Thermal Management Performance and Attachment Reliability Using Urethane Film Adhesives

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Abstract

Three technologies have been predominantly used in electronic applications relative to component and circuit card attachment. Specifically, epoxy chemicals, urethane chemicals, and organic silicones are available for various adhesive applications. Each has relative advantages, technically, as well as economically. For example, silicones have exhibited exceptional low temperature performance. However, recent advances in urethane-epoxy technologies have significantly narrowed this difference. In today's competitive environment, it is necessary to consider manufacturability issues. In this regard, epoxies have had the unique advantage of availability in B-stage films. These are essentially partially cured adhesive sheets. They can be die cut or punched. Sheets are applied between the surfaces to-be-bonded, and final cured, completing the process.

Advantages include manufacturing .friendliness, elimination of mixing / measuring, zero waste, no chemical disposal issues, and production assembly time savings. However, epoxy adhesives are significantly less compliant than urethanes or silicones, especially at low temperatures, an important consideration for commercial and military high reliability applications.

Urethanes and silicones, although available as cured sheets, have previously not been manufactured as B-stage films. A method has been developed by one adhesive manufacturer to produce the equivalent of a B-stage urethane film (termed B/CIB), with a variety of unique properties. Advantages include good thermal conductivity, exceptional low temperature performance, very high compliance Le. Low elastic modulus, flexibility in the cure schedule, capability to be die punchea; and a history of performance.

Density of cirCllit card designs has increased considerably. The introdtlction of flip chips and ball grid an-ays has contributed to this development. Thermal issues, specifically thermal conductivity, are now a prime consideration in many adhesive choices for electronic applications. The B-stage urethane technology significant0/ addresses these issues. This paper describes the perfomlance and applications of one such urethane sheet adheshle, including thermal, and mechanical modeling results, and an end-use application.

Key words: Urethane adhesive, thermal management, elastic modulus, B-stage, sheet film adhesive, surface mount technology, electronic packaging, component bonding.

1.0 Introduction

With the cost of components, including high reliability devices, continuing to fall relative to overall manufacturing costs, it is critical to find methods to reduce the cost of assembly, in order to maintain market competitiveness. Adding to this scenario is the demand for materials to perform in difficult environments. Commercial designs now include such requirements, traditionally relegated only to the military environment, e.g. cell phones, under hood automotive, and aircraft. Higher density packaging, whether for commercial or military applications, has placed new demands on interfacial materials, such as adhesives, used to assemble components and modules. Specifically, thermal management and wide temperature operating performance are required in many new designs.

The attachment between a component and a printed circuit card (PWB) and / or a heat sink surface to a PWB requires an adhesive with good thermal and mechanical properties. High thermal output component packages will necessarily require a careful selection of the adhesive for the particular application. Considerations such as, thermal coefficient of expansion (TCE) mismatch between substrate and package, thermal conductivity requirements, adhesive compatibility with production soldering and cleaning operations, re-workability, long term reliability, etc. must be addressed in order to meet the total module design requirements.

Adhesives are available in a variety of configurations. The two basic are a one-part material, sometimes kept frozen to assure shelf life, and a two-part mix requiring a specific combination of the resin and hardener or catalyst for proper balance in order to achieve the ideal material properties. The one part approach has several sub-categories. Typically however, the one-part is a premixed frozen adhesive ready for use directly from the storage container. One-part materials, especially epoxies, are also available in sheet form from a number of sources. This format is categorized as a B-Stage adhesive, and kept frozen until applied. The adhesive is brought to room temperature in a dry cabinet, and then placed between the components to-be-bonded. It requires only pressure and heat in order to complete the reaction. Some materials, such as urethanes and silicones, are used in a format called C-Stage. These sheet materials are completely cured and serve as 'gaskets' between two surfaces. In that scenario a secondary operation / adhesive is necessary to perform the function of bond contact. Additional manufacturing costs will be associated with the C-stage approach.

The B-stage approach has a distinct manufacturing advantage, and hence a cost savings potential since it is essentially a one-step operation. However, until recently, only epoxy adhesives were available in B-stage formats. Unfortunately, only silicones and modern urethane composites have the necessary low temperature performance and thermal conductivity necessary to meet many high-density packaging requirements. A new approach, which has been termed a "B/C/B" urethane, has been developed and tested. It combines the unique advantages of both B-stage epoxies and C-stage high performance urethane sheet materials.

2.0 Theoretical and Experimental Data
2.1 Desired Material Properties

Adhesives used in electronic packaging applications must have properties specifically suited to the end-product environment. In the case of component to PWB attachment and board to heat sink attachment, the particular adhesive must remain compliant over the operating and storage temperatures, and should exhibit the necessary thermal conductivity in order to perform as a transfer agent for heat dissipation purposes. Tg, should be out of the operating range, and it must remain stable over the expected life of the product. Secondary, but no less important considerations include manufacturing friendliness, that is ease of application in a production setting, compatibility with follow-up processes such as conformal coating or soldering, and cost. Modern urethanes are a good match for these criteria.

Table 1. Desired material properties.

Desired Property	Desired Value	ASTM Standard
Tensile / Shear Strength	> 1.4 MPa (200 PSI)	D-412
Young Modulus @ -55C	< 34.5 M)Pa (5000 PSI)	D-412
Room Modulus typical	3.45 MPa to 6.90 MPa (500 - 1000 PSI)	D-412
Thermal Conductivity	> 0.40 W / m-C (>0.01 W / in-C)	Calora or Eqv.
Tg in C,	- 60 C or colder	E831-86
Cure temperature/time	100 C or less 3 hrs or less	N/A
Bond pressure	<0.07 MPa (10 PSI)	N/A

The "Desired material properties" detailed in Table 1 were developed based upon three areas of experience.[1] First, the prior development, modeling, and application of a highly compliant, urethane-based liquid bonding adhesive which had been successfully applied in a real-world environment, and to date has a multiple year history of performance. Second, the specific high reliability applications were carefully considered by the design and manufacturing engineering teams, which led to additional, design related, material property requirements for the proposed sheet adhesive. The B/C/B urethane adhesive must also have a moderate durometer and very low out gassing per ASTM E-595.

Finally, manufacturability concerns, given the use of components and boards with considerable TCE mismatch differences, generated additional requirements.

2.2 Material Comparisons

Design of the B/C/B urethane consisted of the development of a technique to print a B-stage adhesive onto both sides of a cured C-stage urethane sheet, a proprietary process developed by Aptek Labs, Inc., Valencia, CA. The C-stage sheet serves as the mechanism to control thickness and thermal properties. The combination B/C/B sandwich is die cut to the end-users requirements, then frozen to preserve shelf life. The final product is a urethane-based sheet comparable to the typical epoxy B-stage sheet sold by a number of vendors. Below, the B/C/B material is compared to existing products for purposes of material property descriptions. Refer to Table 2, "B-stage material comparisons", for a summary of typical data.

Table 2. B-stage material comparisons.

Sheet Material	Urethane B/C/B	Epoxy *
Measured Parameter		
Thermal Conductivity 70% fill PBW	0.87 W / m C (0.022 Watts per inch-C)**	1.02 W / m C (0.026 Watts per inch-C)
Tg Temp. C	- 72 typ.	+ 130 typ.
Tensile / Shear Al. / Al. at bond pressure	3.10 / 2.07 MPa (450 / 300 PSI)	6.76 / 3.52 MPa (980 / 510 PSI)
Modulus bulk at - 60 C	9.66 MPa (1400 PSI)	3448 MPa (500 KPSI)
Modulus bulk 25 C (room)	3.66 MPa (530 PSI)	1379 MPa (200 KPSI)
Modulus bulk at + 55 C	3.62 MPa (525 PSI)	1034 MPa (150 KPSI)

Note:
(*) average of measured data for three selected vendors epoxy-based B-stage sheet adhesive
(**) thermal conductivity difference due to difference in specific gravity between epoxy and urethane chemicals, if loaded to percent fill by volume, the thermal difference would be negligible

The epoxy materials, although a degree higher in adhesive strength, are much less compliant than the urethane sheet as reflected in the bulk modulus data at temperature extremes. For applications with large TCE differences, the degree of compliance, especially at cold temperatures, is critical. The ramifications of high TCE differences combined with wide temperature ranges is a significant increase in stress within the matrix of the adhesive.[2] If the adhesive is sufficiently strong, the stress will be transferred to the components bonded together, hence causing potential micro-cracking, and eventual component failure should the crack propagate.[3] However, if the adhesive is sufficiently compliant, it will allow the two bonded surfaces to move relative to each other, thus minimizing the induced stress. Thermal conductivity is comparable when considering adhesives are loaded by weight (P.B.W.). Accounting for the lower specific gravity of urethanes, a fill loading by volume will yield similar thermal values. The glass transition, typical of most epoxies, is around the 130 C range. This is on the upper limit of many high reliability applications, where the high temperature point is 125 C.

2.3 Strain Estimate for a Given Product Application

An application required bonding a 0.0508 m (2-inch) by 0.1520 m (6-inch) epoxy polyimide G-12 PWB to an aluminum heat sink for a 125 watt dissipation module assembly. The TCE difference board to heat sink was empirically measured at 14 PPM/C. The operating temperature range was –55 C to +110 C, a delta temperature of 165 C. Originally, the board was attached (bonded) using one of the B-stage epoxy sheet films. During initial product testing, which included temperature cycling as specified above, several PWB topside surface mount (SMT) chip components cracked causing electrical failure. Cross sectional failure analysis results indicated excess deflection (strain) as the root cause of component failure. The strain was a direct result of board warp due to TCE differential. In this specific case, the calculated differential strain is 14 PPM/C times 165 C times the distance from neutral, about 0.0762 m (3 inches).[4] The strain difference was computed to be 1.760 E-04 m (6.93 mils) at the board / heat-sink perimeter. Since the adhesive was essentially non-compliant, the stress at the board perimeter exceeded 103.5 MPa (15 KPSI), from strain gauge data. Much of this stress was transferred to the SMT components soldered to the board surface due to warp; hence cracking of many of the soldered component resulted, mostly near the perimeter of the PWB.[5]

Corrective action was to change the adhesive to the much more compliant B/C/B urethane sheet film. Extensive thermal cycling indicated the induced stress, originally exhibited using the epoxy sheet film adhesive, was sufficiently absorbed by the urethane. Strain gauge measurements, and subsequent stress computations indicated the board was free to 'float' relative to the heat sink, preventing any re-occurrence of topside SMT component damage. A typical sample of the product is depicted in Figure 1, "Product sample".

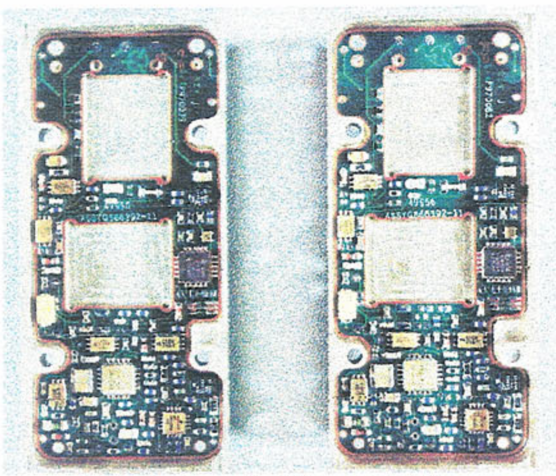

Figure 1, Product sample, 125 watt module.
Photo courtesy Raytheon Corporation

From a manufacturing consideration, the differences between the original epoxy sheet and the B-stage urethane were simply a change in the oven cure temperature. It was essentially transparent to the production process.

2.4 Thermal Performance Analysis

Thermal performance is critical in the aforementioned product. For this application, the particular B-stage urethane sheet is 35.56 E-05 m (14 mils) thick, including 5.08 E-05 m (2 mils) of thermally conductive B-stage adhesive on each side of a precision thickness urethane C-stage inner sheet. Changing the thickness of the internal urethane C-stage sheet can vary total thickness. From measured data, Thermal loss across the composite sheet is computed as follows:

Measured Thermal Data:
Al_2O_3 70% fill ratio P.B.W.

C-stage urethane, K = 0.87 W / m C (0.022 W / in-C)
B-stage filled to yield 1.02 W / m C (0.026 W / in-C)

The sum of the B/C/B sheet conductivity is computed, in order to estimate system losses:

5.08 E-05 m (2 Mils) of B $\Rightarrow$ 20 KW/m^2 C (13 W/ in^2-C)
2.54 E-04 m (10 Mils) C $\Rightarrow$ 3425 W/m^2 C (2.2 W/in^2-C)
<u>5.08 E-05 m (2 Mils) of B $\Rightarrow$ 20 KW/m^2 C (13 W/ in^2-C)</u>
35.56 E-05 m (14 Mils) sheet

Normalized thermal loss computed summing the inverse:

B-stage loss = 4.98E-05 C m^2 / W (0.07692 C in^2 / W)
C-stage loss = 2.92 E-04 C m^2 / W (0.4545 C in^2 / W)
B-stage loss <u>= 4.98E-05 C m^2 / W (0.07692 C in^2 / W)</u>

TOTAL LOSS = 3.92 E-04 C m^2/ W (0.6083C in^2 / W)

The 125 watt module in Figure 1 is configured 0.0508 m (2 inches) by 0.1524 m (6 inches), an area of 0.00772 square meters (12 sq. in.). The thermal drop is 125 watts times TOTAL LOSS divided by the area; a loss of 6.35 C average across the adhesive. Thermal couple data measured at critical components confirmed a drop of this magnitude, within experimental error.

3.0 Stress Data Analysis

The importance of adhesive compliance becomes apparent when using such materials as a thin 'gasket' between two surfaces, which exhibit differential motion, i.e. high strain ranges. When considering solder joint reliability, high strain ranges correlate to shorter reliability life. Generally, when considering rigid components such as chip capacitors, resistors, and flip chip components, high strains convert to high stress levels, hence the potential for micro-crack inducement. Consequently, attachment using more rigid materials potentially increases component stress levels. Temperature cycling, power cycling, product operation, and shock/vibration are key elements that generate high stress, due to TCE differences. Compliant bonds act as mechanical 'shock absorbers' for the TCE induced deflection, within the limits and capabilities of the adhesive over the operating temperature range.

When compliant adhesives are applied in thin sheets, and are adhered to surfaces which are very rigid the capability of the adhesive to absorb differential motion is reduced.[6] The 'effective' modulus is a measurement of the relative compliance of a thin film of adhesive adhered to rigid members. Using extenciometers, the shear deflection of several adhesives was measured against the force required to cause a specified level of deflection. A typical test set-up is depicted in Figure 2, "Modulus measurement".

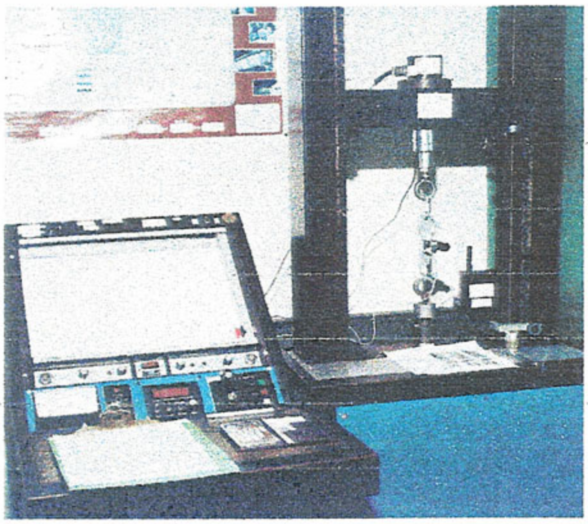

Figure 2, Modulus measurement.
Photo courtesy Raytheon Corporation

Figure 3a and b, "Urethane effective / bulk modulus plot", summarizes a comparison between Urethane bulk and thin film data.[1]

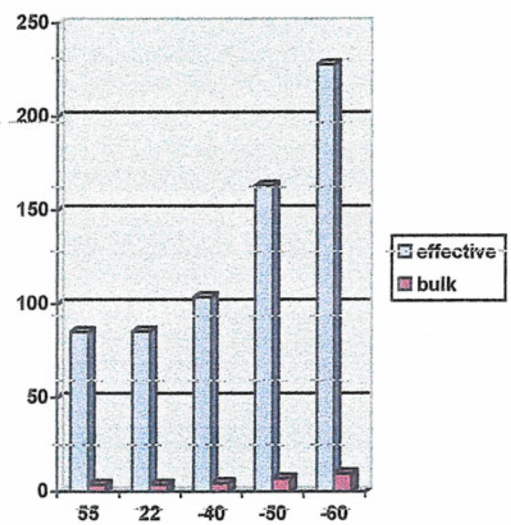

Figure 3a. Urethane Effective / Bulk Elastic Modulus in MPa vs. Temperature in Centigrade

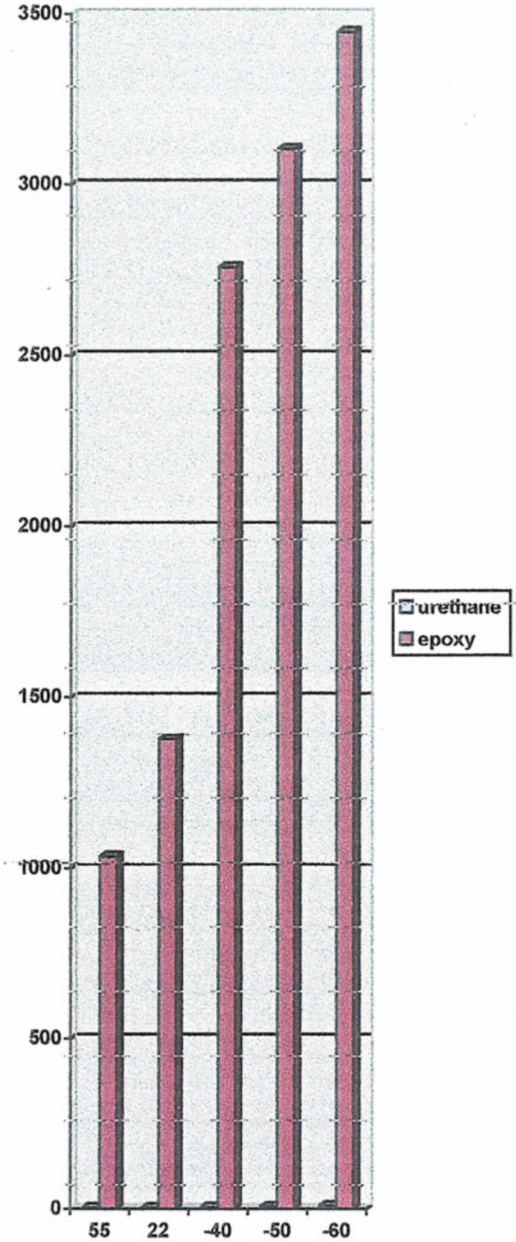

Figure 3b. Bulk Elastic Modulus urethane and epoxy in MPa vs. Temperature in Degrees C.

Two properties are immediately apparent in Figure 3a and 3b. Noteworthy is the stability of the B/C/B urethane over temperature, essentially a flat curve with a measured bulk modulus from 3.63 MPa (527 PSI) at +55 C to 9.72 MPa (1409 PSI) at –60 C. The urethane adhesive remains compliant well below the low temperature product-operating limit of –55 C. This is not unexpected as the Tg for this material is near –70 C. The effective modulus of the urethane sheet remains under 234.5 MPa (34,000 PSI), well below the bulk modulus of either of the profiled epoxy adhesives. Interestingly, the modulus ratio between the highest and lowest temperatures is about 3:1 for both material technologies, an indication of the affect of the rigid aluminum heat sink.

The need for the adhesive to remain compliant at cold temperatures is explained as follows: The bonding operation usually takes place at elevated temperatures, in this case 100 C. At that temperature the adhesive solidifies, mechanically attaching the two surfaces together, in this example, a PWB and aluminum heat sink. Subsequently, as the product cools, the two surfaces will (attempt to) shrink at different rates in direct proportion to their TCE's. Furthermore, as the product is exposed to thermal cycling and / or normal operation in the expected environment, the differential motion will continue to increase as each surface continues to shrink during cool-down at the rate proportional to their respective TCE's. If the PWB is constrained, stress levels will increase in proportion to the induced strain, this may translate into board warp or deflection at the PWB component (top-side) surface. Hence, the need for the adhesive to effectively de-couple the PWB and heat sink, while maintaining adhesion quality over the expected life of the product.[6]

The epoxy is rigid at room temperature as compared to the urethane adhesive counterpart. At cold temperatures, the typical epoxy is extremely rigid. The urethane, however, exhibits almost 4 orders of magnitude greater flexible in shear at –60 C, where the greatest deflection ranges are expected as previously explained. Consequently, the urethane B/C/B adhesive will best de-couple the two bonded surfaces, reducing stress transferred to the board surface. Strain gauge data measured on several SMT components at strategic locations confirmed the stress reduction in a number of trial evaluations. The particular product profiled in this dissertation has been in field operation for over five years, with no deflection induced, component related failures.

4.0 Conclusions

A (B-stage) B/C/B urethane has been developed, profiled, and tested in a real-world application. The sheet adhesive effectively de-couples bonded surfaces with severe TCE differences over a wide operating temperature range. The adhesive can be die cut or punched. It demonstrated similar thermal performance compared to the epoxy-based counterpart, while exhibiting much greater compliant properties. The new technology is a cost effective approach to component attachment in difficult environments and in high reliability applications.

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