Cost Analysis of Flip Chip Assembly Processes: Mass Reflow with Capillary Underfill and Thermocompression Bonding with Nonconductive Paste

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Abstract

Many factors affect the selection of the assembly and interconnect processes used to package a die. For example, the size of the die and package, the type of substrate, and the number of IOs all must be considered. In this paper, two processes are compared: a flip chip process using mass reflow with capillary underfill versus a flip chip thermocompression bonding process using nonconductive paste.

Activity based cost modeling is used for the analysis. Both of the process flows are presented in detail, then multiple cost comparisons are presented. Examples of the variables that will change are package size, material cost, and equipment cost. In most cases, the bonding and material portions of the process flows are focused on rather than the entire assembly and substrate processes—this allows for a better analysis of particular details. Conclusions are drawn about which design scenarios are suitable for each process flow. Key cost drivers that may affect future cost comparisons as the technologies advance are also indicated.

Key words

Cost analysis, Flip chip package, Mass reflow with capillary underfill, Thermocompression bonding with nonconductive paste

I. Introduction

There are many packaging choices available in the industry today, from mature processes like wire bonding through more complicated processes such as wafer level packaging and its various incarnations. In addition to determining which packaging technology to use, designs often must also make selections within each type of packaging. Flip chip is a good example of this.

Although flip chip technology has been around for a long time, there are variations within the available processes. A key item of interest with flip chip technology is the method of bonding the die to the substrate. The most established process flow is arguably flip chip assembly that relies on mass reflow and capillary underfill for die bonding [1]. Thermocompression bonding, which may use nonconductive paste or film, is also an option. Although thermocompression bonding is generally viewed as the more expensive option, only to be used when the design rules require it, it can nevertheless sometimes be more cost effective than mass reflow with capillary underfill. This paper explores the process flows and cost drivers behind both types of flip chip assembly processes.

Activity based cost modeling was used to construct basic process flows for this study. In activity based cost modeling, the process flows are divided into a series of activities and the total cost of each activity is accumulated. The cost of each activity is determined by analyzing the following attributes: time required, amount of labor required, cost of material required (consumable and permanent), tooling cost, equipment cost (including factors such as depreciation), and yield loss.

II. Process Flows

In this section, the process flows are introduced. The general flip chip process flow is described on a summary level in Table I, then the main flip chip cost drivers are highlighted. Parts A and B of this section explain in more detail the steps (activities) that are different in the bonding portions of the process flows.

Table I – Overview of a Flip Chip Process Flow

Substrate Fabrication	Includes inner layer and core processes, creation of through holes, build-up layer processing and lamination before concluding with surface finish
Die Preparation	Inspection, test, wafer bumping and wafer mounting followed by singulation
Assembly	Begins with bonding the die, includes BGA ball attach, singulation (if strips), then inspection and testing

Package size is a major cost driver for this process flow, as is the substrate structure [2]. The substrate structure required will depend on the size of the die, because this determines the amount of routing that has to be included in the build-up layers. The fact that wafer bumping is required for flip chip technology can also be seen as a cost driver, particularly if comparing it to a technology that doesn't require wafer bumping (e.g. wire bonding).

The method for bonding the die is an important cost driver, and the rest of this paper focuses on a process flow and cost analysis of the die bonding method.

A. Flip Chip with Mass Reflow and Capillary Underfill

Table II details the bonding steps required for a mass reflow with capillary underfill flip chip process. Unlike the previous summary of the entire process flow, here the steps are broken down into the individual activities that make up the bonding process. These steps take place after the substrate has been diced and before moving on to ball attach.

Table II – Mass Reflow + CUF Bonding Activities

Setup for die bonding
Dispense flux for die bond
Place die
Reflow solder
Plasma clean
Optical inspection
Bake the substrate
Setup for underfill
Dispense underfill + underfill flow out
Move underfill dispenser to next die
Cure underfill
Laser marking

The die bond process itself is relatively quick, and the material cost of the flux associated with that activity is low. The equipment required for mass reflow is not very expensive, so that is not considered a major cost driver. The underfill process contributes a high cost, primarily due to the cost of the material itself and the fact that a relatively high volume of underfill is necessary [3]. The underfill is dispensed along the sides of the die and capillary action pulls it under (the rate at which it flows depends on pitch) [4]. Due to this process, there are fillets left on the side(s) of the die, and these fillets represent a not insignificant portion of material cost when looking at the process as a whole.

B. Flip Chip with Thermocompression Bonding and Nonconductive Paste

Table III details the steps required for thermocompression bonding using nonconductive paste. Note that there are differences between the two flip chip process flows not captured by listing the bonding process steps alone. For example, copper pillars are required earlier in the thermocompression bonding flow, which is not the case for mass reflow. However, the focus of this comparison is the costs associated with the bonding portions only. Furthermore, and somewhat surprisingly, the cost of a solder bumped wafer is not very different from the cost of a wafer with copper pillars [5].

Table III – TCB + NCP Bonding Activities

Setup for die bonding
Dispense NCP
Perform thermocompression bond
Cure die bond
Plasma clean
Optical inspection
Bake the substrate
Laser marking

Some of the differences between the flows present themselves immediately. From a process flow standpoint, there are fewer steps here than in the mass reflow and underfill process, which is an advantage. The most expensive portion of the mass reflow process—the use of underfill—is missing from this shorter flow. On the other hand, nonconductive paste carries a higher cost per gram than underfill. This creates an interesting trade-off when it is considered that one bonding option requires a greater volume of a cheaper material, while the other requires less of a more expensive material.

There is more to consider beyond material costs. The thermocompression bonding process is slower on a per die basis, and thermocompression bonding equipment is more than twice as expensive as the equipment needed for a mass reflow and underfill based process [6].

III. Cost Comparison

Table IV shows the key assumptions that were made for the bonding parameters in both flows. These are considered to be the baseline numbers for all trade-offs unless otherwise stated.

Table IV – Process Flow Assumptions

	Mass Reflow	TCB + NCP
Die bond time	3000 die per hour	327 die per hour
Bonding equipment cost	$350,000	$1,000,000
Material cost	Underfill cost: $1.7/gram and $2.4/gram	NCP cost: $3.074/gram
Underfill dispense/flow-out time	1.86 min per die area	N/A

A calculator provided by Nordson ASYMTEK was used to calculate the volume of underfill required in various areas—beneath the die, in the fillet, etc. This was used to obtain the volume of underfill required for numerous die sizes at two die thicknesses. The volume of NCP required was assumed to equal the volume of underfill beneath the die plus a twenty percent increase to account for dispensing irregularities.

Table V shows the die sizes and basic design characteristics that were included in the analysis.

Table V – Die Sizes and Characteristics

Die Size (mm)	Package Size (mm)	Substrate Structure	IO Count
2x2	3x3	1-2-1	49
3x3	5x5	1-2-1	64
5x5	9x9	2-2-2	256
7.5x7.5	15x15	2-2-2	512
10x10	20x20	3-2-3	780
12.5x12.5	29x29	3-2-3	1024

Two die thicknesses were included in the analysis, with different fillet width assumptions.

- 0.8mm thick die (fillet width 1.6mm)
- 0.15mm thin die (fillet width 1mm)

The baseline results are shown in Fig. 1, 2, and 3. Fig. 1 shows the total cost of the package. The scale makes it difficult to see details, but the crossover point for the total package cost occurs near the largest package size. Although the impact on total package cost should not be disregarded, the focus of this analysis is how the cost of the bonding portion of the flow changes. Fig. 2 and 3 show the cost of the bonding steps and associated material costs.

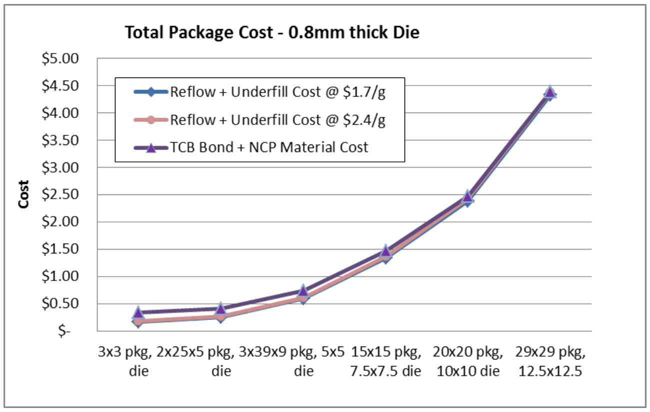

Figure 1 – Total Package Cost for 0.8mm Thick Die

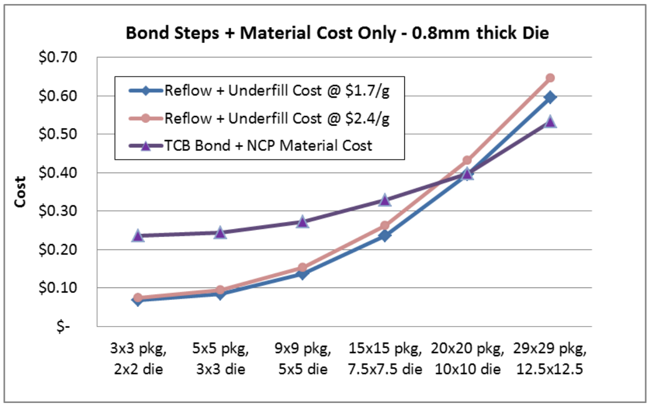

Figure 2 – Cost of Bond Steps Only for 0.8mm Thick Die

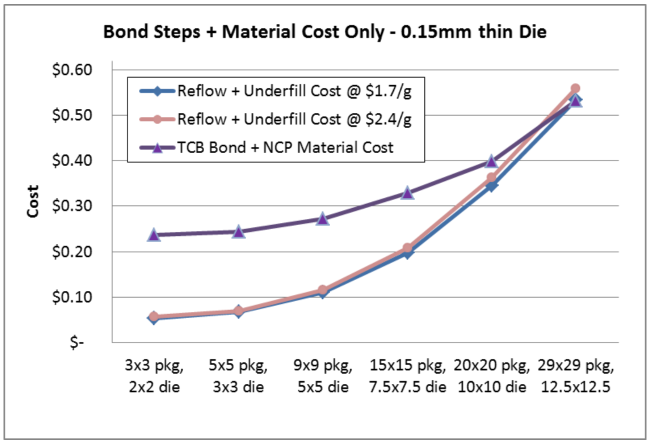

Figure 3 – Cost of Bond Steps Only for 0.15mm Thin Die

Both the thicker and thinner die show that the thermocompression bonding process becomes more cost effective when looking a larger package. In the 0.8mm thick die scenario, the reason thermocompression bonding becomes cost effective sooner than in the thin die scenario is that a thicker die means more underfill is required, so there are higher material costs associated with that flow. Once the die becomes thinner in the second graph (Fig. 3), the underfill material cost drops because less underfill is needed. This pushes the crossover point with thermocompression bonding toward larger die sizes.

Another interesting way to look at this initial data is to examine how the different types of cost break out. The following two pie charts in Fig. 4 show a breakdown by percentage of the different categories of cost. Both charts are for the 5x5mm die scenario.

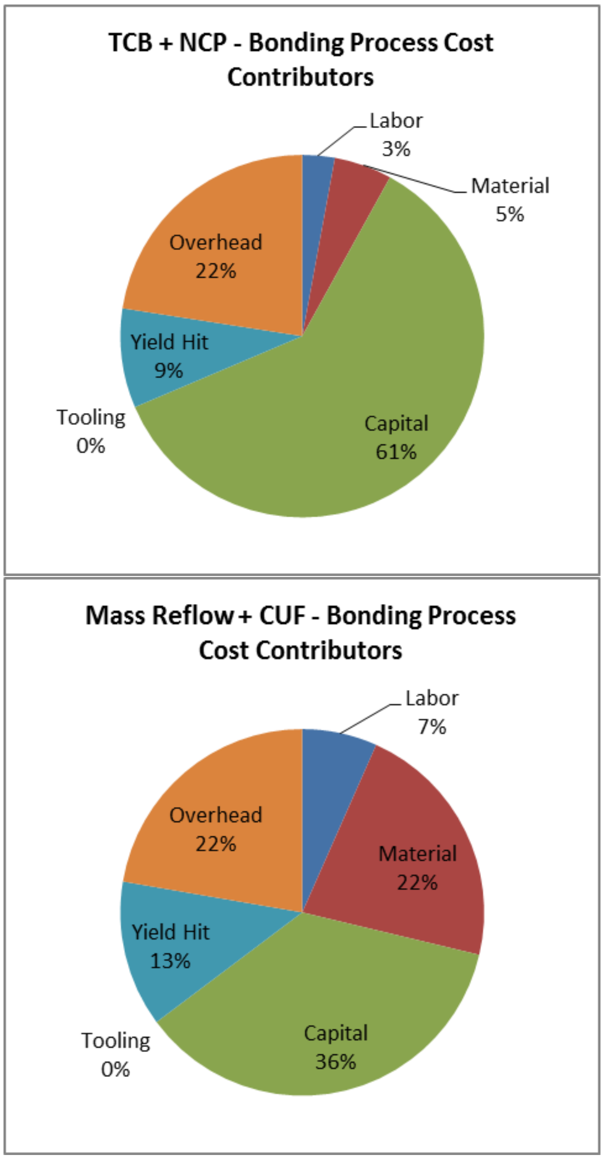

Figure 4 – Bonding Process Cost Contributors

These charts highlight the key points made about each flow in the initial process introductions. Thermocompression bonding requires more expensive equipment, and this accounts for over 60% of the cost of the bonding process. Despite the fact that nonconductive paste is expensive, material costs are not a large contributor for the overall process. Mass reflow carries a much higher material cost, accounting for one fifth of the total bonding cost, due in large part to the necessity of using so much underfill.

The conclusion of this section is fairly straight-forward: thermocompression bonding as a process is generally more expensive, but there are crossover points to be found with certain die characteristics. In the next section, the analysis moves a step farther, determining the ways in which the thermocompression bonding process may become more cost competitive.

IV. Cost Trade-offs and Sensitivity Analyses

This section focuses on how the cost numbers and crossover points shift when details about the processes change. The focus here is on thermocompression bonding parameters. The mass reflow and capillary underfill process is already mature; there is not much expectation of impactful changes occurring with regard to material cost, equipment cost, or other process parameters.

The first trade-off focuses on the cost of the thermocompression bonding equipment. The previous results for both mass reflow scenarios are charted in the graph in Fig. 5, while the thermocompression scenarios were re-run with the equipment cost for the bonding step set at $750,000.

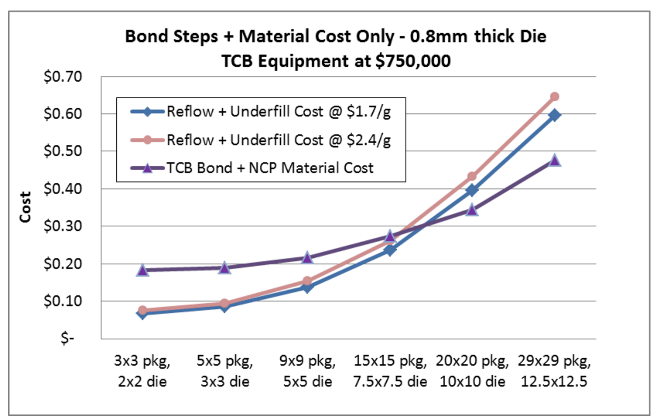

Figure 5 – Cost of Bond Steps at New TCB Equip. Price

This $250,000 change in equipment price has a noticeable impact. The crossover point at which thermocompression bonding becomes more cost effective occurs closer to the 15x15mm package size scenario, whereas it was closer to the 20x20mm package size scenario in the baseline results.

Another way to look at this trade-off is by varying the throughput of the thermocompression bonding step. From a cost modeling standpoint, capital costs are not based only on the price of the equipment itself, but include factors such as how often that piece of equipment is utilized, how long the product spends on that equipment, etc. The following chart shows the impact of shaving a few seconds off of the bonding time, which is 11 seconds per die in the baseline scenario. Similar to the previous example, this pushes the crossover point closer to the 15x15mm package size scenario.

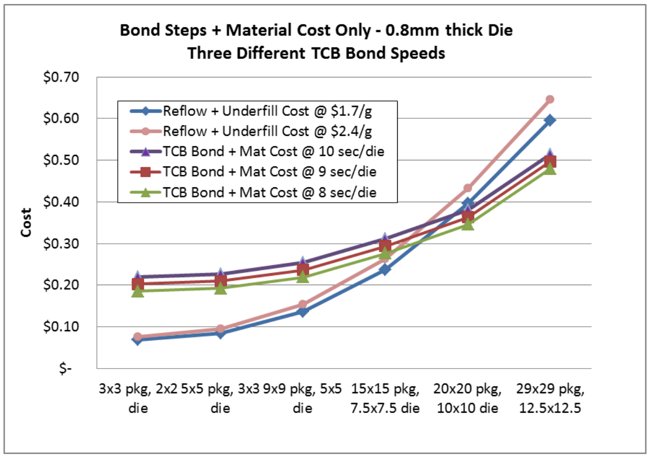

Figure 6 – Cost of Bond Steps at Different TCB Speeds

Next, the impact of changing the cost of the nonconductive paste was evaluated. The thermocompression bonding scenarios were re-run with the nonconductive paste cost dropping by about 40 cents per gram. The impact on total bonding cost is not as noticeable, as shown in the graph in Fig. 7. The crossover point between mass reflow and thermocompression does occur sooner than in the baseline comparison, but only slightly. The difference between the cost of the bonding steps for a 20x20mm package with nonconductive paste costing $3/gram and costing $2.6/gram is about 0.7 cents.

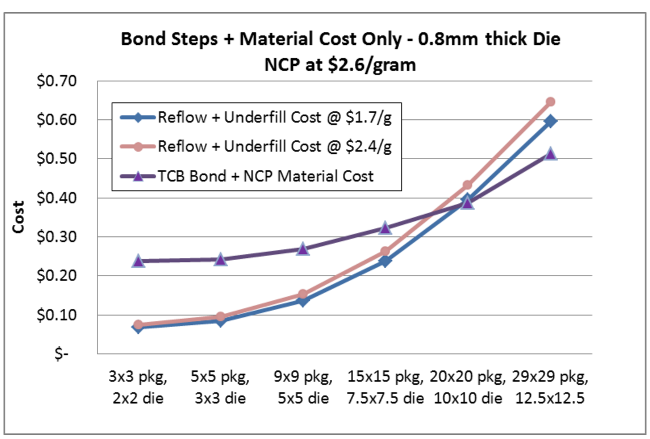

Figure 7 – Cost of Bond Steps at New NCP Price Point

While there are other variables that could be tested for sensitivity in the thermocompression process, material cost, equipment price, and equipment throughput were selected as the key cost drivers. The purpose of this analysis was not only to analyze and compare the steps and cost drivers associated with both assembly processes, but to highlight the ways in which the less mature of the two processes—thermocompression bonding—may be able to become more cost competitive. Bringing down capital costs (such as through equipment price reduction or equipment throughput capability improvement) or the NCP material cost are both key methods for making thermocompression bonding more cost competitive.

III. Conclusion

Two types of flip chip assembly bonding processes were presented in detail, and their cost drivers were analyzed. While mass reflow with capillary underfill and thermocompression bonding both have material costs to take into account, it is a less than straight-forward comparison because one requires a high volume of a less expensive material and the other requires less material that comes at a higher price point. Capital cost considerations such as equipment price and equipment throughput were also identified as cost drivers for the thermocompression process.

Baseline results using process flow parameters based on industry averages revealed that thermocompression bonding can be cost effective for larger packages. More importantly, further analysis revealed that thermocompression bonding—the less mature of the two assembly processes—has the potential to become cost effective in more applications if capital or material costs are improved.

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