Optimising Rheology for Package-on-Package Flux Dip Processes

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The continued drive for more compact and lightweight handheld mobile devices has forcibly pushed the electronics assembly industry to look for novel packaging and assembly technologies. One of the newest advances in recent years is for semiconductors to be stacked, one on top of the other, in a single package. This die stacking allows system designers to take advantage of the often more readily available "Z" axis of the cubic area while saving on the valuable "X" and "Y" square dimensional space on PCB layouts.

Stacking chips in a package is one method to realize this concept, forming the Stacked Chip Scale Package (SCSP) (Figure 1) and the Integrated Devices Circuit (IDC) manufacturers are responsible for building these units.

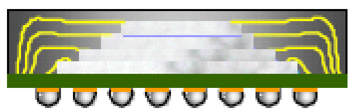

Figure 1. Stacked Chip Scale Package

As can be seen from the above diagram, this package is simply another area array package to the PCB assembly house, which requires no changes to existing assembly technology.

This paper focuses on a newer alternative to stacked chip scale packages. This technology involves the novel design of a bottom package containing a high performance logic device to receive a mating top package typically containing high capacity or combination memory devices to form the PoP structure (Figure 2). The key difference here is from the assembly perspective, as the assembler will inherit the assembly process. The driver in adopting this application is cost-effective miniaturization for logic & memory integration.

Figure 2. Package-on-Package Design

The package-on-package assembly process offers many cost and space saving advantages for designers and manufacturers of miniaturized electronics, but brings challenges to both the assembly operation and the developers of the assembly materials. The PoP process stacks two BGA device packages - one on top of the other - on the PCB and reflows both at the same time. There are several different approaches to PoP assembly. One popular method is to stencil print a solder paste deposit on the PCB, place the bottom BGA on the board, then dip the balls of the second BGA in a tacky flux, with or without solder powder and place it on the top of the BGA which is already in place.

In order to achieve high yields, the ball dipping process must be consistent. Similar amounts of flux must adhere to each ball. Insufficient flux can lead to open or insufficient solder joints; excessive flux can lead to solder shorts or electrical reliability issues. One bad solder joint requires the entire device to be reworked. Factors that influence the consistency of the flux deposition include machine parameters like dip depth and speed, and material properties like viscosity and rheology.

In order to optimize the rheology of paste fluxes for dipping, a study was undertaken to characterize the materials and optimize them for the PoP process. When optimizing flux rheology for dipping, a balance must be struck between the viscous and elastic moduli of the flux such that the recovery time is within an acceptable range. If recovery time is insufficient, streaking or voiding in the deposited flux layer may result. Conversely, excessive recovery time will result in the flux layer not being able to hold its shape and hence will decrease in thickness over time. Both cases can result in inconsistent flux deposition quantities. The key variables in controlling the rheology of a flux are: the amount and polarity of the solvents, the amount and molecular weights of the resins, and the type(s) of rheological modifier(s) used. By varying these parameters, a flux with the proper balance of elastic and viscous moduli for PoP assembly was achieved.

THE ASSEMBLY PROCESS

As with all assembly processes which are driven by throughput speed and continual miniaturisation, repeatability and process robustness are of critical importance in the PoP assembly process. The first thing to consider is the method by which the top package will be assembled. In all probability the assembler will be in a high volume environment so this must be taken into account when selecting the assembly methodology.

As with all new assembly processes, there is no text-book method guiding the pioneers of the technology. A recent brainstorming session looked at numerous possible methods for attaching the upper package in the PoP process. They are as follows:-

(i) Print solder paste on the top of the lower package: This would require the use of an off-line printer and a sophisticated stencil, squeegee blade configuration to print over the protruding die encapsulant, making it an unattractive method.
(ii) Print Spheres onto top of lower package: This would require a 2 stage process of tacky flux deposition followed by sphere deposition.

(iii) Jet Dispensing of Flux: This is a very flexible method of dispensing. A tacky flux could be dispensed over the whole area of the top-side of the lower package. The negative is that this would require additional capital expenditure for many assemblers.

(iv) Pin transfer of Flux/Paste: This would require specific tooling and is used in applications when final volume transfer is not critical.

(v) Dip transfer of Flux/Paste: This technology exists in many placement machines, with a programmable dipping module. It is this route which is being commonly considered and used by PoP assemblers and will be covered in this paper.

ASSEMBLY PROCESS WITH FLUX

The Dip Transfer Process

As with all processes the goal of the engineer is to implement a process with predictable and repeatable results. In the case of the dip transfer process we want to ensure that each and every ball (of the upper package) has an adequate amount of flux or paste material after the dipping process. So now we will start to break this down into stage to understand how the material and the process can affect the transfer yield.

The process begins with a reservoir of the transfer medium, which needs to be able to form a flat level film to enable a consistent immersion depth for the parts when they are dipped. There are broadly 2 kinds of dipping units on the market: The first has enclosed sides, which allows for a relatively low viscosity dipping medium, which levels the material by the use of a “doctor” blade ; the second is a larger open system which has a larger dipping area but has open sides and relies on the material to hold its form in, which means that the material must have thixotropic properties. It must also leave a smooth uniform surface for initial application and re-application, or smoothing of the surface.

For high volume production it is important that the material wets the surface of the balls quickly, but also breaks off in a uniform manner, leaving a consistent volume of material on each and every ball. This would steer the product development towards a material which is lower in viscosity, and in the extreme be a liquid with no thixotropic properties. Of course this would lead to a number of unsatisfactory properties. The first being the fact that the material would not work in an open walled system, and secondly the material would have very little tack properties to hold the component in place after placement and before reflow.

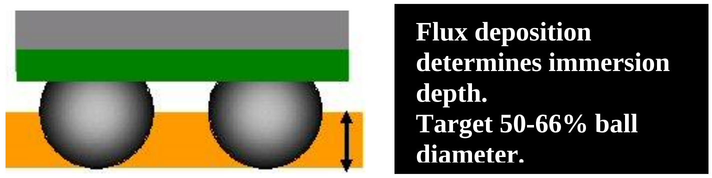

Figure 3: Flux Immersion depth control

A simple experiment was set up in house to test for consistency of dip performance of different flux types to test the theory of which rheological profile would give the most consistent results. A small offline placement machine was set-up to dip a BGA256 component into a fixed thickness of flux material for 0.5 seconds, which was then weighed on a high accuracy scale measuring to 0.0001g. Ball size for the device was measured at 400 microns (µm) and so the flux deposit was set at 200 µm by using a 200 µm stainless steel stencil. The placement machine was programmed to dip the component all the way to the base laminate on which the flux deposit had been printed. Figure 4 shows that high tack, high viscosity materials give very variable results. This is due to the high variation in stringing, and break-off as the component exits from the medium.

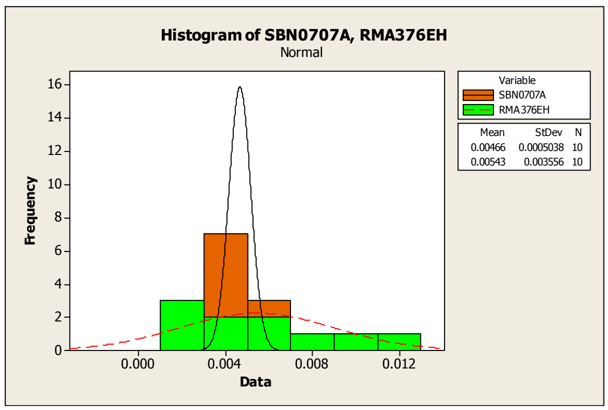

Figure 4: Dip Transfer Consistency

As in any material development this starting point allowed us to start to understand the compromises to be met between the following material performance attributes:

- Material Tackiness
- Material Viscosity
- Material Thixotropic Index

Sufficient tack is essential in the PoP assembly process as the top package is required to stay in position on the lower package (which itself is on wet paste) during conveyor transport from the pick and place machine to the reflow oven, all the way up to the reflow zone. It is for this reason that some level of gel structure is required and therefore a liquid flux would not be sufficient. A number of material structures were then investigated to identify the ideal rheological fingerprint for an optimised PoP flux.

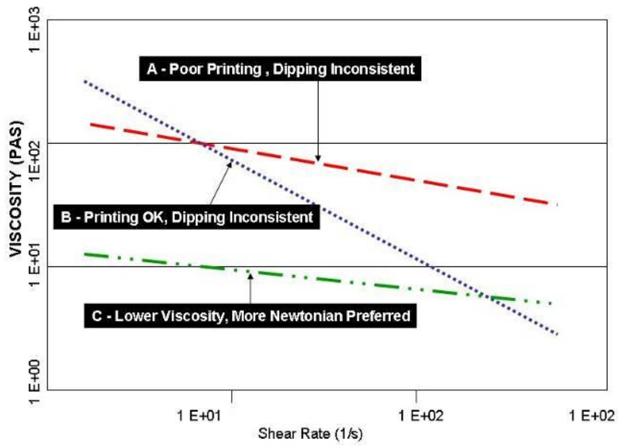

Figure 5: Rheological Characterization of 3 Fluxes

In figure 5 we have three very different rheological profiles. Material “A” is a high viscosity material which exhibits a low amount of shear thinning when kinetic force is added. Material “B” is also a high viscosity material, but unlike “A” it shear thins considerably when sheared. Material “C” is a low viscosity material which shear thins a small amount when moved.

It was mentioned earlier that in addition to dip transfer performance, the material must allow the fluxing unit to consistently produce a perfectly flat surface. The high viscosity materials which do not shear thin exhibit very poor printing performance as the material is too tacky to roll, and break cleanly from itself as the printing blade passes. This result is that we have a an uneven surface for dipping, with excess flux in some areas and insufficient in others. Insufficient flux is a major hazard as most processes do not allow for dip process verification. The net effect is poor or no solder joints between the upper and lower packages. Even more dangerous is the fact that this could pass ICT and only be picked up by intermittent failure. This is shown as profile “A” and would be typical of a very high solids content paste flux from the early days of SMT.

Profile “B” shows a material which displays a high degree of shear thinning, i.e. its viscosity drops when sheared. This is very positive for printing as printing process ensures that the material viscosity drops as it is applied, allowing for a flat even surface. This material also will have a high tack force which is of benefit for holding the component in place after printing. However, it has one major flaw in that its dip transfer consistency was shown to be poor. This is because the dipping process is a low shear operation (left side of graph), in which flux “B” performs almost identically to flux “A”.

Profile “C” shows a material which has a low static viscosity, which allows for consistent dip transfer performance. Also, because of its low starting point it is not required to shear thin considerably to achieve good printing results, while it has enough gel like structure to maintain its shape after printing. It was this material which selected as the baseline for the PoP assembly flux.

There is one significant limitation with the gel flux method of processing PoP assemblies. The issue is caused by the inevitable effect of package warpage during the heating stages prior to reflow. The following diagram shows the typical package warpage effect at different stages of the reflow profile.

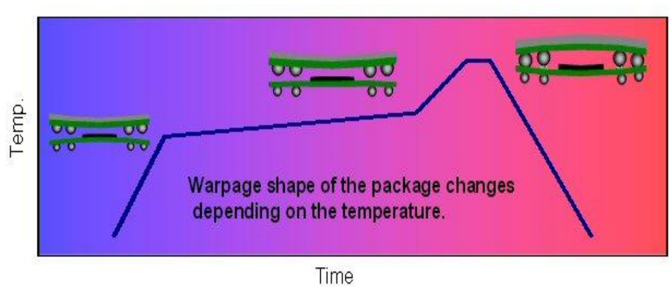

Figure 6: Effect of Package Warpage

As can be seen from figure 6 above, there is a real risk of open circuits between the upper and lower packages caused not be a solderability problem, or an alloy wetting problem, or by a profiling problem, but by the warping affect of PBGA packages due to TCE mismatch within their own structure. It is for this reason that many companies are beginning to favour PoP assembly with the use of a low viscosity solder paste.

Assembly Process with Solder Paste

It was discussed previously that one of the key considerations for a company implementing PoP assembly, is the method for applying the soldering medium to the top of the lower package. The attraction of using solder paste is that it can act as a metallic bridge between the ball and the pad even during periods of significant warpage, whilst flux gel cannot.

The solder paste is simply a gel flux system with a specific loading of spherical solder particles of a known size distribution. Assembly solder paste is usually applied by stencil printing, but this is not an option for applying to the pads on the top-side of the lower package as it is not a flat surface, on account of the moulding compound which encapsulates the silicon. Another option is to dispense the paste onto these pads. One of the problems with this is that the placement process flow would be interrupted as the dispense phase would require the partly built board to move to a dispenser after placement of the lower PoP component, but before placement of the upper component. In addition to this inconvenience, the rate of dispensing, and the number of upper component I/O on the PCB/panel will determine the throughput speed. As PoP device use increases, this could well become the bottleneck process.

The exclusion of stencil printing and solder paste dispensing is driving conventional thinking towards a dipping process, as with the flux process.

Development of a PoP Solder Paste for Dip Transfer

Most solder paste systems are used in a printing or dispensing process. For stencil printing a high viscosity paste is required which is achieved by using a high metal powder to flux ratio, known as "metal loading". This would typically be in the region of 88%-91% of powder by weight for tin solders. Dispensing, by mechanical or air displacement requires a solder paste which is much lower in viscosity, and would typically be in the region of 83-85% of powder by weight. For this PoP development the material needed to have the ability to flood print onto the dipping unit, and leave a perfectly flat and even surface. After the surface preparation the material was required to coat the component balls on dipping with a high degree of repeatability. To achieve this, a very low metal loading was used and the optimal point was found to be between 75-80% metal loading by weight. This low metal loading yields a material which could be described more as a gel flux (with a metal powder dispersion), rather than the stiff paste material with which many PCB assembly process engineers are familiar. It is important to note that the flux has a the major impact of the static and dynamic viscosity (rheology) of the paste system, but when this is kept constant dramatic changes can be made with apparently small changes to the metal powder loading levels. It is for this reason that solder paste manufacturers control metal loading very tightly.

Dip transfer using a solder paste medium is not a well understood process, so the first stage for the development team was to understand the impact of powder particle size on transfer amounts. Initial investigations showed the following:

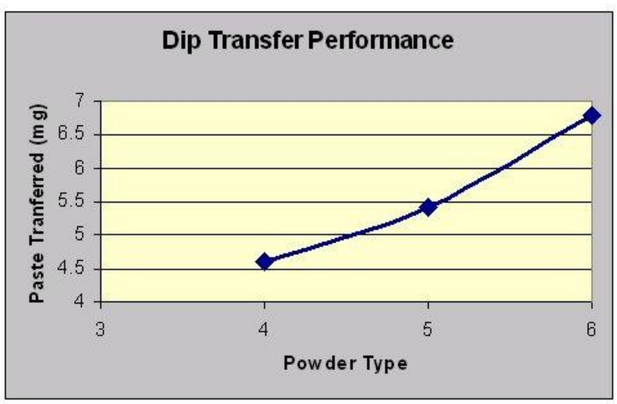

Figure 7: Effect of Powder Type on Transfer Performance

Repeated dip testing of BGA's in identical set-up except for a change in particle size showed that finer particle sizes resulted in an increased amount of solder paste being transferred onto the solder spheres.

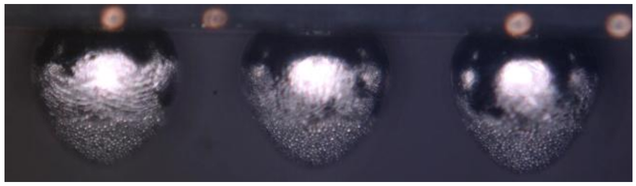

Figure 8: Component spheres after paste dipping

Type	<0.005% larger than	<1% larger than	>90% between	>10% smaller than
1	180µm	150µm		20µm
2	90µm	75µm	75-45µm	20µm
3	53µm	45µm	45-25µm	20µm
4	45µm	38µm	38-20µm	20µm
5	32µm	25µm	25-15µm	15µm
6	25µm	15µm	15-5µm	5µm

Table 1: Powder size Classification from IPC J-STD-005

The fact that the finer particle size gave better coverage in these trials makes sense intuitively. This fact alone would lead development towards the use of the finest possible powders for PoP paste, but there are other factors to be considered.

The first fact is the reflow capability of the flux medium to be used. The vast majority of powder used in conventional assembly is type 3 and type 4 (25-45µm and 20-38µm respectively). These overlapping ranges perform similarly, with the type 4 powder allowing for more efficient aperture packing during the stencil printing process. As soon as we move into type 5 and beyond, the paste flux performance becomes critical. The reason for this is that the amount of particle surface area per unit weight increases dramatically, which means that the flux has much more work to do in terms of oxide removal. If we take many fluxes which have been formulated for "standard" powder sizes, and then load them with type 5 and 6 powders, the reflowed result is very likely to include a large number of non-coalesced solder powder particles in the flux residue surrounding the joint.

As component termination spacings have decreased over the years, the acceptability of solder particles in the residue has also decreased. At a minimum these particles will reduce the dielectric strength of the residue causing potential cross-talk and in the extreme will form a clear current path between two adjacent i/o's – i.e. a short.

So flux performance is critical and must be robust enough to cope with variations in oxide levels on both the powder and the component and BGA ball surfaces. The use of a nitrogen atmosphere in reflow is very beneficial as long as the oxygen content is below 2000ppm. The reason for this is that it limits the build up of further oxidation during the pre-heat phases which in effect eases the oxide reduction burden on the flux system. In most cases the pads on the topside of the lower device are NiAu which is also advantageous when compared to Cu-OSP finishes.

The Dipping Process

In order to understand the critical elements of the dipping process a number of experiments were devised to see the impact on single process input variation. To do this the process of dipping was broken down into 3 sub-process stages, as shown in figure 9. The first of these was the immersion depth of the ball into the paste, the second was the time that the component dwelled in the fully immersed position, and the third was the exit velocity of the part from the paste.

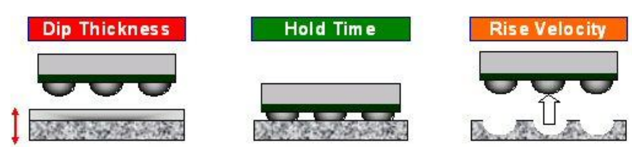

Figure 9: Critical sub-processes in the dip cycle.

Immersion Depth

Prior work with flux systems had shown that the optimal immersion depth should be between half to two thirds of the ball height. This is more critical with the paste process because we do not want paste to get onto the component substrate through excessive immersion depths. If this were the case then it is possible to have a major reliability hazard caused by bridging and dielectric breakdown between adjacent conductors. At the other end of the spectrum is insufficient paste which could lead to an intermittent open between the upper and lower package.

Some simple experiments were carried out to determine the effect of immersion depth on the amount of paste transferred to the components balls. As can be seen from the following graph the results are linear, and we concluded that the ideal depth is about 50% of the ball height to achieve a robust yet safe dipping process.

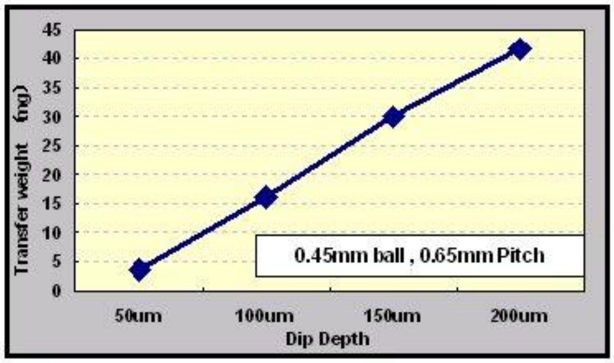

Figure 10: Effect of Immersion Depth on Transfer Weight

Hold Time

The process of dipping requires the soldering medium to wet the surface of the component balls to ensure a sufficient and consistent transfer volume. With this in mind it was deemed important to explore the effect of varying the hold/dwell time in the medium. As the popularity of PoP assembly increases there will be increased pressure to minimize cycle times.

The results of the hold time investigations are shown in the figure 11 below.

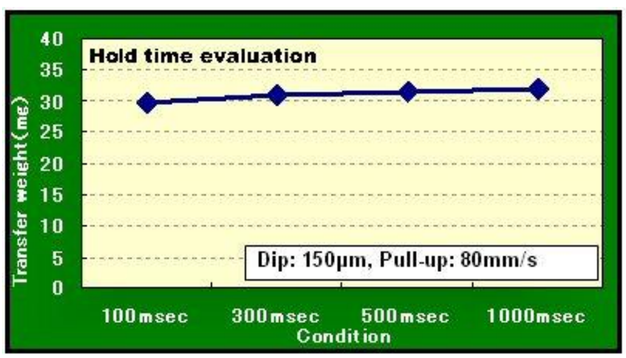

Figure 11: Effect of Immersion Duration on Transfer Weight

The investigation showed a marginal increase in transfer volume between 0.1 seconds and 1 second, although the difference could be considered to be insignificant.

Exit Velocity

It is well known in stencil printing that there are two fundamental parts of a successful deposition process. The first challenge is to get the paste into the aperture, followed by the equally important process of ensuring the paste comes out of the aperture. Without a successful and repeatable release, then successful aperture fill is of no consequence. In the dipping process we need the paste to wet the surface of the component balls with enough adhesion, as to overcome the cohesive forces within the paste on exit. For this reason it was deemed necessary to study the effect of transfer weight as a function of component lift velocity from the paste. The results from this investigation are shown below.

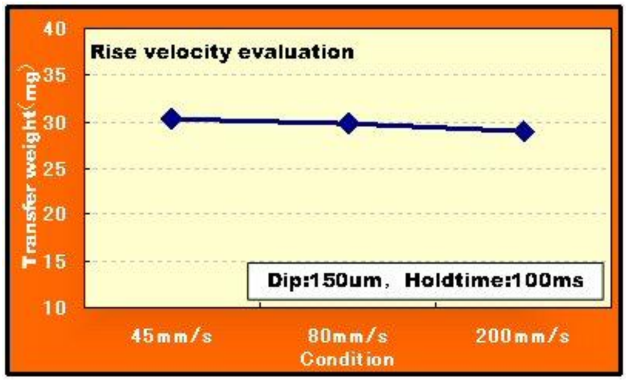

Figure 12: Lift Speed Effect on Transfer Weight

It should be noted that this performance is largely dependant on the rheological properties of the paste system and should be independently evaluated.

The Soldering Process

After successful placement of the upper package the unsoldered assembly needs to be transferred to the reflow process with the minimum of vibration. The main considerations in reflow are to minimize the amount of component/PCB warpage whilst maximizing the efficacy of the soldering process.

The amount of warp is largely determined by the PCB and package design and construction, but can be controlled to some degree by the means of minimizing ΔT within the assembly at all stages of the reflow process. This can be achieved by the use of a highly efficient heat transfer source (convection essential) and minimizing any steep heating gradients. It is recommended that 2°C per second is not exceeded.

Conclusion

The transition of package on package assembly from the component manufacturers to the PCB assemblers has added a new layer of complexity for assembly process engineers.

The cost and complexity of reworking the PoP construction is so significant such that the main aim for any NPI engineer is to introduce the most robust process, whilst ensuring that throughput requirements are met. As the process becomes more widespread both materials and equipment manufacturers continue to develop their products to deliver the production solutions which support our continual quest to miniaturise electronics.