Advances in Fast Underfill of Flip Chips

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Abstract

One of the barriers to mainstream use of flip chips was the underfill process. The time required for capillary flow out of the underfill was perceived as a process bottleneck in the production line. Consequently, flip chips have been used when the performance and other cost considerations allowed no other alternative. Recently there have been advances in the underfill processes that allow faster throughput. A combination of new materials, dispensing patterns, and high capacity equipment can reduce flow out times such that the machine dispensing times completely mask flow out time thereby optimizing throughput. The correct choice of substrate temperature, material, equipment and dispense pattern can achieve flow out under a 25mm square die with 60μm gap in under 35 seconds.

This paper describes the dispensing processes and equipment configurations that provide throughput optimization. Analysis confirms that capillary flow analytical models are valid for large die with small gap (LDSG). Flow out time data for LDSG with several thousand interconnections is presented. The second method of reducing flow out time being examined today is forced underfill. Forced underfill eliminates the physical flow out time constraints of capillary underfill. Over recent years there have been several patent disclosures on forced underfill processes that offer new opportunities for throughput enhancements for LDSG production. This paper provides an overview of the forced underfill process.

Introduction

Today, almost all high-performance microprocessors are packaged in flip chip configurations. The reasons to choose flip chip packaging techniques are related to high performance requirements of speed and heat dissipation. In order for flip chip assembly to be considered a mainstream process, the barriers caused by perceptions of slow underfill and complex processes must be dispelled.

There are five dispensing processes involved in flip chip in package (FCIP) assembly:

1. Applying flux for the bump reflow using jet dispensers.
2. Underfilling the attached flip chip by dispensing adhesive with linear pumps.
3. Dispensing solder paste using a needle and a rotary auger pump.
4. Applying thermal grease on top of the die for good heat transfer with a linear pump.
5. Attaching the heat spreader with a lid sealant material dispensed with a rotary auger pump.

See Figure 1.

The first two processes listed above are used on flip chip attach to a printed circuit board (FCOB). Flux may be applied by dipping the flip chip bumps prior to placement or the more desired approach of jetting an ultra thin layer of flux. The rule of thumb for the best amount of flux is usually the least amount. Very little flux is required for reflow; excess flux may cause reliability problems. The standard underfill dispensing process involves dispensing the underfill in a "L" or "I" pass using single or multiple passes and following with a "seal pass." The underfill adhesive flows under the die by capillary action.

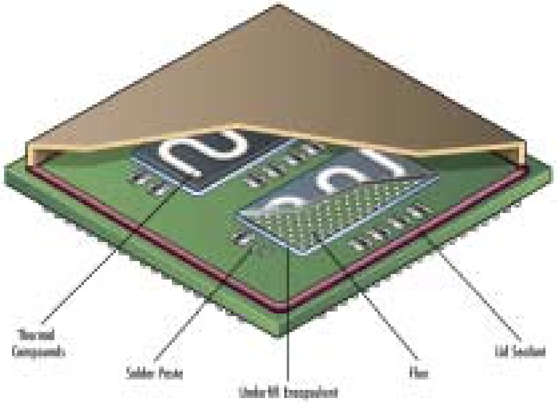


Figure 1

The flow out process is the primary barrier to using flip chips because the flow out time may cause throughput issues. The trend for flip chips is large die (25mm) with high I/O (8K to 20+K) with smaller bumps and pitch (35μ). However, with new dispensing techniques, faster flow materials, and equipment configurations the dispensing process is not the bottleneck in the production line.

Underfill Basics

The trends to larger dies and smaller gaps challenge underfill in flow out times and in the adhesive's ability to enhance reliability. The time it takes for capillary action to flow completely under the die is inversely proportional to the gap, and directly proportional to the square of the die length. Therefore, a smaller gap and larger die increase the time to complete flow out. See Figure 2.

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

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

Capillary Flow out time

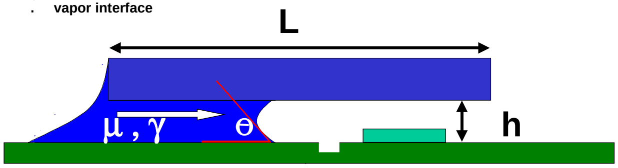


Figure 2

The underfill dispensing process is fairly simple. See Figure 3. First, the correct amount of underfill to dispense is calculated using a software tool called the "Flip Chip Calculator" (available at the Asymtek website at www.asymtek.com). The material is then dispensed by moving a dispensing needle close enough to the interface between the die and the substrate such that the dispensed fluid immediately wets the gap and begins to be drawn under the die via capillary flow.

Typically 60 to 75 percent of the calculated mass of material is dispensed in the "L" or "I" pass and the balance is dispensed in the "seal" pass.

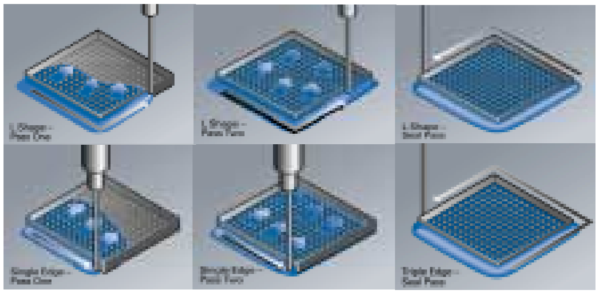


Figure 3

Underfill is used primarily to reduce the strain on the flip chip solder bumps, which is induced by thermal mismatch between the die and the substrate. Mechanical and geometric analysis of interconnects under strain show that as the bumps get smaller and the die gets larger, the strain increases. See Figure 4.

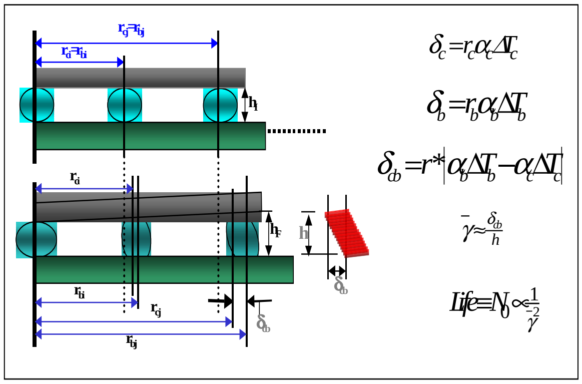


Figure 4

The model shows that the strain is directly proportional to the differential thermal strain times the distance from the neutral point and inversely proportional to the bump height. The fatigue life of the flip chip joint is given by the Coffin-Mason equation, which states that the life is inversely proportional to the square of the strain. However, a good underfill will show better fatigue resistance due to three additional features of underfill adhesives:

1. The bump is kept in "hydrostatic" compression as the adhesive shrinks upon cure, which increases the joint fatigue life.
2. The adhesive restrains the completely encapsulated solder bump.
3. The complete encapsulation of the bump allows no free surfaces, thereby minimizing crack initiation.

Many times, the flip chip fails in ways not related to thermal fatigue. The most common ways for interconnects to fail for secondary reasons are:

1. Loss of epoxy adhesion at substrate or die. Loss of adhesion means the bumps will experience excessive strain and fail as if no underfill were present.
2. Separation of the fillers in the adhesive. The epoxy loses its material properties and fails to contain the strain.
3. Epoxy failure at the fillet. A crack in the adhesive forms and propagates to the perimeter bump. The perimeter bumps are under the highest strain, and the bump will fail once the underfill has lost its integrity.
4. Voids near a bump. A void near the bump means the bump is no longer in hydrostatic compression.
5. Excessive or residual flux on the bump. Flux on the bump acts just like a void.
6. Die cracking at the edge due to dicing stress concentration.

See Figure 5.

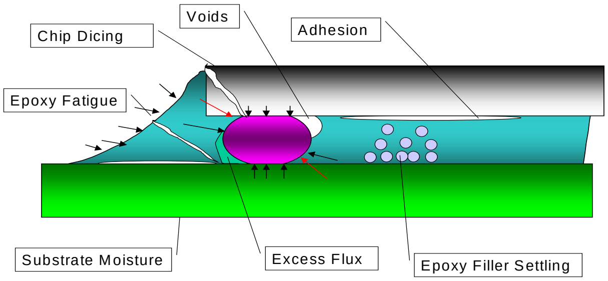


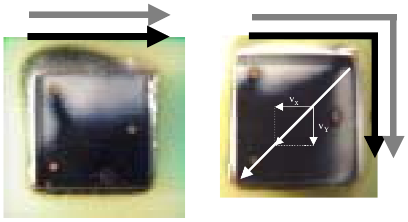
Figure 5

Dispensing Analysis

Several dispensing pattern experiments were run to better understand the effect of the pattern on the flow out speed. The first experiments were to determine the flow out time effect of an "I" pass and an "L" pass. Through vector analysis, the time effect can be show to be:

$$t_{Line} = \sqrt{2} \cdot t_{L-shape}$$

Since the flow out time is directly proportional to the square of the die length, the "L" shape dispense pattern has the effect of decreasing the effective length of the die. See Figure 6.



Time to Underfill
100% Area =27 s

Time to Underfill
100% Area =19 s

Figure 6

The next experiment was designed to show the flow patterns of the dispensed lines. In this experiment, black and white underfill materials were used. By using different colors, the flow results could be observed during multipass dispensing. The white material had lower viscosity and smaller particle size than the black material, and the results were quite revealing. In the following figures, the gray arrow refers to the white fluid and the black arrow refers to the black fluid. The inner arrow was the first pass, and the outer arrow was the second pass. In the case of the "I" pass, the two-pass flow showed how the leading edge was the primary forcing function and that stagnation zones could occur behind a bump in the direction of flow. See Figure 7.

Figure 7

When the "L" pass was dispensed with ½ white and ½ black, a diagonal "knit" line was revealed along the 45-degree line. In some scans of underfilled flip chips, available in the literature, the "knit" line can be observed as a discontinuity in the filler distribution. The two-color split "L" pattern verified this stagnation front. See Figure 8.

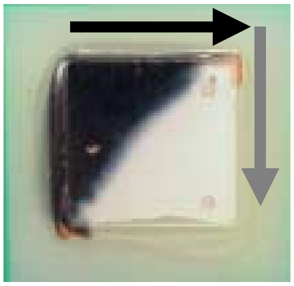


Figure 8

When the "L" passes were dispensed in two colors, another important flow characteristic was observed. A stagnation zone occurred along the 45-degree center of the die. See Figure 9.

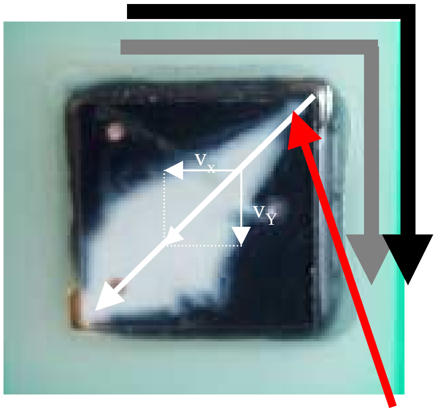


Figure 9 – Stagnation Zone

This observation can lead to new dispensing patterns that may decrease flow out times. Since the apex at the 90-degree angle of the "L" is a stagnation zone, dispensing additional adhesive at that point will not contribute strongly to the total flow. Therefore, new dispense patterns along the edges rather than just in "L" patterns have the potential to speed up flow out. In one large die capillary underfilling experiment, a 25mm square die with 40μ gap and 10K I/O was underfilled in 23 seconds. See Figure 10.

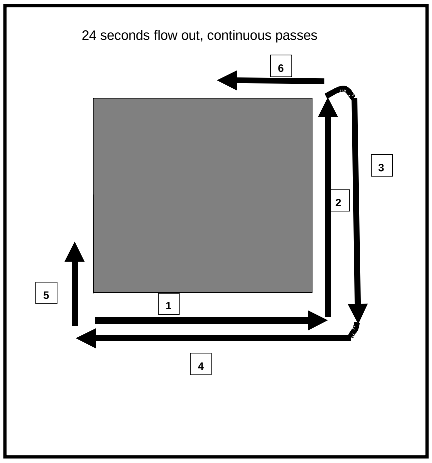


Figure 10

This pattern can be further enhanced by avoiding the apex of the "L" pattern altogether after the first pass and continue to dispense along the other edges of the die. See Figure 11.

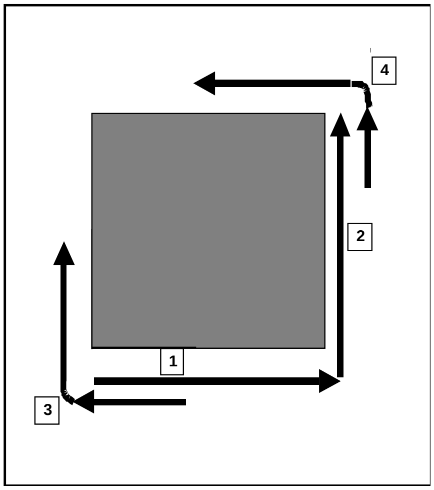


Figure 11

High-Speed Throughput

One of the perceived barriers to using flip chips in high volume in-line production has been the effect on throughput. If the flow out time of the underfill were too long, the dispenser would be the bottleneck in the line. The best way to minimize the effect of flow out on throughput is to get the maximum number of parts into the work area of the dispense machine. See Figure 12. The graph shows that the throughput increases quickly as dispensing on other parts masks the flow out time on previously dispensed parts. The maximum throughput is achieved when the dispenser is not waiting for flow out to occur before proceeding with another dispense process.

As an approximation, dispensing on a part that needs 80 mg of material can be accomplished in two seconds. The additional overhead of finding fiducials, height sensing, purging, and conveying adds about 1.8 seconds per part. Therefore, the total processing time is about 3.8 seconds per part or about 950 UPH (units per hour).

The optimum number of parts to have in the machine work area can be approximated by dividing the flow out time by the total processing time per part. If the flow out time were 50 seconds, the minimum number of parts on a pallet would be 13. In this case, if there were 6 parts per pallet, a dual-lane configuration would bring two pallets into the machine for optimum throughput.

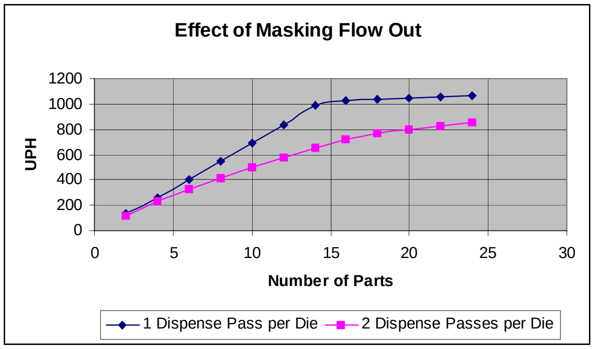


Figure 12 – 80 mg / part, 100 mg / second, 50 seconds total flow out

Forced Underfill

There are discussions and work in the industry on methods of accomplishing underfill without the restrictions of capillary flow. Some major reasons for molding are as follows:

1. Less restrictions on the adhesive chemistry.
2. Lower cost material sets.
3. Utilization of the large molding machine capital base.
4. Fast underfill, where 5000 UPH is the expectation.

The flow out equation for forced underfill is given by the following equation: (See Figure 13)

Pressure Forced flow out tir

T = Time in seconds
μ = Fluid viscosity
L = Flow distance
h = Gap or bump height
P = Pressure

$$t(\chi)\big|_{\chi=L} = \frac{6\cdot\mu\cdot L^2}{(P_v - P_a)}$$

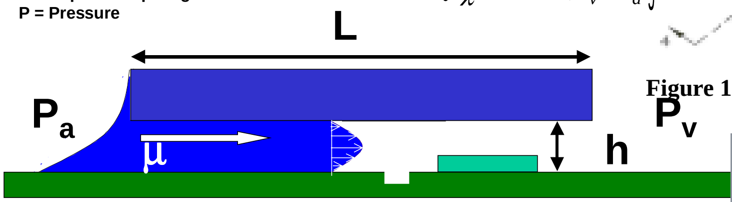


Figure 13

A patent (US 6000924) issued to Wang et al, of Cornel Research Foundation, Inc. on December 14, 1998 illustrates the injection molding process for underfilling. See Figure 14. By building a mold that closes at the top of the die and substrate, a cavity is created that provides a proper fillet and allows the mold compound to be injected under the chip. The molding cycle is only one or two seconds. By using a multi-cavity mold, several chips can be processed at the same time. There are many other patents that cover other methods of underfill molding from the sides or through the substrate. Research of injection molding underfill is in the beginning stages and the effects of the high pressures on bump reliability and the substrate are not well known.

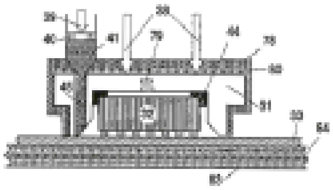


Figure 14 – Patent 6000924

The primary purpose of injection molding is to speed the flow out process, however the capillary flow can be assisted by fluid injection or by applying suction to one end of the die. As in molding, there are several US patents describing various means of assisting underfill. See Figure 15. A similar assisted-underfill process described in this patent can be approximated in the lab. By dispensing dams along two opposite sides of the die, the flow out can be accelerated by curing the dams and then applying pressure and suction on the open opposing sides of the die. See Figure 16.

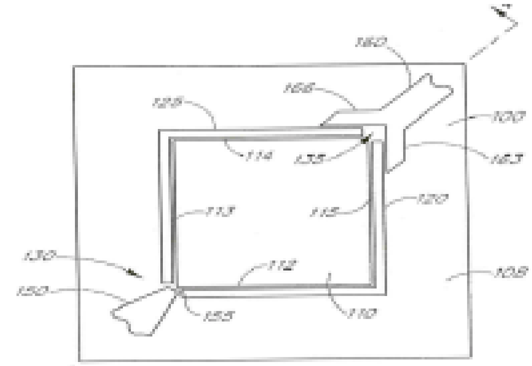


Figure 15 – From Patent 6048656

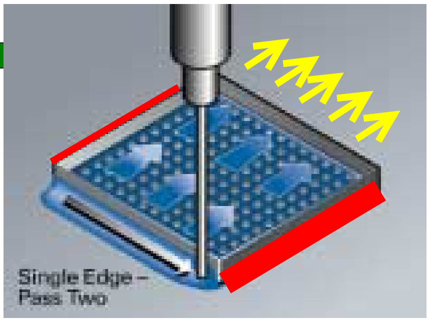


Figure 16

Assisted flow out will always be slower than pressurized molding techniques, but the assisted flow avoids the reliability questions raised from subjecting the flip chip assembly to high molding pressures. However, the process may require a complex tool and a two-step dispensing process. Also, the adhesive used to create the dams would differ from the underfill material and may not meet the specifications for a proper fillet. In any case, a considerable investigation is required to bring this method into production.

Conclusions

1. There are dispensing patterns beyond the standard “I” and “L” pass methods that can significantly decrease flow out times.
2. New material advances have produced underfill adhesives that can flow out in a 10mm die in 30-50 seconds.
3. The optimized dispenser is not the bottleneck for a production line. Optimization of the underfill dispenser throughput is accomplished by increasing the number of die in the workspace until the flow out time is masked by the dispense time.
4. Pressurized underfill flow out through injection molding or assisted underfill can provide very fast flow out. These methods require further investigation for reliability and viable production tooling.

ACKNOWLEDGEMENTS

Research and Process Work by: Horatio Quinones, David Padgett, Brett Huey, of Asymtek; and Mandar Painaik of State University of New York.