PARTICLE-FLUID SIMULATION OFFLIP CHIP CAPILLARY UNDERFILLPROCESS USING DISCRETE PHASE MODEL

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Abstract— This paper investigates a capillary underfill flow in flip-chip encapsulation with the consideration of filler-particles that is being dispersed in the epoxy resin to form underfill fluid. Two-ways coupled particle/fluid simulation have been implemented for the application of capillary underfill using discrete phase model (DPM). The flow front together with the instantaneous positions of filler particles and its velocity have been depicted at selected filling progression. The pressure contour and velocity streamlines of the underfill flow were computed and presented. The necessity of considering the particulate phase of filler particles in simulating the underfill process have been emphasized. While past numerical studies regard the underfill as single immiscible fluid upon neglecting the filler, current methodology would shed a new light in the future of underfill researches and optimization of filler technology.

Indexed Terms—Capillary underfill,Discrete phase model (DPM),Flip-chip encapsulation

I. INTRODUCTION

Capillary underfill process is carried out to enhance the reliability of flip-chip devices, protect it from external unfavorable environment and contamination, as well as served as heat sink and prevent the occurrence of thermal mismatch [1]. Due to the growing importance of underfill encapsulation in electronic packaging, various researches have been conducted using both numerical simulation and experiments during the past decades [2] – [4].

Some typical numerical methodologies are fluid-structure interaction (FSI) [2], lattice Boltzmann method (LBM) [3] and finite element method (FEM) [4]. There are also mathematical models being constructed to predict the underfill flow in flip chip [5], [6]

It noteworthy to mention that almost all numerical simulations conducted in relevant topics have made a critical assumption that underfill fluid to be in the form of immiscible fluid. This effectively neglected the presence of dispersed filler particles in the underfill material. In an actual preparation of underfill process, polymeric resin,such as epoxy, are filled with silica fillers to reduce the effective coefficient of thermal expansion (CTE) of the underfill fluid [7].

This composite underfill material will enhance tensile strength and therefore improve the package's reliability [8], [9]. In the conventional underfill researches conducted, the filler particles were not being modelled. Instead, the underfill material is treated as a non-Newtonian fluid that assume both the filler particles and epoxy resin are well-mixed. The drawbacks are the simulation made with such critical assumption may not accurately describes the actual situation and the phenomenon associated with the filler particles such as filler settling and filler accumulation.

Euler-Lagrange (EL) two-ways coupling strategy is implemented in the numerical scheme to simultaneously track the particles motions in fluid flow and both phases that continuously interact with each other [10], [11].

This becomes the main frame of particle-fluid simulation. One commercially available particle-fluid simulation is the discrete phase model (DPM) that is commonly applied on finite volume based software [12]. DPM has been proven as viable method in simulating various physical and engineering application, for instance fluidized beds [13] and powdered flow in junction [14]. Recently, DPM using finite volume method (FVM) discretization scheme had successfully being applied in electronic packaging for flip-chip application to optimize the filler loadings in composite-underfill [15]. Therefore, it is justified that DPM is a viable methodology to study the particle/fluid flow that is essentially applicable for the current case of composite-underfill with the consideration of filler particles.

In this research, DPM together with conventional volume of fluid (VOF) model is being utilized to visualize the three-dimensional flow of underfill through the gap beneath a micro-scale flip chip device during encapsulation process. Silica (SiO2) filler particle will be modelled together with the epoxy resin and upon mixing will form a composite-polymeric material, known as underfill. The rheological advancement of underfill across the flip-chip will be presented in this paper, together with the pressure contours and velocity streamlines. The silica filler particle's instantaneous position and distributions that rarely are reported in literature, would be implemented in the current paper.

II. NUMERICAL SIMULATIONS

The capillary underfill process in flip-chip is modelled as a three-dimensional, laminar, incompressible and unsteady fluid flow. The rectangular fluid domain in this simulation measures 6.7 × 6.7 × 0.25 mm^3, consisting of a square array of 10 × 10 spherical solder bumps with diameter of 0.3 mm arranged with pitch size of 0.6 mm. Fine tetrahedral mesh for the fluid domain is generated as shown in Fig. 1, containing a total of 838,689 elements.

Volume of fluid (VOF) is used to track the multiphase Eulerian flows of air (primary phase) and epoxy resin (secondary phase); while discrete phase model (DPM) is adopted to track the particulate phase of silica fillers in Lagrangian frame. The governed equation for continuous phase is Navier-Stokes while the Newtonian force balance is prime equation to be solved in the particle tracking, given in Eq. (1) and Eq. (2) respectively [12].

$$\frac{\partial}{\partial t}\left(\rho_f \vec{\mathbf{u}}\right) + \nabla \cdot \left(\rho_f \vec{\mathbf{u}} \cdot \vec{\mathbf{u}}\right) = -\nabla p + \nabla \cdot \bar{\bar{\boldsymbol{\tau}}} + \rho_f \vec{\mathbf{g}} \quad (1)$$

$$\frac{\mathrm{d}\vec{\mathbf{v}}_p}{\mathrm{d}t} = F_D\left(\vec{\mathbf{u}} - \vec{\mathbf{v}}_p\right) + \vec{\mathbf{g}}\frac{(\rho_p - \rho_f)}{\rho_f} + \vec{\mathbf{F}}_L + \vec{\mathbf{F}}_{VM} \quad (2)$$

Such Eulerian-Lagrangian two-ways coupled simulation for particle/fluid system have been established through the Fluent module using jointly implicit, SIMPLE algorithm scheme and second-order upwind scheme solver. In this simulation, silica filler particles are assumed to be perfect sphere having diameter of 0.1 µm and density of 2650 kg/m^3, with mass loading of 20% (9.8% by vol.). The epoxy resin is assumed to be Newtonian fluid having density of 1500 kg/m^3 and viscosity of 1.0 Pa-s. The surface tension of liquid/gaseous interface is 0.0102 N/m and contact angle at bumps and walls being constant at 32.5°.

The capillary underfill is modelled based on the boundary condition such that inlet/outlets pressure are set equal to the atmospheric pressure (0 Pa). On the flow front, the gaugepressure is equal to the capillary pressure, $\Delta p_c \approx \frac{2\sigma\cos\theta}{h}$, for liquid/gaseous interfacial. Initial velocity for inlet for fluid flow and silica fillers is zero, implying a pure capillary driven process. At upper and lower walls (corresponds to the flip-chip and substrate respectively) and walls of solder bumps, stationary boundary condition is being imposed, such that all velocity components are zero (refers to Fig. 1).

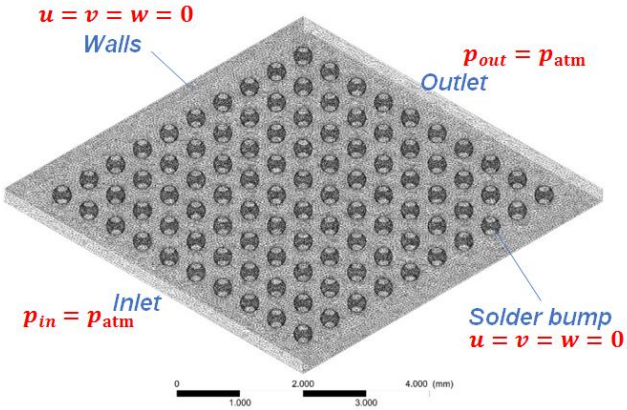


Fig. 1. Tetrahedral mesh models of the fluid domain in 10 × 10 grid array of solder bumps, together with an overview of boundary condition.

III. RESULT AND DISCUSSIONS

Through the implementation of discrete phase model (DPM) in Ansys, the three-dimensional underfill flow with the consideration of mono-dispersion of silica-fillers in epoxy resin have been successfully simulated. The flow front advancement together with the instantaneous position and velocity of fillers at selected filling stages of 40% and 80% are presented in Fig. 2. It is found that generally the particle distribution of silica fillers in the epoxy resin are uniform, consistent with the fact of uniform dispersion and mixing of silica fillers during preparation of underfill material. However, minor fillers accumulation being observed at the region near-inlet, causing slight localized increase in filler number density. This is caused by the collision and bounce-back of silica particles with the first-row solder bumps near the inlet. Furthermore, the velocity magnitude of silica particles are much lower near the inlet compared to elsewhere, as the inelastic collision with the bumps have partially depleted the kinetic energy. Silica fillers possess higher velocity as the flow progresses at the unobstructed pathway due to no collision with the solder bumps. Such filler accumulation near the inlet become more prominent at later stage of underfill (80% filling) as more fillers being noticed in the first two row of bumps. This is due to the occurrence of bump collision that increases as more fillers were being introduced into the flip-chip's gap.

Fig. 3 displays the gauge pressure contours for the fluid phase (epoxy resin) during capillary underfill flow through the gap of flip-chip at different fillings progression of 40% and 80%. As the underfill flow is assisted by capillary action, it is expected that the flow front possesses a constant negative gauge pressure throughout the flow that is equal to the magnitude of capillary pressure of about 60 Pa. Both inlet or outlet pressures are equal to the atmospheric

pressure (0 Pa) as preset in the boundary conditions. The dynamic pressure of the fluid decreases almost linearly from inlet toward the flow front, such that the pressure gradient gradually decreases as the underfill fluid advances through the solder bump. Therefore, based on the Darcy's law, the lower in pressure gradient would causes the underfill fluid to gradually decelerate, such that slower underfill flows would be observed at higher filling percentage.

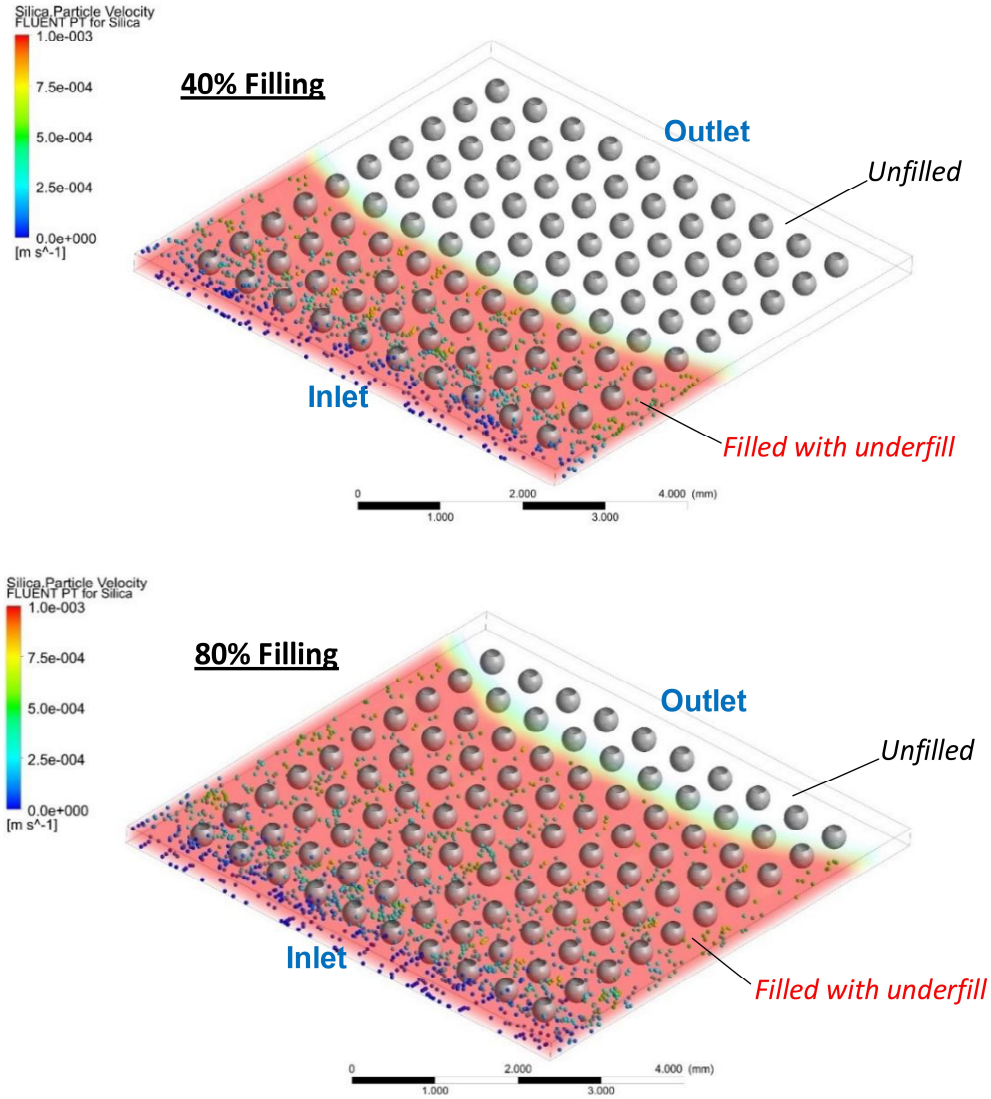


Fig. 2.Underfill Flow In Flip-Chip With The Depiction Of Instantaneous Silica Particle's Position And Velocity At 40% And 80% Fillings.

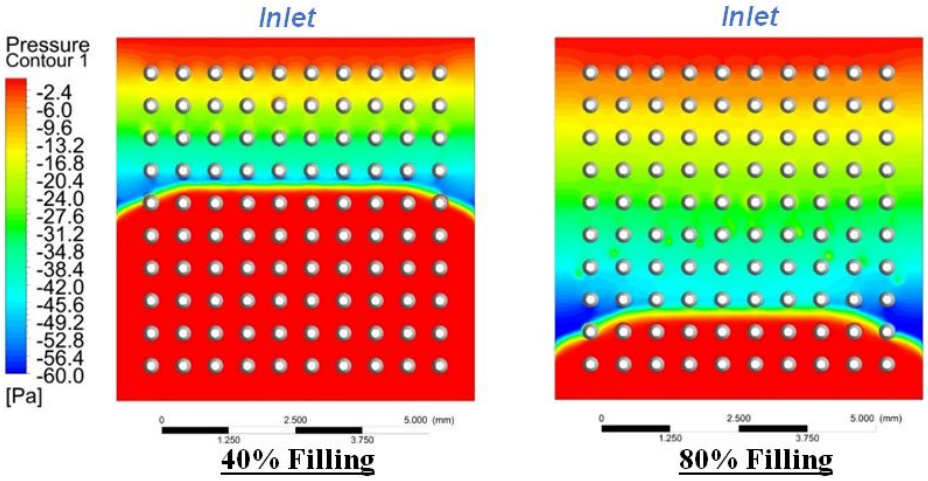


Fig. 3. Gauge pressure (Pa) contours for the epoxy resin phase in underfill fluid at filings progress of 40% and 80%.

Fig. 4 depicted the velocity streamlines for fluid (epoxy resin) together with the velocity magnitude of silica fillers when the underfill process is about near completion (approx. 100% filling). First observation can be made is that the fluid streamlines is sinusoidal along the unobstructed path and did not fully pass the regions hindered by two vertically adjacent bumps along the flow direction. Generally, it is noticed that silica particles tend to follow closely the fluid's streamlines and both velocities of particle/fluid at small region are relatively similar. This is consistent with the argument that the dispersion of small silica filler in highly viscous, slow moving epoxy resin would yield a very low Stokes number, $\mathrm{Stk} = \frac{\rho_p d_p |\vec{\mathbf{u}}|}{18\mu_f} \ll 1$ [16]. Through these velocity data, ones can have inferred that the silica fillers interacted with the fluid phase of epoxy resin in this two-ways coupled simulation, which also accounted the particle's collision with the wall of bumps.

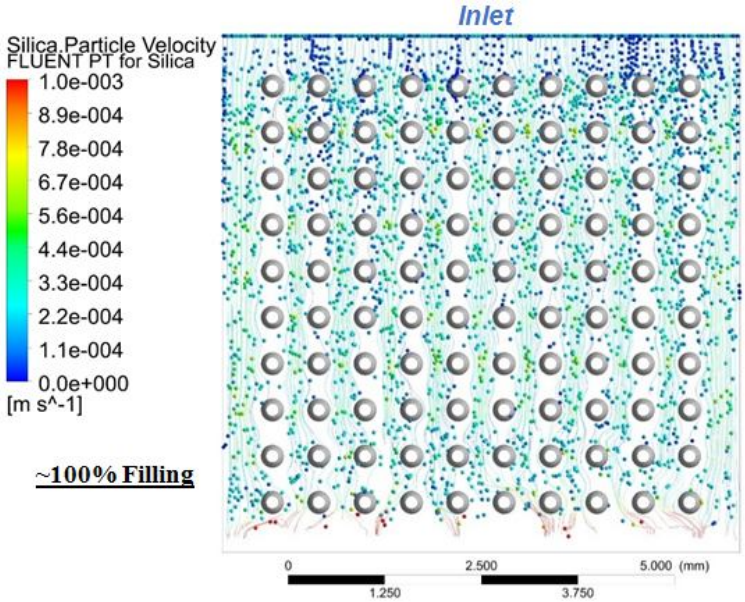


Fig. 4.Fluid's velocity streamlines with particle's instantaneous position and its velocity at near filling completion.

CONCLUSIONS

In this paper, underfill fluid had been modelled as the heterogeneous mixture of epoxy resin and silica fillers through two-ways coupled particle-fluid simulation, known as discrete phase model (DPM). While almost all existing underfill researches did not separately consider the dispersed filler particles as secondary phase during simulation, an improvement was made on the numerical methodology in the underfill application to include the fillers particles aimed to attain more accurate results and able to gain insight of the influence of fillers particles to the overall flow. It is found that during capillary underfill process of flip-chip, the particle distribution of silica filler is relatively uniform. However, minor fillers accumulation was found near the inlet due to the collision with the first-row solder bumps being observed leading to reduction of the filler's velocity. The pressure of the fluid (epoxy resin) gradually drops along the filling progression with the pressure at flow front maintained at 60 Pa equals to the capillary pressure. Further, it is found that the velocities of silica fillers and epoxy resin are relatively similar at certain region, suggesting the filler particles closely follow the fluid flow which might be attributed to the low Stokes number used.

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