Jetting- a New Paradigm in Dispensing

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Abstract
Today's advanced packages for electronics are required to meet a wide range of requirements for reliability, size and cost. Surface mount technology still prevails in low cost electronics (televisions, VCR's, washing machines, etc). Most surface mount IC's are wire-bonded, molded devices, and not considered "advanced packaging". The challenges in packaging increase as the need for portability, performance, or reliability increases. The size and performance constraints of notebook computers, mobile phones, gaming devices and other handheld portable electronics are drivers, as is automotive electronics. The mantra "smaller, faster, cheaper" has turned into a fevered battle cry in electronics manufacturing today.

Automated Fluid dispensing is a process found throughout electronics manufacturing. Notable among the applications are die attach adhesives, wire bond encapsulants, and flip-chip underfills. Materials manufacturers continue to innovate, enabling new processes to develop, as well as bringing the cost to manufacture down. Traditional needle dispensing is a mature solution to many of the manufacturing challenges that exist. But a new application method, known as jetting, is breaking formerly established barriers and enabling new applications that simply were not possible with traditional techniques.

This presentation discusses the physical action of jetting and highlights the fluid parameters that relate to jetting. The main advantage to jetting arises from the fact that the fluid is imparted with momentum and is actually shot from the nozzle. This property not only affects the flow rate through the nozzle, but also considerably affects the overall rate of the entire process. The jetting process is independent of the dispense gap, a highly important parameter in needle dispensing. (The surface of the substrate is used to pull the fluid deposit from the needle.)

Because proximity to the dispensing surface is a critical parameter of needle dispensing, it is usual for the robot controller to use precious time moving the needle to the correct Z-location for each deposit. With jetting the robot can literally fly above the surface and shoot from a distance, eliminating Z-axis motion time as well as many of the dwells and delays used to account for the flow of the material from the needle.

Additionally, the dimensions of the fluid stream from a jet permit control of the fluid to never-before-possible restricted areas. Stacked Die, RF shields, and sub-250 micron fillets for underfill are now not only possible but a production reality.

The bulk of underfill processing throughout the semiconductor industry has turned to jetting as a new and improved method because of its inherent speed and precision. A brief review of the many dispensing applications in electronics will establish the landscape into which jetting fits. Specific dispensing applications are detailed; with traditional fluid application methods shown. The impact that the new jetting technology has on cost and productivity is then discussed.

General overview of electronics packaging
Electronics packaging involves making connections between components and then protecting those connections and components for the life of the product. Early electrical circuits were created by connecting 2- and 3-legged devices by hand using discrete physical wires with solder. As the complexity of circuits increased it became too difficult to make all those connections by hand. Printed circuit boards and monolithic integrated circuits were developed using printing and photo-defined tools. This assured that a repeatable circuit could be produced in high volume.

Many variants of circuit interconnection have been developed over time, including 50-layer backplanes, flexible circuits and CNC wire-wrapped circuit boards. It is interesting to note as wireless technology takes off the conspicuous elimination of physical connections. Even wireless devices often need a power connection of some sort, so the elegant simplicity of a passive RFID circuit is notable for the fact that it can even draw power through a wireless connection. But within the RFID package you can be sure there are the ubiquitous connections that make it an electronics assembly.

Often, after the current-carrying, metallic connections are made, they are insulated in such a way that the signal paths are kept isolated from each other and the user. The insulator also provides the assembly some mechanical form and strength. Similar constructs of conductors and insulators are realized in creating bare PCBs, cables, and tiny IC's in the form of wafers. It happens at multiple levels in electronics assembly, as singular devices are combined into ever more complicated assemblies. Dispensing plays a role in virtually all of these levels of operation, primarily in applying encapsulants, coatings or adhesives that bond parts together. Even conductors such as conductive epoxy and solder paste are dispensed in many electronic packages.

Bare Die Packaging

Traditionally, the vast majority of IC's ("bare chips") are attached to a copper lead frame using conductive epoxy. After dispense a pick and place machine puts the die into the epoxy and the epoxy is subsequently cured. At the next stage wire bond connections are made between the IC and the lead frame. The assembly is over-molded and the leadframe is then excised, leaving a robust package for the fragile IC (Figure 1). This is a package that can be handled by stockroom personnel and robotic assembly systems without damage, as long as precautions are taken to prevent build-up of static electricity.

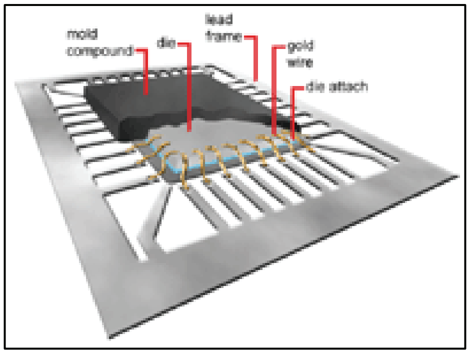

Figure 1 - Over Molded Leadframe

Flip-chip attachment of the bare chip to the next level of assembly has some performance advantages over the traditional wire bond method highlighted above. At the same location where a wire would be bonded, a conductive bump is attached. When the bumped die is applied face down to a substrate, the bump provides both mechanical standoff as well as electrical connection (Figure 2). The advantage is the package can be made to fit a smaller volume. The short interconnect paths of flip chip have electromagnetic advantages as clock rates go up. Additionally, flip-chip attachment exposes the backside of the die for possible attachment to a heat extraction device. Virtually all of the microprocessors that are made in high volume today are assembled as flip-chips.

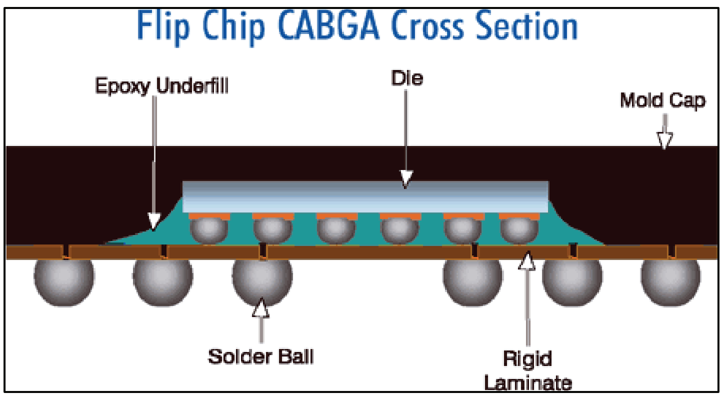

Figure 2 – Flip Chip

An intermediate packaging step that preserves the size and performance of the flip-chip, while enhancing the handling characteristics, is chip scale packaging (CSP's). In this case the device is typically <20% larger than the bare die, but it can be handled by traditional SMT assembly equipment and device testers. Virtually all mobile phones and other handheld devices today include at least one CSP.

The predominant dispense operation that is used in conjunction with flip-chips and CSP's is underfill. While it is solder or some other conductor that connects the device to the substrate, it is glue that holds it together. Capillary action draws the adhesive in between the device and substrate interface layers and surrounds the bumps. As this adhesive (typically epoxy) cures it locks the parts together to withstand both mechanical shock and thermal cycling stresses. I n particular, portable devices such as cell phones need to withstand drop shocks, as they must survive the abuse that comes with being "portable".

High performance devices such as microprocessors see large temperature swings due to circuit density and high clock speeds. When thermal cycling poses a threat to the device reliability, the adhesive is filled with particles that give the underfill a composite thermal coefficient of expansion (TCE) that matches the flip-chip, bumps and substrate. These particles must be of a very well controlled size and shape to assure the capillary flow required, while at the same time not adversely affecting the viscosity or as-cured properties of the epoxy. Newer alternatives to flip-chip underfill that show promise but are not well established yet involve additional packaging steps, such as wafer level applied underfill and no-flow underfill.

Printed Circuit Board Assembly

Over-molded IC's, CSP's and flip chips are assembled to bare printed circuit boards (PCB's), by robotic machines. Automation has been developed for the benefit of repeatability and speed, resulting in low costs. Typically solder paste is applied (using stencil printing techniques) to bare PCB's and then components are placed in the paste. When this combination is taken to a temperature high enough to melt the solder, then a physical and electrical connection is made at each metallic connection point between the devices and the PCB. Similarly, discrete components (resistors, capacitors, inductors, crystals, and many other devices) are also assembled using this process.

A similar process is used to connect other electrical components (known as "odd form") such as speakers, connectors, cables, displays, and sensors. Less automation is available due to the great diversity of part shapes. Another method of making an electrical connection is with the use of a spring loaded contact, such as those found in virtually all cable connectors. These are chosen when a certain number of connection cycles are necessary over the life of the assembly. When no disconnection is anticipated, the parts are "hard-wired" via a permanent and reliable means such as solder.

Dispensing operations at the PCBA level include surface mount adhesive (SMA), solder paste, gasketing and bonding, conformal coating and encapsulation, and thermal management materials. (See Table 1.)

Table 1 - Dispensing Applications in Electronics Manufacturing

Conventional printed circuit board assembly (PCBA)	**Semiconductor Packaging**	**Specialty processes**
Adhesive, non conductive (SMA)- holds devices in place through wave solder or reflow process	***Die attach adhesive***- epoxy, usually filled with silver particles to effect a back side electrical ground of the device as well as a mechanical bond	***UV-cure bonding***- alternative formulations of silicones or epoxies that are photo-initiated. Generally used on clear optical or plastic components, and coatings
Solder mask- Prevents solder from wetting to metallic surfaces where solder is undesirable	***Flux***- Acts as a reducing agent to clean oxidation away from soldered surfaces prior to reflow. Becoming more important in lead-free processes	***Photoresist and wafer coatings***- new and emerging alternatives to front end processes
Potting- provides physical protection and a degree of hermeticity to wires and sensitive devices	***Underfill-*** provides encapsulation and bond strength against thermal mismatch of components or against drop shock mechanical stress	***Bump reinforcement-*** Pre-applied encapsulant to the wafer level or chip-scale package bumps prior to assembly at the next level
Flux- Acts as a reducing agent to clean oxidation away from soldered surfaces prior to reflow	***Encapsulation-*** either glob-top or dam and fill, provides protection of wire bonds and, sometimes, intellectual property	***Silver epoxy interconnections-*** An ever increasing lead-free alternative, also requires lower temperature curing than is needed for solder reflow, (e.g. for plastic substrates)
Conformal coating- provides protection from corrosion, contamination and environmental effects	***Thermal grease and thermal adhesive-*** Filled with thermally conductive particles to promote the transfer of heat from source to dissipative path	***Liquid crystal***- material used in liquid crystal displays (LCD's) the material is more expensive than gold in some cases.
Encapsulation- provides protection of wires and fragile components	***Lid seal, gasketing and general bonding-*** mechanical bonding and sealing of package components	***Hydrophilic getters-*** A material that absorbs airborne moisture and preserves the service life of various moisture sensitive products

Solder paste- Complements the application of paste from printing, in places where the printing process is insufficient or not possible- such as rework and where large and small components combine	***Solder paste***- Discrete capacitors and other components that require very small dots or flexible selection of regions. Also used for connection of RF shields	***Hot wax, Hot melt thermoplastic*** Generally used in temporary bonding applications

There are many machine variables that relate to dispensing. Attention has to be paid not only to the valve control but also the approach (and departure) of the valve to the dispense position, i.e. the robotics. Typically dispense processes have at least one temperature controller for the valve system, often several for the substrates in the queue as well. There are also typically many sensors throughout the system, adapted to measure proximity, flow, and pressure as a means for monitoring and controlling the process.

Types of Dispensing Valves

In developing dispensing processes, electronics manufacturers typically start small, with prototypes at the bench level (Figure 3). Dispensing operations typically are developed in conjunction with some expertise contributed by the fluid manufacturer's recommendations. Process engineers aim to simply express an arbitrary amount of fluid from a hand-held syringe, to test the behavior of the fluid. The operator monitors and controls the amount of fluid using visual feedback.

Figure 3 – Benchtop Dispenser

The experienced process engineer at this point has a thought for automation, but often design for manufacturability (DFM) is neglected at this stage. To obtain a repeatable shot size, a "time-pressure" controller, foot switch operated, is often utilized. This mechanism uses a controlled pulse of air pressure, both in magnitude and duration, to meter the dispense volume. Greater pressure or longer time yields larger shot sizes. Note that for low viscosity fluids, the "off" pressure may actually be adjusted to a slight negative value (suction) to prevent dripping.

Naturally, the progression from prototypes to production runs often includes starting with time-pressure (Air-over) syringes. Advantages in this method are in simple maintenance and low cost of ownership. However this practice is notorious for poor shot size control especially as the viscosity increases over the duration of the pot life. Also air pressure alone is rather inadequate for very high viscosity fluids that need a motorized force to achieve reasonable flow rate and throughput.

Auger Valves

Thousands of electronics manufacturing lines developed in the 1990's employ a dispensing technology known as auger valves or rotary positive displacement valves. The auger is a machine screw connected to a motor that spins selectively under computer control. The screw is enclosed in a cartridge with a bore just greater than the diameter of the screw. Material fed at the inlet end of the cartridge is forced by the flights of the screw out through a needle connected at the exit end of the cartridge. Needle diameter, motor speed and fluid feed pressure are the main controls for managing flow rate and shot size (Figure 4).

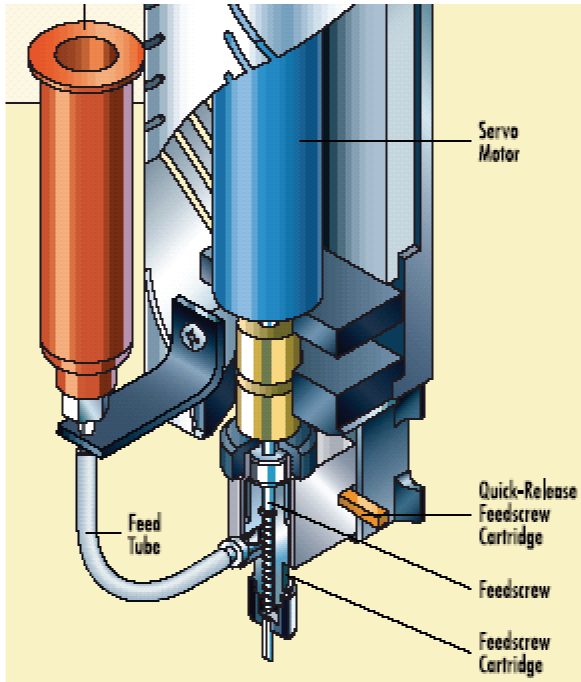

Figure 4- Auger Valve

The auger valve is at its best performance when the fluid is highly viscous. This includes solder paste, damming fluids and thermal greases /adhesives. These fluids are highly filled and therefore hard to push through a needle. The auger motor provides a pumping force that is proportional to the motor speed and is also a function of the auger geometries. The auger valve is capable of both lines and dots. When very small dots or lines are needed, very fine pitch, small diameter screws are appropriate. For larger shot sizes, such as high volume damming operations, larger screws are better, typically carbide hardened for durability.

With all dispensing valves that deliver fluid through a needle dispensing tip, the management of the position of the needle tip relative to the substrate is of paramount importance. Surface tension of the substrate is used to pull the material from the needle tip. If the needle is not close enough to the substrate, the droplet will hang on the needle tip. If the needle is too close, the material may not flow properly (the substrate acts as an obstruction to the flow) or may build up around the outside of the needle, resulting in contamination at the next dispense site. Inventions such as standoff pegs, mechanical and laser height sensors, tapered and coated needles have all been directed at solving the problem of transferring the material clinging to the tip of the needle to the substrate with some repeatability.

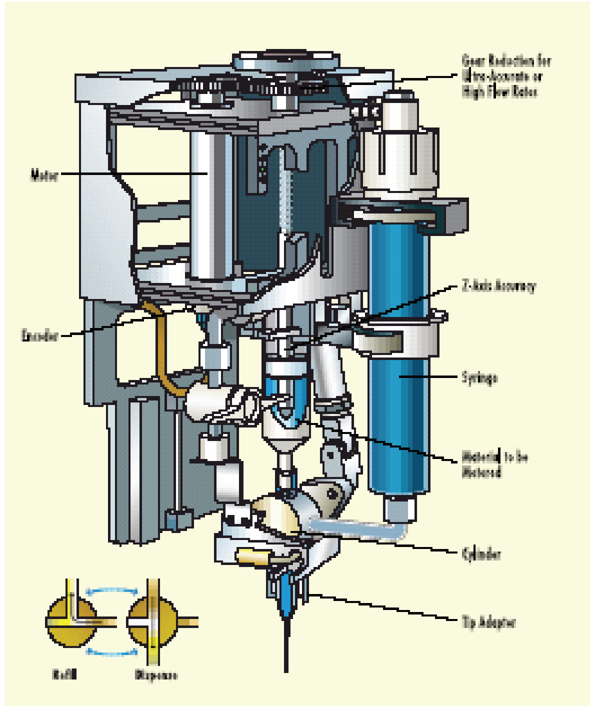

Figure 5 – Linear Piston Pumps

Linear Piston Pumps

An auger valve is not well suited to dispensing underfill. Underfill is characterized as a low viscosity, short pot-life and highly abrasive fluid. In the late 1990's linear piston pump technology was developed to achieve very high shot size accuracy with these fluids. Linear pumps work on the operating principal of a piston pushing fluid from a chamber (Figure 5). They have the beneficial characteristic that the volume of the piston coming into the chamber is exactly the volume of the fluid coming out, when operated correctly. They do not drip, as would an auger valve. They are rather complicated by design, requiring multiple wetted chambers and gate valves to achieve the true positive displacement effect, and thus have a high cost of ownership. As with auger dispensing, the fluid orifice is a needle and still requires careful management of dispense gap so the last drop of fluid is transferred to the substrate.

Jetting

Jetting technology has created an upheaval in the electronics dispensing scene in the past 10 years, and the last 3 years especially. The jet has provided for major increases in throughput in many flip chip packaging and CSP underfill production lines. Jetting has also opened up some process capabilities that were not possible or not economically feasible before.

The operating principle of the mechanical jet is the creation of dots and lines formed from a very small fluid stream, ejected from an orifice. The fluid is ejected by the motion of a fast acting, ball-end piston. The piston drives the fluid through the orifice from the inside of the jet. A mechanical seat provides a precise stopping point on the motion of the piston, with a microscopic shock vibration that helps to break off the fluid stream from the surface of the orifice. (Figure 6.)

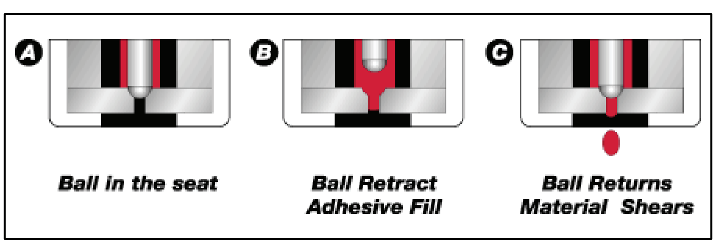

Figure 6 - Jet Mechanism

The list of fluids that can be dispensed by mechanical jet has increased exponentially. (Figure 7.) The shot size resolution has concurrently improved exponentially. Twelve years ago the only fluid that was considered suitable for jetting was surface mount adhesive (SMA). Today, well over 20 types of fluid are being jetted in production, and when each product part number is considered within each product type, the number of different fluids being jetted is now in the hundreds.

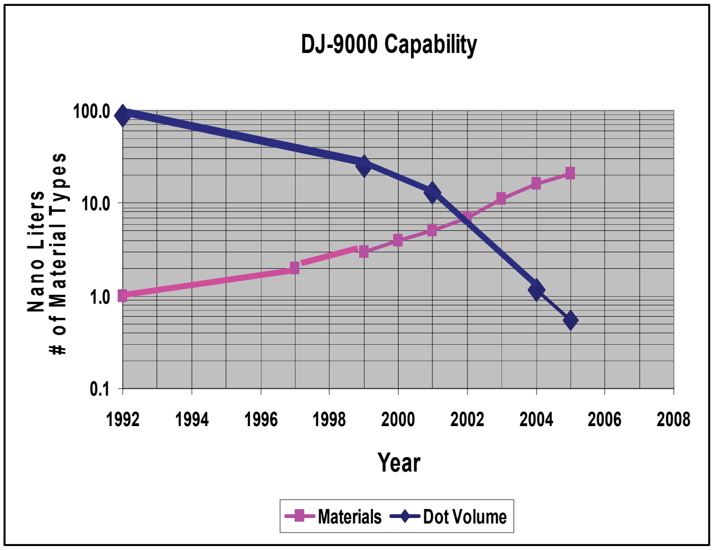

Figure 7 - Jet Mechanism

Most people think of ink jet printers when they hear of jetting. Although both devices make small dots, the mechanical jet operates under a different set of physical principles. Ink-jet printing only works with low viscosity inks. Bubble jet printers have a fast-acting heater, which vaporizes the ink, forming a bubble within the inkjet head. The expansion of this bubble is what ejects the ink. This technology is not feasible with many of the (filled) fluids that are used in electronics manufacturing.

It is interesting to view the industry's approach to underfill dispensing over the last 10 years. Although IBM invented the C4 process over thirty years ago, flip chips were not in significant production volumes at any other companies, as recently as 1996. Ten years ago only the world's largest electronics manufacturer's, with substantial R&D budgets, were willing to attempt to develop a production-ready process around flip chip technology. Flip chip requires careful handling of bare die and possibly a different reflow profile from the surface mount devices (SMD's). Then a subsequent dispensing and curing operation is required. Cured epoxy has never proven to be rework-friendly either, although the fluid formulators have made significant strides recently.

However through the cooperation of fluid formulators, equipment manufacturers and early adopters, the price per interconnect point has come down significantly, making flip chip competitive with wire-bonding and other alternatives. Flip chip production volumes have exploded, and not just at large multi-national companies. Even small contract manufacturers are developing the capability. The auger valve was well established back then as the applicator of choice for most electronics dispensing applications. It quickly proved to be inadequate for underfill. Since that time, the linear pump was developed and commissioned into ~90% of all the underfill production lines around the world. Most recently the same manufacturers who embraced the linear pump have been upgrading their production lines to use jetting technology, for its higher speed and lower cost of ownership. Jetting technology has essentially brought about the demise of linear pump technology, as quickly as the linear pump was developed as an effective solution.

Advantages of jetting

Jetting imparts momentum to the dispensed shot; it actually shoots the material from the orifice. Proximity to the substrate surface is not critical, as with needle dispensing. Remember that managing the needle tip position in Z is an important aspect of needle dispensing. A needle has to use surface tension of the substrate to pull material from the needle. With jetting this is typically not critical so time is not wasted on delicate Z-axis motion.

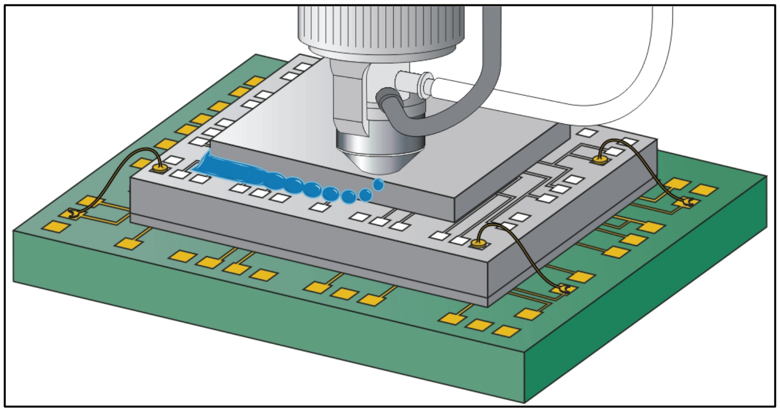

Figure 8 - Stacked die

It is possible with jetting to control more precisely where the fluid is deposited, away from "keep-out" zones. The fluid stream dimension is typically only 75 - 150 microns in diameter. This compares quite favorably with the dimension of a conventional needle used typically in these applications. The trade-off with the needle selection is to keep the ID large for flow consideration, but to keep the OD small for proximity reasons. Jetting allows for the best of both worlds, as the orifice outside dimension can be removed from the equation. This has been an enabling consideration when it comes to aiming the jet nozzle vs. positioning of the dispense needle. Manufacturers are able to bring passive devices and other parts closer to the flip-chip, helping to reduce overall package size. Dispensing processes that were simply not possible (or not feasible in volume production in any case) are now in widespread production. In one prominent application, a 100 um stream of fluid is jetted into a 200 um gap between semiconductor devices.

Another challenge in manufacturing of handheld devices has been met by jetting. In this case there is analog (RF) circuitry that must be isolated from the digital circuitry, typically by use of an RF shield. These shields are designed with a hole size on the order of half a wavelength of the RF energy that is being shielded (< 1 mm). It is easiest to reflow the solder for the shield, electrically test the phone, and then underfill the CSP's under the shield. In this process order, rework can be managed easily before underfill, if necessary. The challenge is to insert the fluid through the hole in the RF shield, directing the fluid to where it needs to go and at production rates. To insert a needle in the hole is an alternative, but the flow rate through the small needle, and the time taken to insert it, are both prohibitive of the throughput rates required.

The ever-present push to miniaturize electronics meshes well with the introduction of jetting to manufacturing lines. Stacked die packages and wafer scale packages are two relatively new electronics designs that both tend to be characterized by placement of devices in close proximity to each other. (Figure8.) Additionally, UV cure adhesive is used in the manufacture of liquid crystal display (LCD) modules as a gasket between sandwich layers of glass and circuitry. The jet enables a very sharp corner to be achieved on the rectangular gasket pattern. This is necessary to maximize the pixels available to displays used in mobile handsets, computer displays and many other end products.

Jetting in the other electronics manufacturing operations

There are many other dispensing operations found in electronics, including die attach, bonding adhesives, encapsulation, coatings, gasketing, phosphor deposition, liquefied wax, thermoplastic adhesives, desiccants and liquid crystals. All of these materials have been successfully dispensed using jetting, with the same benefits to speed and ease of use as highlighted earlier. The challenge has been to jet silicones, which tend to be compliant and sticky. By working with the fluid formulators and through understanding the physics of jetting, even these challenging fluids can be jetted.

A common inquiry in regards to new applications is "what makes a fluid suitable for jetting?" The answer is proving to be less restrictive than previously thought. Viscosity is clearly an important variable, but it is encouraging to note that even damming fluids (near one million centipoise at room temp) have been jetted, as well as liquid crystals that are water-like in viscosity. The basic function is to match the correct amount of energy in the piston travel to the amount of energy needed to break the fluid stream off from the nozzle tip without atomizing the fluid.

As with needle dispensing, temperature control is important for fluids such as epoxies that drop in viscosity as the temperature increases. At the same time, a minimum of the fluid reservoir should be heated to prevent early cross-linking of the polymers before application. Fluids that have air bubbles in them are as much trouble to jet, as they are to needle dispense and should be de-gassed. Today there are many choices in jet seat and nozzle construction, the materials and dimensions selected to make it possible to jet most of the fluids that are currently used in electronics production.

Nozzle sizes range from 75 microns up to 1 mm, and seat dimensions range from 200 microns up to 1.5 mm. With this range of parts, a single jet can be configured to make shot sizes as small as 1 nanoliter or as large as a milliliter per dot. The choice is made based on the requirements of the application, usually balancing throughput with required shot size resolution. As jetting can provide dot rates of up to 200 dots per second, it can be seen that the fluid can be deposited at significant flow rate when necessary.

Summary

Consumer demand for product improvement and innovation drives electronics manufacturers to continuously create products and processes that exceed the prevailing standards. Often, the improvements are obtained through manufacturing practices that produce more products from fewer resources, in order to preserve and enhance shareholder interests. This certainly is the case with products such as notebook computers, mobile phones and gaming devices.

Some form of dispensing process attends the assembly of virtually all electronic devices. Manufacturers are continuing to find benefit s from applying flux, adhesives, encapsulants and coatings as a way to assure the reliability of their products. To process engineers who are already familiar with needle dispensing, jetting has appeared as a compelling alternative and in fact has enabled new processes that previously could not be justified. For example, manufacturers who thought underfill was too expensive or difficult are now taking a second look and finding the effort to be well worth the while, and their customers realize the benefits as well. Jetting is expected to be applied in more and more electronics production lines in the future.