environment, steps must be taken to ensure that batch processed chemicals, such as underfill and potting, are properly mixed. Hoang, Murphy, and Desai (26) suggest a two-phase test when one is screening underfill materials for high performance applications. Both tests should use components of the same configuration as used in the actual application. The components can be non-functioning dummies or electrically rejected actual components.

The first test determines the flow rate of the underfill. Underfill should be dispensed along one side of the component. The time for the underfill to flow to the other side should be monitored. The preheat temperature of the substrate could be varied to determine the impact of process variability. After curing, the components should be inspected with an acoustic microscope for void formation.

After a full cure, the flow rate specimens can be used for an adhesion test. A shear test appears to provide the best measure of adhesive strength. The shear test tends to concentrate failures at the underfill boundaries as opposed to cracking the die or delaminating the substrate. A similar series of tests could also apply to potting properties. Although Hoang et al. envisioned these tests for choosing appropriate underfill, they are also appropriate to be used as a screening process (26).

An adhesion test of the potting compounds would provide a good screen to ensure that the potting is consistent. A tensile test of a homogeneous material specimen would be a good augmentation of the adhesion test to ensure that the constitutive properties of the potting remain constant.

9.2 Component Selection

This technique for hardening is predicated on the fact that different components with the same specifications may exhibit dissimilar mechanical response. A critical facet of this hardening technique is to ensure that a component manufacturer has not changed processes, thus resulting in a change in mechanical properties. Screening tests that verify the mechanical properties of incoming parts are an extremely important part of the supply chain management process to ensure high-g survivability.

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