Comparative Study of the Scaling Effect on Pressure Profiles in Capillary Underfill Process

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Abstract. Optimization of the capillary underfill (CUF) encapsulation process is vital to enhance the package’s reliability. Therefore, the design and sizing of the newly developed ball grid array (BGA) device must be considered so that it is compatible with the CUF process. The scaling effect of BGA on CUF flow and its dynamic properties is thoroughly investigated by means of fluid-structure interaction (FSI) numerical simulation. This paper generally highlighted the differences in CUF flow behaviours, together with the pressure distributions between the actual industrial size BGA and the scaled up models for large BGA setup. While flow front profiles appeared to be similar across BGA of various sizes at relative error less than 10%, the CUF filling time gradually increases as the BGA become larger. The scaling limit is found to be at 20, based on the analysis of dimensionless number. The entrant pressure however decreases when the BGA device being scaled up. These findings will assist in the future BGA designs for various sizes used in the CUF encapsulation process.

1. Introduction

Capillary underfill (CUF) encapsulation is important to enhance the electronic package’s reliability, cushion it from external contamination, dissipates mechanical streets away from the solder joints as well serves as a heat sink [1]. Hence, in the past decades, various researches were conducted particularly on this field with the aim of improving and further optimize the CUF process.

On the other hand, ball grid array (BGA) is a type of surface mount packaging that utilizes an array of solder bumps as joints. BGA possess various advantages and is introduced to succeed the pin grid array (PGA) that is susceptible to damage due to excessive bending [2]. This generally accounts for the popularity of BGA as the main electronic mounting type used in the industry. Indeed, there have been various studies of CUF encapsulation process. Power-law constitutive equation-based analytical models were constructed to predict the underfilling flow during the encapsulation process [3]. The technique used here is rather cost effective and the CUF flow in the package can be successfully visualized.
For many years, finite volume method (FVM) simulation has been the most favourable method in simulating the CUF flow. Recently, the fluid structure interaction (FSI) library based on FVM simulation has been mainly used in the research works related to encapsulation and electronic packaging, notably in the works by C.Y. Khor [4–6]. He demonstrated that FSI simulation is capable of producing highly accurate results rather than relying solely on solving the fluid domain alone. Among his FSI works, various parameters has been analysed: inlet pressure, outlet vent [4], silicon chip thickness [5], solder bump arrangement and sizes [6]. In addition, Lattice Boltzmann method (LBM) has also being adopted to study the encapsulant flow in BGA and similar flow profiles upon side by side comparison to the FVM simulation were obtained [7]. However, the LBM based software is found in certain test cases to be much costly as the computing time is generally longer than using FVM.

Various experimental works have been concerted to validate the numerical simulation study. Most researches generally used a scaled-up flip chip model with replacement fluid instead of the actual device and underfilling machine [3–8]. This is mainly to enhance the visualization of the CUF flow across the device and also to minimize the expenditure of the research work. It had been reported that the shape and arrangement of solder bumps in flip chip are seen as the most influential factors in determining the outcome of the CUF process [9]. The CUF filling time of middle empty BGA is found to be shorter compared to the full array BGA and has relatively low number of voids formed [6, 8].

Certain literatures have also investigated the effect of dispensing method on the underfilling encapsulation process. It is reported that L-type dispensing method is regarded as the best option available due to its ability to yield relatively faster and uniform filling [10]. Additionally, air void and incomplete filling are rarely found when L-type dispensing method is being adopted [11]. The presence of void in the encapsulated package will critically affects the reliability of the manufactured package and tend to cause higher stress concentration typically at the proximity of the void region and subsequently leads to device malfunction. Furthermore, the impact of varying the BGA’s gap height is investigated and it was reported that the increase in gap height is capable of reducing the void formation as well as further promote the CUF flow [12]. The scaling effect however is not being emphasized here as only one dimension of the BGA gap height is being manipulated, instead of its width and length dimensions.

It appeared that the study of FSI numerical simulation on CUF encapsulation is rather limited in number. Eventually it is also found that there is no research has been conducted to investigate the scaling effect of BGA on the CUF process. To date, there is no existing FSI study on the scaling effect of the CUF encapsulation of BGA device has been found that is concentrated on the pressure and velocity distributions of the CUF encapsulation process. Pressure and its gradient are crucial parameters in deciding the flowability of the encapsulant into the gap of the BGA. Fortunately these parameters is able to be determined precisely through the use of FVM based FSI simulation. Generally this is something that is difficult to be detected through experimental works, unless expensive apparatus are used. The impact of altering the package’s size by scaling based on the actual size BGA can be clearly visualized and will provide an insight to package designers on relevant scaling issues. This definitely would aid them in designing future miniature-size or even more complicated device in the future.

2. Problem Descriptions

In Fig. 1, the CUF encapsulation process of BGA flip chip is carried out by dispensing a controlled amount of underfill epoxy mold (EMC) at one side and the encapsulant will flow into the gap between flip-chip and
substrate via capillary action. The separation between flip chip and substrate is known as the gap height and is effectively the parameter that will define the strength of the capillary flow \([8, 13]\).

![Fig. 1. Schematic of BGA chip underfilling boundary conditions \([14]\).](image)

In this study, a finite volume method (FVM) based numerical simulation is used to visualize the three-dimensional CUF flow in middle empty BGA that is subjected under L-type dispensing method. Middle empty BGA is chosen as the primary subject of research due to its popularity usage in the industrial applications compared to full and perimeter orientations. Similarly, L-type is much more favourable in the industry as the probability of void formation and incomplete filling are relatively less compared to other dispensing method \([1]\). The combination of L-type dispensing and middle empty orientation for CUF encapsulation is found to be the most ideal setup for an actual industrial application. To account for the effect of different scaling, the CUF process in applied on four scaled-up BGA model of different sizes. Subsequently, all of these models will be compared with an actual miniature size BGA.

3. FSI Numerical Simulations

The numerical simulation of the flow analysis will be based on the well-known Navier-Stokes equation that consists of the continuity, momentum and energy equation that is solved simultaneously during the flow advancement. Furthermore, multiphase formulation is used to distinguish the primary phase (encapsulant) and the secondary phase (air) in CUF flow.

Finite volume method (FVM) based software, Ansys was used to simulate the fluid flows and its dynamic properties in the CUF encapsulation process of middle empty orientation BGA for various scale sizes under L-type dispensing method. Multiphase fluid structure interaction (FSI) was adopted to enhance the accuracy of the simulation works since it will enable precise prediction of the interactions between both fluid and structure domains. The dimensions of the actual size BGA and scaled-up BGA models were shown in Table 1. The material properties of Sn-3.0 Ag-0.5 Cu solder bumps in BGA and the underfill encapsulant used were given in Table 2. The thermal properties of encapsulant were neglected as all CUF dispensing were carried out at same room temperature, such that isothermal is assumed.

| Scale size | Dimensions of BGA models (mm) | |
|-----------|-------------------------------|---|
|           | Bump diameter | Bump pitch | Gap height | Length |
| 1.0       | 0.5            | 1.0        | 0.45       | 12.5   |
| 4.4       | 2.2            | 4.4        | 2.0        | 55.0   |
| 6.0       | 3.0            | 6.0        | 2.7        | 75.0   |
| 8.0       | 4.0            | 8.0        | 3.6        | 100.0  |
| 11.0      | 5.5            | 11.0       | 5.0        | 137.5  |

**Table 1.** Dimensions of actual size BGA (scale size 1.0) and various scaled-up BGA models.
Table 2. Material properties of the Sn-3.0 Ag-0.5 Cu solder bump and underfill encapsulant used.

| Surface tension | N·m | 0.06 |
|-----------------|-----|------|

Path conforming tetra meshing technique is used in all of the simulation works presented here. This meshing technique was selected to create high quality mesh that are properly discretized that compatible with FLUENT. Figs. 2 (a), (b) and Figs. 2 (c), (d) depicted the meshed geometry of the structural and fluid domains respectively.

All CUF encapsulation simulations are set under constant temperature, $T_0$. Both initial inlet and outlet pressures are set to as 0 Pa to demonstrate the capillary flow. Generally, all initial and boundary conditions (BC) are set in the numerical simulation as shown below:

(a) **On wall:** $u = v = w = 0$; $T = T_0$; $\frac{\partial p}{\partial n} = 0$

(b) **At inlet:** $P = P_{in}(x, y, z, t)$; $T = T_0$

(c) **On flow front:** $P_{atm} - \frac{\sigma}{R} = P_{atm} - \frac{2\sigma\cos\theta}{b}$

L-type dispensing method is modelled in the simulation by designating the sides of the inlet and outlet BC, as illustrated in Fig. 3. A no-slip boundary conditions are applied on all wall surfaces and FSI regions. Wall adhesion setup is enabled to accurately predict the shape of the flow meniscus.

FSI simulation is achieved by using the built-in System Coupling module that iteratively coupling the results from Transient Structural and FLUENT. Transient pressure-based solver is selected in the simulation works. Multiphase formulation is enable by specifying the two Eulerian phases that are involved in the simulation models. In the current setup, the encapsulant will be set as the primary phase and air as the secondary phase. Additionally, continuum surface force (CSF) model is applied to simulate the phase
interaction between both mentioned phases. Subsequently, an implicit solver is selected as the volume of fluid (VOF) scheme to solve the phase continuity equation in sub time steps together with the momentum and pressure calculations.

4. Results and Discussions

4.1. Validations of Scaled-up BGA Model

To better understand the scaling effect, BGA models of different scale are compared to the actual size BGA based on the front advancement of the encapsulant flow at certain filling percentage. Accordingly, the flow front profiles of each BGA models are compared side-by-side at a selected filling percentage of 40% as shown in Fig. 4. It appears that the flow front profile of CUF flow in the actual size BGA compares well and is found to be almost similar to the profiles in the scaled-up BGA models. Thus, the usage of scaled-up BGA models as a replacement of actual sized device to enhance the visualization aspects in the study of CUF flow is valid as the relative deviation in visualized flow fronts in scaled-up models is within 10%. Furthermore, our validations study does compare well with that reported by Aizat et al. [8] in Fig. 5.

![Fig. 4. Comparison of flow front profiles at filling percentage 40% in actual size BGA and scaled-up BGA model.](image1)

![Fig. 5. Comparison of scaling effect and the underfill flow in actual size device based on the works of Aizat et al. [8]](image2)

4.2. CUF Filling time of actual size BGA and various scaled-up BGA

The filling time of CUF process at different percentage of flow front advancement filling for actual size and various scaled-up BGA models are presented in Fig. 6. The flow front advancements in CUF encapsulant process of the actual size and scale-up BGA of magnifications 4.4, 6.0 and 8.0 at filling percentages 20% and 40% are shown to quite similar. However, noticeable increase in the scale-up BGA’s filling time can be observed after the filling percentage of 60%. The largest BGA of scale size 11.0 is found to have the largest filling time deviation, nearly thrice that of the actual size BGA; while least deviation is recorded in the smallest BGA with 4.4 scale size. It is noteworthy to mention that the overall trends of flow front advancements are homogenous, as the scaling effect will increases the filling time in certain proportional trend. The plot also indicated that all CUF flows exhibit a decelerating trend which the encapsulant tends to
slow down toward the end of the CUF process. This is due to the cumulative resistance of progressive array of solder bumps as the flow progresses.

4.3. CUF Pressure Variations near the Dispensing Inlet

Entrant pressure at the dispensing inlet plays a vital role in the CUF process to indicate capability of the encapsulant to fill in the gap of between the cavities via capillary action. The inlet gauge pressures of CUF flow at different filling stages, as indicated by filling percentage, for actual size BGA and scaled-up models are plotted in Fig. 7.

It is shown that the overall entrant pressures at all filling percentages decrease with the increase of BGA’s scale size and thus the gap height. The small gap produces larger capillary pressure for the CUF flow and register a larger entrant pressure. It is found that the inlet pressure of the scale up BGA diminished by approximately the same factor as the scale size of the model itself. This serves as the evident of scaling effect on the dispensing pressure of the CUF flow as the BGA is being scaled up while the inlet pressure trend is shown to decline proportionally, based on the scale size itself. For example, the pressure is reduced by approximately 4 times when the size is scaled up with a factor of 4.4. As the flow progresses through the
chip cavity, the inlet pressure gradually increases due to the continuous dispensing that build up the hydrostatics and dynamic pressures. Consequently, the pressure of the encapsulant increases to overcome the resistance during the inelastic collisions between the solder bumps array. Therefore, the outlet pressure gradually increases as the cavity is being filled by the encapsulant, with its peak value recorded at 80% filling percentage.

4.4. CUF Pressure Variations near the Dispensing Outlet

The gauge pressures of CUF flow at selected filling percentages are illustrated in Fig. 8. Generally it is found that all the outlet pressures values are significantly low with a value that is slightly above the atmospheric gauge pressure. These non-zero gauge pressures account for the dynamic pressure to displace the air from the outlet vent. Figure 8 also shows that the scaled-up BGA have a relatively lower outlet pressure in contrast to significantly higher pressure shown at the outlet of actual size BGA. In fact, the trend in outlet pressure is similar to the inlet pressure, where it varies inversely proportionally to the scale size. When the BGA is scaled up by 4.4, the outlet pressure reduces approximately by 4, which is consistent in the view of dimensionless number analysis. Furthermore, the outlet pressure also increases as the CUF flow progresses through the solder balls array. However, as the magnitude of outlet pressure is relatively low for all models and at all underfilling stages, its impact on the encapsulant’s flow and filling time are minimal and thus negligible.

![Outlet pressure against filling percentages in actual size and scale up BGA.](image)

In Fig. 8, the outlet pressure trends in all scaled-up BGA models are similar with a slow increase detected throughout the whole CUF process. Nevertheless, anomalous outlet pressure trend is being observed in the CUF of the actual size BGA model. The pressure increases gradually at the onset of the CUF process before drastically increase at 40% of filling until it attains peak outlet pressure of about 0.006 Pa at 80% of filling. This value is substantially larger than those recorded in the scaled-up BGA models.

5. Conclusions

This paper compares the CUF encapsulant flows in the actual size BGA and different scaled-up BGA models using FVM numerical simulation based on Fluid Structure Interaction (FSI). While the flow front profiles among the actual size BGA and scaled-up BGA models of various sizes are fairly similar and comparable with relative error within 10%, there exists various differences in their CUF process particularly at the filling
rate and entrant pressure values. The filling time increases as the size of the BGA becomes larger. In addition, the entrant pressure near the dispensing inlet of the encapsulant also increases as the flow progress and it is inversely proportional to the scale size. The study also recorded that the outlet pressure shares similar trend with the inlet pressure, however its relatively low magnitude can considered negligible in comparison to the overall CUF flow. The numerical data presented in this paper have provided decisive justifications on the impact of scaling effect to the overall flow behaviour of the CUF process of BGA from the perspective of pressure. These findings will provide a good insights for future optimization works on the BGA chip design to attain the optimize CUF encapsulation process as well as overall chip performance and reliability.

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