

Effect of solidification on solder bump formation in solder jet process: Simulation and experiment

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Abstract: To investigate the influence of the solidification on the solder bump formation in the solder jet process, the volume of fluid (VOF) models of the solder droplets impinging onto the fluxed and non-fluxed substrates were presented. The high speed camera was used to record the solder impingement and examine the validity of the model. The results show that the complete rebound occurs during the process of the solder droplet impinging onto the fluxed substrate, whereas a cone-shaped solder bump forms during the process of the solder droplet impinging onto the non-fluxed substrate. Moreover, the solder solidification results in the lift-up of the splat periphery and the reduction in the maximum spread factor.

Key words: solder bump; solder jet; solidification; simulation; volume of fluid(VOF)

1 Introduction

Solder jet is widely used to fabricate bumps on chip in electronic packaging[1–3]. It is well-known that the bump shape determines the reliability during service[4–6]. Accordingly, it is crucial to predict the solder bump shape in microelectronic component packaging.

In recent years, various theoretical models, such as the truncated sphere model, the force-balanced solution and the energy-based method, have been developed to predict solder geometry in electronic packaging[7–8]. Among these models, the surface evolution based on the minimum energy is most frequently used to evaluate and optimize the packaging processing[9–11]. However, these models are based on the static or quasi static theories, and can only predict the final bump shape rather than the solder shape evolution. They are competent for predicting the bump formation under the equilibrium conditions, such as the hot-air reflow bumping, which is long enough for the solder to reach its wetting balance on the substrate. For the solder jet bumping process, the solder will solidify during the impingement because the solder droplet itself has a small amount of heat. It is necessary to develop a model that accounts for the

kinetic and solidification effects to predict the solder bump formation under nonequilibrium conditions.

Development of the free surface flow modeling technique provides feasibility for modeling the droplet impingement onto the substrate. At present, the studies on the prediction of the molten metal droplet impingement are almost limited in the field of thermal spraying of liquid metal droplet[12–15]. The process parameters for thermal spraying, such as the droplet materials, the droplet diameter, the impact velocity and the substrate materials, are completely different from those in the solder jet bumping process. Only a few studies are about the solder bump formation, but are still restricted either to the SnPb[16–17] and pure indium solders[18], or to partial computational fluid dynamics(CFD) models based on a lot of unrealistic assumptions[19]. The global trend of lead free soldering makes lead-free solders, especially the SnAgCu solder, gradually substitute for the Sn-Pb solder in solder jet packaging. However, few studies have been devoted to simulating the SnAgCu solder bump formation during the solder jet process.

The aim of the present work is to develop a full CFD model based on VOF method to predict the solder bump formation during the solder jet process, which will provide a fundamental understanding of the role of the

solidification in the solder jet bumping process.

2 Computational model

2.1 Mathematical formulation

The governing equations for incompressible fluid flow can be written as follows using two-dimensional cylindrical coordinates. The equation of mass continuity is

$$\frac{1}{r} \frac{\partial}{\partial r} (urA_r) + \frac{\partial}{\partial z} (wA_z) = 0 \quad (1)$$

where u and w represent the velocity components in the radial and axial directions, respectively, and A_r and A_z represent the fractional areas open to flow in coordinate directions r and z . The momentum equations for the radial component and the axial component can be respectively written as

$$\frac{\partial u}{\partial t} + \frac{1}{V_f} \left\{ uA_r \frac{\partial u}{\partial r} + wA_z \frac{\partial u}{\partial z} \right\} = -\frac{1}{\rho} \frac{\partial p}{\partial r} + f_r + F_{sr} + S_u \quad (2)$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_f} \left\{ uA_r \frac{\partial w}{\partial r} + wA_z \frac{\partial w}{\partial z} \right\} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + f_z + g + F_{sz} + S_w \quad (3)$$

In the above equations, V_f denotes the fractional volume open to flow, ρ is the fluid density, p is the pressure, g is the gravitational acceleration, f_r and f_z are the viscous accelerations, F_{sr} and F_{sz} are the surface tension terms, and S is a temperature-dependent source term required for the solidification model, which is based on the drag concept. S is equal to zero, when the solder is fully molten, which becomes a very large value when solidification is completed, and will have a finite intermediate value depending on the solidification in the mushy zone.

The free face of fluid is tracked using a volume of fluid function, F , which has a value between zero and unity, satisfying the conservation equation:

$$\frac{\partial F}{\partial t} + \frac{1}{V_f} \left[\frac{1}{r} \frac{\partial}{\partial r} (FA_r ru) + \frac{\partial}{\partial z} (FA_z w) \right] = 0 \quad (4)$$

The energy conservation equation can be expressed in terms of a macroscopic enthalpy balance as

$$V_f \frac{\partial}{\partial t} (\rho H) + \frac{1}{r} \frac{\partial}{\partial r} (\rho H u A_r r) + \frac{\partial}{\partial z} (\rho H w A_z) = -p \cdot \left\{ \frac{1}{r} \frac{\partial u A_r r}{\partial r} + \frac{\partial w A_z}{\partial z} \right\} + \frac{1}{r} \frac{\partial}{\partial r} \left(k A_r r \frac{\partial \theta}{\partial r} \right) + \frac{\partial}{\partial z} \left(k A_z \frac{\partial \theta}{\partial z} \right) \quad (5)$$

where H is macroscopic internal energy, k is heat conductivity. In this formulation, we follow a customary procedure of treating the melt and the solid as a continuum, which may be represented in terms of their

enthalpy.

Here, energy is assumed to be a linear function of temperature and can be expressed as

$$H = c\theta + (1 - f_s)L \quad (6)$$

where c is the specific heat, f_s is the solid fraction and L is the latent heat. The latent heat associated with the melting or freezing can be defined by specifying the solidus temperature, θ_s , the liquidus temperature, θ_l , and the specific energy of the phase transformation will occur between these two temperatures, L . In this case, the latent heat is removed linearly with temperature between θ_l and θ_s .

2.2 Boundary conditions, initial conditions, assumptions and grid

The boundary conditions needed to specify the fluid flow problem are

1) Symmetry about the centerline.

2) Free surface: the surface tension force is replaced by an equivalent surface pressure using continuum surface force (CSF) method [20]. The equivalent surface pressure can be written as

$$F_{sr} = -\sigma \left(\nabla \cdot \left(\frac{\nabla F}{|\nabla F|} \right) \right) \frac{\partial F}{\partial r} \quad (7)$$

$$F_{sz} = -\sigma \left(\nabla \cdot \left(\frac{\nabla F}{|\nabla F|} \right) \right) \frac{\partial F}{\partial z} \quad (8)$$

In addition, the tangential stresses on the free surface are set to be zero.

3) No slip at the solid boundaries.

4) Wall adhesion: The wall adhesion was modeled in a manner similar to that of the surface tension in the case of a gas/liquid interface, except that the unit normal $\hat{n}$ in this case was evaluated using the contact angle θ as follows:

$$\hat{n} = \hat{n}_w \cos \theta + \hat{t}_w \sin \theta \quad (9)$$

where $\hat{n}_w$ and $\hat{t}_w$ are the unit vectors normal and tangential to the wall.

The boundary conditions pertaining to the heat-transfer problem are

1) Symmetry about the axial centerline;

2) Adiabatic free surface;

3) The rate of heat extraction by the chill at the droplet/substrate interface is given in terms of a convective heat-transfer coefficient h :

$$q = h A_w (\theta_w - \theta) \quad (10)$$

where q is the local heat flux, A_w is the contact area between the solder and the substrate, and θ_w is the substrate temperature.

In addition, the initial temperature of solder droplet is 250 °C, and the initial temperature of substrate is 25 °C.

The principal assumptions made in the modeling are as follows: 1) the contact angle between the wall and the tangent to the interface at the wall is assumed to be constant; 2) no undercooling or recalescence phenomenon is considered; 3) the interfacial heat transfer coefficient is assumed to be constant; and 4) all material properties are assumed to be independent from temperature.

The equations are solved using a code based on VOF finite-difference technique. Most terms in the equations are solved using an explicit computational scheme, but the coupling between the pressure and velocities is implicit. This semi-implicit formulation is solved using the successive over-relaxation(SOR) method, with a modified alternating-direction-implicit (SADI) iterative scheme to accelerate convergence. Fig.1 shows the typical definition of the flow region, as well as the spatially uniform grid used in the simulation of droplet impingement on the substrate. Table 1 lists the solder properties used in the model.

3 Experimental

In order to examine the validity of the simulation, a high speed videography system was designed to capture the solder profile at each moment. The main components of the apparatus are a translation stage, a solder droplet generator, a gas chamber, an x - y precision work stage, and a high speed camera with data acquisition system. A schematic drawing of the experimental setup is shown in Fig.2. The solder droplet chamber is fitted with the translation stage at the top of the gas chamber. The solder droplet generator utilizes a temperature controlled unit to

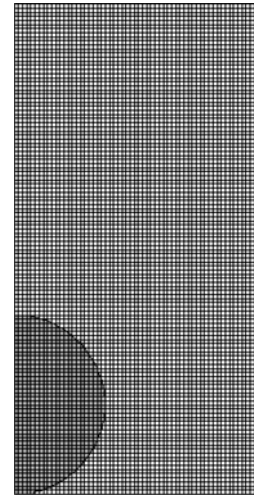


Fig.1 Definition of fluid region (dark region) and typical computational domain mesh for calculations of droplet impingement onto substrate (z - r plane: 60×120 grids)

heat the Sn3.0Ag0.5Cu solder to the molten state and a pressure-driven unit to squeeze molten solder droplets out of the nozzle. The droplet would fall in the chamber filled with ambient gas and Ar, for a distance before it impacts on the substrate. The substrate is placed on the x - y work stage to reach the intended location precisely. The falling height can be adjusted to achieve an intended impinging velocity. The high speed camera (DALSA 0256) is capable of recording 955 frames per second and is fitted with a Japan AVENIR CCTV 16 mm lens to magnify the small solder droplet throughout the spreading process. The rapid motion involved in the solder impingement was captured by EPIX video acquisition system. The XCPTM image analysis system

Table 1 Physical properties of Sn3.0Ag0.5Cu

$\rho/(\text{kg}\cdot\text{m}^{-3})$	$\mu/(\text{Pa}\cdot\text{s})$	$\sigma/(\text{N}\cdot\text{m}^{-1})$	$\theta/^\circ\text{C}$	$\theta_s/^\circ\text{C}$	$k/(\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{C}^{-1})$	$c/(\text{J}\cdot\text{kg}^{-1}\cdot^\circ\text{C}^{-1})$	$L/(\text{J}\cdot\text{kg}^{-1})$
7 500	0.002	0.431	221	216	73	250	64 762

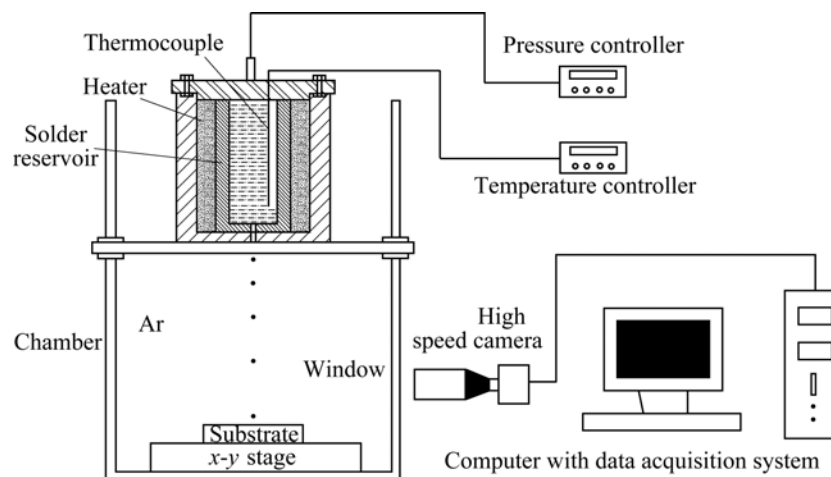


Fig.2 Schematic diagram of experimental setup

was used to control the beginning of the capture and analyze the pictures captured to achieve some useful data.

Two kinds of substrates, collar clad (CCL) plate coated with RMA flux and CCL plate coated without flux, were used as the experimental substrates. It is known that flux is often used to remove the surface oxide of the substrate in electronic manufacturing. However, herein, the flux does not remove the oxide but provides a comparison case without solidification for solder bump formation. No solidification occurs in the case of droplet impingement on the fluxed substrate because the flux will be heated to vapor as the droplet touches the substrate, which efficiently prevents the heat dissipation from the solder to the substrate. So the fluxed substrate has a low interfacial heat transfer coefficient. The non-fluxed substrate contrarily has a high heat transfer coefficient due to a high heat conduction of pure copper foil on the surface of substrate. The substrates must be cleaned in the ultrasonic machine to remove the surface contaminants before the experiment.

4 Results and discussion

4.1 Solder droplet impingement onto fluxed substrate

The dimensionless parameters, Reynolds number $Re = \rho d_0 w_0 / \mu$, Weber number $We = \rho d_0 w_0^2 / \sigma$, Capillary number $Ca = \mu w_0 / \sigma$, and Bond number $Bo = \rho g d_0^2 / \sigma$, are used to impart a measure of generality and qualify the relative importance of each force in the droplet impingement spreading process. Here, d_0 is the initial droplet diameter; and w_0 denotes the impact velocity. For the case of a 2.2 mm-diameter droplet impinging on the

substrate at a velocity of 0.5 m/s, the values of the four numbers are as follows: $Re=4\ 125$, $We=9.57$, $Ca=0.002\ 3$, $Bo=0.825$. It is obvious from the above values of the dimensionless parameters that the inertial and surface tension forces dominate the solder impingement process, whereas, the viscous and gravitational forces are negligible.

Fig.3 shows the simulated solder shape evolution of a 2.2 mm-diameter solder droplet impingement on fluxed substrate at a velocity of 0.5 m/s in the absence of solidification. Here, we examined the calculated results with different contact angles and found a good agreement between the calculated and the experimental data when the contact angle is equal to 140° . The average contact angle measured by MEGARIDIS et al[21] in the partial rebound of molten metal droplet impinging on a solid substrate is 145° , which is very close to the value used in this work. Heat transfer and solidification were negligible in this analysis for no solidification was observed in the impingement process. In the droplet spreading process, the inertial and gravitational forces are the driving forces, while the viscous and surface tension forces are resistance forces. Because the driving forces are far greater than the resistance ones at the beginning, the spread diameter increases greatly and the surface energy increases correspondingly. The outflow molten solder will accumulate at the periphery to form a toroidal rim. The spread diameter reaches the maximum value at the moment $t=3.1$ ms, when most of the kinetic energies are converted into the surface energy and partly dissipated by the viscous force. Subsequently, the spreading lamella will recede toward the center to release the surface energy. The surface and the remaining kinetic energy in the liquid lamella at the end of the spreading

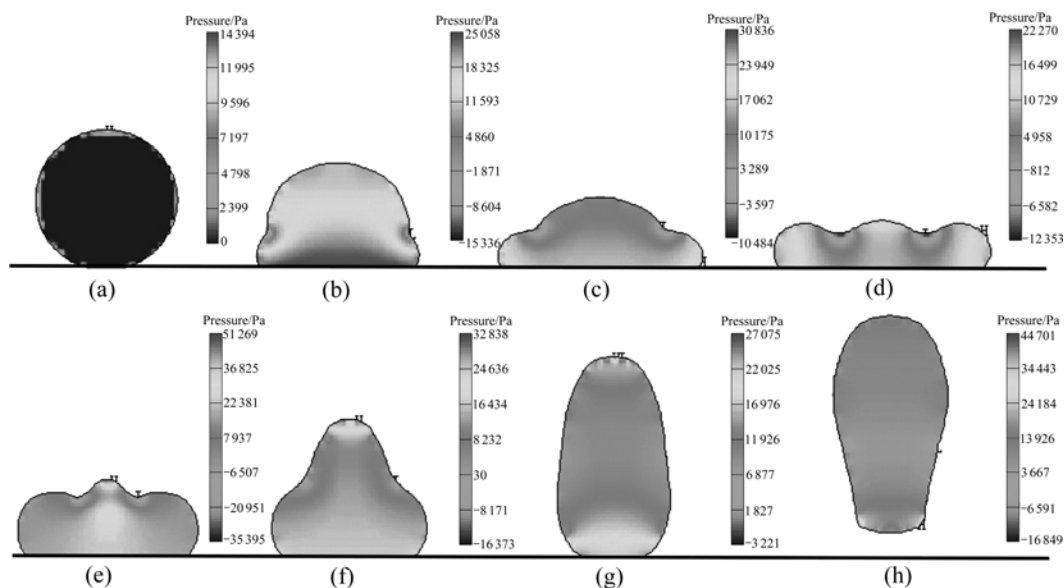


Fig.3 Simulated deformation and pressure distribution of 2.2 mm-diameter solder droplet impingement onto fluxed substrate at velocity of 0.5 m/s: (a) $t=0$ ms; (b) $t=1.1$ ms; (c) $t=2.1$ ms; (d) $t=3.1$ ms; (e) $t=5.2$ ms; (f) $t=6.3$ ms; (g) $t=8.4$ ms; (h) $t=10.5$ ms

stage may be sufficiently large but not to be fully dissipated at the receding stage. In such case, the kinetic energy may suffice to squeeze liquid upward from the surface to form a rising liquid column. And then the droplet is elongated and detaches from the surface as an intact drop (complete rebound). The subsequent droplet behaviors are impossible to be observed for the visualization limitations of high speed camera. So only the first spreading cycle was studied.

Fig.4 shows a series of pictures captured by high speed camera of a 2.2 mm-diameter solder droplet impinging onto the fluxed substrate at a velocity of 0.5 m/s. Clearly, the calculated solder profile is in good agreement with that from the experiment by comparing Fig.3 with Fig.4 except the last one, which corresponds to the completely rebound stage. MEGARIDIS et al[21] used Froude number, $Fr = w_0^2 / (d_0 g)$, a number scales the importance of inertia compared with gravity, as a partial rebound criterion, and found that partial rebound will occur if $Fr > 144$. As a complete rebound scenario, the impingement droplet should be with a higher value of Fr . In the above case of droplet impinging onto the fluxed substrate, the value of Fr is equal to 11.58, which does not agree with the MEGRAIDIS's criterion. This indicates that factors other than inertia and gravity may affect the rebound behavior in the present study. Previous research[22] has shown that rebound is facilitated by elevated surface temperatures, especially when the Leidenfrost effect sets in and the drop is propelled

upward by vapor at its base. Although the substrate is cold in this work, the flux will be evaporated during the solder droplet impinging, and this serves the same function with the Leidenfrost effect. The difference of the last picture in Fig.3 and Fig.4 is just ascribed to action of the flux vapor to the droplet impingement. To predict the completely rebound behavior more accurately, a vapor flow by film boiling must be incorporated in the model[23]. However, the rebound behavior is not the focus in the present study. It is primary as a comparison of the case with solidification. Although the action of the flux vapor on the droplet is not considered in the present model, the predicted results are in good agreement with the experimental ones except that the moment of the droplet completely rebounds. It can be concluded that the vapor plays only a minor role at the early stages of the droplet spreading.

4.2 Solder droplet impingement onto non-fluxed substrate

Predictions from the computer model of droplet impact are sensitive to the values of two input parameters: the liquid-solid contact angle(θ), and the thermal contact resistance(R_c) at the droplet/substrate interface. Due to the similar initial spreading behaviour compared with the case impingement onto the fluxed substrate, the same value of $\theta = 140^\circ$ was used in the simulation. The thermal contact resistance is caused by the roughness of the solid surface and gas entrapment. It is expressed as the reci-

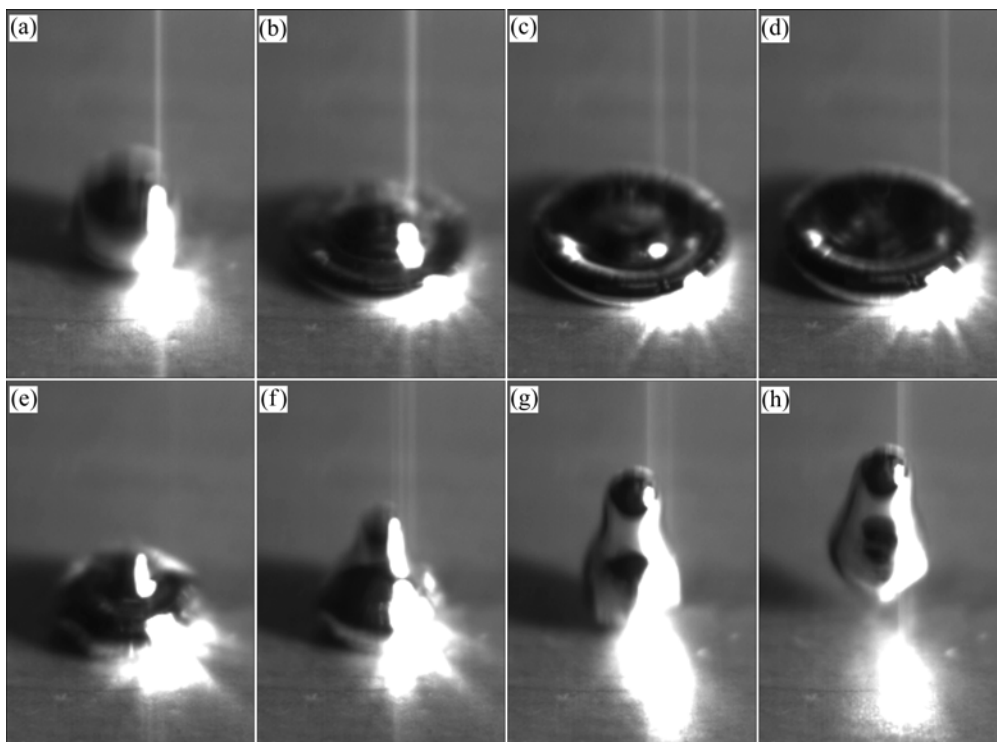


Fig.4 Experimental results of 2.2 mm-diameter solder droplet impingement onto fluxed substrate at velocity of 0.5 m/s: (a) $t=0$ ms; (b) $t=1.1$ ms; (c) $t=2.1$ ms; (d) $t=3.1$ ms; (e) $t=5.2$ ms; (f) $t=6.3$ ms; (g) $t=8.4$ ms; (h) $t=10.5$ ms

procal of an interfacial heat transfer coefficient. The rate of the heat transfer from the molten metal to the substrate is often limited by the thermal contact resistance. However, as a practical matter, interfacial heat transfer coefficient is quite difficult to be evaluated directly from the experiment. The usual solution method is to fit the experimental results to either a numerical[24] or analytical[25] model. In this work, the convective heat transfer coefficient is determined to be $1 \times 10^6 \text{ W}/(\text{m}^2 \cdot \text{K})$ by fitting the instant solder profiles captured by high speed camera with the numerical predictions.

Fig.5 shows the evolution of the solder bump formation onto the non-fluxed substrate. As a result of directional heat removal, the lower layers of the droplet solidify at a planar mode after it contacts with the substrate. The deformation behaviours of the solder droplet at the first 3 ms are similar to those in the case of impingement onto the fluxed substrate. Solidification seems to play a minor role in the early stages of droplet spreading. However, the solidification leads to a lift-up of the periphery of the splat compared with the tight touch with substrate in the case of droplet impingement onto the fluxed substrate. In addition, the loss of kinetic energy due to the solder solidification will cause a decrease of the maximum spread factor. Afterwards, the accumulated molten solder at the periphery will recede under the surface tension forces, and then bridges at the center of the splat (5.2 ms). The receding molten solder will fill the gap between the bridge and the bottom solidified solder, and finally a very thin gap remains. The lift at the splat periphery diminishes with the proceeding of the receding process. Moreover, the solidification direction in this stage is not vertical but from the side to center. And then the molten solder rises from the center. Subsequently, a spreading and recoiling oscillation process occurs coupled with the solidification of the

solder. Some ripples will form on the bump surface. Because the maximum capturing speed of high speed camera used in the present study is 955 frame/s, which is too low to capture the rapid oscillatory motion. In addition, due to a low resolution of high speed camera and the solidification shrinkage, the ripples are not evident in the captured pictures. The total solidification time of the droplet in the case is 15.8 ms and the final bump is approximately cone-shaped. Fig.6 shows the captured solder droplet evolution process. It is found that the predictions are in excellent accordance with the experiment.

The spread factor variation with time was used to qualitatively examine the validity of the prediction. Here, the spread factor is defined as $\xi = d/d_0$, where d denotes the dynamic contact diameter. Fig.7 shows the comparison of the predicted spread factor with the experimental one. This figure clearly indicates that the maximum spread factor of the droplet impingement onto the non-fluxed substrate is less than that of the impingement onto the fluxed substrate due to the kinetic energy loss by solidification. The predicted results of droplet impingement onto the non-fluxed substrate show that the spread reaches its maximum at about 2.1 ms, and then remains at a constant contact value. But the experimental results illustrate that the spread reaches its maximum at about 2.1 ms, and then recedes, after 3 ms it remains at a constant value. The difference between the results predicted and those of the experiment is because that the spread factor here is defined using contact diameter, not the maximum diameter of the solder profile. Owing to the poor resolution of the captured pictures, it is optically blurry in the region between the equator diameter and the substrate. It is difficult to recognize the contact boundary from the picture. So the measurement errors are unavoidable. However, in general, the model can

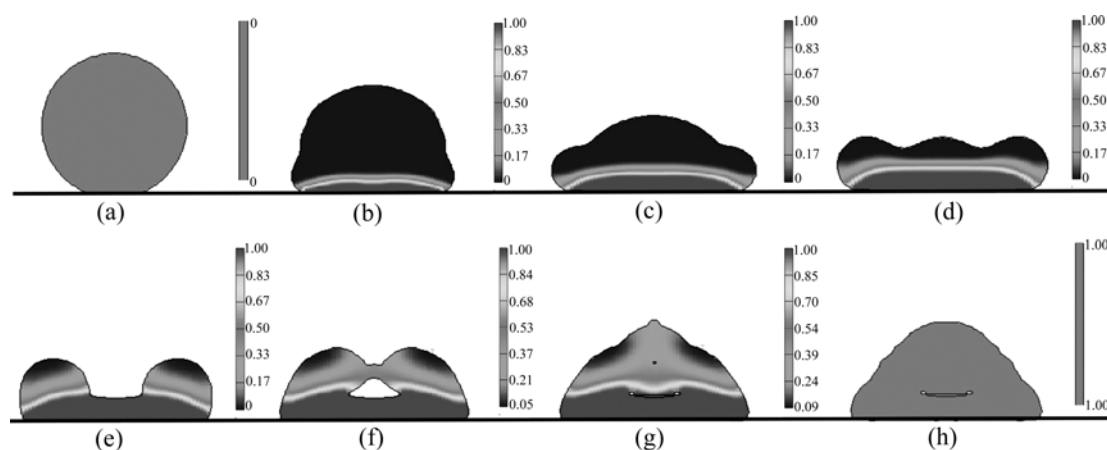


Fig.5 Simulated deformation and solidification of 2.2 mm-diameter solder droplet impingement onto non-fluxed substrate at velocity of 0.5 m/s: (a) $t=0$ ms; (b) $t=1.1$ ms; (c) $t=2.1$ ms; (d) $t=3.1$ ms; (e) $t=4.2$ ms; (f) $t=5.2$ ms; (g) $t=6.3$ ms; (h) $t=15.8$ ms

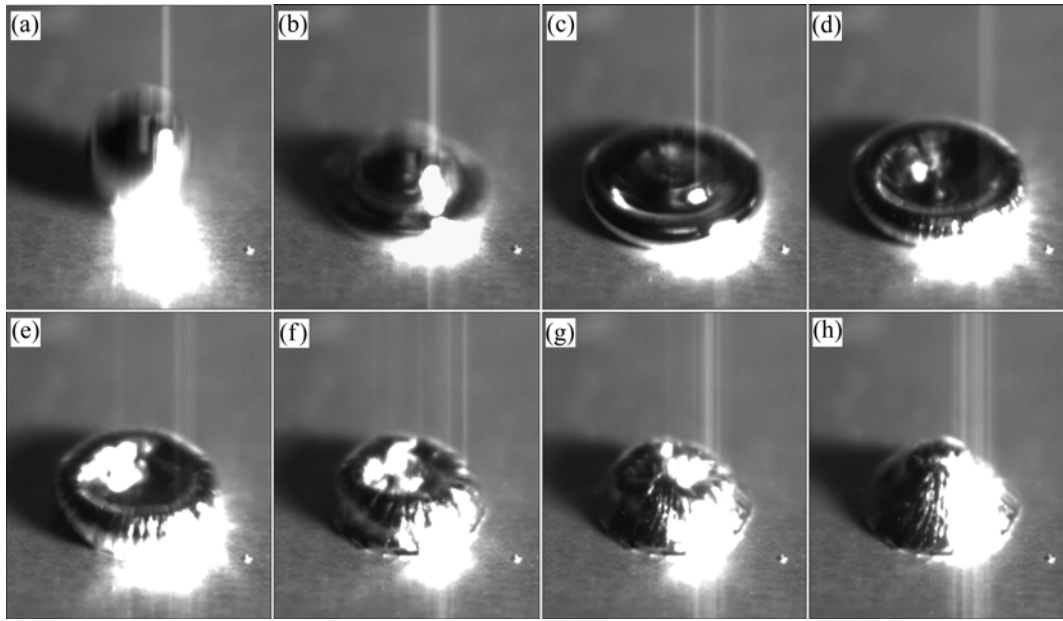


Fig.6 Experimental results of 2.2 mm-diameter solder droplet impingement onto non-fluxed substrate at velocity of 0.5 m/s: (a) $t=0$ ms; (b) $t=1.1$ ms; (c) $t=2.1$ ms; (d) $t=3.1$ ms; (e) $t=4.2$ ms; (f) $t=5.2$ ms; (g) $t=6.3$ ms; (h) $t=15.8$ ms

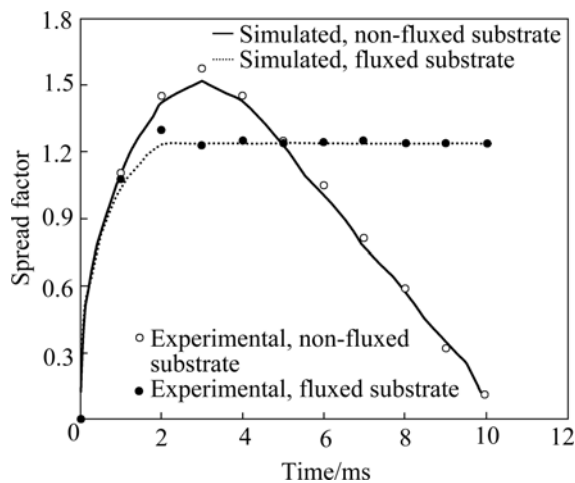


Fig.7 Comparison of experimental and numerical spread factors for 2.2 mm-diameter solder droplet impinging onto fluxed and non-fluxed substrate at velocity of 0.5 m/s

give an accurate prediction of the spread factor as a function of time.

5 Conclusions

- 1) The model can give an accurate prediction of the solder bump formation during solder jet process.
- 2) The solder droplet will rebound completely when it impacts on the fluxed substrate.
- 3) The final solder bump is cone-shaped after the solder droplet impinging on the non-fluxed substrate.
- 4) Solidification leads to a lift-up of the splat periphery during the spreading process and a reduction in the maximum spread factor.

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