Visualization of Underfill Flow in Ball Grid Array (BGA) using Particle Image Velocimetry (PIV)

Fei Chong Ng¹, Aizat Abas²*, Ismail Abustan³, Z. Mohd Remy Rozainy³, MZ Abdullah⁴, Ali b. Jamaludin⁵, Sharon Melissa Kon⁶

¹,²School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300, Penang.
³School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300, Penang.
⁴School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300, Penang.
⁵TNB Research Sdn. Bhd., No. 1, Lorong Ayer Itam, Kawasan Institusi Penyelidikan, 43000 Kajang.
⁶School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300, Penang.

*Corresponding author: aizatabas@usm.my

Abstract. This paper presents the experimental methodology using particle image velocimetry (PIV) to study the underfill process of ball grid array (BGA) chip package. PIV is a non-intrusive approach to visualize the flow behavior of underfill across the solder ball array. The BGA model of three different configurations – perimeter, middle empty and full array – were studied in current research. Through PIV experimental works, the underfill velocity distribution and vector fields for each BGA models were successfully obtained. It is found that perimeter has the shortest filling time resulting to a higher underfill velocity. Therefore, it is concluded that the flow behavior of underfill in BGA can be justified thoroughly with the aid of PIV.

1. Introduction

In electronic packaging (EP), underfill process is utmost crucial in enhancing the reliability of microelectronic device, particularly flip-chip, ball grid array (BGA) and chip device. It not only cushions the package from external contamination, but also relief the thermomechanical stress experienced by the chip and solder bumps due to the difference in the coefficient of thermal expansion (CTE) [1]. Upon realizing the importance of this underfill process and its impact to the electronics’ reliability, various research on underfill process and its optimization study have been actively conducted on various approaches and point of views [2 – 7]. Various optimizing parameters and operating conditions that critically affect the underfill flow have been identified, for instance the gap height, pitch/clearance, dispensing method, bump arrangements/ball count, operating temperature and inlet pressure.

On the other hand, particle image velocimetry (PIV) is a non-intrusive optical method for flow visualization. This technique allows for the velocity of a fluid on a two-dimensional (2D) plane to be
measured simultaneously. The kinematics of the flow is obtained by tracking the flow following tracing particles seeded into the fluid of interest. These particles are illuminated with the aid of high power light source. The motion of the illuminated particles is then recorded. The use of strobing laser light makes it easier to freeze the movement of the particles in view, especially in fast movement. The velocity of the flow is then calculated by knowing the distance travelled by the tracking particles between the time intervals set between camera exposures, together with the magnification of the camera.

The usage of PIV had previously reported in the underfill application of flip-chip in two literatures [8, 9]. They have successfully setting up a PIV system to study the flow in flip-chip and determine the dynamics properties of the underfill flow. However still the application of PIV in sector of electronic packaging is very limited. Therefore, this paper is devoted to outline a simple and easy-to-construct experimental setup to visualize the underfill flow based on the PIV. Furthermore, such PIV experimental approach allows researcher to identify additional data on flow vector and velocity profiles of underfill flow which unable be attained in conventional experimental in electronic packaging.

2. PIV formulation

Particle image velocimetry (PIV) is an optical method that can be used to determine the instantaneous vector measurement throughout the cross-sectional view. The motion is followed via the use of small tracer particles. Based on the positions of these tracer particle at two different instances of time can we obtained the particle displacement to infer the flow velocity field [10, 11]. Velocity vector of the fluid through the tracer particles are computed based on the movement of tracer particle between two light pulses:

$$V = \frac{\Delta x}{\Delta t}$$  \hspace{1cm} (1)

The primary source of measurement error relies on the influence of gravitational forces, \(g\) when the density of the tracer particles is different to the density, \(\rho\) of work fluid.

$$V_g = d_p^2 \frac{(\rho_p - \rho)}{18\mu} g$$  \hspace{1cm} (2)

The velocity lag, \(V\) of a particle in a continuously acceleration fluid is given by:

$$\vec{v}_s = \vec{v}_p - \vec{V} = d_p^2 \frac{(\rho_p - \rho)}{18\mu} g$$  \hspace{1cm} (3)

$$\vec{v}_p(t) = \vec{V}(1 - \exp(-\frac{t}{\tau_s}))$$  \hspace{1cm} (4)

$$\tau_s = d_p^2 \frac{\rho_p}{18\mu}$$  \hspace{1cm} (5)

This technique consists of the measurement of the fluid displacement, \(\Delta x\) over a given time interval, \(\Delta t\). The LED light will illuminates the tracer particles by creating a thin laser light sheet [12]. Then subsequently, the image will be captured using a camera specifically at the target area [10].

3. Experiment

Figure 1 depicts the general experimental setup for conducting the underfill process on ball grid array. It consists of a light box where the BGA assembly is directly above the light source, forming a backlighting system. Camera video is placed perpendicularly above the BGA assembly to record the underfill flow into the gap of array. There are three different BGA models being studied of various balls arrangements, for instance full, middle empty and perimeter arrays as shown in Figure 2. Each
solder ball has a diameter of 2 mm with clearance of 2 mm and gap height of 1.5 mm. The length of bump-less edge is 8 mm, resulting the overall 6 × 6 array package has a dimension of 38 × 38 mm2. For better visualization aspect, the chip/substrate is replaced by a clear smooth Perspex that exhibits the similar capillary properties as the actual surfaces. The underfill fluid that exhibits property of a Newtonian fluid with density 1042 kg/m³ and viscosity 2.2 Pa-s was carefully injected into the inlet of the BGA model, by using a syringe. All the underfill flow in the BGA will be recorded using the camera video for subsequent PIV analysis.

For each case, two consecutive images of interval 0.1 s at particular stage of 80% filled from the underfill video were obtained for the image pre-processing, to be ready for the PIV analysis. The original image obtained will be changed to greyscale before being pre-processed to remove as much noise as possible through high pass filter and intensity capping. Afterward, the processed images are loaded into the Matlab PIVlab software to obtain the flow vector and velocity contours in each underfill cases.

4. Results and Discussions

Figure 3 presents the unprocessed underfill flow front in three different BGA models, namely perimeter, middle empty and full array. All these underfill stages are approximately near completion, at about 80% filled. The time taken for the underfill to flow till this stage are 152 s, 147 s and 140 s, respectively for the full, middle empty and perimeter array bumps. It is clearer than the underfill flow faster in perimeter array, later follows by middle empty array and the underfill flow in full array being the slowest. This is due to the presence of large amount of solder balls in full array (36) and middle empty array (32), constitute a larger bump resistance to the underfill flow as compared to the least ball count in perimeter array (20). Such filling time trending in BGA different bumps arrangements are similar as reported in past literatures [5, 6].
The underfill flow pattern across the perimeter, middle empty and full array ball grid array models (from left to right). Pinkish fluid indicated the underfill; while the white regions are unfilled.

Figure 4, Figure 5 and Figure 6 respectively show the flow vector and velocity contour profile for the underfill flow in ball grid array of different array arrangements, perimeter, middle empty and full. It is noticed that the velocity of underfill flow near the vicinity of solder ball are comparably lower than in bump-less region. As a result, for BGA with high ball counts such as the full array, there are more region of low velocity, resulting lower overall flow of underfill and causing longer filling time. This had correlated the number of solder ball present in the BGA to the flow velocity and filling time. On the side of flow vector, it is found the underfill flows directly from the inlet toward the outlet in all cases. The presence of solder balls in the array did not alter the flow direction of underfill significantly.

Figure 4. Flow vector and velocity contour for underfill in perimeter bump array.

Figure 5. Flow vector and velocity contour for underfill in middle empty bump array.
5. Conclusions
This paper had demonstrated the viability of particle image velocimetry (PIV) experimental approach in the study of underfill flow in ball grid array (BGA) packaging. Through PIV analysis, the flow vector and velocity profiles of underfill flow in the BGA can be obtained. Particularly, three BGA models of different ball arrangements and ball counts, namely perimeter, middle empty and full array are considered in this research. It is found that the trend of shortest filling time and faster underfill flow are in the ascending order of perimeter, middle empty and full array. The shortest filling time of 140 s is registered by the perimeter array; meanwhile the full array took the longest time of 152 s to reach 80% filled. However, the flow appears did not significantly affected by the presence of solder ball as justified by almost similar flow vector obtained for all three cases. Ultimately, PIV is a reliable yet simple approach to visualize the underfill flow and therefore could have its application extended in future.

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