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LATTICE BOLTZMANN AND FINITE VOLUME SIMULATIONS OF MULTIPHASE FLOW IN BGA ENCAPSULATION PROCESS

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ABSTRACT

The paper presents the results of the simulation of the flow visualization of multiphase flow for I-type flow on full array solder bump arrangement of ball grip array package simulated using both Lattice Boltzmann method (LBM) and Finite Volume Method. For the LBM model, the pseudo-potential model called the Shan-Chen method is employed to track the flow front of under fill material. The filling percentage and time is studied and compared between both LBM and FVM. From the findings, it was shown that the filling time obtained using LBM are in good agreement with the established flow Finite Volume software ANSYS. High level of details can be observed in the LBM simulation with formation of bubbles can be observed towards the end of the filling percentage.

Keywords: lattice boltzmann method, finite volume, advanced packaging, under fill process.

INTRODUCTION

The past decade has seen substantial improvement in the modelling of transport equation for one way fluid-structure interaction (FSI) problems with various applications including electronic packaging (Ohta *et al*., 2011), hemodynamics (Maciej *et al*., 2013) and civil structures (Andrea, 2013). In simulating the one way FSI problem, two main approaches are considered; continuum and discrete method. The former is by far the most well-known method for modelling of various FSI problems. For the continuum approach, finite difference (FD), finite volume (FV) and finite element (FE) methods are used to convert differential equations with initial condition and boundary into a system of algebraic equations. The domain is then discretized into volume or element that contains a collection of particles (macro scale) where physical properties which include the velocity, pressure and temperature are represented by its nodal value.

On the contrary, in the discrete approach, the numerical models are constructed on micro scale level in which the medium is made up of small particles that consistently collide with each other. Historically, the Lattice Boltzmann method is based on Lattice Gas Automata (LGA) problem in which the location and velocity of each particle is identified and solved (Mohamad, 2001). Given the huge number of particles available in microscopic scale, the current LGA method is merely impossible to solve considering the amount of computational resource required. For this reason, the lattice Boltzmann method (LBM) is introduced by considering a collection of particles as a unit.

LBM considers the fluid as a volume element consisting of collection of particles that is represented by particle velocity distribution function at each grid point. The important characteristic of LBM equation is to estimate the collision operator with Bhatnagar-Gross-Krook (BGK) equation. This BGK allows for more flexibility in the setup of the transport coefficients making the overall simulation more efficient (Goodarzi *et al*., 2014). An important development in LBM was made by Chapman-Enskog model where derivation can be made on the governing continuity and Navier-Stokes equation from the LBM distribution function equations (Yuanxun, 2011), (SCS, 2003).Various literatures have been concentrated on the comparison between the microscale LBM and macroscale numerical method, for instance FE, FD and FV. Based on the findings, it shows that all macroscopic numerical models results considered are in good agreement with the LBM computation. However, the accuracy of the computed results might vary according to the numerical algorithm, discretization scheme and problem configuration.

In contrast, Ranjan *et al*. combined LBM, FVM and genetic algorithm to solve transient conduction-radiation heat transfer problems (Das *et al*., 2008), (Mishra *et al*., 2009), (Ajith *et al*., 2010). An inverse analysis was then used to tackle the conduction-radiation problems (Das *et. al*., 2008), (Das *et al*., 2011). It was shown that good agreement can be obtained between LBM-FVM combinations compared with the conventional FDM-FVM.

Recent trends have seen industrial applications concentrating more into production of smaller and lighter electronic package (Techopedia, 2013). The way to achieve this goal is by reducing the size of the individual components. The main obstacle, however, is to design a package that is small and reliable enough in terms of strength and durability for the long run (Bailey, 2006), (Yuanxun, 2011), (Khor *et al*., 2011), (Khor and Abdullah, 2013), (Khor *et al*., 2013), (Khor *et al*., 2014). With the size of package reducing up to nano size, the importance of micro scale cannot be overemphasizing.

To the author's knowledge, no other researchers have attempted to apply LBM for Electronic Packaging application. With the advancement in LBM formulation over the past few years, strong foundation has been laid for more accurate micro or mesoscale analysis. In the next few

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years, this LBM research will gain strong foothold not only in the electronic packaging field but also in other field relating to fluid-structure interaction.

MATHEMATICAL FORMULATION

Navier-Stokes Formulation

In this paper, the governing equations based on Navier-Stokes equations used to simulate the fluid flow of encapsulant material and air using the conservation of mass and momentum. In the encapsulation process, both fluids are assumed to be incompressible and laminar.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + +\nabla.(\rho\vec{u}) = 0 \qquad (1)$$

Navier-Stokes equation:

$$\frac{\partial}{\partial t}(\rho\vec{u}) + \nabla.(\rho\vec{u}\vec{u}) = -\nabla P + \nabla.\bar{\bar{\tau}} + \rho\vec{g} \qquad (2)$$

Energy equation:

$$\rho C_P\left(\frac{\partial T}{\partial t} + \vec{u}\nabla T\right) = \nabla(k\nabla T) + \Phi \qquad (3)$$

In the model, EMC and air are distinguished suing multiphase formulation. The volume of fluids (VOF) for both phases are described using transport equation whilst the distribution of fluid is represented by volume fraction, f within the range of $0 < f < 1$. Generally, $f = 0$ indicate the absence of EMC while $f = 1$ indicate the cell is completely filled with EMC.

Transport equation:

$$\frac{df}{dt} + \nabla.(\bar{u}f) = 0 \qquad (4)$$

where $\vec{u}$ is the fluid velocity vector, ρ is the fluid density, P is the static pressure, T is the temperature, $\bar{\bar{\tau}}$ represents the stress tensor, k is the thermal conductivity, C_P is the specific heat and Φ represents the energy source.

Lattice Boltzmann Equation

The results shown at this section (basically fluid flow velocity) are based on simulation of Palabos coding which calculated by using D3Q19 model of lattice Boltzmann method (LBM). The LBM equationcan be summarized in Equation (5):

$$f(r + cdt, c + Fdt, t + dt) - f(r, c, t) = \Omega f(r, c, t), \qquad (5)$$

in which the right hand side represents the streaming step. The left hand term denotes the collision term which can be represented using the well-know Bhatnagar-Groos-Krook (BGK) model as given in Equation (2).

$$\Omega = \omega(f^{eq} - f) = \frac{1}{\tau}(f^{eq} - f) \qquad (6)$$

The ω and τ denotes the relaxation frequency and time. f^{eq} represents the equilibrium function relating to the lattice arrangement.

The equilibrium function f^{eq} can be described as:

$$f^{eq}(\rho, u) = \rho w\left[1 + \frac{1}{c_s^2}(c.u) + \frac{1}{2c_s^4}(c.u)^2 - \frac{1}{2c_s^2}(u.u)\right]$$

Where w represents weighting function across different lattice links. In the case of D3Q19 lattice model as depicted in Figure-1, the weighting functions can be described in Table-1 as:

Table-1. Weighting functions for D3Q19.

Model	c_s^2	Node no.	Weight
D3Q19	1/3	f_0	1/3
		$f_1 - f_6$	1/18
		$f_7 - f_{18}$	1/36

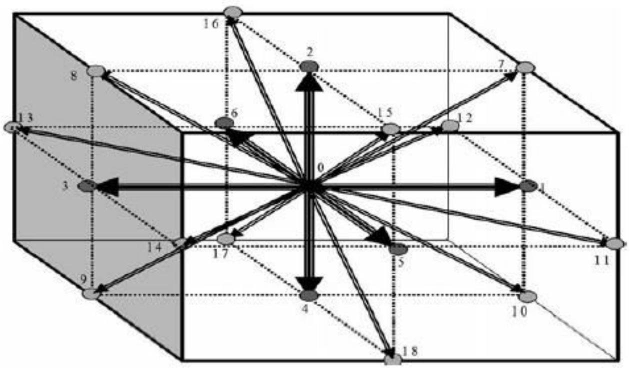

Figure-1. 3D Lattice arrangements for D3Q19.

Microscopic velocities for a D3Q19 lattice model of lattice Boltzmann method is given as:

$e_0 = (0,0,0)$
$e_{1,2} = (\pm1,0,0)$
$e_{3,4} = (0,\pm1,0)$
$e_{5,6} = (0,0,\pm1)$
$e_{7-10} = (\pm1,\pm1,0)$
$e_{11-14} = (\pm1,0,\pm1)$
$e_{15-18} = (\pm1,0,\pm1)$

Finally the hydrodynamic and thermal variables can be obtained as:

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$$\rho = \sum_i \tilde{f}_i$$

$$\rho\mathbf{u} = \sum_i \mathbf{c}_i \tilde{f}_i$$

$$\rho e = \boldsymbol{\rho} RT = \sum_i \tilde{g}_i - \frac{\Delta t}{2} \sum_i f_i Z_i$$

PROJECT BACKGROUND

Ball Grid Array Design

This project is related to 3-dimensional fluid flow simulation through a ball grid array (BGA). Figure-2 depicts the schematic diagram of under fill process for the flow. The BGA consists of square array of spherical balls across the surface attached to another piece of printed circuit board (PCB). The under fill process will be simulated using Palabos that is based on LBM theory.

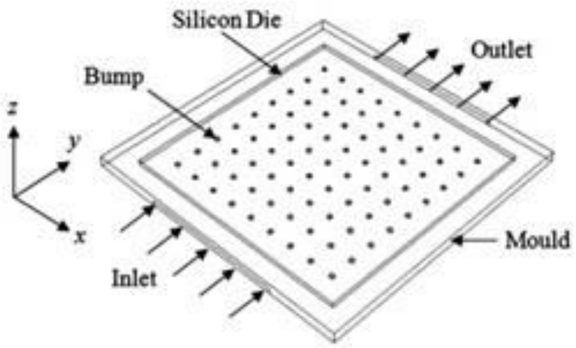

Figure-2. Schematic diagram of flip-chip boundary conditions.

Historically, BGA is actually derived from pin grid array (PGA) technology. BGA solder balls are spaced evenly and will not bridging or sticking them together. The advantage of BGA package is apparent since it has better performance at high flow speed (Bailey, 2006). The BGA uses the underside of the package for the connection where the pins are arranged in grid pattern as depicted in Figure-3. Balls of solder are used for replacement of the pins to provide the connectivity. Moreover, BGA also offers lower thermal resistance within silicon chip allowing more heat to be conducted out of the device (Yuanxun, 2011).

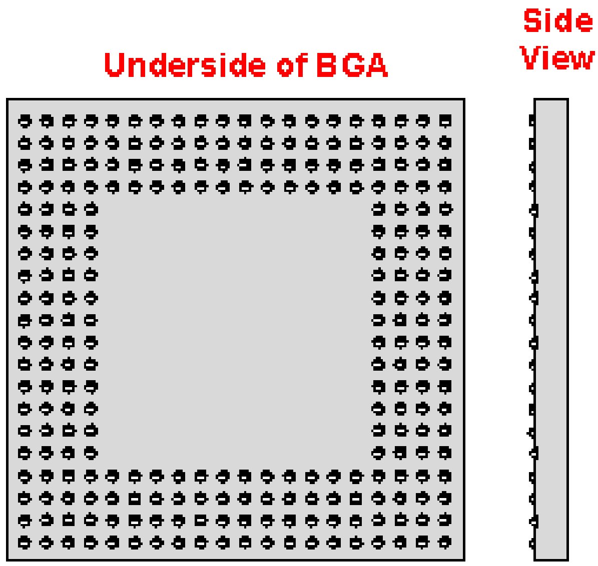

Figure-3. Ball Grid Array (BGA) package diagram.

Figure-4 shows the under fill process involving the dispensing process of controlling the amount of material into the gap between the chip and substrate. The under fill encapsulation of ball grid array (BGA) is important in protecting and increasing reliability of the electronic packaging (EP) as it can reduce the global thermal expansion, stresses and strains between the silicon chip and substrate. The gap between the chip and silicon has to be completely filled with under fill material (under fill material flow correctly) in order to protect life of the chip assembly (Khor, 2011).

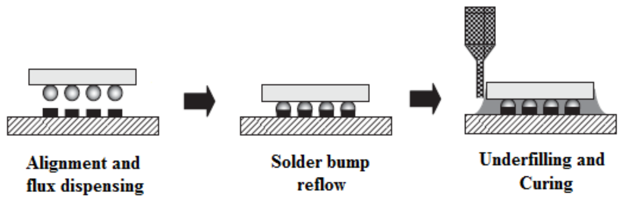

Figure-4. Under fill process flow.

A 2D IC package model was generated by using Palabos software that based on the Lattice Boltzmann Method (LBM) theory for simulating the fluid flow across ball array.

Figure-5 depicts the full array BGA of the size, 6 × 6array of solder balls. The geometry of simulation is depicted in Figure-6. The flow is based entirely on capillary pressure with zero inlet velocity specified. Under fill material Hitachi CEL-9000 (LF) (Schwiebert and Leong, 1996) and air are defined in the analysis. Table-2 summarizes the material properties. The bottom and top surfaces in the left half of the channel are shown with a bounce back boundary condition imposing a given static contact angle.

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Periodic boundary conditions are imposed in the right half of the channel at top and bottom surfaces in order to mimic an "infinite reservoir". Periodic boundary conditions are also imposed at the two lateral sides such to ensure total mass conservation inside the system (Sukop, 2007). At the solid surface, bounce back boundary conditions for the particle distributions are applied (Succi, 2011).

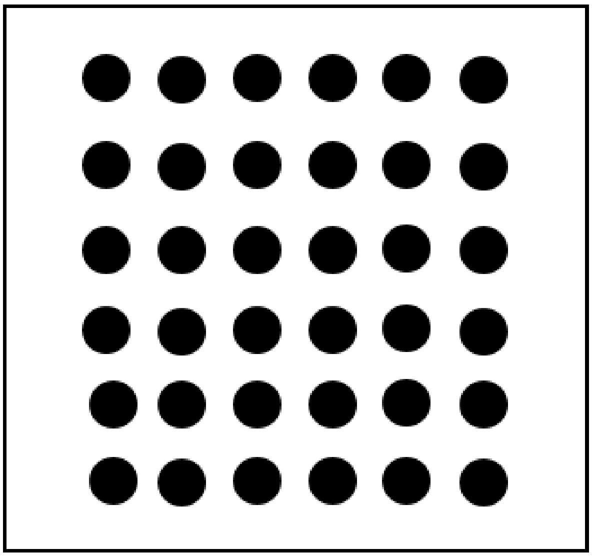

Figure-5. 3D Full array BGA orientation.

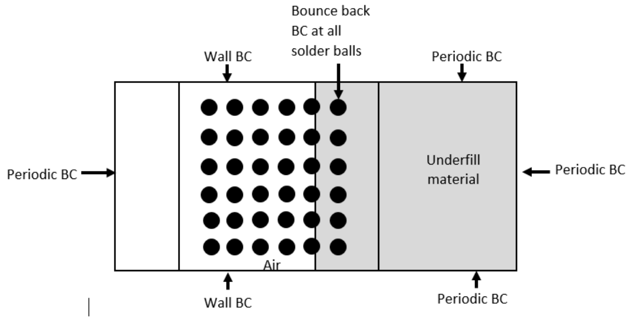

Figure-6. LBM boundary conditions setup for periodic and bounce back conditions.

Table-2. Material properties of under fill material [11].

Parameter	Value
ρ (g/cm^3)	1.7
c_p(erg/g K)	9.46E+06
k (erg/cm K s)	6.56E+04

RESULTS AND DISCUSSIONS

Filling Time Comparison between LBM and FVM

During encapsulation, the filling time was assessed at different filling percentage for both LBM and FVM. Figure-7 depicts the multiphase flow front propagation at different filling percentage. The level of detail observed in LBM based software is apparent compared to FVM based software. The formation of bubble can be observed towards the end of 80 percent filling. This bubble could lead to localize stress concentration which in time leads to cracking at this area.

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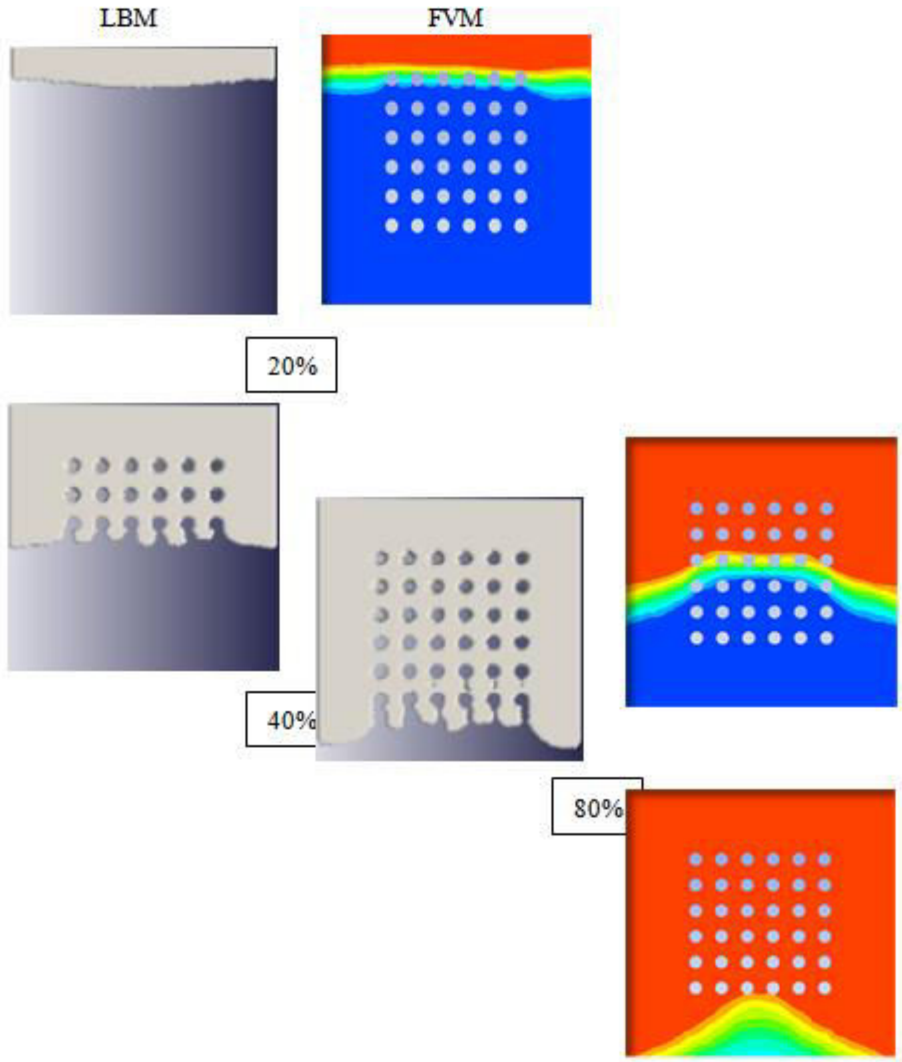

Figure-7. Percentage of volume of fraction (VOF) contour at different filling time.

In terms of filling time, comparable filling time can be observed for both LBM and FVM based software as observed in Table-3. Slight difference might be due to different numerical setup between the two softwares.

Table-3. Filling time for both LBM and FVM at different filling percentage [11].

Filling (%)	Filling time (s)	
	LBM	FVM
20	20	20
40	95	100
80	185	187

Grid Independent Study

The reliability of the obtained results is ensured by optimizing the mesh size for FVM or the number of lattice for LBM. The value of velocities are computed at 20% filling for both FVM and LBM formulations. Table-4 shows the convergence of velocity for FVM formulation as the number of tetrahedral elements is increased. In contrast, Table-5 shows velocity convergence with increasing number of D3Q19 lattices.

Table-4. Velocity at 20% filling for FVM formulation.

No. of elements	Velocity (m/s)
180444	0.0016288
251493	0.00103243
377596	0.000738456
397146	0.00079649

Table-5. Velocity at 20% filling for LBM formulation.

No. of lattices	**Velocity(m/s)**
3220	0.000836594
25760	0.000794981
86940	0.000746982
206080	0.000763779

In comparison, better convergence can be observed for LBM formulation with D3Q19 lattice. High number of lattice points per lattice meant more accurate results is achievable even with low number of lattices. For FVM formulation, for mesh with number of elements higher than 3.7×10^5 the velocity solution is comparable up to significant figures. It can be concluded that the mesh is independent of the number of elements beyond this point.

CONCLUSIONS

The preliminary simulation provides a brief visualization of the BGA encapsulation process with respect to its filling percentage and time. The results have shown that comparable results can be obtained between both LBM and FVM based software. In terms of filling time, slight difference in time could be attributed to different setup between both LBM and FVM based software. Given the capability of LBM in modelling of high level 3D flow, it could provide a viable option in years to come. For future work, the current full array 6 x 6 BGA orientations will be varied according to other cost effective design. Reducing the number of solder balls could provide good cost saving opportunity for the developer.

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