Journal of Materials Processing Technology 243 (2017) 291–298

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Experimental investigation on the height deviation of bumps printed by solder jet technology

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ARTICLE INFO

Article history:
Received 18 September 2016
Received in revised form
28 December 2016
Accepted 31 December 2016
Available online 31 December 2016

Keyword:
Solder bumps
Height deviation
Oscillation
Solidification

ABSTRACT

Solder jet technology is considered as a flexible and low cost method to print bumps directly for flip-chip packaging. However, the height deviation of solder bumps, which decides the quality and reliability of the packaging, is significantly influenced by the fluid dynamics and solidification behaviors during solder droplet impact. Here, an experimental investigation was first conducted to understand the influence of impact parameters on the height deviation of solder bumps. The results showed that the underdamped oscillation of droplets before complete solidification was the main reason for the bump height deviation, because this oscillation resulted in different bump shapes under different solidification rates. A clear threshold, dividing the regions of the large and small deviation of the solder bump height, was found by estimating the droplet total solidification time scale. "Deposition and reheating" process was presented and proved to be an effective method to reduce the height deviation. A solder bump array with the height of $223 \pm 2\,\mu m$, was printed through this process. The dimensionless height deviation ($\Delta h/h$) of printed bumps was remarkably less than 1%. The present work provided a method of printing uniform height solder bumps.

1. Introduction

Packaging electronic devices has become a considerable manufacture challenge due to the integration and multifunction of electronic circuits. Luo et al. (2012), Liu and Orme (2001) considered the solder jet technology as a flexibility and low cost method to print bumps directly for flip-chip packaging. During the process, the micro solder droplets are ejected from a nozzle and deposited onto a moving substrate directly to form solder bumps, then a chip is placed in contact with the pre-deposited solder bumps (also called solidified droplets) on the substrate. The common used solder bump materials include the PbSn solder and the lead-free solder (such as SnAg and SnAgCu). The study on micro molten droplet spaying and deposition was first originated by Orme et al. (1993). Later, various uniform droplet spraying apparatuses were developed. Luo et al. (2012) developed a pneumatic droplet generator and proposed a 2D axisymmetric model to understand the mechanism of droplet ejection. Amirzadeh et al. (2013) and Luo et al. (2016) produced droplets whose diameters were smaller than the nozzle diameters. He et al. (2014), Lee et al. (2008), and Fan et al. (2008) also developed a variety of generators to produce micro solder droplets. The basic theories and method to eject uniform droplets has been widely investigated, and how to print solder bumps with a uniform height became a crucial problem for the application of this technology to microelectronic packaging.

The height deviation of solder bumps has a significant effect on microelectronic packaging quality and reliability. In order to provide an efficient electronic contact, it is essential to ensure the solder bumps with a uniform height. However, it is difficult to print uniform height solder bumps directly, because the fluid dynamics and solidification behaviors have a significant effect on the bump formation and many factors can caused the height deviation. Wu and Hwang (2015) recorded the impacting process of a single solder droplet using high-speed camera, and found several surface ripples on the solder bumps. Haferl et al. (2001) provided a numerical method to study fluid flow phenomenon of solder droplets impacting onto a substrate, and indicated that the increases of impacting velocity caused the final bump shapes changed from a "ball" shape

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http://dx.doi.org/10.1016/j.jmatprotec.2016.12.031
0924-0136/

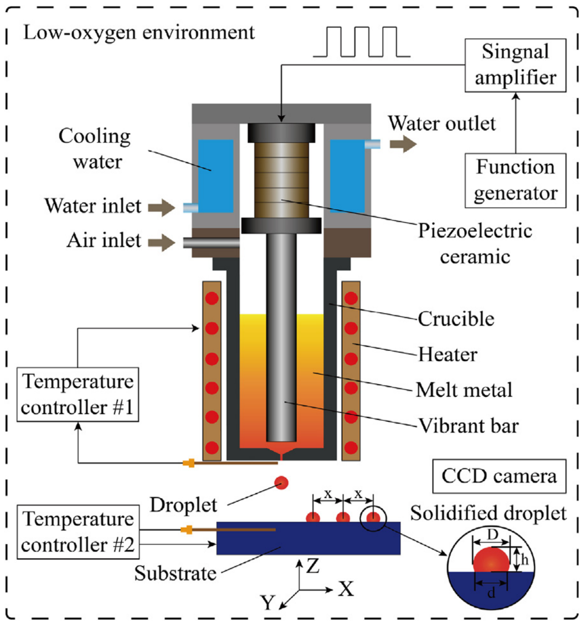

Fig. 1. Schematic diagram of micro-droplet deposition experimental system.

to a "Christmas tree" shape. Waldvogel and Poulikakos (1997) presented a theoretical model to elucidate the solidification behavior of molten droplets on a substrate. Their results revealed that increasing substrate temperature prolonged the total solidification time, and in turns, affected the final bump shapes. Naidich (1981) performed wetting experiments using metal droplets on different material metal surface under different substrate temperatures, which showed that an increasing substrate temperature usually led to an increased wettability. However, the influence parameters on the bump height deviation and the method of printing uniform height solder bumps were not further discussed.

This research aimed to understand the influence of impact parameters on the printed bump height deviation. In the present work, a series of deposition experiments of solder droplets onto a smooth metallic substrate were carried out using a self-developed micro-droplet deposition experimental system. The dynamic formation of solder bumps was analyzed by calculating some dimensionless parameters theoretically and observing the solder droplet impacting process experimentally. Because the solidification behavior cannot be visualized, the droplet complete solidification time was estimated to characterize the solidification rate quantitatively, and then the effect of solidification on the bump height was obtained. Based on the above research, a method of reducing the bump height deviation was presented and proved by printing a solder bump array. A method of printing uniform height solder bumps was provided in this work.

2. Experimental approach

The schematic diagram of micro-droplet deposition experimental system is shown in Fig. 1. It mainly consisted of a self-developed drop-on-demand (DOD) generator, a droplet deposition system, a low-oxygen environment control system, and a high speed image recording system.

The self-developed DOD generator was used to produce uniform droplets. It included a crucible, a micro nozzle, a piezoelectric ceramic, a vibrant bar, a heater, a temperature controller (Shimax, Japan) and cooling water. The droplet ejection process can be summarized as follows: The metal material was melted in the crucible. A micro displacement was induced by the piezoelectric ceramic and transmitted to the nozzle by the vibrant bar. A velocity transient was caused by the micro displacement and resulted in ejecting a solder droplet from the nozzle.

Table 1
Physical properties of Sn 63 wt% Pb.

Density	ρ_d	8474.4	(Kg/m3)
Surface tension	σ_d	0.494	(N/m)
Dynamic viscosity	μ_d	0.0013	(N s/m2)
Latent heat of fusion	L_d	47560	(J/kg)
Specific heat capacity	C_d	186.2	(J/(kg K))
Thermal conductivity	k_d	48	(W/(m K))
Melting point of metal	T_f	456	(K)

The droplet deposition system was used to deposit droplets at precise locations. It included a Program Multiple Axes Controller (PMAC) (Delta Tau, America), an X-Y-Z motion platform, a substrate with a heater inside, and a temperature controller (Shimax, Japan). A copper substrate was chosen as the deposition surface. In order to remove the oxides and organic contaminants from the surface, the copper substrate was mechanically polished and cleaned before the experiment.

A low-oxygen environment control system (Mikrouna, China) was used to maintain a low oxygen content below 20 ppm, so that the formation of oxides was hindered during the droplet generation, flight, and deposition process. The system was filled with inert gas (Nitrogen, 99.99 percent purity). Both the droplet generator and deposition system were located inside.

The high speed image recording system was used to record images of impinging droplets during deposition. It included a high-speed CCD camera (MotionBLITZ cube1, Germany), a microscope (Computar, Japan) and a 100 W LED light. The high speed CCD camera was able to record 1000 images per second.

Since the properties of Sn 63 wt% Pb alloy is close to those of the lead-free solder alloys, the lower cost Sn 63 wt% Pb alloy was used in the experiment to represent the solder materials. Its main properties were shown in Table 1. Before melted, the Sn 63 wt% Pb alloy was ground to remove the oxides from its surface.

In the experiments, a sequence of pulse waveforms was applied to the piezoelectric ceramic, and each individual pulse created one droplet. Droplets were ejected at the frequency of 1 Hz and deposited onto the moving substrate. The droplet and substrate temperatures could be modified by temperature controller #1 and temperature controller #2, respectively. In addition, a tool microscope (Nikon MM400, Japan) was used to observe the final bump shape and measure the height of its contours.

3. Result and discussions

3.1. The dynamic formation process of solder bumps

A spherical liquid-metal droplet was ejected from the nozzle, and then impacted on the substrate and solidified a bump. In order to analyze the reason for the bump height deviation, it is essential to achieve a comprehensive understanding of the dynamic deposition process. According to Schiaffino and Sonin (1997), the dynamic and thermal behaviors of droplets during impact can be characterized by some dimensionless parameters, which include Weber number (We), Ohnesorge number (Oh), Stefan number (Ste), Prandtl number (Pr), and melt superheat parameter (β). Those dimensionless parameters are shown in Eqs. (1)–(5).

$$We = \frac{\rho_d U_d^2 D_d}{\sigma_d} \quad (1)$$

$$Oh = \frac{\mu_d}{\sqrt{\rho_d \sigma_d D_d}} \quad (2)$$