Throughput vs. Wet-Out Area Study for Package on Package (PoP) Underfill Dispensing

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Abstract:
Package on Package (PoP) has become a relatively common component being used in mobile electronics as it allows for saving space in the board layout due to the 3D package layout. To insure device reliability through drop tests and thermal cycling as well as for protecting proprietary programming of the device either one or both interconnect layers are typically underfilled. When underfill is applied to a PoP, or any component for that matter, there is a requirement that the board layout is such that there is room for an underfill reservoir so that the underfill material does not come in contact with surrounding components. The preferred method to dispensing the underfill material is through a jetting process that minimizes the wet out area of the fluid reservoir compared to traditional needle dispensing. To further minimize the wet out area multiple passes are used so that the material required to underfill the component is not dispensed at once requiring a greater wet out area. Dispensing the underfill material in multiple passes is an effective way to reduce the wet out area and decrease the distance that surrounding components can be placed, however, this comes with a process compromise of additional processing time in the underfill dispenser. The purpose of this paper is to provide insight to the inverse relationship that exists between the wet out area of the underfill reservoir and the production time for the underfill process.

Key words: Underfill, Package on Package, 3D packaging, Jetting

Introduction:

Industry trends are driving mobile electronics such as cell phones, digital cameras, and multi media devices to smaller form factors with increased functionality. This trend is resulting in thinner circuit boards, smaller components, and 3D packaging to provide greater functionality in a smaller sized device. These mobile products are also expected to have functionality after being dropped and thermal cycling. To provide the intended robust functionality underfill is applied to PoPs to provide a mechanical connection between the substrate and package. The underfill material absorbs the mechanical stresses between the substrate and component as the PCB flexes upon impact of a drop or CTE mismatches during thermal cycling. This prevents the solder joints from fracturing which would result in an electrical short and device malfunction.

Underfill is dispensed in a weight-controlled pattern along one or two sides of a component, and then capillary action draws the underfill to the other side of the component completely encapsulating the solder joints under the component holding them in hydrostatic compression once cured. When initially dispensed the underfill forms a fluid reservoir that requires a wet out area. The fluid reservoir is depleted once capillary forces have pulled the material to the other side of the component and underfilled the package. With PoP both interconnect layers are underfilled simultaneously from the same fluid reservoir as seen in Figure 1.

Figure 1: Underfill reservoir and Flow Fronts

The size of the wet-out area determines the proximity of neighboring components. For manufacturing reliability and rework requirements the underfill should only come in contact with the component being underfilled. If underfill comes in contact with other components surface tension pulls the material to that area and can cause an incomplete underfill of the desired component.

A reliable underfill process is achieved when enough material is dispensed to completely flow under the component. The use of equipment with integrated weight scales allows for closed loop processing of the dispensed mass ensuring that the appropriate amount of underfill is dispensed for each component. If too little material is dispensed there is an incomplete underfill leading to a lack of reliability in the underfill process. If too much material is dispensed there is a waste of valuable underfill material increasing the process cost, excessive wet out areas, and the possibility that in contaminating surrounding components the intended package is starved for material resulting in an incomplete underfill.

When the appropriate amount of underfill is dispensed, there is a direct correlation between the amount of material dispensed in a single pass and the size of the fluid reservoir corresponding to the wet-out area. The more material dispensed at one time, the larger the wet-out area and conversely the less material dispensed the smaller the wet-out area. This is the major factor when investigating the inverse relationship between throughput and the wet out area required for complete underfill.

PoP Package Types

This study focused on two different PoP package types; the current generation PSvfBGA PoP (figure 2) and the next generation Through Mold Via (TMV) PoP (figure 3). The PoP typically has a logic device in the bottom package and a memory device in the top package.

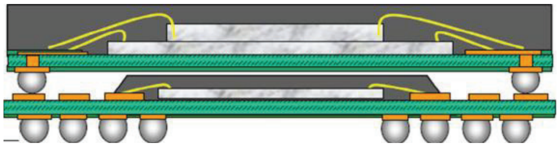

Figure 2: PSvfBGA PoP

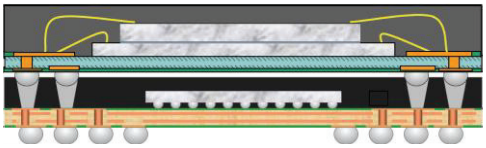

Figure 3- Through Mold Via (TMV) PoP

The next generation TMV PoP allows for higher density memory interface as well as higher data transfer rates. The trends for PoP mimic that of the devices themselves in that they are being reduced in footprint size and height while increasing in functionality. As this footprint is reduced the available area for underfill wet out will also be pushed to smaller distances with reduced underfill keep out zones. There is a drive to improve the solder joint reliability without the use of underfill at one or both layers. [1]

Underfill Material

A single underfill was used in the study to limit the number of variables. The chosen underfill was a two part epoxy premixed and frozen prior to use, non-reworkable, 3,000 centepoise (cps), fast flowing underfill with 50% filler content. The scope of this paper was to investigate the flow properties of a representative underfill, however, as the rheological properties of the underfill changes with chemistry, viscosity, and filler content the results will differ slightly. Generally speaking, as the material viscosity goes down the wet out area will extend further away from the edge of the component and the time to flow under the component will decrease. If the viscosity is too low it can be challenging to achieve a complete underfill of the second layer interconnect as the material will not support itself to stay in contact with the bottom layer of the top package. Conversely, as the viscosity increases the wet out area will decrease and the flow out time will increase.

It is important to note that for device reliability there should be careful consideration given to the underfill material's cured properties. While underfill in general improves the reliability of the device during drop tests, the CTE, Tg, and filler content are properties to consider when evaluating the device performance with respect to thermal cycling. [2] Additionally the uses of reworkable underfills are a process consideration as well as a consideration for protecting the package logic.

Throughput vs. Wet Out Area Study

The experiment was designed to first qualify the amount of material required to completely underfill both of the interconnect layers and only the first interconnect layer. This was done first by approximating the amount of material required based on the volume in the interconnect layer and taking the underfill material's specific gravity to convert to a mass. The approximated mass was then dispensed using an Asymtek S-920 dispenser with integrated weight scale capable of Calibrate Process Jetting (CPJ) with a DJ-9000 Dispense Jet to further refine the mass based on the way that the fluid filleted on the non-dispensed sides. It was found that 120mg was required to completely underfill both layers while only 65mg was required to completely underfill the bottom layer. The dispense pattern was an "I" pass (single side) to minimize any chance of incomplete underfill. The flow out time is less when the underfill reservoir utilizes multiple sides of the package (L-pass), however, the testing was designed to only look at a single side as that incorporates the longest flow out time and the highest probability for a void free underfill. The parts were prebaked to drive out any residual moisture in the organic substrate and 90^{o}C substrate heat was used to ensure proper flow of the underfill. The dispenser was programmed so that the center of the DJ-9000 Dispense Jet Nozzle was 0.3mm from the edge and 0.5mm above the top of the component for each weight controlled line. Sample parts were destructively tested to ensure that complete underfill was achieved on the intended interconnect layer(s) so that the testing reflected optimal underfill.

The wet out area was studied utilizing one, two, or three passes to dispense the underfill material. As the cumulative mass of dispensed material is the critical variable in a successful underfill process the total mass was divided equally between passes. The wet out area respective to the number of passes on the PSvfBGA PoP was qualified for underfilling both interconnect layers simultaneously as well as underfilling only the bottom interconnect layer; the wet out area for the TMV PoP only qualified for underfilling both interconnect layers simultaneously. Due to similarities in the volume of the bottom level interconnect level and the height of the solder joints results should be similar between package types when holding all other variables constant.

Testing also qualified the amount of flow out time required for the underfill to flow under the component with each of the passes. This allowed for software programming of the S-920's multi-pass wait timers to be set so that subsequent passes were not dispensed prior to the fluid reservoir flowing out thus increasing the wet out area and skewing the results. The dispense and wait times are given in Table 1.

Table 1: Time requirements relative to number of passes

# of Passes	Dispense Time per Pass	Wait Time Between Passes	Flow Out Time on Last Pass	*Approximate Time to Dispense One Device
1	2 sec	0 sec	30 sec	2 sec
2	1 sec	10 sec	20 sec	12 sec
3	0.66 sec	6 sec, 10 sec	20 sec	18 sec

*The Asymtek S-920 dispenser can be equipped with Pre-heat and Post-heat stations in addition to the standard heated dispense station allowing for the parts to ramp to temperature prior to dispensing and to be subsequently held at temperature after the last pass has been dispensed. This allows maximum throughput out of the dispenser as the DJ-9000 is not sitting idle while parts are at the dispense station ramping to dispense temperature or waiting for complete flow out. As such, the approximate time to dispense one device does not include bringing the parts to temperature in the pre-heat station or holding them at temperature in the post-heat station as that is masked in most applications. For maximizing throughput on the dispenser the number of parts per load cycle need to be considered as the flow out time with multiple passes can be masked because dispensing of other PoPs and the wait time between passes can be done concurrently. For very high throughput applications the time to ramp the parts to temperature also needs to be considered as common preheating ramp rates are between ~2^{o}C/sec to ~8^{o}C/sec.

Results

The wet out area, and thus the distance that surrounding components can be placed, is directly proportionate to the number of passes that the material is dispensed in and if one or both interconnect layers of the PoP package are being underfilled (Figure 4). Increasing the number of passes results in decreasing the wet out area allowing for tighter surrounding component density. The reduced wet out area comes at a cost of process throughput as increasing the number of passes also increases the time that parts are in the dispenser (Table 1).

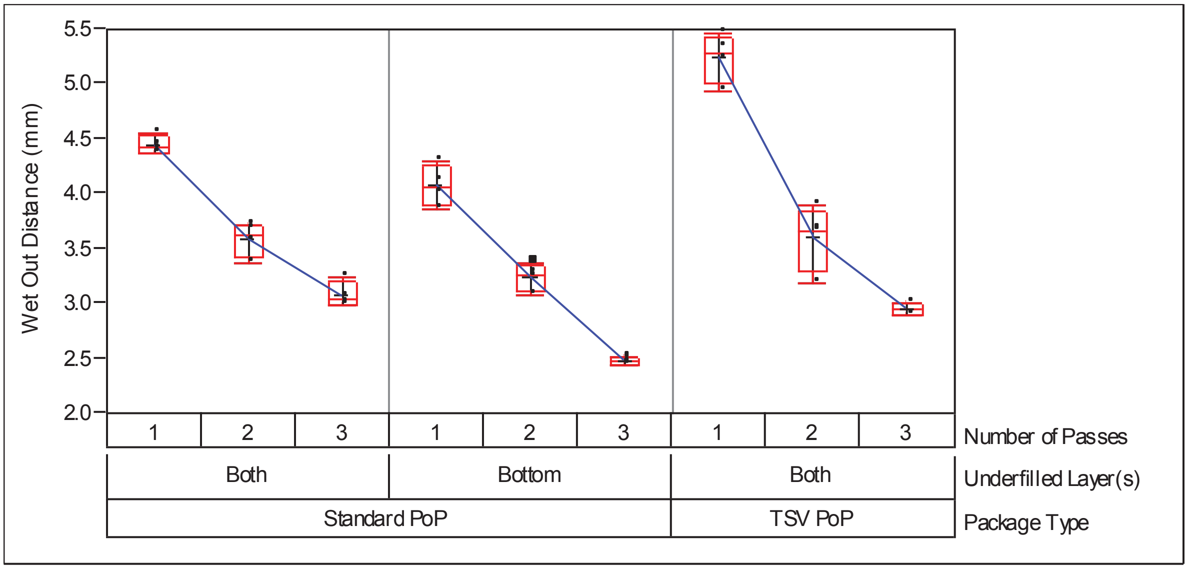

Figure 4: Variability Chart for Wet Out Distance (mm)

This study showed that the 2nd generation TSV PoP requires slightly more wet out area than the 1st generation PSvfBGA when using a single pass. While this was a small sample size, it is possible that the slower flow on the 2nd level interconnect on the TSV PoP (due to the smaller gap between packages) caused the underfill material to wet out slightly more than with the PSvfBGA when all the material was dispensed in a single pass. Interestingly both packages showed similar wet out areas if multiple passes were used. This points to a logical correlation between wet out area and flow out time; the longer the flow time the further the wet out area.

The wet out area is heavily dependent on if one or both interconnect layers are underfilled. When comparing the wet out distance on the bottom interconnect vs. both interconnects we see that the smallest wet out area occurs when only the bottom level interconnect is underfilled. This is understandable when looking at the height required to underfill each layer and the associated fillets on the non-dispensed edge. Figure 5 shows how the wet out and fillet areas are related to interconnect level. This is also supported by the difference in wet out and fillet areas between CSPs and Flip Chips, where the lower solder bump height of a flip chip allows for significantly less wet out than with a CSP [3].

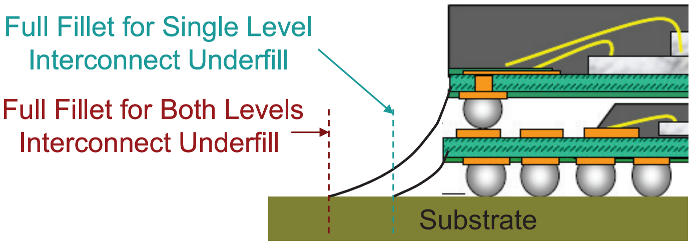

Figure 5: Fillet Wet Out Relative to Interconnect Height

The underfill reservoir is greater than the underfill fillet; the fillet is the underfill that is visible around all sides of the component in a cured package. The dimensions of the fillet are determined by the underfill material contact angle, the height of the solder joints, and the amount of material dispensed relative to the amount required for complete underfill. Wet out areas can become relatively close to the fillet dimensions; however, this occurs with numerous dispense passes where more material is deposited once the fluid reservoir has flown underneath the component. In this study the fillet on the non dispensed sides was ~0.5mm when both interconnects was dispensed and ~0.2mm when only the bottom level interconnect was dispensed. Figure 6 illustrates both level underfill fillets (not the dispense edge corresponding to wet out) and single level underfill fillets.

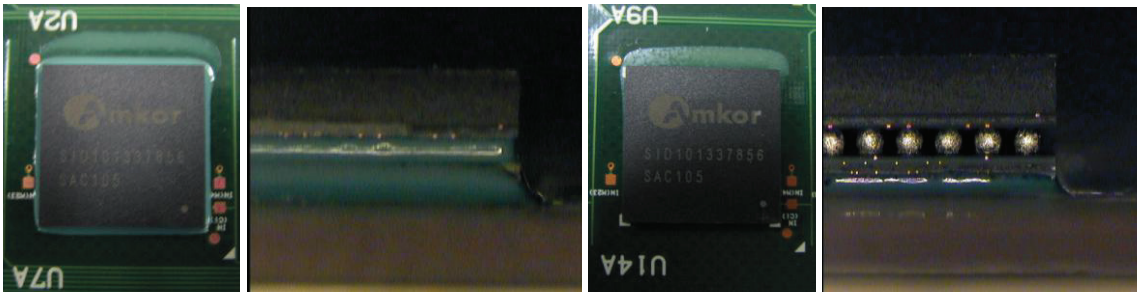

Figure 6: Underfill Fillets for Both Level Interconnects (L) and Single Level Interconnects (R)

Conclusions

With underfill dispensing for PoP the wet-out area is greater the fewer the number of passes. The wet out area is also greater if both interconnect layers are being underfilled. For devices that are lower cost and not designed for minimal size it is advantageous to allow for a greater area for underfill wet out so that the underfill process takes less time and thus requires less capital equipment for manufacturing reducing cost. For devices that are on the leading edge of technology for small form factors and high functionality the use of multiple passes and jet dispensing allows for minimal wet out areas and the highest component density. It should also be studied as to if one or both of the interconnect layers require underfill as underfilling both layers requires additional wet out area and material.

When laying out a board with a PoP the keep-out zone should not necessarily be symmetrical as the dispense side(s) require a wet out area and the filleted sides of the package are primarily dependant on the height of the interconnect layer and contact angle of the material. This study showed that the wet out area on a PoP was approximately 6- 10x the fillet dimensions (~3-5mm vs. ~0.5mm). While the intent of the study is to show the relationship between wet out area and throughput, it is not optimized for the absolute minimum for wet out area. In looking at the slope of the curve with additional passes it appears to stay relatively linear with a downward slope. It is reasonable to expect the curve will flatten out with additional passes giving the absolute limit to the wet out area. Based on the data, there appears to be the capability to increase the passes and decrease the wet out area further. The caveat is that if the passes do not dispense enough material the fluid reservoir will not be high enough to underfill each layer. This is because a limiting factor is how high the material must build up in order to underfill both layers. This is illustrated in Figure 7. A material viscosity change using a material that flows less (higher viscosity or lower substrate temperatures) may also be capable of providing higher dispensing aspect ratio stacking the material to reach the 2nd interconnect layer while reducing the wet out area. This would most like add additional flow out time as well.

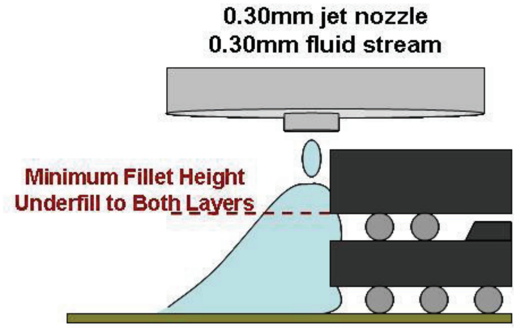

Figure 7: Minimum Height to Underfill Both Interconnect Layers

The proximity to other components determines the percentage of the total amount of material required to be dispensed in each pass. Dispensing less fluid in a pass enables the wet-out areas to be closer to the fillet dimensions because the fluid doesn't spread as much and can flow under the component more quickly. Obviously, more passes take more time. If boards are not designed for underfill, the only solution is a high number of passes, which requires more processing time and adds to the cost of the underfill process due to the equipment investment. It therefore becomes advantageous from a cost and reliability standpoint to design the boards with an appropriate wet out area for either single level interconnect or multiple level interconnect underfill.

Acknowledgements:

The authors would like to thank Amkor for the assistance in providing the test vehicles for the study and for the PoP drawings. TMV is a registered Trademark of Amkor. The authors would also like to thank the application's engineering team in Carlsbad for the assistance in defining the PoP underfill process considerations.

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Throughput vs. Wet-Out Area Study for Package on Package (PoP) Underfill Dispensing

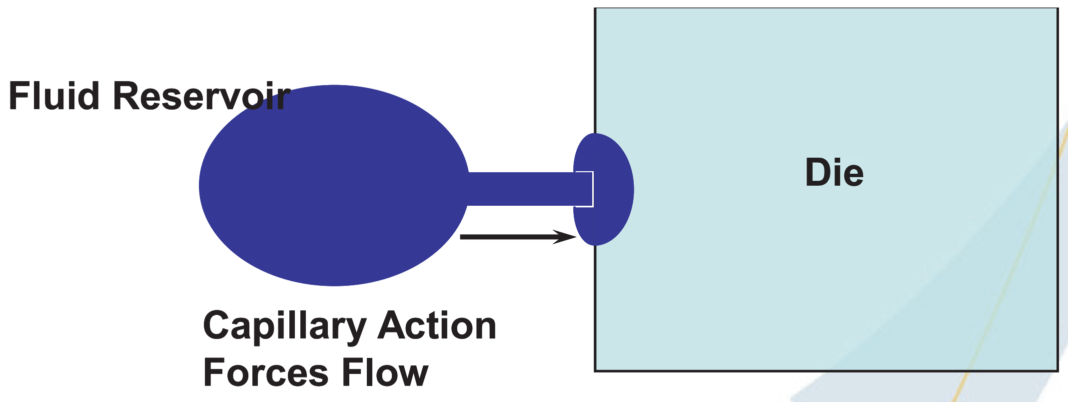
Brad Perkins, Asymtek

Presentation Outline

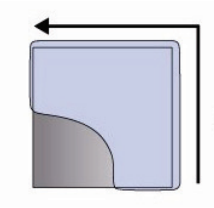
- Why Underfill PoP’s
  - What is Underfill
  - Reliability Overview
- Throughput vs. KOZ study
  - Test Plan
  - Materials and Equipment
- Study Results and Conclusions
  - Fluid Reservoir Wet Out Distance Relative to number of Passes
  - Throughput decreases with increased passes
- Manufacturing Considerations
  - Dispense Optimization
  - Dual Lane, Pre-heating
  - Considerations for RF Shields

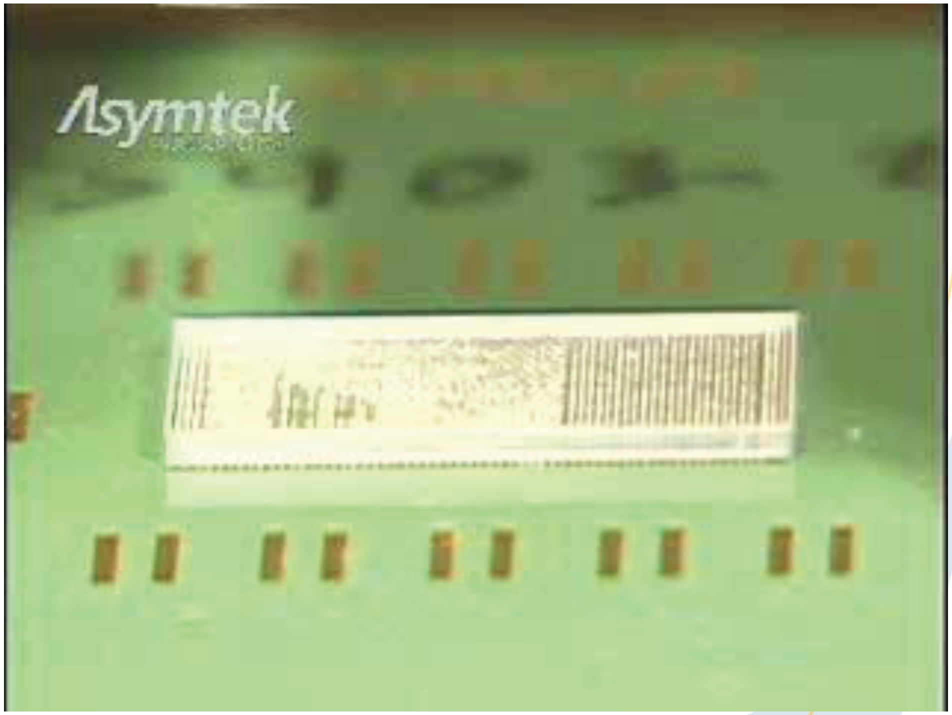
Underfill Dispense Process

- Underfill is an epoxy that is dispensed along edges of a component that subsequently flows under the component.
  - Silica Filler is commonly used to help with CTE mismatch between component and substrate.
- Surface tension forces draw the material under the component (Capillary Action)
- The underfill needs to be dispensed close enough to wet the component edge so that Capillary action can pull fluid under the component.
  - The proximity the underfill can be deposited next to the component is dependant on the dispensing technology used.
  - The area of the fluid reservoir is related to the volume of material required to underfill the component and number of passes used to deposit the correct volume.



Example of Capillary Action

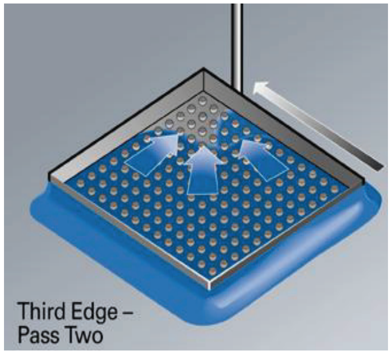


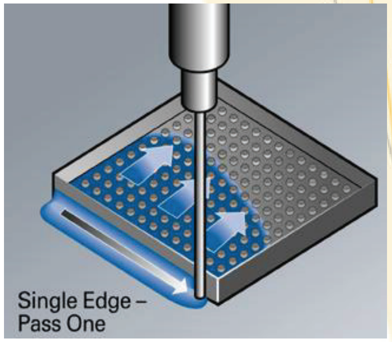


- Material is Jetted in an “L” Pass along the side of the die
- A fluid reservoir is first formed when the material is dispensed, the space for this is the wet out area.
- The non-dispensed sides reference a material fillet.
- The wet out area determines the proximity that other components can be placed.
- Understanding how fluid flows and the best method of delivering fluid to assist flow is critical to a successful process

Dispense Patterns

- The dispense pattern for underfill affects the quality and throughput.
  - I Pass
  - L Pass
  - U Pass
- Multiple passes of one or more of the patterns are often used for minimizing wet out area.
- With each pattern and number of passes there is a trade off between robustness, wetted area, and throughput.





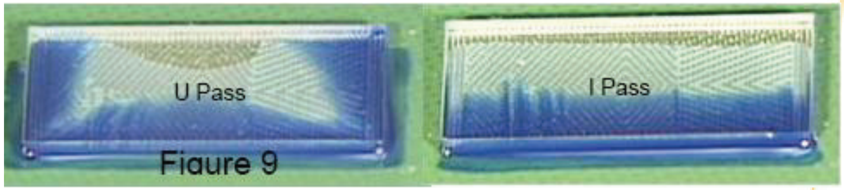
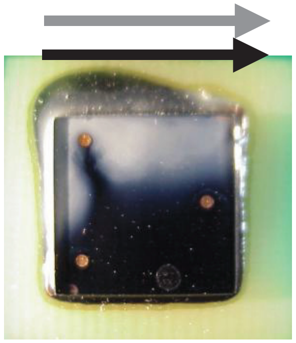
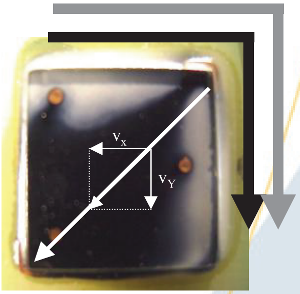


Figure 9



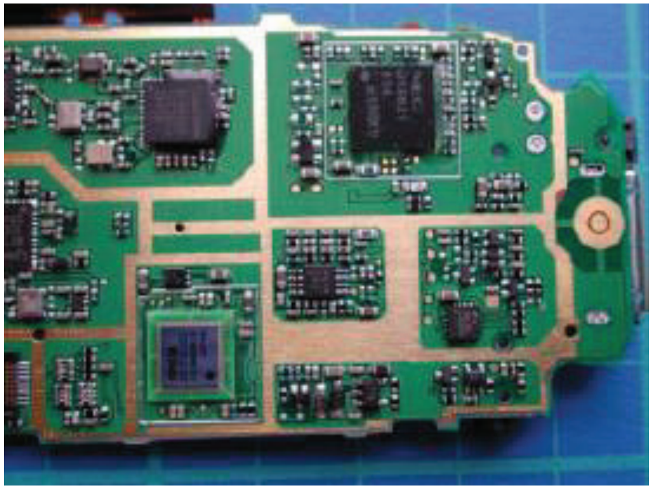
Time to Underfill
100% Area =27 s



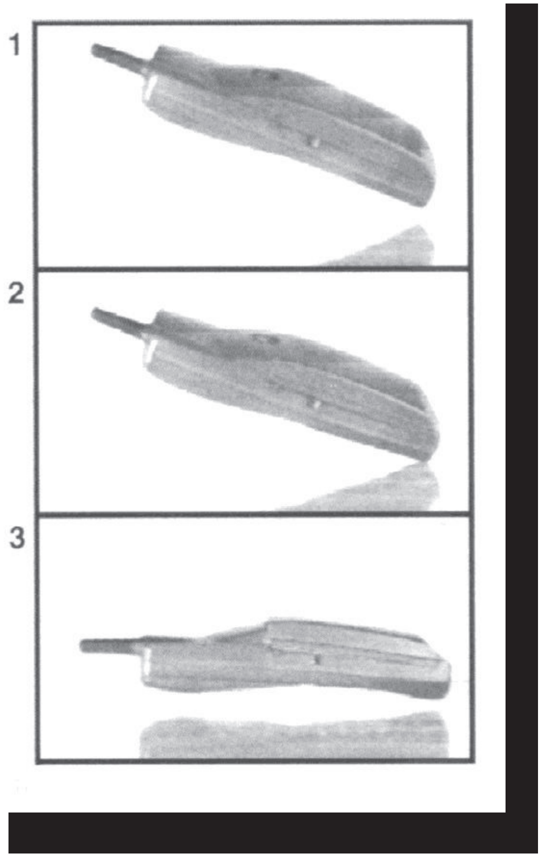
Time to Underfill
100% Area =19 s

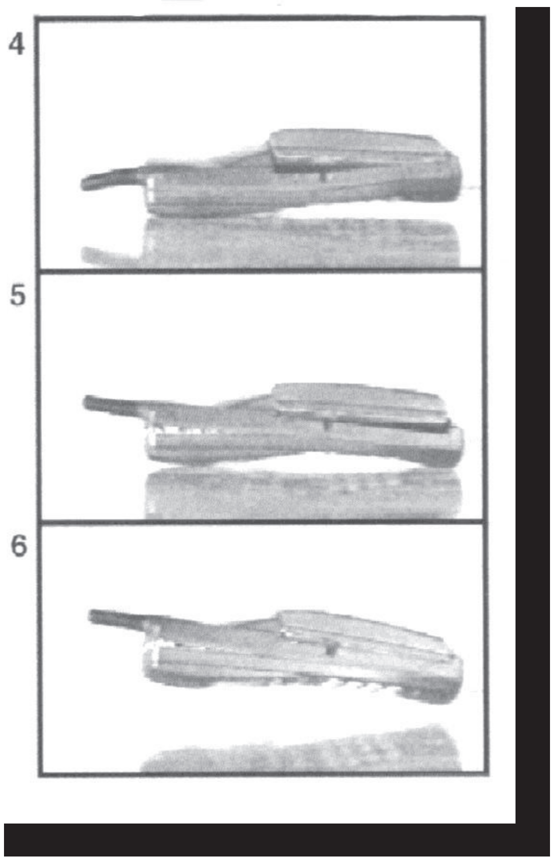
Why Underfill

- Mechanical Bond providing compensation for Thermal Mismatch, Mechanical Shock, Proprietary Protection
- Required Due to:
  - Thinner PCB’s
  - Lead free solder
  - Impact Shock CSP to Board Displacement in the Z-Axis
- The underfill holds the Bumps in Hydrostatic Compression and is the Main Reason for Fatigue Resistance
- Protects bumps from environment / contamination / moisture

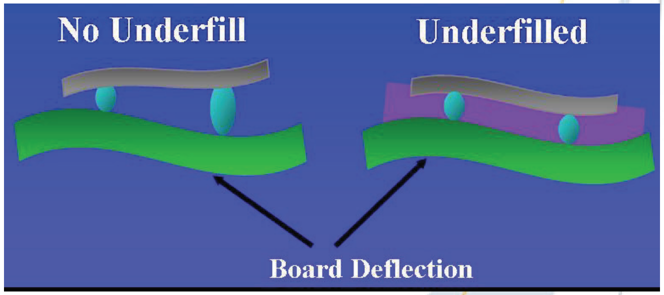


Drop Test for Portable Devices



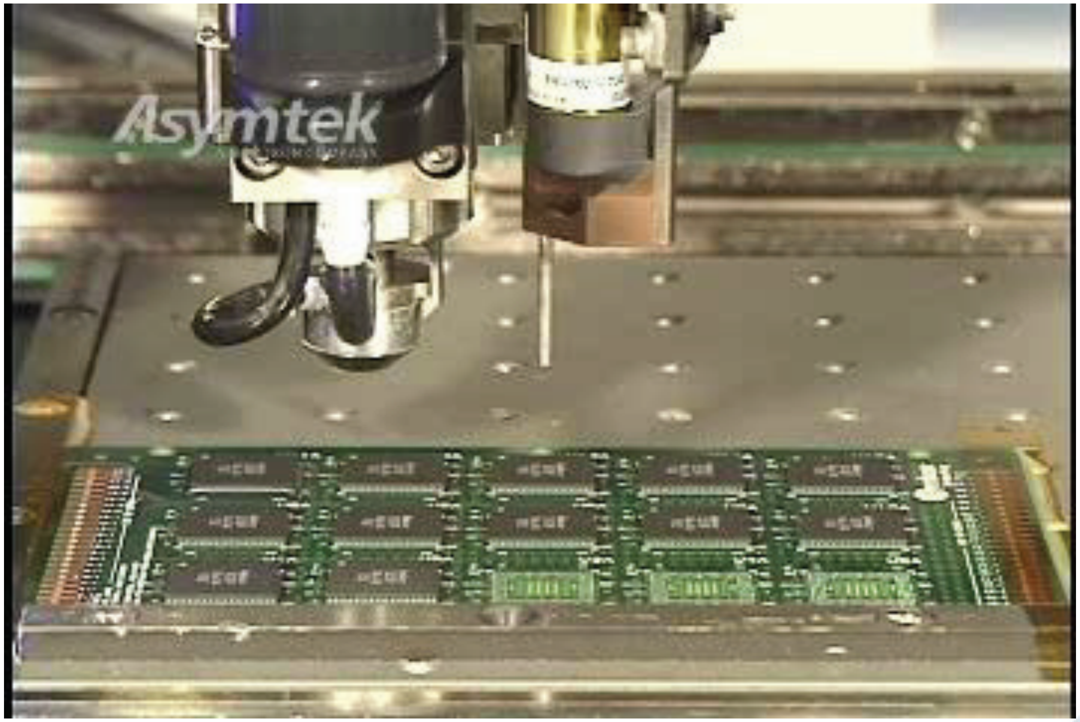


A cell phone
being dropped
from 1 meter
onto a hard floor



PoP UF Considerations

- It’s critical that enough material is dispensed in the first pass to start capillary flow on both the top and bottom interconnect layers.
- 2nd and 3rd dispense passes must be timed and material delivered to keep flow front moving until underfill is complete.



Throughput vs. Wet Out Area Test Plan

- Two different PoP package types and one underfill.
- Define the appropriate mass of underfill required to completely underfill PoP.
  - Destructive testing to verify complete underfill.
  - One and both interconnect layers defined.
- Utilizing an weight controlled “I” pattern, dispense the required mass of underfill in 1, 2, and 3 passes.
  - Substrate temperature held constant at 90^{o}C.
  - Nozzle distance from PoP held constant at 0.3mm.
- Qualify the wet out area and required wait time for each run.

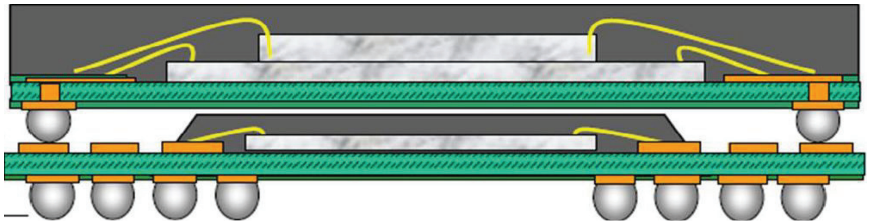
Underfill Material

- The scope was to investigate the flow properties of a representative underfill.
- Only one underfill was used to limit the number of variables.
- Material was a two part epoxy premixed and frozen, non-reworkable, 3,000 centepoise (cps), fast flowing underfill with 50% filler content.
- Rheological underfill properties changes with chemistry, viscosity, and filler content the results will differ slightly.
- It is important to note that for device reliability there should be careful consideration given to the underfill material's cured properties

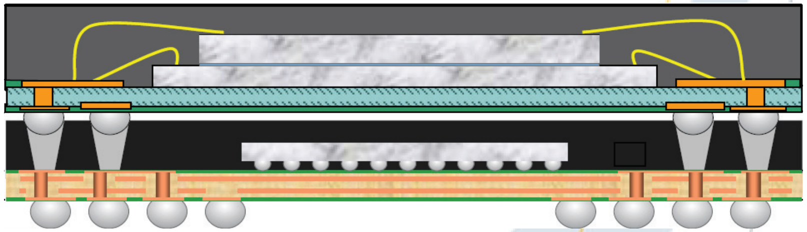
PoP Package Types

- The PoP typically has a logic device in the bottom package and a memory device in the top package.
- The PSvfBGA is more common today, the Through Mold Via (TMV) is increasing due to performance improvements.
- The TMV PoP has a reduced interconnect height on the 2nd layer.
    - The difference in 2nd layer interconnect height between PoP’s results in potential different requirements for underfill

PSvfBGA PoP

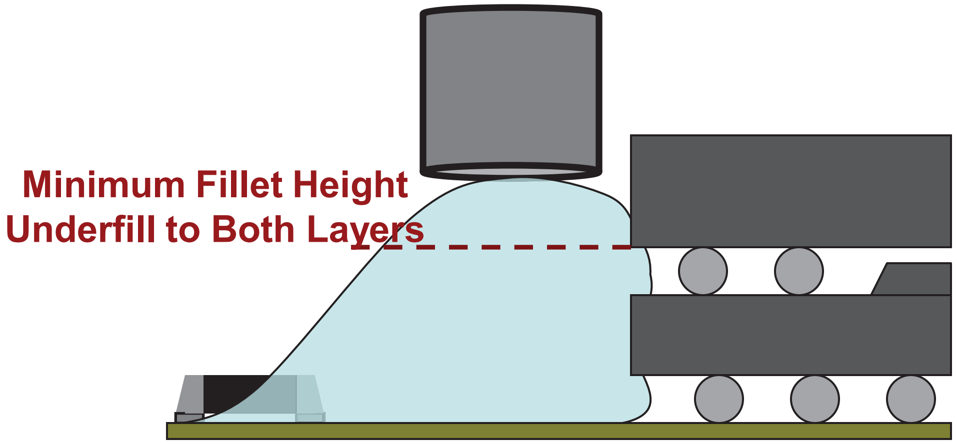


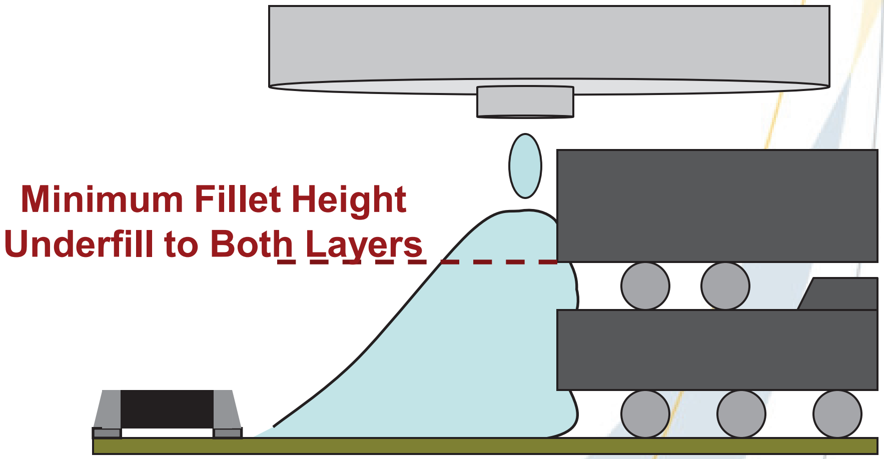
TMV PoP



Dispense Technology

- To underfill both package layers it is critical that the underfill reservoir reaches the top of the 2nd interconnect layer.
- Needle Dispensing requires a greater Keep Out Zone (KOZ) for Surrounding Contamination due to the needle Outer Diameter.
- Jet Dispensing requires less of a KOZ and material because the fluid droplet is placed closer to the Package as the jet dispenses above the top of the component.
  - The study only qualified the distances for the preferred jet dispensing technology.

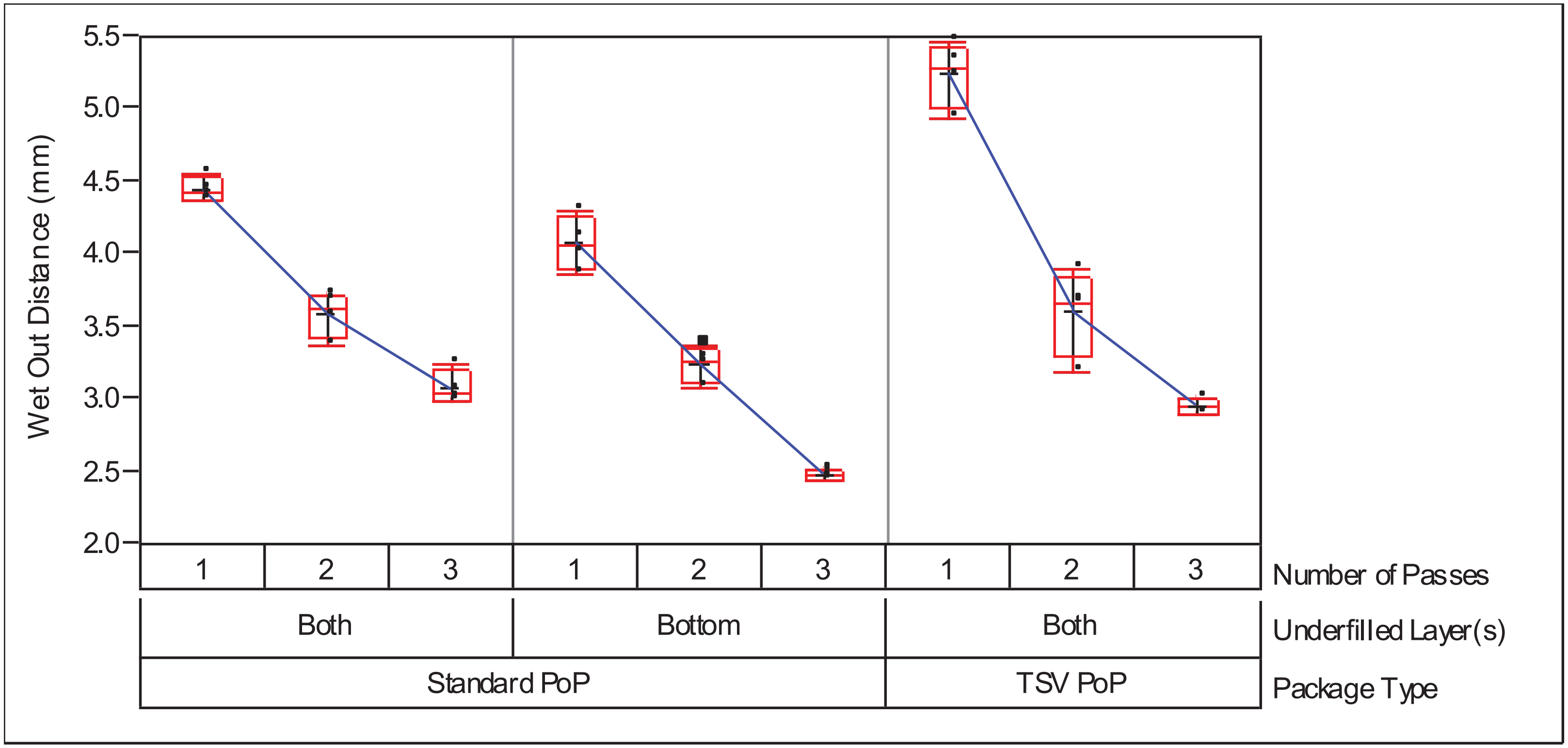




Results

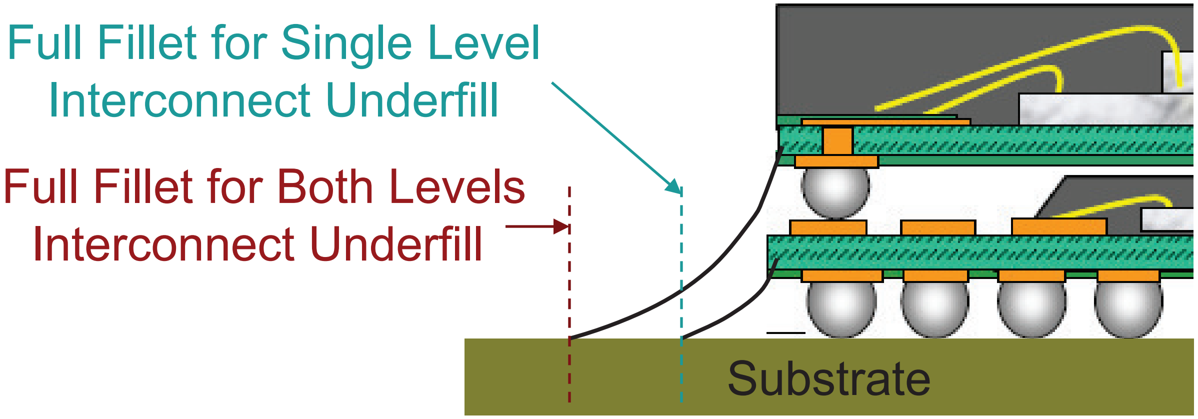
- The number of passes used to dispense the appropriate mass of material was significant.
- Whether one or both interconnect layers was underfilled was significant.
- The underfill dispense process time is proportionate to the number of passes and the flow out time.

Fluid Reservoir Wet Out Distance Relative to number of Passes



- The fewer the passes the greater the wet out area.
- Single level underfill has less wet out than both levels.
- Slope of the curves suggests that further optimization is probable.

Interconnect Layer relative to wet out area and material properties

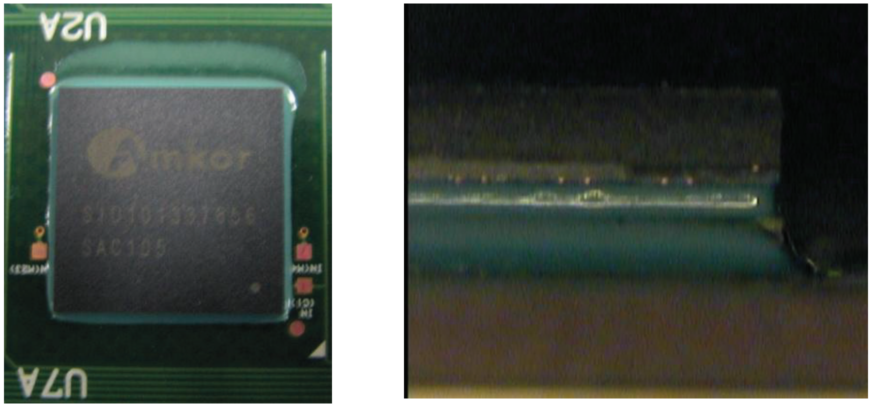

Full Fillet for Single Level Interconnect Underfill

Full Fillet for Both Levels Interconnect Underfill

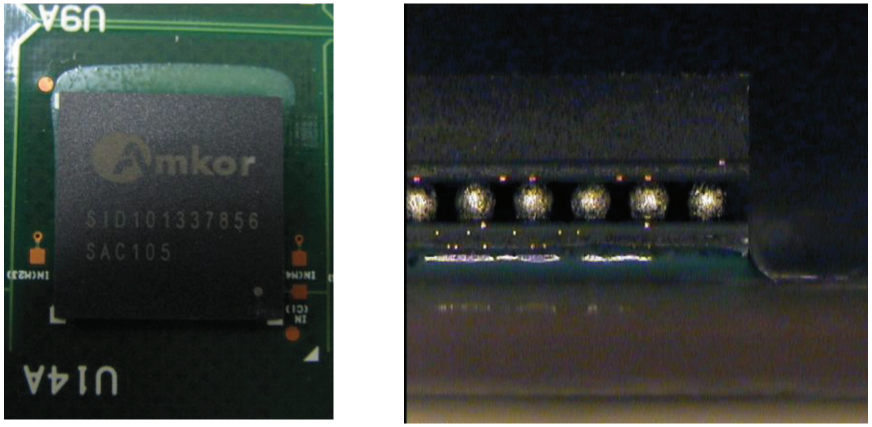
- The distance that the fluid reservoir wets out from the edge of the PoP is dependent if one or both interconnect layers are underfilled.
- The material viscosity and contact angle will effect the distance of the wet out area.

Wet Out Area Relative to Interconnect Layer

Both Interconnect layers dispensed



Single Level Interconnect layer dispensed



- The Wet out Area is greater when both interconnect layers are underfilled.

- When Underfilling a component there are two main considerations to the keep out Zone; Dispense Side and Fillet Side.

- The material fillets less when only one interconnect layer is dispensed.

- KOZ should be offset asymmetrically due to difference in dispense side and fillet sides.

Throughput decreases with increased passes

# of Passes	Dispense Time per Pass	Wait Time Between Passes	Flow Out Time on Last Pass	*Approximate Time to Dispense One Device
1	2 sec	0 sec	30 sec	2 sec
2	1 sec	10 sec	20 sec	12 sec
3	0.66 sec	6 sec, 10 sec	20 sec	18 sec

- The greater the number of passes the longer the flow underfill dispense process time.

*The approximate time to dispense one device does not include preheating or final flow out time as that is masked in most applications by the dispenser configuration.

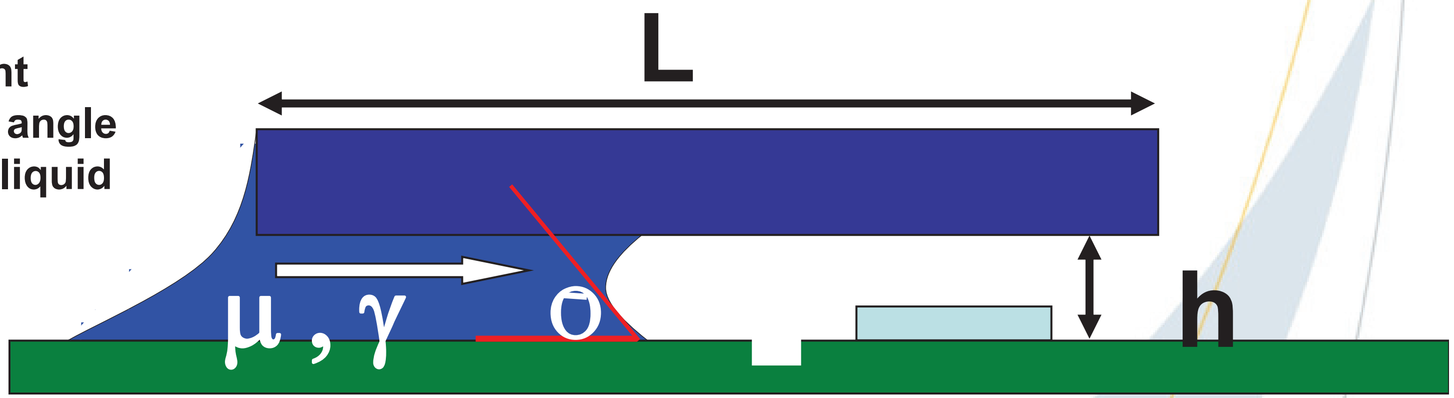
Underfill Process- Time to Flow Out

- Changes in “h” change flow out rate
- Shorter flow out distance reduces flow out time
- Contact angle θ, a measure of surface energy γ
- Viscosity, γ, and θ are temperature dependent

$$T=(3\mu L^2)/(h\gamma\cos\theta)$$

Capillary Flow out time

T = Time in seconds
μ = Fluid viscosity
L = Flow distance
h = Gap or bump height
θ = Contact or wetting angle
γ = Surface tension of liquid
. vapor interface



Optimization for PoP Underfill

- The diameter of the fluid stream and the distance it is applied from the chip edge affects wet out area and selectivity.
    - The distance from the edge of the PoP can differ with number of passes as nozzle diameter often reduces with increased pass numbers.
- The dispense pattern affects the mass dispensed as well as the flow out time.
    - “L” passes can be used to reduce time, though consideration needs to be taken to ensure a void free underfill.
- Substrate temperature affects the speed of the underfill flow out and the distance of the wet out area.
- Timing between passes is critical for successful processing.
    - Optimized platform configuration does not have the dispenser idle for flow out time.
- Selected underfill should be chosen for both cured properties for final reliability and liquid properties for dispense purposes.
    - Higher viscosity underfills typically take longer to flow out but will wet out less from the edge of the component.
    - Too low of a material viscosity will not allow for a complete 2nd interconnect layer underfill.

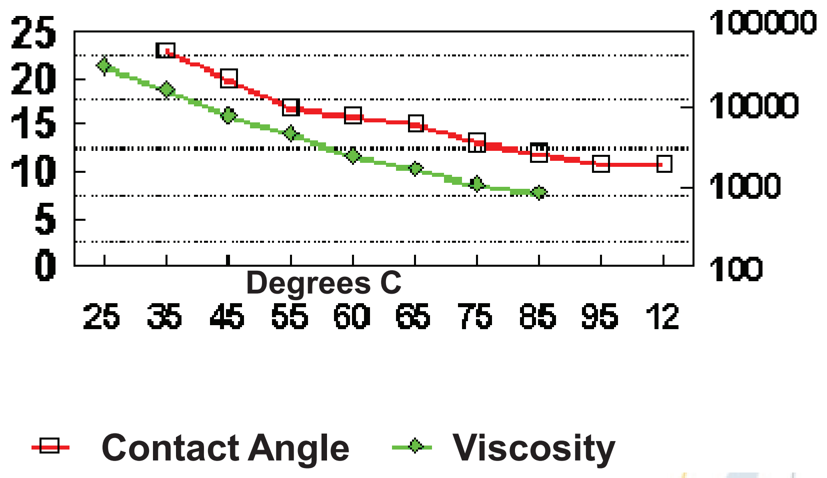
Thermal Considerations

- Substrate heat allows for a reduction in the time required for capillary flow.

- Substrate Heat provides a uniform thermal gradient across substrate surface, which helps insure uniform wave fronts.
  - A uniform wave front is important to avoid filler separation and to prevent entrapping voids.

Possible Negative Affects of Substrate Heat

- Premature Material Gelling (cross-linking) prior to completion of Underfill
- Increase in the ambient temperature inside the dispensing equipment resulting in a reduction of material pot life.



Multiple Heat Stations for Optimized Process Time

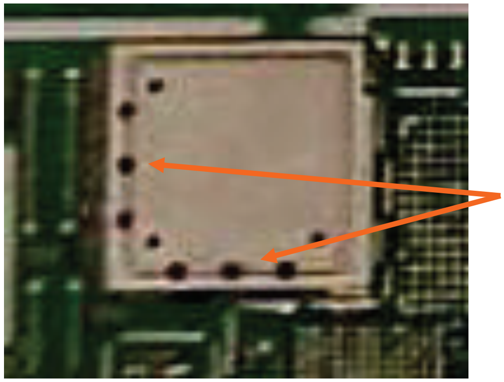
- Heating Decreases the amount of time to underfill a component.
- Multiple Stations are used for Pre-heating, Dispensing, and Post-heating
  - Preheat Station Brings PCB to Optimized Underfill Flow Temperature, Dispense Station Keeps at Temp, and Post heat Station allows flow to complete after all underfill is dispensed.
- PCB temperature controlled
  - Typical temperature range is 60-120 ºC, ± 5 ºC

Dual Lane Equipment to Compensate for multiple pass Flow Out Time

RF Shield Considerations

- Many mobile devices have RF Shields to block RF energy.
- Underfill Processing can be done after RF Shield Placement.
- Dispensing is though access holes or slots sized to the droplet diameter.
  - Holes often oversized to account for placement tolerance of the Shield.
- Jet Dispensing is done above the plane of the RF Shield to avoid topside contamination issues.

RF Shield Over PoP



1mm Holes
for Underfill
Dispensing