When Are Conductive Adhesives an Alternative to Solders?

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Abstract

Our industry continues to heat up, sputter and often smolder with Lead-Free (L-F) issues. The good news is that there are plenty of L-F alloys. That's also the bad news. Substantial data is available on lead-free systems this year. The challenge has been answered but the answer is the challenge! A quick study of the "new" solders lets the impartial observer conclude: (1) no drop-in replacement has been found, (2) L-F solders are reliable and (3) **higher processing temperatures are almost certain**.

The pending L-F "Temperature Tax" is causing concern over damage to laminates, packages and some semiconductors. Will high temperature processing be a cost penalty for using L-F solders? Will BGAs require extra drying procedures, will PCBs degrade and will optoelectronic components fail? The new CPUs with low-k polymers and emerging organic electronics could possibly have problems. What products will fail 240^o to 260^{o}C soldering? And let's not forget high-density stacked die packages, MEMS (MicroElectroMechanical System) and MOEMS (MicroOpticalElectroMechanical System) devices that can be heat-limited.

Conductive adhesives have provided a good solution for temperature-limited assembly for decades. These time-tested polymers can be processed like solder using the same equipment. The good news is that the assembly temperature is 130^o to 150^{o}C. But are adhesives really viable even though used for SMT assembly in medical products and aircraft where reliability is a must? Your business phone, ink jet printer and laptop's display flip chip drivers were probably adhesively bonded. This paper will compare Polymer Solders to Lead-Free solders to show limitations and advantages. Guidelines for designs and applications will be provided. Finally, possible solutions to adhesive deficiencies for suggest, particularly in the mechanical strength area.

Keywords: *conductive adhesives, silver, lead-free, low-temperature, solderless, epoxy, degradation.*

LEAD-FREE ALLOY PROCESSING

The solder community has come a long way since our conference last year. The lead-free alloy list has been narrowed to a handful of good candidates that have been described in much detail during the past year and at this conference. Data is accumulating and success stories have emerged. Some assembly lines have even converted to lead-free.

The accepted alloy will almost certainly be based on tin and probably contain copper, silver or both. This group of alloys is referred to as "SAC" for Sn, Ag and Cu and ITRI and NEMI are recommending them. While solder manufacturers prefer binary systems, the tertiary systems are practical to make. Alloys made with more than 3 metals require more control and attention when we consider all the myriad forms for solder in use today. But even 5-alloy solders can be manufactured in most plants. Producers around the world now offer lead-free alloys. However, L-F solders have been available for a long time although they have not used for general electronic assembly.

WHY SOLDER ANYWAY?

Many material scientists have felt that even today's tin-lead solder processes are too hot. Nearly all-electronic organic materials are more expensive because of the soldering process requirements. Excellent dielectrics like polyesters have been mostly sidestepped because of incompatibility with the extremes of soldering. But, the industry is getting ready to raise the temperature dept limit even higher and this could eliminate some of the today's board and packaging products.

The average processing temperature for SAC alloys is nearly 260^{o}C. The L-F alloys do not wet as well as Sn/Pb, but higher temperatures and the use of N_2 improves the situation. Higher temperatures improve soldering, but laminates, SMT-packages, CSPs, standard packaging materials and semiconductors are subjected to added stress and more thermal degradation. The industry may need to fortify the numerous materials that will be subjected to the new, harsher conditions. But there may be another solution that is compatible with today's materials or even low cost, lower temperature types. Let's now explore that versatile, gentler and more sophisticated world of organic polymers.

POLYMERS

Polymers have been the enablers of the electronics industry for many decades. The majority of electronic products are only possible by using a wide range of polymers. These include laminates, die attach adhesives, packaging encapsulants, underfills, wire coatings and many more. Polymers are used for their excellent dielectric properties, high strength, thermal stability, lightweight, ease of use and low cost. Unique processing characteristics, however, are an important reason for the popularity of polymers.

Polymers are easily shaped into flat sheets for laminates, 3-dimensional forms for packaging, thin coatings for solder masks or any other form required. Processing simplicity and versatility are significant attributes. The key to ease-of-use is in the chemistry of these remarkable polymers. We can begin with reactive ingredients that are liquids, called precursors, resins or pre-polymers. The ability to begin with liquids that are transformed into highly durable solids, is one of the most useful properties of any material. While the starting point can the liquid phase, the final product for thermosets is a tough, rock-hard structure that doesn't melt or dissolve in solvents. Thermoplastics, however, can be remelting repeatedly and this class is useful for reworkability. Polymers can also be a flexible or even elastic coating or films that can take millions of flexural cycles. Properties can be tailored and carefully engineered!

Polymer Classification

Polymer chemists divide their materials into two broad classes, thermoplastics and thermosets. This division makes chemical sense (the level of cross-linking between polymer chains) and also categorizes the handling and processing that will be necessary by the user. Thermoplastics are fully polymerized materials with independent polymer chains. There is essentially no interlinking between the long polymer chains and the application of heat allows most thermoplastics to flow and take on new shapes. Most injection-molded materials, like the plastic housing on a computer keyboard or monitor, are thermoplastics.

The addition of chemical bonds, called cross-links, between neighboring polymer chains, creates the other class known as thermosets. The user carries out their polymerization and these materials take on the permanent shape in which they are hardened or cured. Although thermosets may be softened, they have "molecular memory", and revert to their original shape once external forces are removed. The thermoplastics are therefore more akin to eutectic solder where the melting point remains unchanged by hardening. But thermosets have produced the best mechanical and electrical properties when formulated into conductive adhesives. Although the thermosets are best performing *polymer solders* at present, thermoplastics should not be counted out for the future.

Thermoset Polymerization

The polymer precursors must possess or generate reactive chemical groups that can form linkages, or chemical bonds, with co-reactants or with one another. Today's most common systems in electronics are epoxies. The epoxy group is a highly reactive structure containing oxygen and two carbon atoms that forms a ring structure. This oxirane group reacts with a variety of other agents. Materials that are specifically designed to produce polymers are called hardeners. The epoxy resins generally have two (or more) epoxy groups that react with the hardener. The number of reactive groups per molecule is referred to as functionality. The hardener will also have two (or more) reactive groups. The combination produces a polymer chain made up of repeating blocks of epoxy and hardener. Many other reactions occur that produce links between the growing chains, called cross-links. The final result is a network of polymer chains that are connected in a 3-dimensional array to produce a strong, non-melting mega-molecule that retains whatever shape it had when the linkages formed. Figure 1 shows epoxy polymerization.

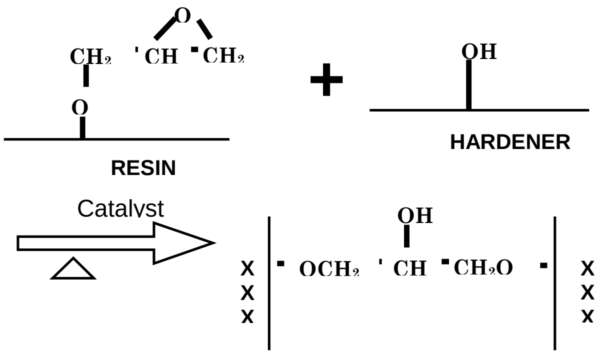


Figure 1 – Polymerization

CONDUCTIVE ADHESIVES

Classes of Conductive Adhesives

Polymers are the workhorse insulators for the electronics industry. Although intrinsically conductive polymers (ICP) are known, none have yet been commercialized with a balance of good electrical and mechanical properties required for joining materials. Often, conductivity is only in one geometric plane and mechanical strength is low.

Polymers with good mechanical and chemical properties are excellent dielectrics. However, using fillers, insoluble agents that are added to produce composites, can alter them. The filler really determines the class of product. Epoxies can be used for package molding compound, underfill, die attach or SMT conductive adhesive by selecting the right type and amount of filler.

Isotropic Conductive Adhesives (ICA)

The most useful type for SMT assembly is the isotropic conductive adhesive (ICA). This is a highly filled composite that is equally (isotropically) conductive in the X, Y and Z planes. The silver-filled epoxy is the most common ICA product.

Anisotropic Conductive Adhesives (ACA)

The ACA adhesive class conducts in only one plane, the vertical direction, or Z-axis. The Z-axis conductivity is achieved by adding a relatively low level of conductive filler that will not form a continuous path in the X-Y plane. The selective conductivity results when opposing conductors are pressed together to trap the conductive filler that is generally spherical. ACAs can be used for SMT assembly but a very planar interface is needed. The only commercial examples have been flip chips although there are applications where circuits are connected together. Our emphasis will therefore be on the ICA products.

Conductive Adhesive Fillers

All useful fillers for conductive adhesives are initially electrically conductive and must remain so. Virtually all are metals or metal-coated materials. Carbon has been used to make high resistance adhesives that have only limited use. A good conductive filler must be stable throughout the life of the product. Although metals remain conductive, many form oxides on their surfaces that are good insulators and thus barriers. Therefore, practical fillers for conductive adhesives cannot form an insulative oxide. Nobel metals, like gold, do not oxidize and can be used. However, lower cost silver forms a conductive oxide that makes it useful. Silver also can be precipitated into fine powder and is malleable enough so that it can be milled into useful shapes such as flake. This makes silver the dominant filler for ICAs. While silver is commonly used, it does have drawbacks. These include higher cost than base metals, high chemical activity and potential environmental concerns because salts can be toxic to some marine life.

Copper Filler?

Copper, a widely available and lower cost metal, is preferred over silver. Unfortunately, copper oxidizes and no inhibitors or coatings have produced a truly successful product. Silver-coated copper has been used with limited success but may cost more than silver because of the processing difficulty and low volume. Many believe that stabilized copper filler would bring a major breakthrough to conductive adhesives that have not really changed in 30 years. A copper-based adhesive would compete economically with the L-F solders. However, the low temperature processing could allow them to become the new standard for electronic assembly replacing ancient solder.

Only Limited Research

Work continues with the goal of making conductive fillers with copper or other base metals. Some approach may ultimately succeed, but not much work is being done. We can wonder what results would have occurred if even a fraction of the resources invested in L-F alloys were directed toward new adhesives. In the past, the US government has only provided token supported for work on adhesives. The academic community has chosen to either work on L-F solders or simply investigate the traditional silver-based materials. Success in this area could have a much more positive affect on electronics assembly than any that has been done during the last 10 years on alloys.

Intriguing, but only partially successful work was done several years ago aimed at stabilizing copper for conductive adhesives. This ARPA-supported program by Foster-Miller and Alpha Metals, sought to apply thin layers of intrinsically conductive polymers to copper. This approach could boost conductivity and create an electrically stable form of copper filler. The presence of a polymer interface on the copper surfaces would be expected to enhance compatibility and perhaps allow inter-particle bonding. Progress has been slow since coating tiny particles was unexpected difficult. This is certainly an area for further investigation. Figure 2 shows the ICP-Cu filler concept.

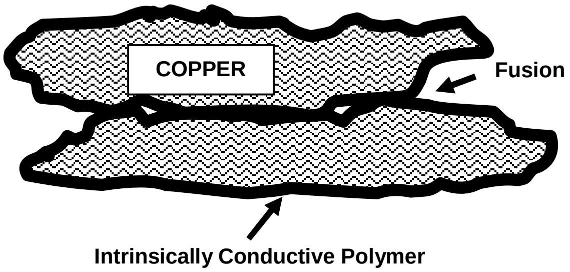


Figure 2 ICP-Cu

Solder-coated metal may also hold promise but unusual problems crop up in dealing with micron-range metal particles. Some have taken a different approach for using copper as exemplified by a product called Ormet®. Organic polymer binder is combined with metal copper powder and solder ingredients. During the curing process, the copper and other metals form alloys, said to be sintered, that produces electrical pathways of continuous metal within the polymer binder. Some feel that these hybrid systems are more like solders with an adhesive assist and not true conductive adhesives. Regardless, the present products do not appear to a viable alternative to solder for component assembly. This leaves us with classical silver-filled conductive adhesives that will be examined in detail.

Conductive Adhesive Compositions

The isotropic conductive adhesives have been used in commercial high-volume SMT assemblies for many decades. More recently, certain flip chip assembly areas, like memory, have switched to conductive adhesives. The present ICA materials consist of polymer binder, a substantial amount of silver filler, wetting agents and rheological additives. The binder is typically a blend of epoxy liquid resins, hardener and accelerator. The resins and hardener determine the pre-cure and post-cure characteristics while the accelerator influences the rate and temperature of curing.

The filler is much more complex that just simple metal particles. The typical composition is a blend of precisely fabricated powder and flake designed to fit together. Fine powder becomes interspersed between flakes to fill gaps. Both are treated with surfactants and proprietary coupling agents (aid in creating metal-to-metal contact). The morphology of the flake is the most important since "flagstone like" micro-particles must over-leaf one another to make electrical pathways. Figure 3 shows the complex orientation in cured adhesive.

Figure 3 – Conductive Adhesive SEM

Even when the particle shape and surface are optimized, adhesive formulating can require a balancing act of art and science. Maximum conductivity is always at odds with maximum mechanical strength, hence the balancing act. Designing for the greatest amount of inter-particle contact produces maximum electrical conductivity. Mechanical strength requires minimum particle contact. Very strong adhesive bonds and joints result when the polymer is a continuous phase, but then there would be no electrical pathway. Said differently, best electrical properties require a minimum amount of epoxy in their path while great mechanical strength is achieved with less filler. The best we can do with this model is to compromise and achieve enough conductivity for most applications while allowing mechanical properties to be the dependent variable. Some argue that conductive adhesives need more conductivity and strength concurrently, so let's look at properties.

PROPERTIES

Solder has been the *de facto* standard for electronics and all joining materials are compared to solder. Eutectic Sn/Pb is the present standard for comparison for both adhesives and L-F solders. Table 1 compares the two products. The adhesives values are a generic average of commercial products. Some adhesives are up to an order of magnitude more conductive. Some are stronger than solder, but none are both more conductive and stronger.

Characteristic	Sn/Pb Solder	Polymer Solder
Volume Resistivity	.000015 ohm.cm	.00006 ohm.cm
Typical Junction R	10 - 15 m	<25 m
Thermal Cond.	30 W /m-deg.K	3 - 5 W/m-deg.K
Shear Strength	100%	40 - 110%
Mechanical Shock	Good	Poor
T & H (85%/85C)	no change	product specific
Finest Pitch	12 mil?	down to 6 mils
Min. Proc. Temp.	210 - 220C	25 - 150C
Envir. Impact	negative	minor?
Thermal Fatigue	yes	can be minimal

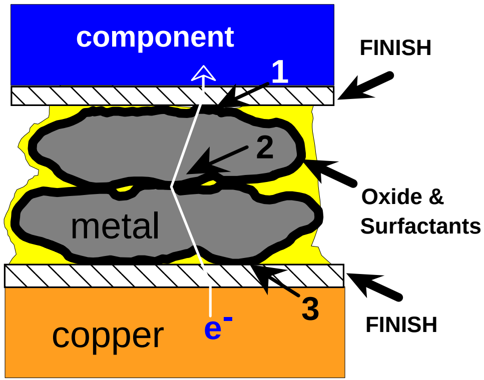
Table 1 – Adhesives vs. Solder

Electrical

There would appear to be a deficiency in volume resistance since it is several times higher than for solder as seen in Table 1. However, this is not a problem for 95% of the applications. Actually, the resulting junction resistance is not that different from solder's. A typical CA junction is higher, but not by 4X as the volume resistivity values would suggest. This is because adhesive joints need only ½ the thickness and shorter resistance paths result. As expected, the adhesive joint follows Ohm's Law. We should also note that internal package resistance could be higher than that of the adhesive joint. High frequency performance is good since electrical conductivity tends to improve at higher frequencies since the adhesive flake can act like a capacitor (capacitor conductivity increases with frequency).

Junction Stability

Solder forms a true metallurgical junction between circuit pads and components so electrical stability is no concern unless the joint becomes fractured. But all adhesives form pressure contacts where conductive filler particles touch the opposing metal surfaces. This is a fundamental difference between the adhesives and solders. A good mechanical joint is no guarantee of electrical properties for adhesives. Worse yet, good initial conductivity is no assurance of future performance. PCB pads, for example, can oxidize in the presence of adhesives to generate an electrical barrier. This doesn't happen with solder joint that is alloyed with the pad. The silver filler particles within the polymer matrix can initially provide a good electrical in as shown in Figure 4 that is a model only. Note that there are 3 types of junctions within a conductive adhesive. The inter-particle contact (2) is not a problem when silver is used since silver oxide is conductive. However, both the component surface (1) and the PCB pad (3) can oxidize and prevent adhesive particle contact as shown in Figure 5. When this happens, junction resistance gets very high or electrical continuity can be totally lost. The junction is said to be unstable.



not to scale

Figure 4 – Initial Junction

The oxide on base metals will oxide grow on the PCB pads and component leads slowly over time. High humidity will catalyze the oxidation reaction and this is why temperature and humidity aging (T&H) is a critical test. This problem was recognized in the 1980's as SMT was becoming popular and adhesives were investigated for this relatively new assembly process. Even when gold-plated circuits were used, adhesive joints showed an increase under accelerated aging. The more critical problem was the tin-lead coating used on nearly all SMDs. The industry addressed the issue and several solutions emerged.

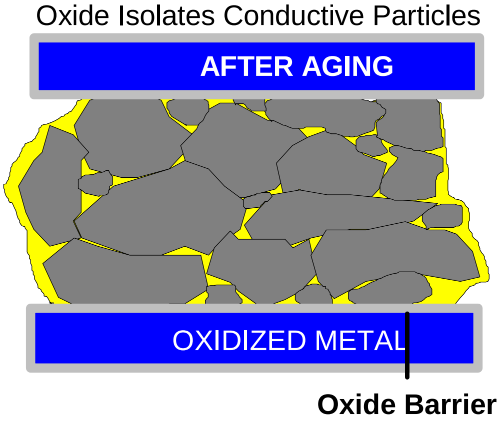


Figure 5 – Oxidation and Junction Instability

Large companies, like AT&T, with immense buying leverage, simply ordered silver-plated components. This allowed them to successfully build millions of business telephones on silver-conductor Polymer Thick Film (PTF) circuits. The AT&T products using conductive adhesives have been successful and reliable. Products built 20 years ago are in service today. In fact, there may not be any mechanism for failure.

Contract assemblers required a more generic solution. One company, Poly-Flex Circuits (now a Parlex Division) launched an intensive search to find a commercial adhesive with good junction stability. Finding none, they developed their own. Around 1990, while testing internally formulated silver-epoxies, an oven thermocouple failed (according to one early developer). The circuit was all but "fried" since it was made of thermoplastic Mylar®. But the circuit and adhesive junctions were in tact so the circuit was placed in a humidity chamber more or less as a joke. Surprisingly, the partially ruined circuit had reasonably good stability. While frying circuits was not a practical solution, it was the key to solving the problem. Months later, a junction-stable adhesive, aptly named Poly-Solder®, was undergoing extensive testing.

Poly-Solder did extremely well. The researchers concluded that polymer shrinkage had forced the conductive metal particles against the component and penetrated its oxide. The compressed particles were thought to also form miniature gas-tight junctions. Later, Dr. Johan Liu, now at Chalmers University in Sweden, did extensive analysis of Poly-Solder at the same institution with assistance from IVF-Gothenburg. Transmission Electron Microscopy (TEM) suggested that particles penetrated the oxide, but no absolute proof was established. Regardless of the mechanism, this conductive adhesive has been shown to have excellent junction-stability on solder surfaces, but not on aluminum perhaps because of its hard oxide. The product is able to pass 1000 hours at 85%rh/85°C and actually increased by up to 8% in electrical conductivity. Figure 6 shows the penetrating particle principle thought to be operating in this one junction-stable adhesive. The caveat is that the mechanism has never been proven - or disproved. Hard particle have been used, but silver agglomerates work well for all but hard oxides. Nothing, not even nickel-plated diamond, has been successful with aluminum, however.

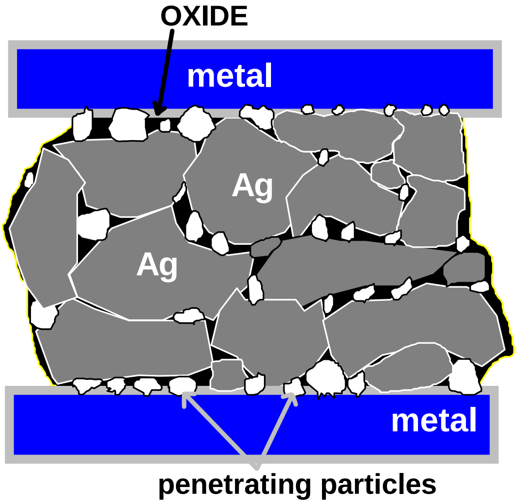


Figure 6 – Junction Stable Penetrating Particle Adhesive

Others have addressed the stability problem using antioxidants and proprietary approaches. Claims are now made that some ICAs are sufficiently stable to be used with solder-coated components. We will assume that the problem has been solved by several and certainly by Poly-Flex Circuits who has shipped commercial assemblies and has produced nearly 1-billion adhesive joints. More than 25-million HP Ink Jet LED assemblies have been made with CAs. Figure 7 shows the HP printer and circuit assembled with conductive adhesives. Figure 8 is more complex since a large printed resistor is used along with several types of components. The product is a touch pad for laptops made using conductive adhesive. The pad is a printed carbon ink resistor that detects location by measuring X and Y resistance where the pad is touched

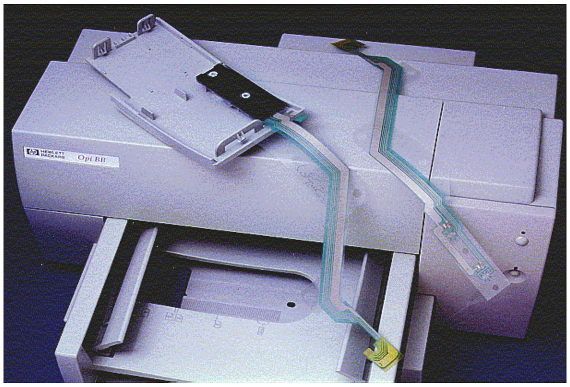


Figure 7 – HP Printer

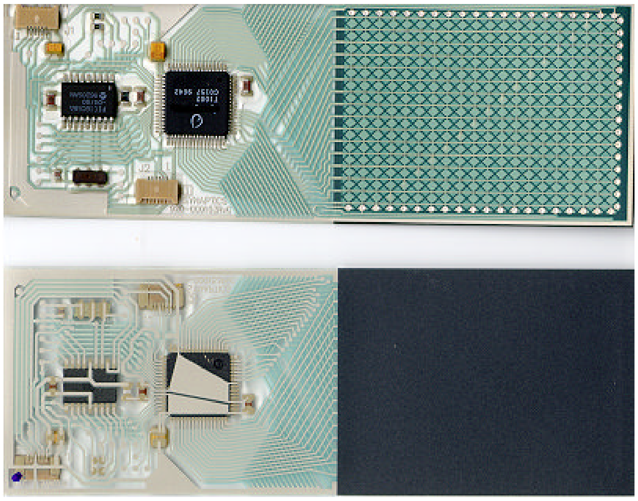


Figure 8 – Mouse Pad Assembled with ICA

Mechanical

Mechanical strength may appear to be reasonable from shear strength data, but this test does not tell the whole story. In some cases, adhesive strength is even greater than solder's. But bond strength is not a dynamic test and only represents a single point. The rate of force application is the critical parameter. Mechanical strength tests using die shear or tension pull methods apply force slowly and adhesives perform well.

The Mechanical Shock Test Problem

A mechanical shock test, such as dropping from a specific height, shows that conductive adhesives are relatively poor compared to solder. This would seem unexpected since epoxies are extremely tough. In fact, solder is a weak material compared to epoxy. So what's going on here?

The issue is in the composite nature of adhesives that was shown Figure 5. The polymer binder cannot be a continuous phase if there is to be electrical conductivity. Sufficient electrical conductivity requires that particle make contact. A good electrical structure looks more like a stonewall made without enough mortar. Even a slight increase in resin can destroy electrical conductivity as the filler becomes encapsulated and therefore insulated.

The mechanical shock force is transmitted to a small boundary of epoxy that must withstand deformation. The forces exceed the bond strength and/or elongation limits of the micro-joint and there is structural failure. In some tests, bonds to the surface-treated silver are also fractured. If we could only reduce the filler level, the epoxy could have excellent mechanical performance. This is seen with epoxy underfills and encapsulants where the filler loadings permit the polymer to be a continuous phase. Note that micro-packages use underfill in cellular phones to pass the *customer drop test*. Unfortunately, just at the level where mechanical shock results improve, electrical conductivity falls off. However, progress continues in this area with new shapes for fillers. But is the basic conductive adhesive construction wrong?

Conductive adhesives have been tweaked and "tuned" for decades, but the basic structure is the same. Is there a better model?

Filler Morphology

We may assume that the 40-year old flake & power morphology for conductive fillers will not give the mechanical strength breakthrough that would help with the shock test. There are two fundamental concepts that could be considered. The first is to bind the conductive particles together. One approach was to coat copper particles with solder. The idea was that particles would fuse together during the curing process. Difficulty in solder-coating the filler and obtaining inter-particle fusion led to early abandonment of this idea. However, it may still have merit, but only if the fusion temperature remains relatively low. The Ormet products appear to obtain the fused particle structure using copper/solder mixers and they have met some level of success. This is a product to watch.

The conductive polymer coating approach also seems promising and could lead to low temperature fusion. However, conductive polymers tend to be non-melting thermosets. Further work, especially by a group that could synthesize novel conductive polymers, could provide the breakthrough. Any interest here?

The second approach is to stay with conductive particles but use a different shape or morphology. Many developers have discussed using rod-like or fiber-shaped conductive fillers. These materials would need to be much smaller than materials that have been commercially available. Micro-metal fibers used to strengthen structural plastics have proved too course. Materials would probably have to be formed chemically or by some new process. One material that has been mention is carbon fibers. Carbon nano-tubes and fibers would have the required dimensions and presumably, the right electrical conductivity. The carbon products have extremely high aspect ratios and would seem to have the desirable small size. This is an area to watch since reinforcing nano-fibers could greatly boost mechanical strength.

Drop Test

But is mechanical shock a "show stopper" for adhesives? Some industries, like automotive, will not consider any joining material that fails a drop test that involves dropping an assembly on edge from several meters. Others argue that the drop test is unfair because components are isolated that would normally benefit from the shock-absorbing properties of the housing. They point out that a calculator can be dropped but its glass LCD would fail if removed and dropped. The counter argument is that solder can pass so any solder alternative must pass. We may note that flexible circuits assembled with CAs easily pass, however, because of their lightness and compliancy. For now, adhesive developers are trying to pass the drop test without compromising all the other hard-won properties.

Thermal Properties

Thermal conductivity is also lower for conductive adhesives. Typical silver-filled adhesives have about one order of magnitude lower thermal conductivity than tin-lead solder. This could be an issue where the joints must carry substantial heat. Some have pointed out that flip chips must use bumps/joints to conduct heat away. However, several recent designs sink the heat away from the opposite side of the die. Thermally conductive underfills may help and they are coming.

SMT ASSEMBLY WITH CONDUCTIVE ADHESIVES

SMT was the enabler for conductive adhesive assembly. Feed-through components have never been practical since there is no adhesive equivalent to wave soldering. Polymers cannot "wick & fillet" like molten metal that has a surface tension that is more than an order of magnitude higher. SMDs form ideal adhesive joints (butt joints) and their assembly process is similar to solder.

Adhesive Application

ICAs can be screen-printed, stenciled or needle dispensed and all processes are used commercially. Stencil printing gives the most precision and is preferred. Some PTF circuit shops use screen-printing because they have the capability of producing screens in-house. Figure 9 shows an automatic stencil printer suitable for conductive adhesive printing.

Figure 9 – Automatic Stencil Printer (Speedline/MPM)

The cardinal rule for adhesive application is "Don't Apply Too Much". While solder paste volume is reduced to about half during powder collapse on reflow, adhesive volume remains nearly constant. This means that only half the volume of adhesive is used. A 4-mil (100-micron) stencil will work well, but an 8-mil stencil will probably give poor print quality as the tackier adhesive clings to the excessive wall area. Stencils for flip chips can be 50 to 75 microns thick. Laser or electroformed stencils are preferred over etched. Laser machining produces a natural taper that helps release adhesive. The "hour-glass" shape of etched stencils can interfere with release. However, improved stencil polishing and smoothing methods have reduced the problem.

The customary rules for SMD stencil patterns apply here provided the thickness reduction is kept in mind. But adhesives will stay where deposited so if the features are oversized, material will not be drawn onto the pads like solder. The only situation with special rules is assembly to PTF-Polyester circuits. PTF conductor traces do not have the high bond strength found with copper circuits. Adhesive applied only to pads will tend to pull them off under mechanical stress. Most circuit layouts therefore have SMT pads that allow adhesive to contact the bare dielectric substrate where a very strong bond will form. Conversely, the stencil can be designed to accomplish the same result. Overall, the adhesive application process is similar to that used for solder and can be run with the same equipment.

Needle dispensing is used for larger circuits with only a small component assembly zone, such as a membrane switch with a few LEDs clustered together. This method has been used for products like the HP printer circuit that was shown earlier in Figure 7. Figure 10 shows an automatic needle dispenser.

Figure 10 – Needle Dispenser (Speedline/Camalot)

Component Placement

The lower surface tension mentioned earlier, have some important ramifications. The adhesive during the curing step will not orient a misaligned component. Molten solder, with a surface tension of over 500 dyne/cm^2, will generate substantial alignment forces as tension attempts to reduce surface area of the liquid metal. Adhesives have surface tension values in the 35 – 40 dyne/cm^2 range and this will not move a component. Furthermore, the adhesive is typically too viscous to climb up the side of a component termination to produce a fillet. All this means is that more care must be taken in setting up the process. Lack of self-alignment is no longer considered an issue with modern placement equipment.

Package Restrictions

The butt joint that results when two parallel surfaces are brought together is ideal for adhesives. Nearly all components produce this joint. The exception is the bothersome "J" lead. The J-lead was contrived with solder in mind and requires a fillet to achieve maximum strength. The adhesive's lack of fillet forming dynamics makes the J-lead package the least desirable. However, J-leads can be used with adhesives with the following caveat. Only solder-plated, not solder-dipped leads should be used. The plated leads, signified by a duller, grayer color, have more surface area and can give a reasonable bond. The adhesive dispensing step is more critical and insufficient material will give low bond strength. Components must be placed accurately. Figure 11 shows adhesive joints for a "J" lead package.

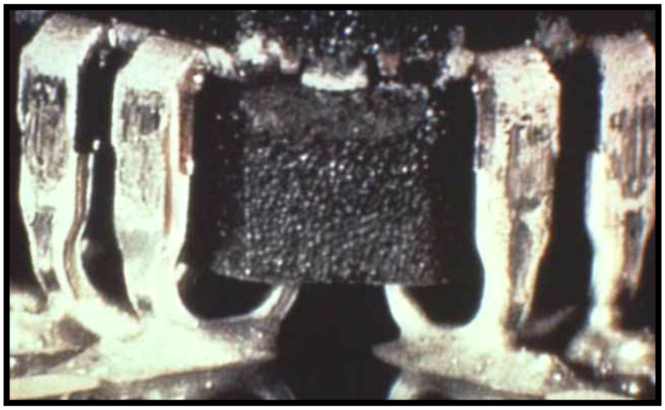


Figure 11 – J-Lead with Adhesives (Poly-Flex Circuits)

Curing/Hardening

Finally, we have reached the region where adhesives excel. Conductive adhesives use a gentle profile compared to even tin-lead solder. And this profile becomes even better when compared to those required for the lead-free solders. Many adhesives are cured at only 130^{o} to 140^{o}C so that temperature-sensitive polyester circuits are not degraded. Compare this to the 250^{o}C to 260^{o}C possibility for L-F products.

Some believe that most electronic materials would have been simpler and cheaper if had adhesives been adopted instead of solder. But solder was discovered in past millennia and made popular by Roman plumbers who used it to seal joints on the aqueducts. Material scientists in electronics were thus been forced to design laminates, coatings, masks and packaging materials with temperature ratings that can withstand the temperature shock of soldering. Few materials really need such high temperature ratings except to survive soldering. And now, we appear ready to raise the bar one more notch for L-F solders. Not only are the alloys higher melting, but also their poorer wetting may require a boost in the oven profile beyond 260^{o}C. This would also seem add an energy burden but some have estimated that the value is not significant. However, a comparison of adhesive assembly at 140^{o}C to L-F at 260^{o}C may be significant.

Potential casualties of higher temperatures include lowest cost laminates, some solder masks, possibly epoxy molding compounds (EMC) and some ICs. The EMC suppliers are saying that the higher temperatures will cause more "pop corning" and that pre-drying will become the norm for all PBGAs. MEMS and Photo-electronic devices can be quite sensitive to heat and this needs to be explored. Opto-couplers used for optical-LAN cards are already adhesively bonded since even Sn/Pb solder processing is too severe. The new L-F solders will create more problems.

Enter the low-temperature adhesives. But before you say that adhesives will never replace solder, be aware that large semiconductor producers have been quietly re-evaluating conductive adhesives. It is perhaps noteworthy, that the premier technology company, IBM, has been granted a large number of conductive adhesive patents in the last few years.

The departure of lead solders will leave a gap in the *solder hierarchy* scheme that has been used for decades. Many, including IBM, have used higher lead alloys to increase the melting point in sub-assemblies. This allowed the melting point to be adjusted so that multi-chip modules could be assembled to PCBs without damaging the joints of the components on the carrier. Granted, there are lead-free alloys that can be used, but this is just one more area where added work is required. What about adhesives?

Adhesives can solve the temperature hierarchy problem that L-F will reintroduce. Flip chip modules and FC-BGAs are typically built using higher lead, higher temperature solders. This allows the package to be assembled to boards without melting the flip chip joints again. Eliminating lead solders will remove this essential temperature hierarchy. There are higher temperature alloys, to be sure, but thermoset adhesives do not melt once cured. This means that FCs could be used to build CSPs, BGAs and multi-chip modules without re-melt occurring. And since nickel or gold bumps are compatible with CAs, the bumps will not melt. Adhesives have another benefit in that no α-particles are emitted that can cause problems with memory chips, ASICS and high-density CPUs.

Right and Wrong Adhesive Applications

Most assemblies will work with CAs, but there are exceptions at this point in adhesive evolution. Adhesives are not recommended for extreme current devices like power transistors and power supplies. Large and heavy components are going to fare poorly in mechanical tests and should be avoided. Assemblies requiring substantial rework are also going to have problems since CAs are much more difficult to rework. Other applications can be considered. The fact is that adhesives are used in high volume but the applications are those where solder poses problems. The rule has been to use solder where it works and adhesives when there is a problem. Mylar circuits use adhesives.

Photonic components on hard board use adhesives. But most of the industry uses solder simply because it works and has a long history. But if lead-free changes the rules it also opens up a new opportunity for conductive adhesives.

PERFORMANCE ISSUES

Limitations

Stated earlier, the mechanical shock test is one of the areas of poorest performance for adhesives. Does it matter? Yes, to some extent! Until better shock test results can be obtained, adhesives will have a limited market. The two exceptions are flexible circuits and flip chips. Flex is compliant and able to distribute force. Even when flex is glued to a rigid platform and dropped, adhesives do well.

Essentially all of the problems with conductive adhesives are eliminated with flip chips. Once a flip chip is underfilled, lower joint strength is no longer an issue. In fact, underfill shrinkage tends to compress the filler to make it more conductive. Any concerns about silver migration are all but eliminated since the joints are encapsulated in a good dielectric. Cost for adhesives is higher with the present silver-filled products, but the difference is small and it could be at parity with the more expensive L-F solders. But a breakthrough that allowed a changeover to copper filler could make adhesives the lowest cost assembly products. However, today's adhesives could bring a lower "installed cost" if L-F solders require a host of more expensive materials, added processes and more cost for the solders themselves. Figure 12 shows an adhesive joint for a flip chip with a conical bump.

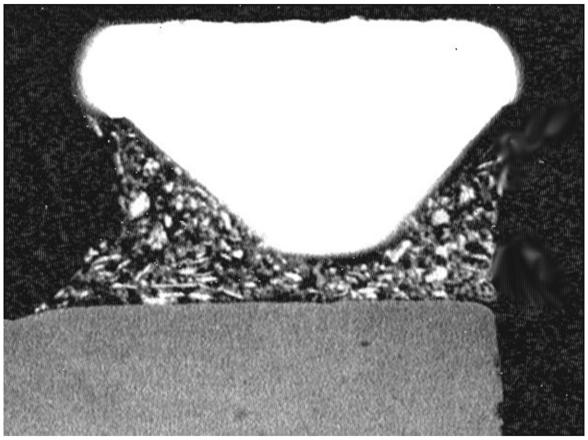


Figure 12 – Adhesively Bonded Flip Chip

Advantages

There are two important advantages for adhesives. They are much more compatible than solder. Adhesives adhere to almost anything including glass circuits. They don't leach away metals. This means they can be used with gold, thin-film circuits and indium-tin oxide circuitry found in flat panel displays. But the real advantage, and the one being made more important by L-F solders, is low temperature processing. The ability to process in a reflow or batch oven at 150ºC or lower is a major plus. Indeed, if the L-Fs require about 260ºC, this advantage could make CAs the *right choice* as it was for AT&T decades ago.

New Adhesives?

A simple breakthrough like stabilized copper, could bring about a major improvement in conductive adhesives, especially if a conductive polymer coating succeed. We would expect better mechanical properties and lower cost. Possibly better electrical and thermal conductivity would also result. A better rework system is definitely needed, but thermosets that "unzip" at specific elevated temperatures are already in use for underfills. There is every reason to believe that these polymers would work for adhesives. Even without a new filler breakthrough, mechanical strength could be improved with fiber fillers. Nano-carbon materials are likely candidates especially since these products are moving to a commercial production phase.

SUMMARY & CONCLUSIONS

Conductive Adhesives could save the industry millions, or perhaps billions of dollars by keeping assembly cooler if lead-free raises the heat. Polymer chemistry long ago addressed the temperature problems that may never be solved by solder. While organic chemists have been lowering temperature curing, metallurgists are turning up the ovens to get the lead out. Will this increase CO_2?

Although conductive adhesives are being used and are gaining popularity, limitations are still a problem. High on the list is lower mechanical shock performance. Expect improvements if researchers take up the challenge.

REFERENCES

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