Simulation of Solidification Process of BGA Tin-Lead Solder ball Based on Cellular Automaton Method

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Abstract. A method based on cellular automata was established to simulate the solidification process of solder balls used in ball grid array (BGA) packaging technology. For the uniform and constant temperature distribution inside the droplets, the equiaxed crystal morphology and the equiaxed crystal solute field were studied. The simulation results are also shown for solidification process with the BGA tin-lead solder ball prepared by uniform droplet spray (UDS) process under the condition that the cooling rate of is invariable.

1. Introduction
With the rapid development of the integrated circuit chip industry, there are more stringent requirements for integrated circuit chip packaging technology. Ball grid array (BGA) packaging technology owns higher transmission efficiency during data transmission and lower power consumption. Therefore, it has been widely used. With this packaging technology, the metal solder ball joining the chip and the circuit board in BGA technology plays an important role in achieving high performance of the chip after packaging. With the development of computer technology, numerical simulation methods are used to study the process of metal solidification, and the technology of predicting the microstructure of metal after solidification through simulation is becoming more and more mature[1,2]. However, the research of simulation of BGA tin-lead solder balls’ microstructure is just in its infancy. Based on the particularity and complexity of the solidification process of BGA solder balls, there are still many problems in modelling process that need to be studied and solved. Uniform droplet spray (UDS) process is a typical method to produce solder balls with high performance and completely uniform size[3,4]. Thus the solder balls produced by UDS are very suitable for BGA packaging. In this paper, based on cellular automata method the solidification process of solder balls are simulated in both the ideal case (simplified condition with invariable temperature inside the droplets) and the UDS preparation process. The present method takes into account the solute conservation conditions of tin-lead solder balls, the heat dissipation rate of the droplet surface, and the effect of the latent heat release factor at the solid-liquid interface on the overall temperature of the tin-lead droplet.

2. Dendritic Growth Simulation of BGA Tin-Lead Solder Balls Under Ideal Conditions
The setting conditions under this ideal condition are assumed that the internal temperature of the solder ball is constant and uniformly distributed during the solidification of the BGA tin-lead solder ball, the composition of the simulated BGA tin-lead solder ball is Sn-5wt.% Pb.
2.1. Simulation of Crystal Morphology
Assume that under ideal conditions (uniform temperature distribution), the undercooling of BGA tin-lead solder balls is 10 K, the anisotropic strength is 0.1, and the growth time is 0.1 s and 0.25 s. Growth morphology simulated results are shown below.

![Figure 1](image1.png)

**Figure 1.** Equiaxed morphology of BGA solder balls at different times, (a) 0.1 s and (b) 0.25 s.

As shown in Figure 1 (a), in the initial stage of solidification, the primary dendrite began to grow in four directions, but there was no secondary dendrite on the primary dendrite arm. As time progressed, the dendrite grew further, as shown in Figure 1 (b). It can be found that a secondary dendrite arm grows on the primary dendrite arm, and the secondary dendrite arm discharges excess solutes to the liquid phase region, which promotes further dendrite growth.

2.2. Simulation of Crystal Solute Field
With the ideal condition (uniform temperature distribution) assumption, the undercooling of the BGA tin-lead solder ball is set to 10 K, the anisotropy strength is set to 0.1 and the growth time is 0.1 s and 0.25 s. Solutal field simulated results are shown below.

![Figure 2](image2.png)

**Figure 2.** Solute field distribution of a single equiaxed crystal at different times, (a) 0.1 s and (b) 0.25 s.

Figure 2 (a) shows that around the solidified equiaxed crystals, the concentration distribution of the liquid composition field is uniform, and there is no solute enrichment. The excess solutes produced by the dendrite solidification will be discharged to the adjacent solid-liquid interface region, resulting in an increase in the concentration at the solid-liquid interface. As time progresses, a dendrite arm continues to grow. In Figure 2 (b), the secondary dendrite arm appeared on the primary dendrite arm. Due to the existence of the secondary dendrite arm, the solute between the dendrites hardly diffuse and there is solutal enrichment.

In addition, under the ideal condition, the influence of the undercooling and interfacial energy anisotropy parameters of the BGA tin-lead solder ball on the dendrite growth is that a larger
undercooling will accelerate the speed of the solid-liquid interface of the dendrite, and the morphology of dendrites will be more stout and the branching process will be more complicated, which is conducive to the rapid solidification of BGA tin-lead solder balls; Low interface energy anisotropy strength will maintain the morphology stability of the equiaxed crystal growth process. Increasing interface energy anisotropy strength will make the morphology of the equiaxed crystals irregular and complicated.

3. Theoretical Description for BGA Tin-Lead Ball Falling and Solidification in UDS Process

The UDS method uses a piezoelectric oscillator to change molten metal fluid into uniform small droplets. The small droplets contact the air during the falling process and solidify by contacting with the air. The falling process of the metal droplets conforms to Newton's second law [5,6].

\[
\frac{4}{3} \pi r^3 \rho_d \frac{dV_d}{dt} = \frac{4}{3} \pi r^3 \left( \rho_d - \rho_g \right) g - \frac{C_d \pi r^2}{2} \rho_g V \left| V \right| - \frac{4}{3} \tilde{C}_d \pi r^3 \rho_g \frac{dV}{dt}
\]

As in equation (1), \( \rho_d \) is droplet density; \( \rho_g \) is gas density; \( g \) is gravitational acceleration; \( C_d \) - resistance coefficient; \( \tilde{C}_d \) - additional mass influence factor; \( r_d \) - droplet radius; The droplet diameter in this article is 750μm; \( V \) - relative velocity.

During the drop process of metal droplets, the speed does not continuously increase. Due to the existence of gas resistance, and the gas resistance is proportional to the falling speed, the final speed remains constant. There are usually three ways of heat loss, heat conduction, heat convection, and heat radiation. Ignore the heat conduction caused by the thermal gradient inside the metal droplet, and only consider the thermal radiation and thermal convection. The gas used in the experiment is argon. Use Newton's cooling law to calculate the enthalpy loss rate of the metal droplet.

The formula is as follows:

\[
m_d \frac{dh_d}{dt} = h_{dG} A_d^p \left( T_d - T_g \right) + \sigma \varepsilon A_d^p \left( T_d^4 - T_g^4 \right)
\]

\( h_d \) - Enthalpy of droplets per unit mass; \( m_d \) - droplets quality; \( h_{dG} \) - convective heat transfer coefficient between droplet and surrounding gas; \( T_d \) - droplet temperature; \( T_g \) - gas temperature; \( \sigma \) - Stefan-Boltzman constant; \( \varepsilon \) - droplet emissivity; \( A_d^p \) - the surface area of the droplet;

Determination of thermal convection coefficient of metal droplets and surrounding gas by Ranz Marshall equation

\[
\frac{dT_d}{dt} = - \frac{h_{dG}}{\rho_d C_{p(d)}} \left( \frac{6}{d_d} \right) \left( T_d - T_g \right)
\]

\[
\frac{dT_d}{dt} = \frac{\Delta H_f}{C_{p(d)}} \frac{df_s}{dt} - \frac{h_{dG}}{\rho_d C_{p(d)}} \left( \frac{6}{d_d} \right) \left( T_d - T_g \right)
\]

\( \rho_d \) - droplet density; \( C_{p(d)} \) - specific heat capacity; \( \Delta H_f \) - latent heat of fusion per unit mass; \( f_s \) - droplet volume solidification percentage.

The above is macro description of droplet drop dynamics of BGA drop dynamics of BGA tin-lead solder balls introduce CA method. Define the equation (4) is the cooling rate term during the drop of metal droplets.

The temperature inside the metal droplet is uniform and equal. The cooling rate term makes it expressed as
\[
\Phi = \frac{h_{gt}}{\rho_d C_p(d)} \left( \frac{6}{d_d} \right) (T - T_g)
\]  

(5)

here \( T \) - cell temperature.

4. Simulation of Solidification Process of BGA Solder Ball Prepared by UDS Process Under Constant Cooling Rate

The UDS method uses a piezoelectric vibrator to generate uniform vibrations and then oscillate molten metal fluid into uniform small droplets. The metal droplets will contact and interact with the air during the drop process, and solidification occurs through heat dissipation. The dendrite morphology and the solutal field at different cooling rates can be found as follows.

![Figure 3](image)

**Figure 3.** Growth of equiaxed crystals at different cooling rates, (a) 10 k/s, (b) 50 k/s and (c) 100 k/s.

As shown in Figure 3, for the drop of tin-lead solder balls during the UDS preparation process, if the cooling rate is higher, the growth of a primary dendrite will be quicker, the growth of higher-order dendrite arms will be more complicated, the competition for higher-order dendrite growth will be more intense, and the solidification speed will be faster. Because of the larger temperature difference between the room temperature and the tin-lead ball, the quicker cooling speed, the increasing solidification speed of the tin-lead ball. Thus after raising the gas temperature, the solidification speed of the BGA tin-lead ball will be lowered.

5. Summary

In this paper, based on cellular automata method the morphology and the solute field of the equiaxed crystals are simulated in both the ideal case (simplified condition with invariable temperature inside the droplets) and the UDS preparation process. The in-flight cooling process for BGA tin-lead solder ball is described theoretically. The Equiaxed dendritic morphology and the solutal field of BGA solder balls at different times during solidification process are shown and analysed under the ideal case.
Furthermore, the effects of different cooling rates on the dendrite morphology and the solutal field are also shown and discussed under the UDS condition. It is finally indicated that the solidification process and microstructure can be simulated by using the cellular automata method for the BGA tin-lead solder ball used in microelectronic packaging.

6. Acknowledgements
The authors acknowledge the support of National Natural Science Foundation of China (No. 51671075), Heilongjiang Postdoctoral Fund for Scientific Research initiation (No. LBH-Q16118), Fundamental Research Foundation for Universities of Heilongjiang Province (No. LGYC2018JC004) and College Students’ Innovation and Entrepreneurship Training Project of Harbin University of Science and Technology University (No. 201810214164).

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