UNDERFILL ENCAPSULANTS AND EDGEBOND ADHESIVES FOR ENHANCING OF BOARD LEVEL RELIABILITY

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ABSTRACT
With the proliferation of area array packages in consumer, enterprise, military, and automotive electronics, a wide range of board level underfills and edgebond adhesives, reworkable and non-reworkable, have been developed to ruggedize these components. While these materials are used to enhance drop test, bend test, and vibration test performance, their use can affect thermal cycle performance, negatively or positively. The trade-offs between process performance, rework, and reliability, along with advances to overcome the trade-offs are discussed.

Key words: underfill, edgebond, cornerbond, adhesive, BGA, CSP, POP, WLP, WL-CSP, drop, bend, vibration, ruggedization, thermal cycle, board level reliability

INTRODUCTION
Underfill encapsulants were first adopted by IBM to encapsulate flip chips assembled using their Controlled Collapse Chip Connection (C4) process, and continue to be used in flip chip IC packages, to enhance thermal cycle performance. In the late 90's, Ericsson and other mobile phone manufacturers adopted underfill encapsulants to encapsulate BGA's, to enhance drop test and bend test performance. The first underfill encapsulants to be used with BGA's were initially developed for flip chip or direct chip attach (board level flip chip) applications. The different needs of the IC packaging industry and the board assembly industry quickly led to a divergence in the design of underfill encapsulants and their properties.

The IC packaging industry continues to need underfill encapsulants that enhance thermal cycle performance. Other key requirements for these applications are survival of MSL preconditioning and lead-free reflow. For larger, high performance IC's, they need materials that will not damage fragile low-k dielectrics.

Board level assembly applications such as mobile phone applications, focus on enhancing mechanical ruggedness while demanding low cost materials, low processing cost, and reworkability. MSL preconditioning is not needed. Thermal cycle performance has become second in priority due to short product life cycles brought about by 2-year mobile phone service contracts and rapid obsolescence of technology.

Two different classes of underfill encapsulants have developed; those for IC packaging and those for board level assembly. Underfill encapsulants designed for IC packaging have high Silica filler content to reduce the material's coefficient of thermal expansion (CTE). Low CTE is a critical property for enhancing thermal cycle performance of flip chips. Because flip chips are often very fine pitch, 0.2-mm or less, the silica particles that are used are very small and very high surface area, resulting in high viscosities and slow flow. These flip chip encapsulants also have low moisture absorption and high thermal resistance for surviving MSL pre-conditioning. And, for low-k dielectric applications, they are designed with lower modulus. IC packages are typically over-molded with an epoxy molding compound that require long batch oven cures, as long as hours. So, underfill encapsulants that require long batch oven cures are tolerable.

Today's board level underfill encapsulants typically do not contain fillers which then lowers the cost of the product and the cost of processing. Without silica filler, CTEs are higher, viscosities are lower, and flow rates are far faster. Chemistries have been developed that cure in 1 to 5 minutes allowing for fast in-line processing of underfilled packages. This class of encapsulants is typically reworkable which allows expensive assemblies to be salvaged if an underfilled package is faulty. Board level underfill encapsulants are typically not capable of surviving MSL pre-conditioning.

In addition to board level underfill encapsulants, edgebond adhesives have been developed. For years, edgebond adhesives have been used in the manufacture of notebook computers, to enhance bend test performance. Notebooks are not dropped as frequently as mobile phones, so they do not need the same level of ruggedness; just bonding the edges of the BGA's is sufficient. The edgebond adhesives are typically reworkable, higher CTE materials.

UNDERFILL ENCAPSULANTS AFFECT BOARD LEVEL THERMAL CYCLING
One of the first board level encapsulants used to underfill BGA's was UF-A, designed by Zymet for direct chip attach, to improve thermal cycle performance of flip chips. It was found to improve drop test and bend test reliability of mobile phones, and impart excellent thermal cycle performance. It is silica filled, to impart a low CTE so, its viscosity is high and it flows slowly by today's standards. It is non-reworkable.

The competitive nature of the mobile phone industry demanded aggressive steps to reduce cost. Towards that end, an underfill encapsulant was specifically designed for BGA's, UF-B. This encapsulant contains no filler and as a consequence, both material and process costs are reduced. The design of the filler particle is highly engineered, making it a costly component of a filled underfill encapsulant. Also, the cost of dispersing the filler into the epoxy is removed with the absence of filler. For the user, process cost is reduced because without filler, viscosity is low and flow is much faster thus shortening the processing time. Removing the filler increases the CTE. Table 1 compares the properties and performance of UF-A with UF-B.[1]

Table 1. Properties and board level reliability of a low-CTE and a high-CTE underfill encapsulants.

	None	UF-A	UF-B
Filler, wt%	-	62	0
Tg, °C	-	150	120
CTE, ppm/°	-	31	60
Viscosity, cps	-	15,000	7,250
Flow Speed, sec	-	60	35
Drops To Failure	63	>250	>250
0°C to 100°C TC, First Failure, BGA	1300	3900	1200

Both underfills have a significant positive effect on drop test performance, the raison d'être for using a board level underfill encapsulant. Using the low CTE underfill has a beneficial effect on thermal cycle performance, raising the number of cycles from 1266 cycles to well over 3000 cycles. However, for mobile phones and many other consumer electronics applications, 3000 cycles far exceeds customer requirements. Lower cost, lower viscosity, and faster flow for lower thermal cycle performance can be a good trade-off.

As a further cost reduction step, the mobile phone industry demanded a reworkable underfill encapsulant. One such product is Zymet's ReUF-A. It has a relatively high Tg of 110°C yet it is reworkable. Also, being unfilled, it has a higher CTE. Table 2 presents property and board level reliability data.

Table 2. Properties and board level reliability of a high-Tg reworkable underfill encapsulant.

	None	ReUF-A
Reworkable	Yes	Yes
Filler, wt%	-	0
Tg, °C	-	110
CTE, ppm/°	-	63
Viscosity, cps	-	2500
Flow Speed, sec	-	20
Failures at 400 drops	100%	0%
-40°C to 125°C TC, First Failure, POP[2]	2000	700

ReUF-A enhances drop test performance and meets the customer's 400 drop requirement. Its higher CTE results in a negative impact on thermal cycle performance but not so much that it cannot meet the 500 cycle requirement. Giving up some thermal cycle performance in exchange for Reworkability is a trade-off many users of ReUF-A accept.

DEVELOPMENT OF REWORKABLE UNDERFILL ENCAPSULANTS FOR HIGH-SPEED PROCESSING

For high volume mobile phone production, ReUF-A is too time-consuming to rework. In response, ReUF-B was developed. To achieve easier rework, Tg was reduced to 70°C so that encapsulant and components could be easily removed at elevated temperatures. CTE also increased to 70ppm/°C. The higher CTE and lower Tg, for consumer applications where thermal cycle requirements are more lenient, with temperature cycles of -40°C to 115°C to as relaxed as -25°C to 85°C, and with relatively low number of required cycles, the trade-off for easier rework is an acceptable one. ReUF-B was adopted for use by mobile phone manufacturers and used for years in the mid-2000's.

Easier rework is not enough, at least not for the high-volume mobile phone industry. In the handheld device industry, the huge volume of components requiring underfill, along with the use of larger packages and smaller spaces has driven the development of fast flow, fast-curing encapsulants suitable for high-speed in-line processing. Materials have been developed that have viscosities less than 500 cps and cure times as little as 1 minute. Table 3 compares the properties and reliability performance of three commercially used underfill encapsulants. All three are reworkable and easily pass the drop test and bend test requirements of multiple mobile phone manufacturers, both at test vehicle level and at product level.

Table 3. Properties and board level reliability of three reworkable underfill encapsulants for mobile phones.

	ReUF-B	ReUF-C	ReUF-D
Reworkable	Easy	Easy	Easy
Tg, °C	70	82	130
CTE, ppm/°C	70	75	64
Viscosity, cps	4500	450	900
Flow Speed, sec	35	15	17
Cure, min./°C	5/165	1/150	1/150
Drop Test, BGA	Pass	Pass	Pass
Bend Test, BGA	Pass	Pass	Pass
-40°C to +115°C TC, BGA	Pass	Pass	Pass
-40°C to +115°C TC, POP	-	Minimum Pass	Pass

Zymet's first fast flow, fast-cure board level underfill encapsulant, ReUF-C, has a viscosity that is an order of magnitude lower than that of the earlier ReUF-B. Flow is considerably faster. In fact, with this encapsulant, some users perform underfill flow at room temperature, without board pre-heat. It was used by mobile phone manufacturers in the mid to late 2000's and continues to be used in other consumer applications where high-speed processing is required.

With the introduction of POP, underfilled thermal cycle performance became more challenging for some mobile phone manufacturers. At one customer, ReUF-C barely passed the thermal cycle requirements, leaving no head-room for next generation packages that would have finer pitch and smaller form factors. To address this issue Zymet developed ReUF-D. Its Tg is higher and its CTE is lower, yet is still a very fast flowing, fast curing encapsulant. It continues to be used to this day by mobile phone manufacturers.

DEVELOPMENT OF REWORKABLE UNDERFILL ENCAPSULANTS FOR ENHANCED THERMAL CYCLE PERFORMANCE

There are enterprise and automotive applications that need enhanced thermal cycle performance, with requirements exceeding well over 1000 cycles using aggressive temperature ranges. For such applications, lower CTE reworkable underfills are more appropriate. Table 4 compares four recently developed reworkable underfill encapsulants.

Table 4. Properties and board level reliability of recently developed reworkable underfill encapsulants.

	None	ReUF-E	ReUF-F	ReUF-G	ReUF-H
Rework	V.Easy	V.Easy	V.Easy	V.Easy	Easy
Tg, °C	-	60	65	65	80
CTE, ppm/°C	-	59	33	26	55
Viscosity, cps	-	600	1800	4300	660
Flow Speed, sec	-	14	37	52	17
-25°C to +85°C, 14x18 mm BGA	-	<500	-	>1500	-
-40°C to +100°C, 12-mm POP	<1000	-	>1500	-	-
-40°C to +85°C, 14-mm POP	-	-	-	-	>2000

ReUF-E is unfilled and has a CTE of 59 ppm/°C. ReUF-F and ReUF-G, through the addition of filler, have CTE's of 33 ppm/°C and 26 ppm/°C, respectively. Both are very easy to rework. Underfilling, to ruggedize the assembly, with the lower CTE encapsulant markedly improves thermal cycle performance, improving -25°C to +85°C thermal cycle performance from first failure below 500 cycles to above 1500 cycles. ReUF-F, with a CTE of 33 ppm/°C improves thermal cycle of a POP from first failure between 500 and 1000 cycles, when not underfilled, to first failure above 1500 cycles when underfilled.

The shortcoming of the lower CTE ReUF-F and ReUF-G are their higher viscosities and slower flow. ReUF-H offers a balance of properties to address the needs of those that require fast, in-line processing. Tg is somewhat higher, CTE is higher, but it flows much faster and is still easy to rework. A POP underfilled with ReUF-H has no failures after 2000 cycles of -40°C to +85°C cycling.

CRACK RESISTANT UNDERFILL ENCAPSULANTS FOR ULTRA-THIN PCB'S AND FOR FPC'S

The consumer electronic industry is driven to ever smaller, lighter products. Towards that end, the use of flexible printed circuits and ultra-thin PCB's is proliferating. This creates challenges for underfill encapsulants. Flexible circuitry and thin PCB's are vulnerable to high deformation during post-assembly operations and in use. The high deflections can cause cracks in the underfill fillet, cracks that then propagate to the solder joints or into the board, causing failures. Figure 1 illustrate such a crack.

Figure 1. Crack in fillet of underfill encapsulant propagates into board.

In this instance, a crack has formed in the fillet and the crack has propagated through the soldermask and a copper trace, into the laminate, resulting in failure. ReUF-J is a low-CTE, highly crack resistant reworkable underfill encapsulant designed to address this failure mechanism. Figure 2 illustrates the crack resistance of ReUF-J.

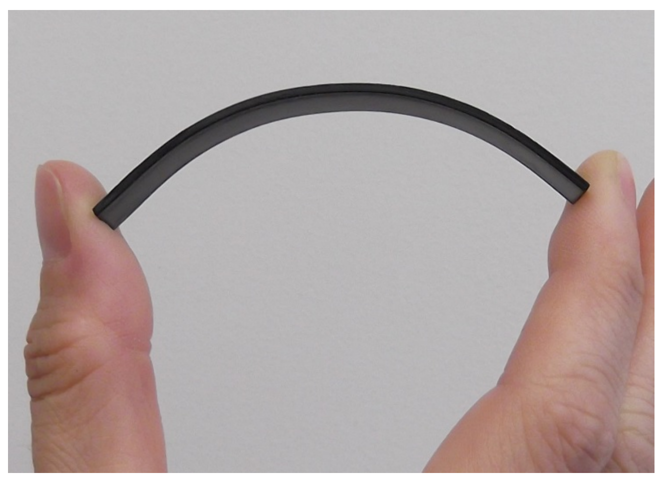

Figure 2. Highly crack resistant underfill encapsulant, ReUF-J.

ULTRA-FAST FLOW UNDERFILL ENCAPSULANTS FOR HIGH RELIABILITY APPLICATIONS

The need for board level underfills has expanded to enterprise and automotive electronics where products are expected to function for 10, 20 years, or more. Automotive applications have exceedingly stringent requirements. To address these applications, board level underfill encapsulants have been developed, whose CTE's are very low, yet they are capable of extremely fast flow.

To achieve high thermal cycle performance, the underfill encapsulant must have a low CTE which is accomplished with the addition of high loadings of silica filler. As we have seen, addition of filler raises viscosity and slows flow (see Table 1). It is now possible to produce low-CTE encapsulants whose viscosities are exceedingly low. Table 6 compares the properties of a new-generation underfill encapsulants, UF-E and UF-D, with older products.

Table 5. Comparison of new, fast-flow underfill encapsulant with older encapsulants.

	UF-A	UF-B	UF-D	UF-E
Tg, °C	150	120	130	135
CTE, ppm/°C	31	60	30	30
Cure, min./°C	40/150	5/165	1/150	1/150
Viscosity, cps	15000	7250	1100	780
Flow Speed, sec.	60	35	54	34
-40°C to 125°C TC, First Failure, 13-mm BGA	-	-	3500	-
-40°C to 100°C TC, First Failure, 14-mm POP	-	-	-	>3500

UF-A and UF-B were compared in Table 1. Removal of filler raises CTE and lowers thermal cycle performance, but speeds flow. That trade-off is no longer necessary. New generation encapsulants, exemplified by UF-E and UF-D, offer low CTE's, with very low viscosities and very fast flow. UF-D has a CTE as low as that of UF-A, yet it flows as fast as the unfilled UF-B. The result is exceedingly good thermal cycle performance from a material capable of high speed in-line processing. Table 7 gives examples of thermal cycle performance.

DEVELOPMENT OF LOW-CTE REWORKABLE EDGEBOND ADHESIVES

Not all applications require the ruggedness imparted by a full encapsulation of an area array package. Edgebond adhesives can also be used to ruggedize electronics assemblies and enhance drop test performance.[3] For example, some enterprise products only require modest enhancement, for post-assembly handling at the factory, for ship-shock. Or, some thin consumer devices are rarely dropped, such as tablets and Ultrabooks™, need to only survive low deflection, low-g, bending stresses arising from normal handling.

Edgebond adhesives are typically applied around the corners of a package. Using a dye and pry method, failure analysis of a BGA drop test shows that it is mainly the solder joints at the corners and at the edges that fail. Subsequent drop test simulation shows that the corner joints are the most highly stressed[1]. So, the best place to deposit an edgebond adhesive is typically around a package's corners, as illustrated in Figure 3.

Figure 3. Edgebond adhesives typically deposited around corners.

The benefit of edgebond adhesives, relative to underfill encapsulants, is that they eliminate the process time and equipment needed for performing underfill flow. Plus, because only the edges of the package are bonded, there are little or no residues under the package, rework is much faster, and risk of damaging pads is eliminated.

The material properties of the edgebond adhesive affect thermal cycle performance. Like underfill encapsulation, low-CTE edgebonding can improve thermal cycle performance too. Table 8 provides some examples of the thermal cycle performance imparted by one of Zymet's low-CTE reworkable edgebond adhesives, ReEB-A

Table 6. Thermal cycle performance of low-CTE edgebond adhesive.

	None	ReEB-A
Tg, °C	-	134
CTE, ppm/°C	-	30
0°C to 100°C TC, First Fail 50-mm CBGA	600	1400
-40°C to 100°C TC, First Fail 14-mm POP	<1000	3000

ReEB-A can both ruggedize and enhance thermal cycle performance of BGA's, POP's, and other area array packages.

CONCLUSION

The growing market for ever-smaller, ever-lighter devices, and the drive towards higher performance IC packages has driven the use of BGA's, CSP's, POP's, WLP's and other area array packages. That in turn has driven the development of alternative ways to ruggedize electronics. Underfill encapsulants and edgebond adhesives have become an important part of an electronic manufacturer's toolkit. They enhance drop test, bend test, and/or vibration performance.

The introduction of an encapsulant or adhesive affects board level thermal cycle performance. Depending on the application, trade-offs in thermal cycle performance for lower cost, reworkability, and/or faster processing can be worth making. New underfill encapsulant and edgebond technologies are reducing the trade-offs that need to be made.

New materials that have been developed include underfill encapsulants, both reworkable and non-reworkable, that have lower CTE's, faster flows and are highly crack resistant. For applications that require a lesser degree of ruggedization, reworkable edgebond adhesives have been developed, including those that have low CTE and can also enhance thermal cycle performance.

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