Dam and Fill Encapsulation for Microelectronic Packages

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Introduction

Contract packaging houses have to contend with a large mix of die types and products. Flexibility and quick turnaround of package types is a must in this industry. Traditional methods of die encapsulation, (i.e., use of transfer-molding techniques), are only cost effective when producing a large number of components. Liquid encapsulants now provide similar levels of reliability[1] , and are cost effective. One of the main advantages of liquid resin encapsulation is obtained from the flexibility of dispensing systems, which enables package formats to be changed rapidly. The encapsulation method we will discuss in this paper is described as "Dam and Fill." To compete with transfer molding's high throughput, the dispensing equipment must not only be flexible but capable of delivering precise amounts of both dam and fill materials at high speeds.

This paper will address the parameters for developing good dams using the weight-controlled line methods and factors that must be considered when specifying fill materials and processes.

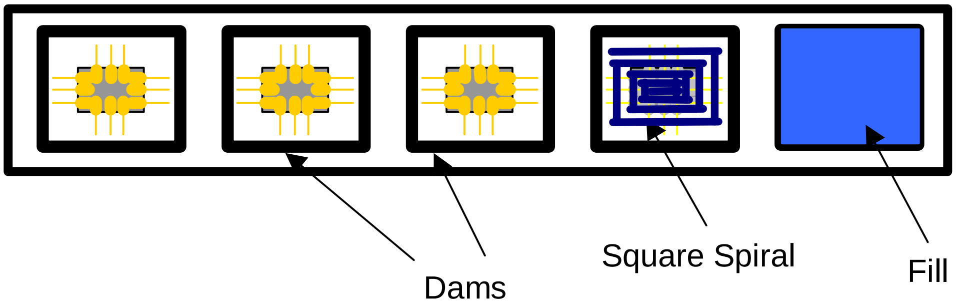

Figure 1: Circuit board strip with wire bonded die

Several methods of designing devices for dam and fill encapsulation have been developed. In Figure 1, a dam is formed around individual die on a circuit board strip. Following the dam formation, fill materials are dispensed over the die.

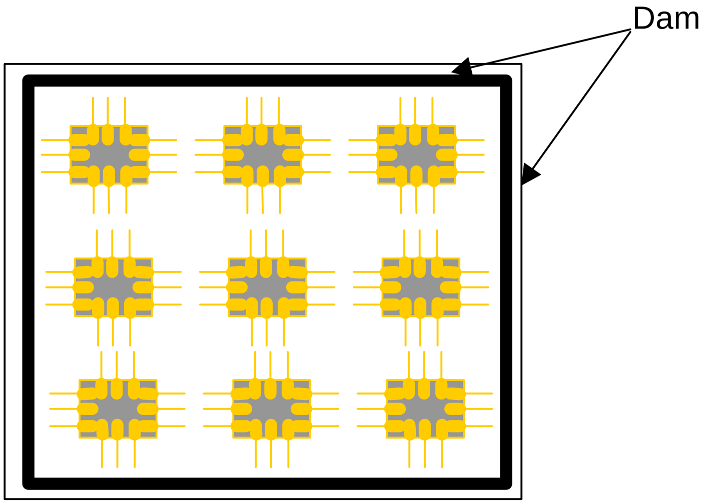

Figure 2: Circuit board with wire-bonded die and a single large dam

Figure 2 depicts an array of devices that are placed inside a single large dam. The advantage of this design is its significantly higher packing density, with very little space between devices and only one dam wall for multiple devices. A subsequent dicing operation is used to singulate the devices. However, a fill of this magnitude creates considerable stress due to mismatches in the coefficients of expansion between the fill materials, the circuit board and die, causing significant board warpage. The warping problem can be minimized by lowering the cure temperature, curing for a longer time, or using the Variable Frequency Microwave (VFM) curing method

Dispensing dams is an important step in the production of CSPs and other types of assemblies. The damming fluid forms a barrier on the substrate that keeps the dispensed encapsulants/cavity fill fluid inside the defined perimeter. Dam and fill is a more precise process than glob top and allows the use of low viscosity encapsulant fluids that can readily flow under wire bonds to help prevent voids without flowing over the board. Manufacturers prefer this method because flat surfaces on the package enable them to print the product identification directly on the finished components and can also be used for vacuum pickup. As die sizes decrease and distances between the adjacent assemblies become smaller, accurate dispensing of the dam becomes very important. The height, width and perimeter (length of the dam) are often precisely specified. Smart Cards typically have a finished cured height window of 50 microns as dispensed. ‘as dispensed?” I think the sentence can end w/50 microns.

An auger screw pump is typically used for dispensing dam fluids. These fluids are thixotropic, and the shearing action of the auger screw reduces the viscosity of the fluid. Once the fluid is dispensed, it quickly returns to the original viscosity and the dam takes on a height and width determined by the amount of fluid dispensed per unit length, called ‘line weight.’ Further, the ratio of the width to height, aspect ratio (AR), is consistent and predictable over a range of line weights. A small amount of control of the AR for a given line weight is possible by changing the height of the dispense tip above the substrate (dispense gap).

Weight is a very accurate method of determining the amount of fluid dispensed. Today, fluid manufacturers control specific gravity of a fluid to ± 1%. Several fluids manufactured by different formulators were tested and the line weight principle was found to hold true for all of them. With the information on line weight (mg/cm) and total perimeter of the dam (cm), the amount of fluid (mg) required to make a dam of a specified height and width can be calculated. If the dispensing equipment can perform flow rate calibration using the weight of the fluid, one can use weight-controlled rectangles to give consistent dams. This is particularly useful as the viscosity of the fluid changes with time.

Dams

The dam is typically a rectangle of epoxy based fluid dispensed as lines or as a complete rectangle onto the substrate of the assembled board. The height of the dam can vary from slightly lower to slightly higher than the height of the parts within the dam perimeter. The encapsulant fluid can overlap the dam and, unless the amount is excessive, it will not flow beyond the outer edge of the dam because of the cohesion between the encapsulant and the damming fluid. Minimizing the size of the dam allows faster dispensing for a given flow rate. However, as the speed at which the dispenser moves increases, the quality of the line dispensed may be affected. Good quality dams can be dispensed up to approximately 4.5 cm/s (1.8 in/s). Slightly higher speeds might be achieved with careful adjustment of dispensing parameters. Larger dams can provide a greater margin for variation in the amount of cavity fill fluid dispensed.

The width of the dam depends on the type of fluid and height. The ratio of the width to the height (i.e., aspect ratio), ranges from about 1.5:1 to 4:1 for different fluids.

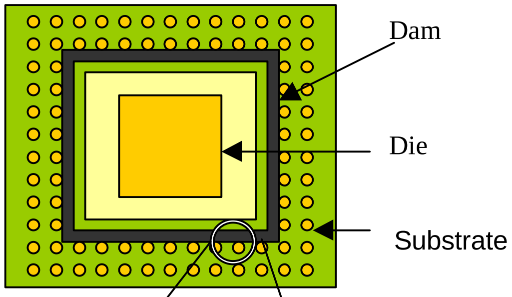

Figure 3: Top View Schematic of Dam

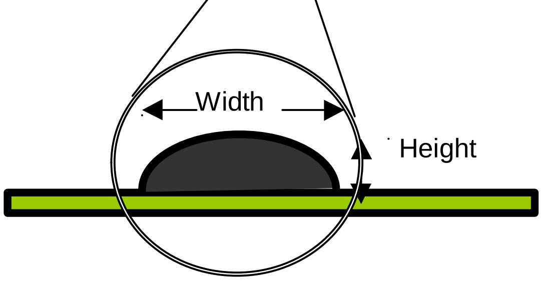

Figure 4: Cross Section View of Dam

Dam Fluids

The thixotropic quality of damming fluids is important to the formation of dams. The viscosity of damming fluids ranges from 50,000 cps to 1,300,000 cps. When the fluid is 'worked' by the auger pump, the viscosity is lowered. For example, one manufacturer's fluid with a specified viscosity of 1,300,000 cps lowers when dispensed with an auger pump to approximately 700,000 cps. This allows larger flows rates for a given pump and dispensing needle or cone tip. The thixotropic nature of the fluid quickly allows the fluid to return to the higher viscosity after dispensing, which helps form the shape of the dam and restricts the fluid from flowing over more of the board. Heat can also be applied to the dispense tip to lower the viscosity of the fluid as it is being dispensed.

Damming fluids manufactured by five fluid formulators were tested. They all formed dams of a predictable height and width as a function of 'line weight' measured in mg/cm. A summary of the Aspect Ratio (AR), viscosity, specific gravity and cured fluid quality is shown in Table 1. The "quality" of the cured fluid appears to correlate to the range of AR and is related to the filler content of the fluid. Fluids with lower aspect ratios (lower ratio of width to height) appeared to cure with a dull appearance and seemed to be more brittle. However, the encapsulant material is the critical fluid for giving the final assembly physical integrity, the cured fluid quality may not be critical to assembly. In some designs, the dam material will be removed by dicing the package to final dimensions. Therefore, the dam material is only required to hold the fill material until dicing.

Fluid	**Viscosity (cps)**	**Aspect Ratio (Width/Height)**	**Specific Gravity**	**Line Quality**
A	1,300,000	3.8 : 1	1.76	shiny, tough
B	690,000	1.5 : 1	1.6	dull, brittle
C	575,000	2.5 : 1	1.75	dull, brittle
D	500,000	3.8 : 1	1.8	shiny, tough
E	1,200,000	2.3 : 1	1.8	dull, brittle

Table 1: Summary of Damming Fluids Tested

Detailed data for Fluid A is shown in Figures 5 through 7. The data points encompass variations in temperatures and dispense tips.

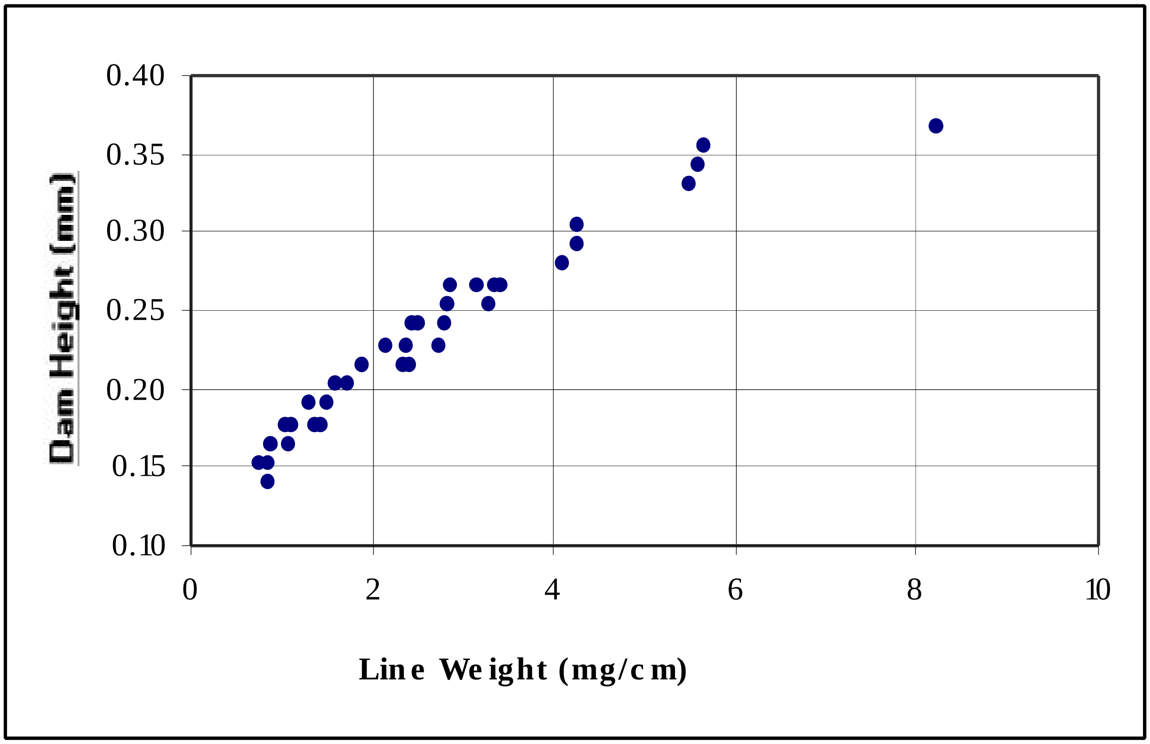

Figure 5: Dam Height vs. Line Weight for Fluid A

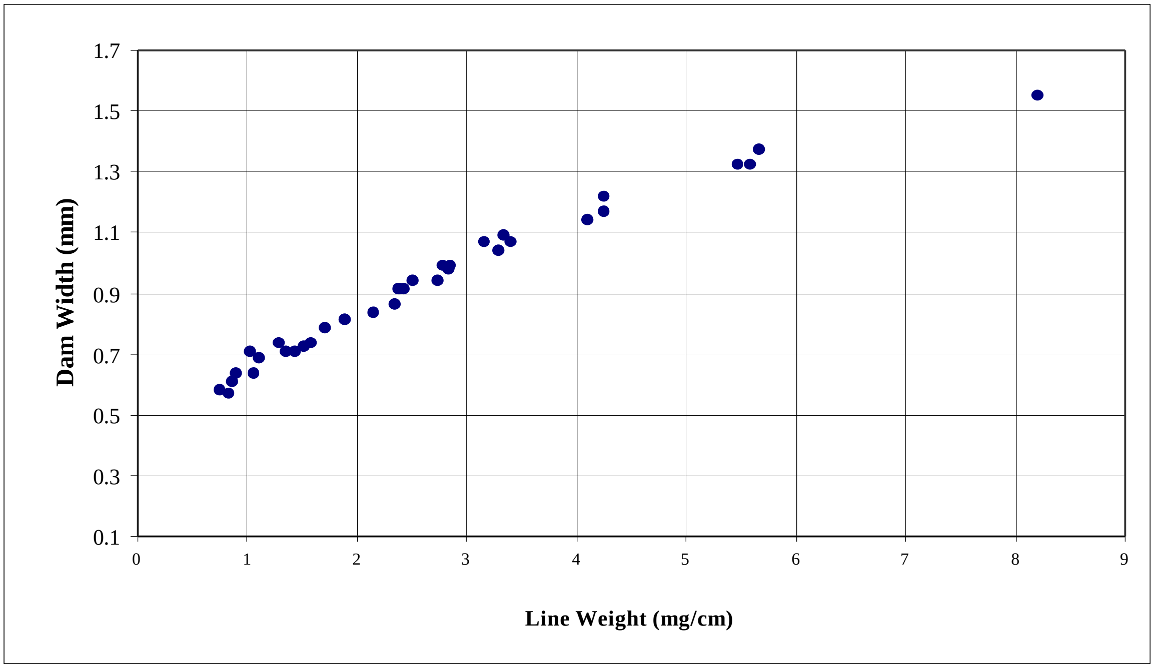

Figure 6: Dam Width vs. Line Weight for Fluid A

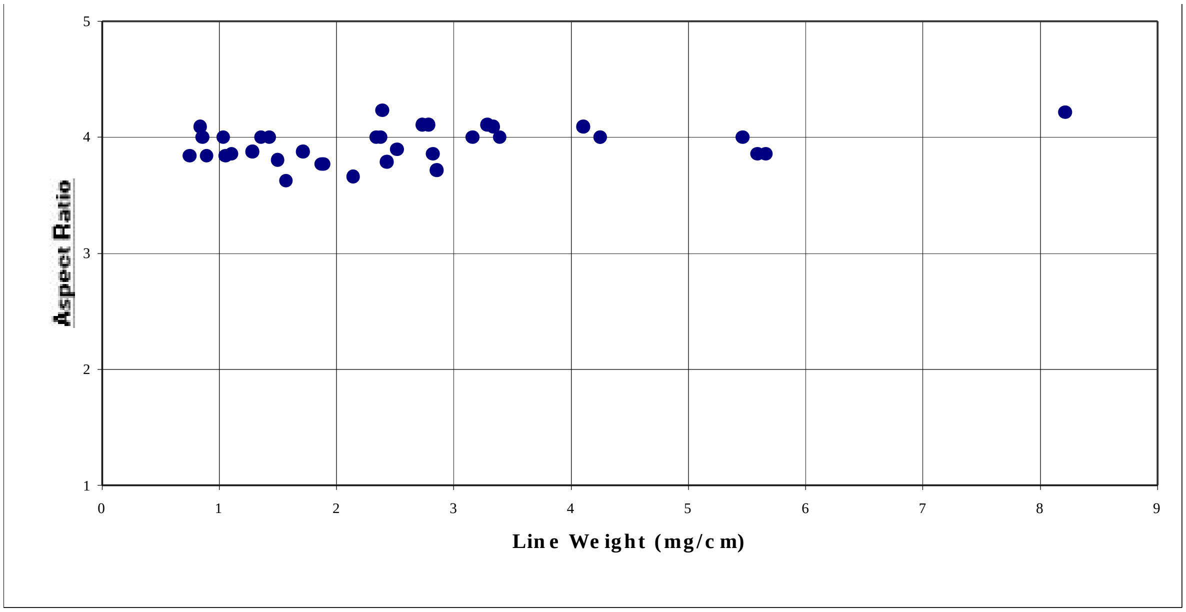

Figure 7: Aspect Ratio vs. Line Weight for Fluid A

Line weight is the result of dividing the flow rate by the speed at which the dispenser is moved (or, in other words, the speed at which the line of fluid is dispensed).

Line Weight (mg/cm) = Flow Rate (mg/s) ÷ Line Speed (cm/s)

The flow rate, in mg/s, is controlled by the following variables:

1. Valve speed – the rate at which the auger screw is rotated
2. Dispense tip, due to pressure flow resistance of auger pumps:
    - The gage or inside diameter of the dispense tip: The pressure resistance to flow is inversely proportional to the inside diameter of the tip raised to the fourth power. A smaller tip size (larger gage number) will give a much smaller flow rate with other settings constant.
    - Length of the dispense tip: The pressure resistance to flow is proportional to the length of the tip. A 13mm (1/2”) dispense tip will yield a lower flow rate than an equal gage 6.5 mm (0.25in) tip with other settings constant.

- Geometry of the tip: A conical dispense tip has the effective inside diameter only over the last part of the fluid path and thus the effective length is minimal. A conical tip of equal gage will give a higher flow rate with other settings constant[4].

3. Temperature of the fluid: Affects viscosity.

4. Air pressure on the fluid supplied to the dispenser.

5. Viscosity of the fluid. The pressure resistance to flow in the fluid is proportional to the viscosity of the fluid. The selection of fluid type is made before the process is set up and normally cannot be changed by the operator.

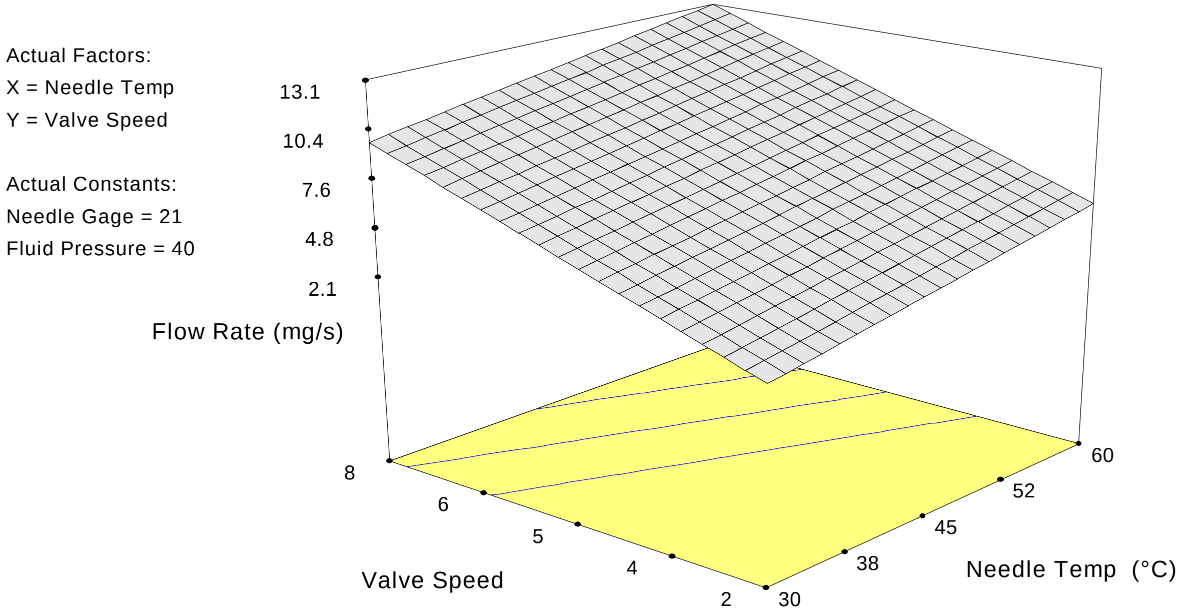

Figure 8: Flow Rate vs. Valve Speed and Needle Temp for 21 Gage

Factors Affecting Geometry of Dams

To determine the effect of four variables on the height, width and aspect ratio for a dam dispensed under typical conditions, a full factorial screening experiment was performed.. The variables and their low (V-), high (V+) and center point values are listed in Table 1 where V- and V+ stand for the letter designation for each value (A,B,C,D).

V: Variable	Low (V-)	Center Point	High (V+)
A: Needle Temperature - °C	60	70	80
B: Substrate Temperature - °C	50	70	90
C: Dispense Gap above substrate – mm (in)	0.3 (0.012)	0.4 (0.016)	0.5 (0.020)
D: Line Speed - cm/s (in/s)	1.9 (0.75)	2.5 (1.0)	3.8 (1.5)

Table 2: Variable Levels for Screening Experiment

In this experiment, the line weight was held constant at 4 mg/cm. Referring to Figures 5 and 6, this line weight is predicted to produce a dam with a height of about 0.30 mm (0.01 in) and width of about 1.0 mm (0.04 in.) The results of the experiment are shown schematically in Figure 9, where the variables with significant influence on the height of the dam are displayed with the V+ and V- values at the corners of the cube. Note that the center point of the cube would be a dam with a height of 0.30 mm (0.01in).

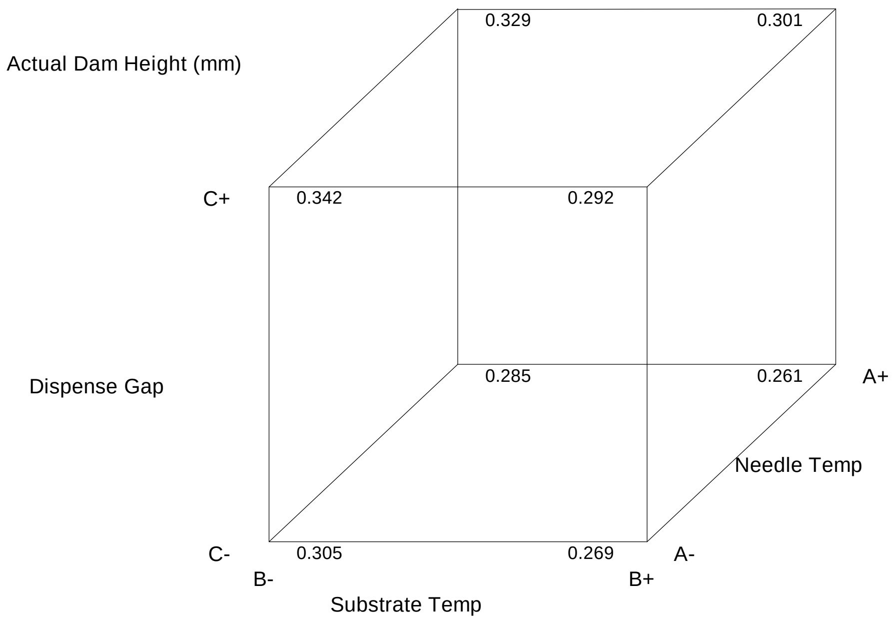

Figure 9: Effect of Variables on Height of Dam for 4 mg/cm Line Weight

The results for the experiment for the width of the dam and the aspect ratio yielded consistent values for those of the height of the dam.

The screening experiment indicates that the dispense gap (C) has the strongest influence on changing the dam height and width from the center point values. Note that the dispense gap was varied from a low value (C-) just above the expected height of the dam to a high value (C+) about 1.7 times the expected height. The manufacturer recommendation for this fluid is to have a dispense gap 0.13 mm (0.5 in.) to 0.25 mm (.009 in.) above the height of the line being dispensed.

The higher dispense gap also produces a smaller aspect ratio. This suggests that higher dispense gaps than recommended would be better since a narrower dam for the same line weight would seem preferable. However, larger dispense gaps contribute to other problems. The rectangle formed with larger dispense gap will not have corners as square as those dispensed with the recommended gap. This can negate the advantage gained by the narrower width when attempting to dispense a dam with close dimensions between components. Additionally, the ability to 'knit' the start and stop point of the dam in an effective manner can be adversely affected.

The 'knit' is primarily an aesthetic consideration, but increased bump height at the start/stop point might interfere with a tight vertical specification. The standard method for achieving a good knit is to overlap the start and stop point of the dispensed line of the dam about 2 mm (0.08 in.). The overlapped fluid will adhere to the part of the dam already in place and give a good break off when the needle is lifted.

The variable with the second strongest affect is substrate temperature (B). Lower substrate temperature yields a smaller aspect ratio. For dispensing damming fluid, the substrate temperature can be minimized but boards are often dispensed with the cavity fill following quickly in time after the dispensing of the dam. It is not necessary to cure the dam before application of the encapsulant. The cavity fill fluids flow better with a higher substrate temperature. Higher throughput can be achieved by dispensing the dam and fill in succession without waiting to heat the board between these two steps. Substrate heat is commonly set between 70° C to 90° C, although higher temperatures can be used.

Needle temperature (A) has a very minor influence on dam height and width. A low needle temperature will give a slightly lower aspect ratio. Needle temperature is typically set to 50 °C to 70 °C in order to maintain a level and consistent flow rate. A higher needle temperature gives a higher flow rate but may cause the material to cure the needle if maintenance intervals are too long. Needle temperature lower than 50 °C result in a lower flow rate, which could have a negative impact on throughput.

Line speed (D) has no significant impact on the height and width of dams dispensed. As stated earlier, there is a practical limit to the speed at which the fluid can be dispensed before line quality might be affected. The wetting effects can work only up to a limit. If the line speed exceeds the limits of the fluid to adhere to the board consistently, the dispensed line will suffer in appearance. The first visible indication of this is often a 'wavy' edge to the line, the next stage being a twisted 'licorice stick' appearance, and finally a series of disconnected 'blobs.' Too low a line speed will negatively affect the throughput. The normal range for dispensing dams is between 2 cm/s and 4.5 cm/s.

Using Weight to Setup the Dispense

If the specification for the height (or width) and perimeter of a dam has been determined, a total fluid weight needed to make that dam can be calculated and dispensed.

Example: It is desired to make a dam of 0.25 mm (.009 in.) height with a square perimeter of dimensions of 1.5 cm (.59 in.). Entering Figure 5 on the y-axis for 0.25 and reading right to the center of the data points along this line, then reading down to the x-axis the approximate line weight for this dam is 3 mg/cm. The total perimeter is 4 x 1.5 cm = 6 cm (2.36 in.). The total fluid weight required is 6 cm x 3 mg/cm = 18 mg.

This figure can be used to calculate dispensing time and speed. For example, if flow rate has been measured at 9 mg/s, it takes 2 seconds to dispense, and the dispense head move at a speed of 3 cm/s. If you are using a dispensing system that can be programmed to measure flow rate, it can automatically adjust the line speed to compensate for viscosity changes since flow rate is linearly proportional to fluid viscosity.

Cavity Fill

Successful dam writing is a critical first step in the dam and fill encapsulation method. The fluids used in the fill operations are epoxy based and are very similar in chemistry to the dam materials except they have a lower filler loading, typically around 70% with viscosity's of 30K cps. This lower percentage of filler loading allows the fluid to flow between wire bonds and wet to all the surfaces of the dam. It is important to know the minimum gap a fluid must flow through and the largest size particles in the fill fluid. As the distance between wire bonds gets smaller, one will have difficulty if the fluid has a maximum particle of 100 microns with spaces between the wires is 70 microns. Fluid can build up in these areas, causing voids in the encapsulation or resin-rich areas, which will have different coefficients of expansion when compared to other parts of the package.

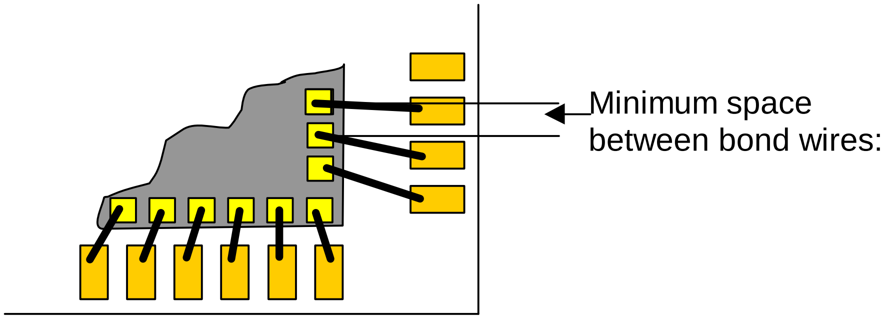

Figure 10: Minimum gaps that fluid must

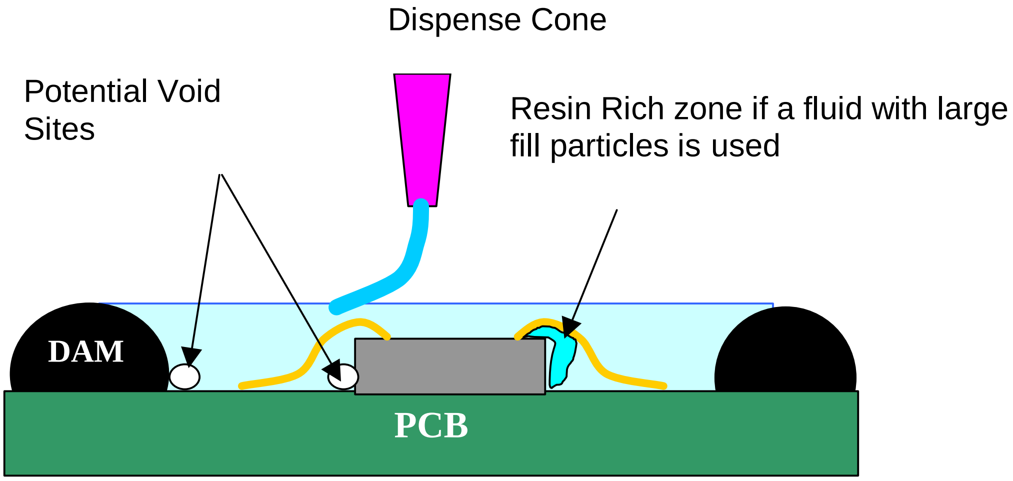

Figure 11: Potential areas of voids in cavity fill encapsulation

To overcome the problem of getting fluid to flow between fine pitch wire bonds, fluid manufactures are producing high flow versions of their products. Maximum particles sizes of 25 microns allows the fluid to pass through the fine wire bond geometries. In the design phase, engineers need to recognize that as geometries get tighter, new fluids for fill may be required, and in turn, a new qualification test will be necessary.

The cavity fill operation has to be fast and accurate for this type of application. Linear positive displacement pumps (see Figure 12) offer fast fill times and precise fill volumes.

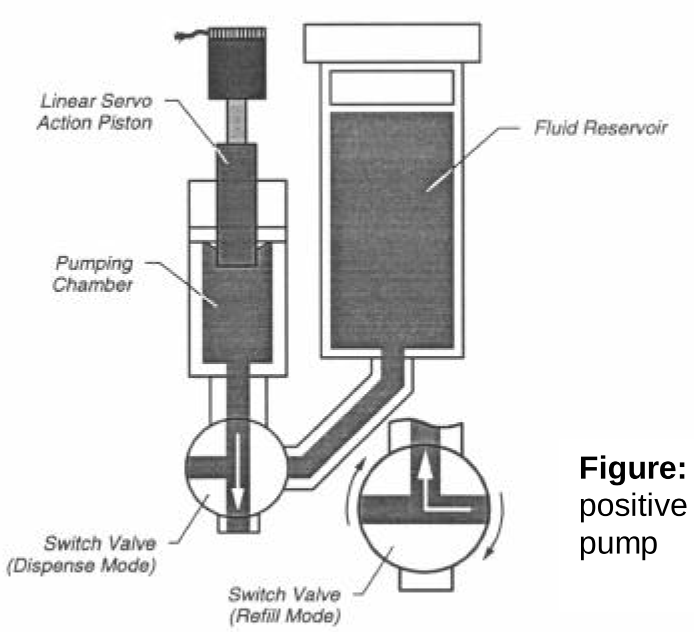

Figure: 12 Linear positive displacement pump

This method provides more control than other dispensing technologies when it is important to have tightly controlled fill volumes to produce flat top parts with consistent height or thickness. Linear positive displacement pumps can dispense as little as 1 micro liter to 2cc shot sizes with an accuracy of 1 to 2% over a viscosity range from 1 to 1,000,000 centipoise (see Figure 12). These pumps work on the principle where the amount of material dispensed is directly proportional to the volume of material it displaces. With precise servo-controlled motors to drive a piston into the fluid chamber, an exact amount of fluid can be dispensed.

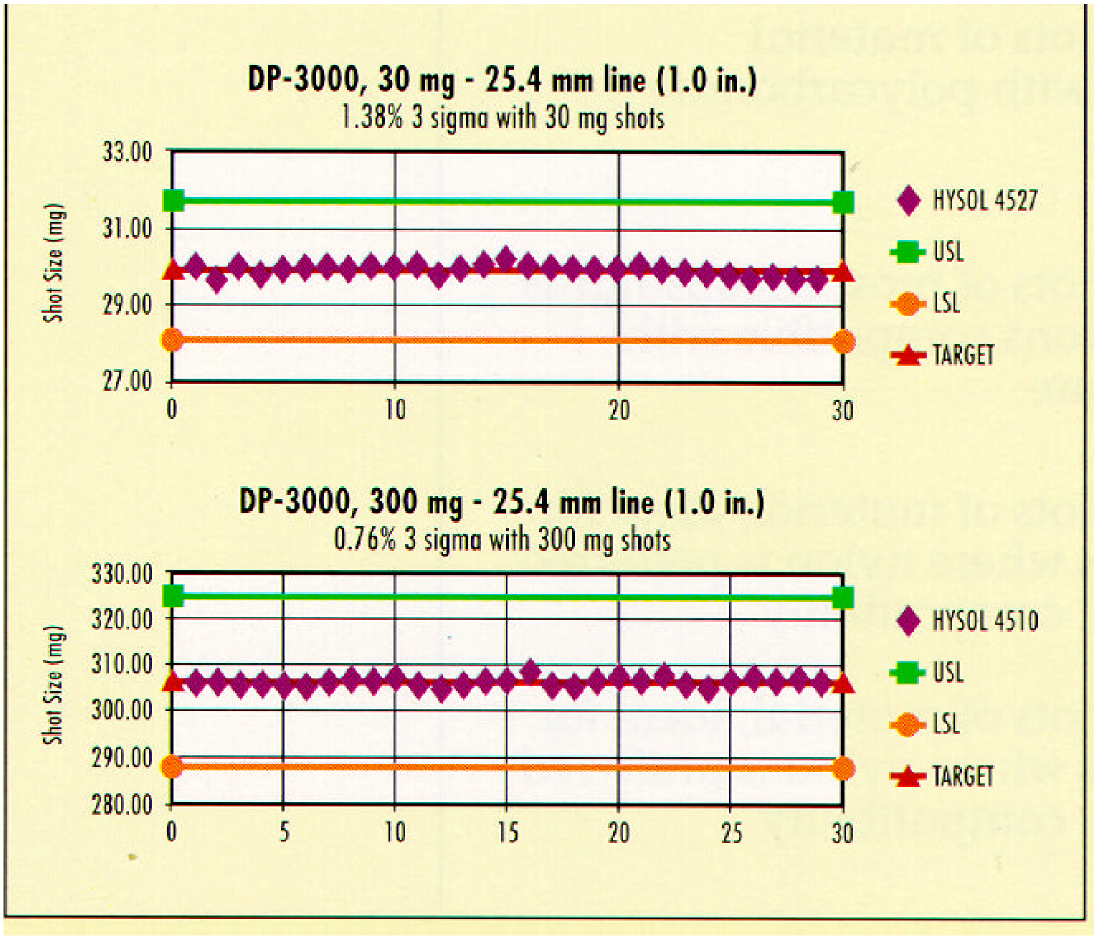

Figure 13: Pump accuracy tests over 30 slides for 30 and 300 mg shot sizes

Fill patterns can have a large effect on throughput and quality. Traditionally, serpentine patterns have been used which start in the center and work out to the dam or from the dam to center of the die. Where two dies of dissimilar heights (see Figure 14) are encapsulated in the same dam area, simple serpentine patterns are no longer adequate. A series of tests are required to find the correct fill amounts over each die and line patterns between die to give a consistent fill height. When filling cavities at high flow rates, wire sweep is often raised as concern. However, this is not a problem with liquid encapsulation because low viscosity fluids combined with the moving needle does not allow forces to build up to the wire yield point. If a serpentine fill pattern is employed, fluid can web across wire bonds creating trapped air pockets. In tight wire-bond package designs, it is better to fill the dam area with a series of dot and line patterns.

Figure 14 shows the path of fluid dispensed over a die. Note in this instance, fluid is moving sideways to wet between wire bonds.

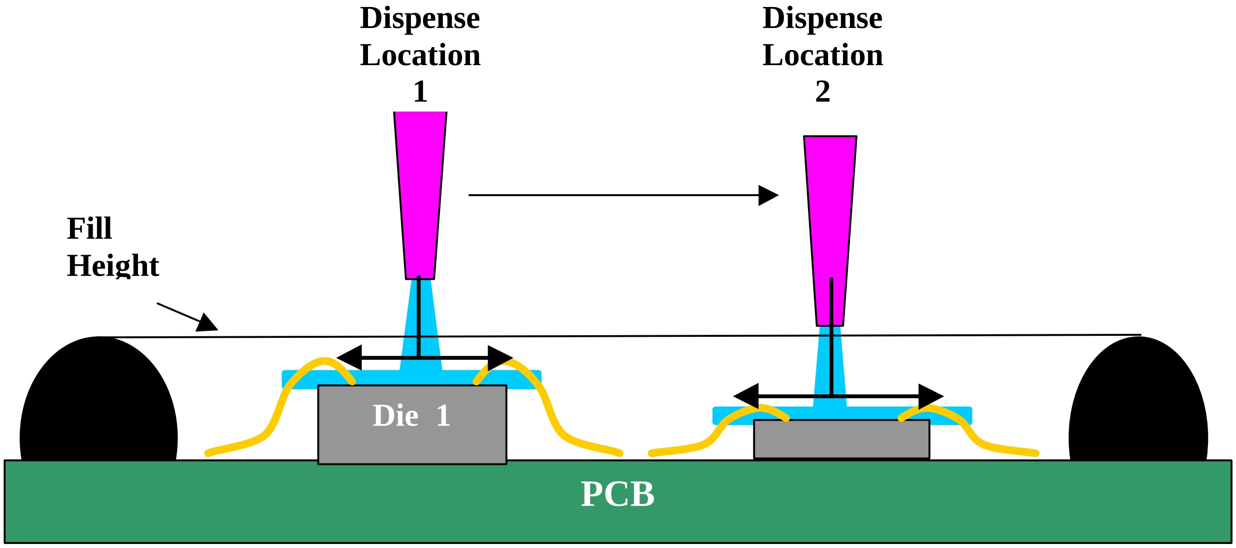

Figure 14: To achieve a consistent height of fill material the volume of fluid dispensed at location 1 is less than location 2.

Substrate Heating

Prior to and during the fill operation substrates are heated between 45^0 C to 90^0 C. The elevated temperature reduces the viscosity of the fluid when it contacts to surface of the parts. This helps the fluid flow through wire bonds and wet to the dam and other components of the package. Typically, viscosities are more than halved when the temperature of the fluid is raised from room temperature to 55 deg C[3]. Needle heaters are also used to lower the viscosity of the fluid in the needle. This helps reduce epoxy strings at the needle tip and facilitates a clean fluid break after dispense.

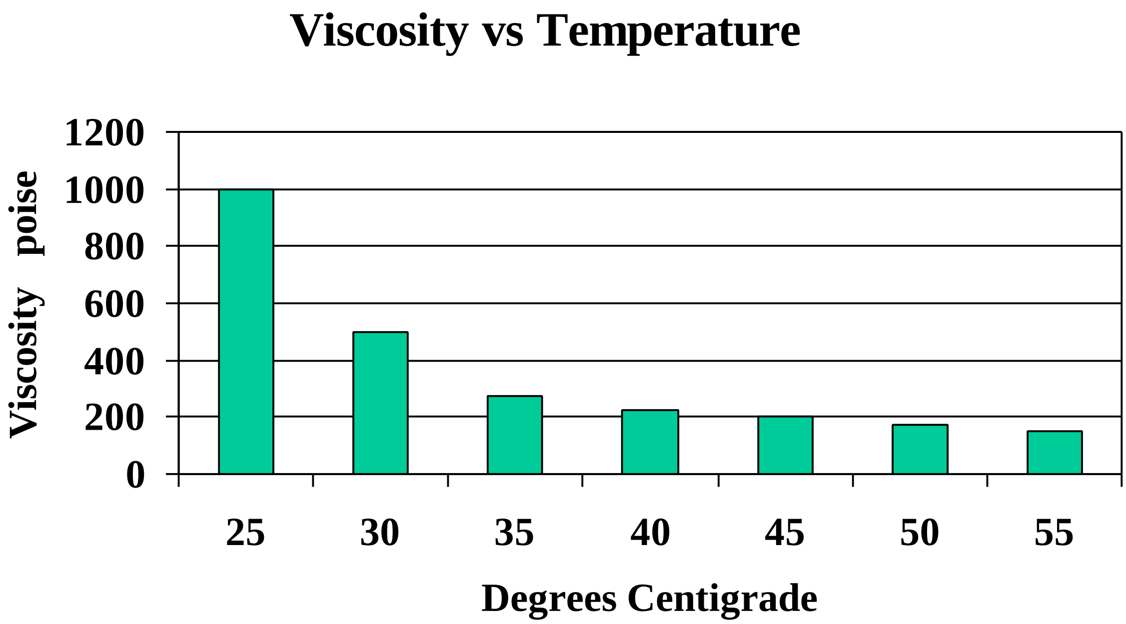

Figure 15: Change in viscosity v temperature of an epoxy fluid [3]

Curing Dam and fill

The goal of the dispensing process is to ensure that the height of the dam and fill are precisely controlled, to produce uniformly flat parts to a fixed height specification. Unfortunately, the thermal coefficients of expansion (CTE) are not exactly matched between the circuit board (12 to 15 ppm/C), die (6 ppm/C) and encapsulation material or fill epoxies (19 ppm/C). Encapsulation materials are typically cured with a two-step process, 30 minutes at 125^0 C to gel the epoxy, followed by 90 minutes at 165^0 C, to get a maximum cure and a high glass transition temperature. The two-step cure minimizes bowing caused by mismatch of the CTEs of the package components. This mismatch of CTEs is particularly prevalent when ceramic substrates Al_2O_3 are used as a package substrate (6.3 ppm/C).

After the package is removed from the curing oven, the substrate can still be bowed. Not only does bowing effect the finished shape of he package, it is also a sign of stress within the package. The radius of curvature relates to the stress level. A larger radius of curvature indicating a lower stress level.

In an effort to reduce stress levels, longer cure times at lower temperatures are used. However, this can lead to the filler in the encapsulation materials settling over time causing a gradient effect in epoxy fill with layers of high filler content and resin-rich areas. This will result in different expansion rates through the body of the fill encapsulation. Stress levels have been observed to be high enough to overcome the adhesion between the package surface and the encapsulation, causing delamination. This is particularly evident where a large area fill has been attempted as in Figure 15. Careful consideration must be given to the CTE values in the package design. The slow cure times decrease throughput and one of the advantages of using large area dam and fill encapsulation will not be achieved.

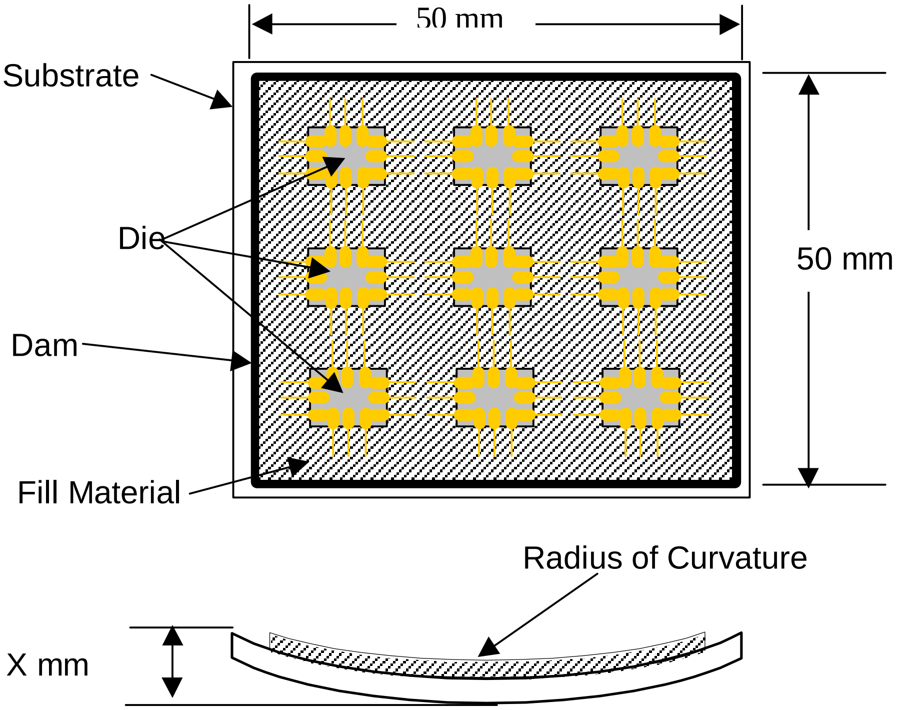

Figure 15: Board warp after cure caused by different CTEs

Variable frequency microwave curing of encapsulation heats only the free polar molecules in the liquid epoxy. In other words, the heat generated by the microwave efficiently cures the epoxy fill materials without heating all of the other components of the package. The epoxy of the board does not couple with the microwave because it is already cross-linked and does not have free polar molecules. This method of epoxy curing can significantly reduce the thermal mismatch of CTE problems resulting in much lower radius of curvature and hence stress levels. A second benefit is much shorter cure times so the filler materials have very little time to settle.

Conclusions

The dam and fill process for integrated circuit encapsulation is a fast, flexible process which is being used by contract packaging manufacturers who have a high mix of component types.

The dam process, critical to achieving overall height specifications, is predictable and controllable using line weight principles. This paper has described a series of experiments using five different damming fluids from five formulators that proves the characteristics of a dispensed line weight determine the height and width of the dam. The aspect ratio of these fluids was consistent over the normal range of dispensing and for a designated dispense gap above the height of the fluid dispensed.

The dispense gap can be used to influence the aspect ratio, but the achievable range is fairly limited. Raising the dispense gap too high can lead to quality problems in dispensing the fluid for making dams and it is best to stay within the fluid formulators' recommended range for the dispense gap, generally 0.13 mm (.005 in.) to 0.25 mm (.009 in.) above the height of the dam. The different fluids showed different aspect ratios ranging from 1.5:1 up to 4:1.

Knowing the aspect ratio of the fluid for making a dam makes it possible to dispense a dam of the correct height by calculating the total amount of fluid required. If the machine can measure the flow rate of the fluid, the dispensing of the dam by weight is easily accomplished.

Dam or cavity fill calculations provide a useful starting point to gauge the amount of material inside a dam. However, there are a number of other factors that cannot be calculated to determine the success of the fill process. During the design stage of package development, an understanding of the substrate materials, density of wires bonds and characteristics of the fill fluid and the interrelationships between these factors must all be made.. Modern dispensing equipment can provide precise delivery of encapsulation fluids. However, only by dispense testing can a fill process be optimized to ensure void-free fill encapsulations. Once a process has been perfected, the dispense equipment can consistently and repeatably reproduce the same results.

References:

1 Dale L. Robinson, Marc Papageorge, Christine Naito, “A New Epoxy Based Liquid Encapsulant With Performance Comparable to Mold Compounds,” International Journal of Microelectronic Packaging, Vol17 #2, 1994 p176

2 *Fluid Mechanics*, Frank M. White, 1979

3 Wei Koh, Ph.D., “Encapsulants for Chip on Board and Chip Scale Packaging,” Pan Pacific Microelectronic Conference, Honolulu, Hawaii, February 1996.

4 B. Panchapakesan, et. al., “Variable Frequency Microwave, A New Approach to Curing,” *Advanced Packaging*, September/October 1997.