KKU Res J. 2011; 16(6): 596-611
http://resjournal.kku.ac.th

The Effects of Capillary Tip Geometry on Solder Jetting Accuracy in Laser Solder Ball Jetting Process

*Sunchai Mata and Sirivit Taechajedcadarungsri**

Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University
** Correspondent author: sirtae@kku.ac.th, sir.tae@gmail.com*

Received February 3, 2011
Accepted June 23, 2011

Abstract

The effects of capillary tip geometry on solder ball jetting accuracy in laser solder ball jetting process were studied in order to review the molten ball behavior. In the experiment, the micro-scale lead free solder ball was melted by laser energy inside three difference types of capillary categorized by tip geometry. A capillary type A was a conventional tip. Type B was manufactured by using micro-fabrication process to form the chamfer tip. And type C was micro-fabricated to have the fillet tip. The molten solder ball was jetted out from the capillary by pressure of inert gas onto substrate. The high-speed camera was used to capture the jetting behavior. The semi-auto visualization method was used to analyze solder droplet deposition on the substrate and compare between these capillary types. Then by using SEM, the quality of solder droplets on the substrate was compared. The results showed that the solder ball, jetted from different capillary types, was not melted completely when it started moving out from capillary tip. Its temperature kept increasing after it was ejected from capillary tube. The ball then reached the melting point, the "glowing" point, when it was totally ejected from capillary tube. The molten solder ball shape still was in spherical shape while dropped onto the target. The conventional capillary tip was given better accuracy than the other two capillaries. And SEM images showed that surface of solder droplet from the conventional capillary was smoother than the surface of the solder droplet that performed by the other two capillary types.

Keywords: solder ball jetting, capillary tube, laser soldering

1. Introduction

The developments of advanced semi-conductor manufacturing technologies and microelectronics assembly are driven by needs of cost reductions, higher output and higher accuracy with miniaturization, and also protection of environment impact. To comply all of needs, lead free solder jet technology is recently increasing in attractive and alternative techniques for the distributions and patterning of materials in wide varieties of applications.

Solder jetting technology was first developed by MicroFab Technologies, Inc. (1) base on inkjet technique. They demonstrated 25-125 micron diameter molten solder bump onto moralized wafer by using piezoelectric drop-on-demand mode. Their development approaches were applied to vehicle print testing, drop size modulation, micro-bump printing and print-on-the-fly. Packaging Technologies (PAC TECH) used laser technology to develop and demonstrate Laser Solder Ball Jetting technology (2). This technology fulfills all the need of flux-less soldering, local heating and reflow, no mechanical contact, less stress during soldering and also high flexibility of solder alloys such as eutectic and high-lead alloy, lead-free solder. The Laser technology was applied to melt a preformed solder ball which was then jetted out of a capillary tube with pressurized inert gas to form an interconnect on the target circuit. The process combined solder ball bumping and re-flow process into the single process. The process gave high output with great accuracy, flexibility, and applicable on micro-sensor assembly.

Laser energy applications on lead-free solder ball was studied by using both experiment and simulation basis. The study focused on the effects of initial temperature of solder ball to inter-metallic compound quality. The results showed that initial temperature on solder ball was the main factor for solder reflow quality (3). In the same way, there was study that compared quality of solder joint produced from conventional hot air re-flow method and laser technique method, it was found that the surface of solder bumps obtained by the laser reflow method with proper parameter was smoother than that obtained by the hot air reflow method (4). There was study that reported the same results as Tian (4). The report showed that by applying YAG laser energy could be used to improve the wettability of Sn3.5Ag solder on copper pad (5). There was concern about assembling process that was also the major product's efficiency. By using three-dimensional finite element model to analyze the temperature distribution and predict pitch motion of micro-sensor component during laser soldering interconnection process, the results was shown that the pitch motion was affected by laser soldering technique which pitch angle in pre-bumping process was smaller than that in reflow process (6). The study about the sagging phenomenon of micro-solder joints fabricated by laser reflow process was performed by using experiment. The study results indicated that the sagging phenomenon, happened after the laser reflow process, came from many factors such as melting and cooling characteristics of the solder, pad and inter-metallic compound, shrinkages of solidified solder and wetting performance of solder (7). The characteristics of Sn3.5Ag0.5Cu solder bump comparing with Sn3.5Ag solder bump was studied by using both simulation and experimental methods. It was reported that shear strength of both alloys was comparable and laser power obviously was not affected the shear strengths of both alloys. The formation of inter-metallic compound growth followed temperature gradient in solder bump. And with increasing the laser power and heating time, the compound dissolved into the bulk solder bump (8-9).

In the meanwhile, there were many research projects about solder droplet that similar to laser solder ball-jetting process. Started by Lord Rayleight (10), the mathematic models of uniform droplet formations from stream liquid issuing from an orifice were described. The growth of radically symmetric initial diameter disturbance on an in viscid jet was investigated. In 1892, he extended his first theory to analysis viscous jets. However, due to the complexity of the relationships made the theory less interest. Weber (11) used similar approach as Rayleight but his equation produced much more practicable results by making simplified assumption. There was study that used both theories to quantify the breakup liquid metal of capillary. The results had shown that the oxygen had significantly effects on molten solder metal jet breakup. By using both Rayleight and Weber theories, they could be used to predict only on the magnitude of the radial disturbance however both theories were not valid for the liquid metal jet case (12). The solder jet driving pressure pulse was studied by using computational model for magneto-hydrodynamic solder (MHD) jet. The results showed that the dispensed molten solder diameter was directly related to the magnitude and duration of pressure pulse (13). In 2004, both experimental and simulation methods were used to develop model of micro-inkjet base on piezoelectric solder driving technology. The study covered the whole process from droplet formation to droplet impact on the target. The simulation model and experimental provided similar results about droplet morphology, break-up time, flying distance and droplet volume (14). There was study that focuses only on droplet impact by using numerical technique to investigate the impingement of liquid micro-droplet onto a grass substrate at different temperatures. Rajneesh's model valid only for eutectic solder (63Sn-37Pb) but not for FC-72 and isopropanol (15).

According to the literatures, the studying of laser solder ball jetting was widely focused on only the "end products". There were few literatures focused on Laser Solder Ball Jetting process. In term of production, the accurate of molten solder ball jetting is the major of concerned to product quality, product defects, production yield and also machine performance. Solder ball jetting accuracy is major of key input that causes to production failures. This research focuses on the capillary that is directly related to jetting accuracy for this process. The capillary is the part that holds solder ball inside and direct contact to molten solder ball and also laser beam during jetting process. It is necessary to understand the phenomena of capillary in the process especially the effects of capillary tip geometry on jetting performance. The study would compare some different design approached of a capillary for laser solder ball jetting process.

2. Materials and Methods

A lead free solder ball was first placed onto a capillary tip which its diameter was smaller than the solder ball (Figure 1). A laser unit with small spot diameter was used for the heating process. The laser irradiates to the solder ball to make it melt. Then inert gas pressure was applied to push the molten solder out from capillary tip to the target (16-21).

2.1 Capillary tip geometry

In this study, three types of capillary categorized by geometry tip design were used for molten solder ball jetting. The first type is conventional design called type A. The capillary type A used sharp edge of tip inner diameter (Figure 2a). The second type of capillary called type B, the tip inner diameter of capillary type B was chamfered with 0.01 mm x 45 degree (Figure 2b). And the last type of capillary called capillary type C. The capillary type C was filleted with R0.01 millimeter (Figure 2c).

2.2 Jetting accuracy theory

In Laser solder ball jetting process, jetting accuracy defined by standard deviation of jetting position error in direction x and y. The jetting position error (E_{nX}) is the difference of actual jetting position compare with target or teaching position at (x_0, y_0). The position of the jetting, (x_1, y_1), (x_2, y_2), (x_3, y_3),

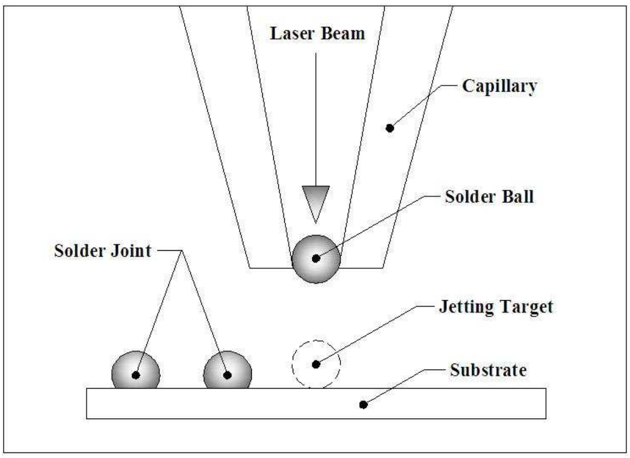
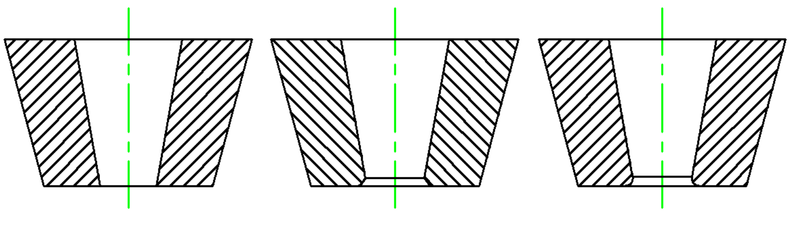


Figure 1. A solder ball was hold by capillary tip and laser energy applied to melt the solder ball.



2(a) 2(b) 2(c)

Figure 2. (a) Capillary type A, (b) Capillary type B, (c) Capillary type C.

(x_n, y_n) are the actual jetting position of jetting position number *1*, position number *2*, position number *3*, and number *n* respectively (Figure 3). So, jetting accuracy in X direction A_X is:

$$A_x = \sqrt{\frac{\sum (E_{nX} - \mu_X)^2}{n}} \quad [1]$$

Where μ_X is absolute jetting accuracy mean that can be written by:

$$\mu_X = \frac{\sum_{i=1}^{n} |E_{iX}|}{n} \quad [2]$$

So, jetting accuracy in Y direction A_Y is:

$$A_Y = \sqrt{\frac{\sum (E_{nY} - \mu_Y)^2}{n}} \quad [3]$$

Where μ_Y is absolute jetting accuracy mean that can be written by:

$$\mu_Y = \frac{\sum_{i=1}^{n} |E_{iY}|}{n} \quad [4]$$

2.3 Jetting behavior observation

To observe the phenomenon of molten solder ball jetting, a high-speed video system was used for capturing the solder shape at any moment. The main components of the system are the solder jetting device with capillary and the high-speed camera with data acquisition system as showed in schematic (Figure 4). The high-speed camera (MotionPro X4, 5,000 frames per second with halogen light source) equipped with a long-distance microscope was used to observe the jetting phenomenon. The magnification of the microscope can be adjusted so that the image could accommodate the maximum size of the jetting. The rapid motion image in the solder jetting was captured with the MotionPro Studio acquisition system (12) which was used to control the beginning of the capture and save the captured images.

2.4 Jetting accuracy experimental setup

The molten Solder Ball Jetting position on the substrate can be measured by using semi-auto visualization measurement method. A high performance CCD camera was used for capture solder drop position on the substrate and then the position can be recorded by using computer base with data

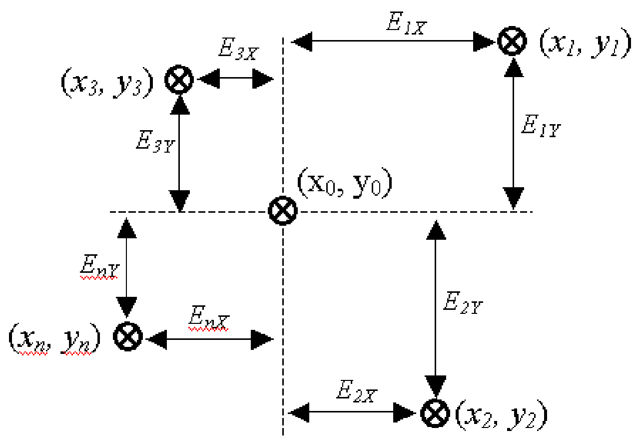


Figure 3. Solder ball jetting accuracy schematics in laser solder ball jetting process.

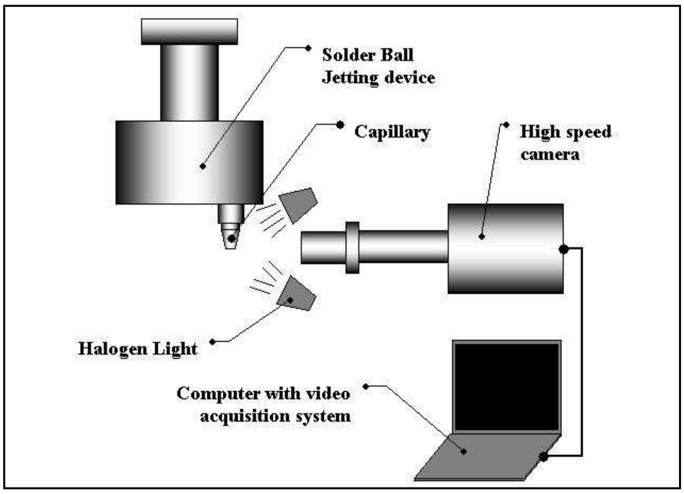


Figure 4. Schematic drawing of experiment setup.

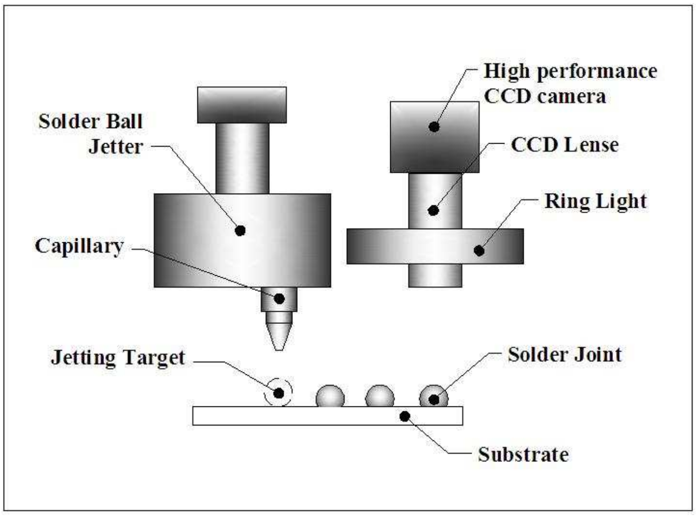


Figure 5. Schematics plot of Solder Ball Jetting Accuracy testing.

acquisition system. The main components of the system are the solder jetting device with capillary and the high performance CCD camera with data acquisition system (Figure 5). The high-performance CCD camera equipped with a CCD 30X lenses and ring type of light source. And the operating software SBB with logging data system was used to record the position of solder drop on the substrate. Then the jetting accuracy can be calculated.

2.5 Jetting accuracy analysis

In this research, there is one factor and 3 levels. The factor is capillary geometry and levels are capillary type A, type B, and type C, and the response of testing are standard deviation of jetting and mean of jetting position error. One-way ANOVA hypothesis testing method without blocking treatment was used to analyze the jetting accuracy difference of between the capillary types. The completely Randomized Design (CDR) will be applied. The ANOVA testing method can be written by:

$$F = \frac{MST_{rt}}{MSE} \quad [5]$$

Where

$$MST_{rt} = \frac{\sum T_i^2 / n_i - (\sum\sum X_{ij})^2 / n}{(k-1)} \quad [6]$$

And

$$MSE = \frac{SST - SST_{rt}}{(n-k)} \quad [7]$$

Term SST is total variance that can be solved from equation:

$$SST = \sum\sum X_{ij}^{\ 2} - (\sum\sum X_{ij})^2 / n \quad [8]$$

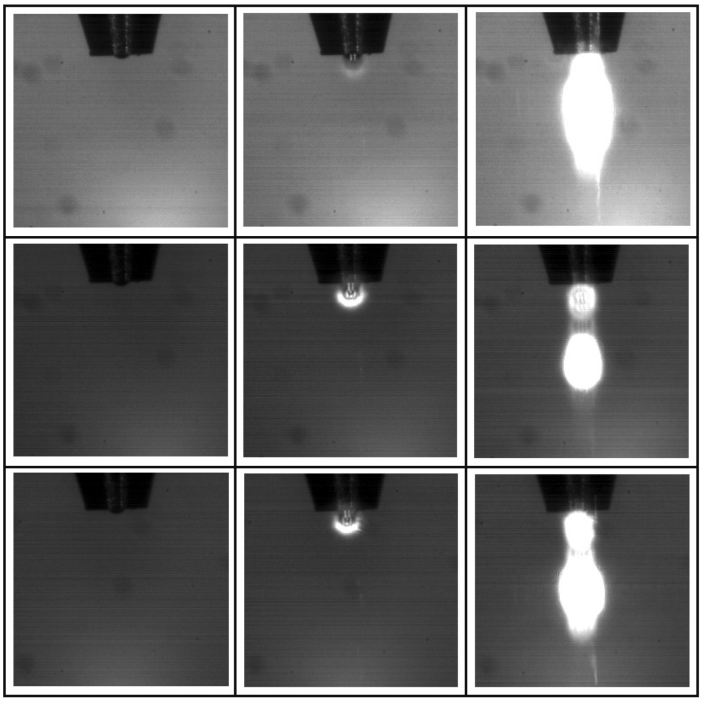
And term SST_{rt} is variance between treatments that can be written as:

$$SST_{rt} = \sum T^2{}_i / n_i - (\sum\sum X_{ij})^2 / n \quad [9]$$

3. Results and Discussion

3.1 Solder ball melting

To observe solder ball melting behavior while it start to move out from all three types of capillary tips using high-speed video, it was still unclear that the solder ball was melt completely while it starts to move out from the capillary tip. From the captured, there was color changing in the solder ball. The color of solder ball changed from dark to flashing light while it was ejected from capillary (Figure 6a, 6b). Changing of color means that the temperature of solder ball was still increased (22) while it moves through a capillary tip. The temperature in solder ball was rising up to flash point after the solder ball was fully ejected from the capillary (Figure 6c)



6(a) 6(b) 6 (c)

Figure 6. Solder ball jetting process. 6a) The capillary with solder ball before laser apply; solder ball is dark. 6b) The solder ball start to move out from capillary after laser energy applied; color changing in solder ball. 6c) Completely melt solder ball jetting from capillary.

However, due to the limitation of temperature measurement on micro scale, the exact temperature could not be captured at this time.

3.2 Molten solder ball shape

To capture molten solder ball shape, the high-speed camera needed to reduce light intensity. It was for reducing light reflection from the molten solder ball. The results showed that after the molten solder ejected from capillary, the solder ball immediately formed to sphere shape (Figure 7). The high surface tension and high viscosity may cause the formation of molten solder ball formed to sphere shape immediately after it move out from the capillary. However, in order to gain fully understanding on the molten phenomenon, further investigation has to be done with higher speed camera and micro-scale measuring equipments.

3.3 Jetting position error

From the experiment, the solder drop position error distribution that performed by three difference types of capillary is collected at the same height of jetting. The solder drop position of each capillary is obtained based on about 300 samples. The results showed that the solder joint position error distribution performed by capillary type A is small than the jetting position error from the capillary type B and type C (Figure 8).

To separate the solder drop position error in to two-direction, the error in X-direction and the error in Y-direction, the result showed the same trend. The error of solder drop position performed by capillary type A in X-direction is 0.0003 μm with standard deviation 0.005 μm that is small than the solder drop position error in X-direction that performed by capillary type B and capillary type C which have average jetting error –0.008 μm with standard deviation 0.019 μm and -0.005 with standard deviation 0.015 μm respectively (Figure 9).

In Y-direction, the error of solder drop position performed by capillary type A is 0.0004 μm with standard deviation 0.006 μm while the error in that performed by

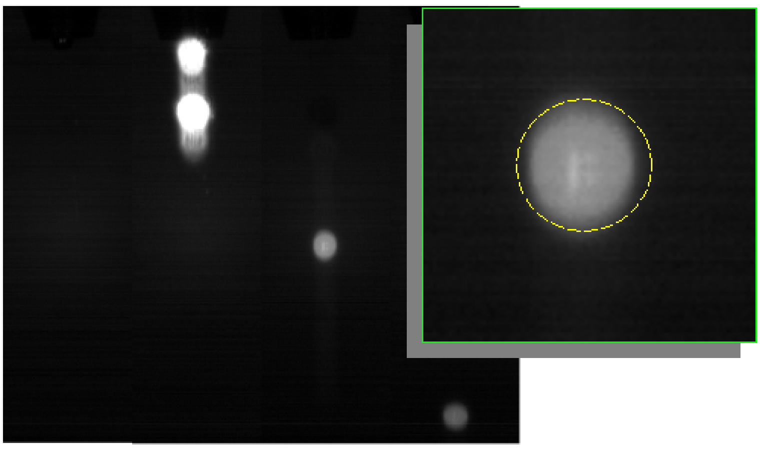


Figure 7. Molten solder ball shape after ejected from capillary.

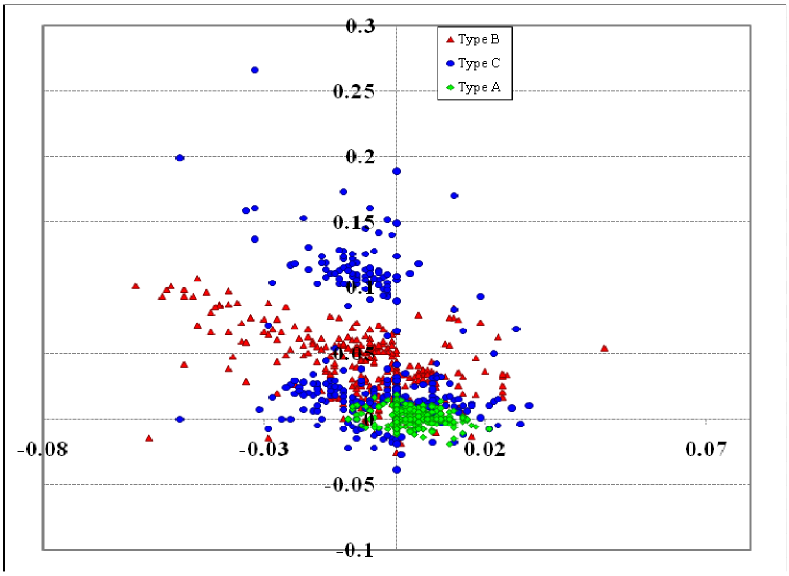


Figure 8. Comparison of solder joint distribution of solder ball jetting from difference type of capillary.

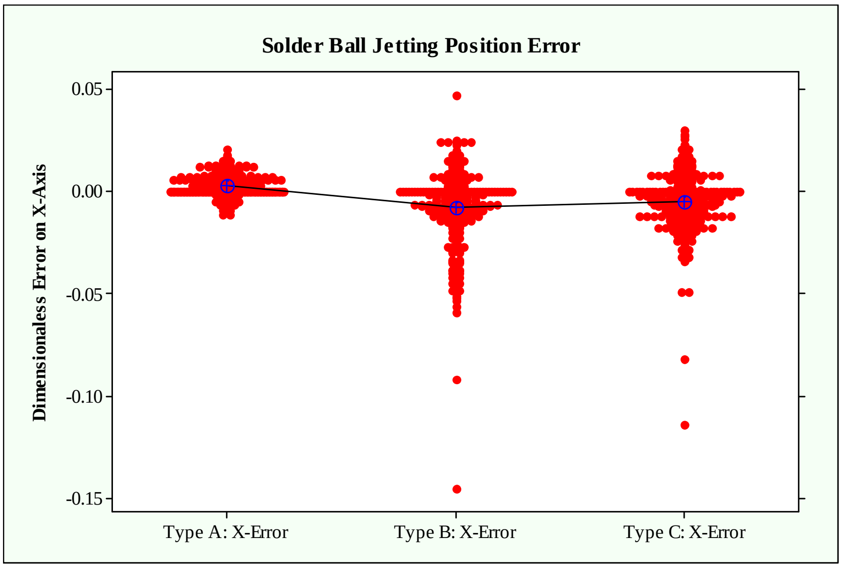


Figure 9. Comparison of solder ball jetting position error in X-direction.

capillary type B and capillary type C that are 0.04 µm with standard deviation 0.026 µm and 0.05 with standard deviation 0.05 µm respectively (Figure 10).

3.4 Jetting accuracy comparison

The solder ball jetting accuracy of each capillary type was tested by one-way ANOVA method. The results showed that the solder ball jetting accuracy in X-direction that performed by capillary type A is significantly better than the capillary type B and capillary type C with P-value of 0.000 (Figure 11).

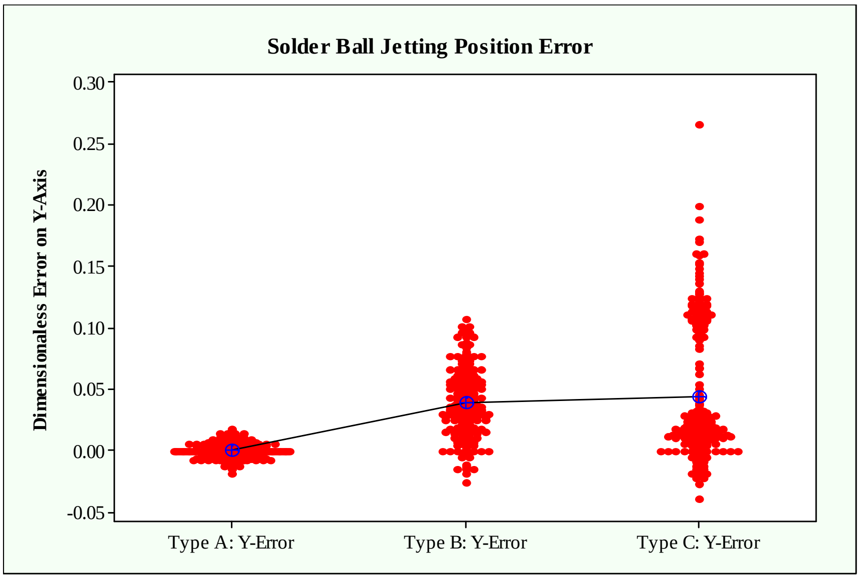


Figure 10. Comparison of solder ball jetting position error in Y-direction

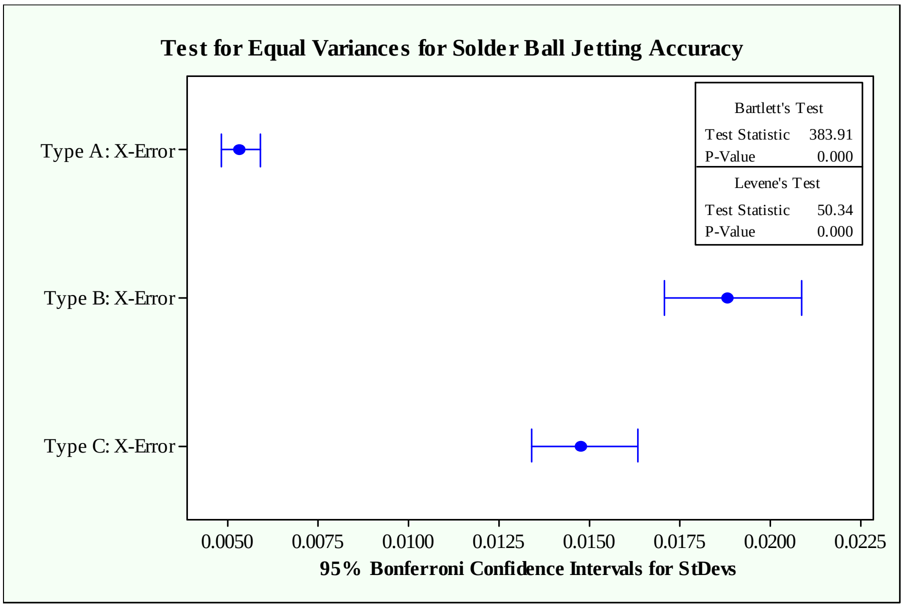


Figure 11. One-way ANOVA testing of solder ball- jetting accuracy in X-direction

And in Y-direction, the solder ball jetting accuracy that performed by capillary type A is also significantly better than the capillary type and capillary type C with P-value of 0.000 (Figure 12).

3.5 Capillary geometry effects

From SEM image, capillary type A, type B, and type C were showed (Figure 13a, 13b, 13c). The images showed that there is no difference surface finishing for those capillary types.

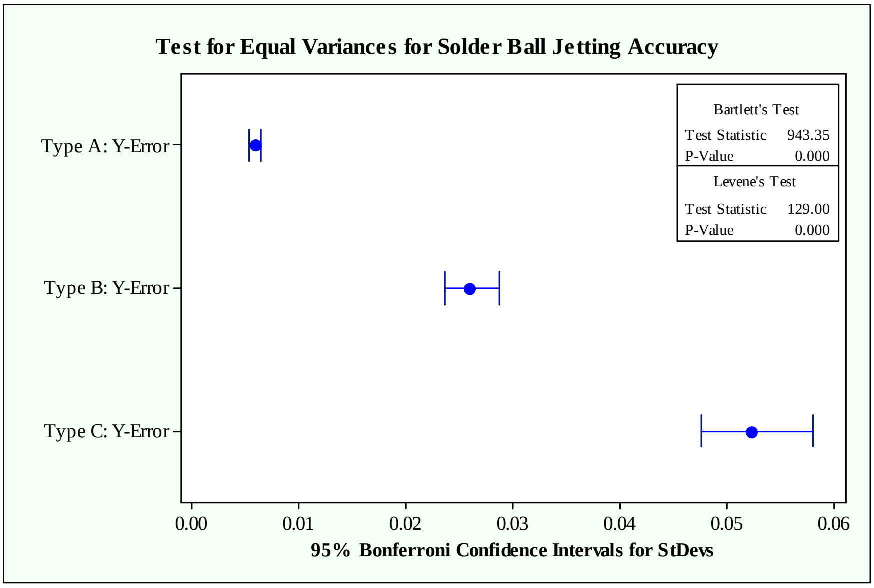


Figure 12. One-way ANOVA testing of solder ball- jetting accuracy in Y-direction

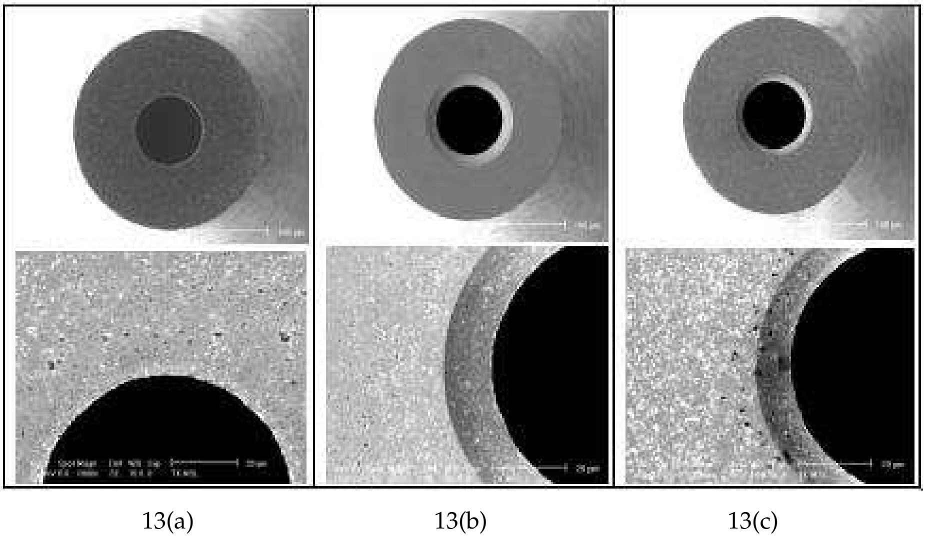


Figure 13. 13a) Capillary type A: Conventional capillary, 13b) Capillary type B: Chamfer edge capillary, 13c) Capillary type C: Fillet edge capillary

By using 3-samples of each capillary type to jet 10x10 array solder balls onto the same substrate. The image from SEM showed that the solder joint array on the substrate performed by capillary type A is more uniform than the other two capillary types (Figure 14a, 14b, 14c)

From figure 14, two patterns of the solder joint can be classified. In the first pattern (Figure 14a), when the molten solder ball flow through the tip of capillary type A that there is no special contact surface between the capillary and molten solder ball, so there is some small liquid adhering

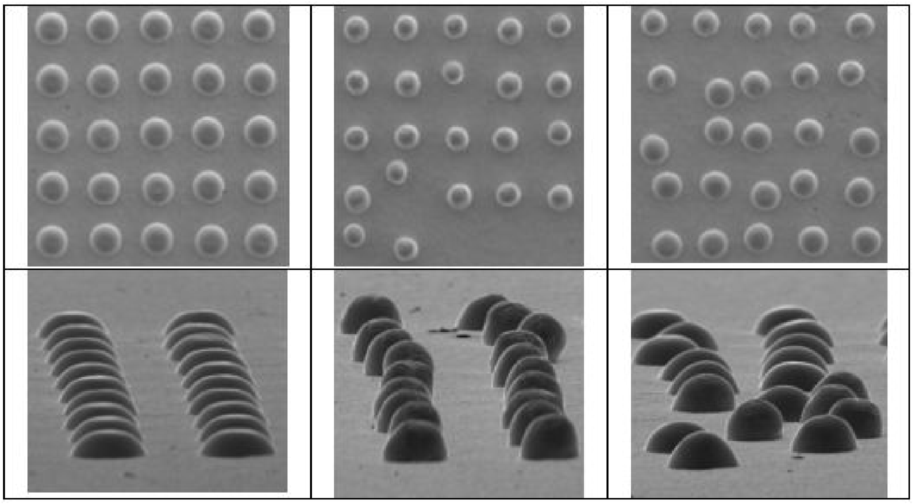


Figure 14. Solder joint array, 14a) Perform by capillary type A, 14b) Perform by capillary type B, 14c) Perform by capillary type C.

on the surface of capillary tip and there is a small molten solder ball skew phenomenon caused by liquid adhering. It makes better jetting accuracy and better uniform of solder drop on the substrate. The second pattern (figure 14b, 14c), the molten solder ball has a high viscosity and surface tension that causing a difficulty in jetting and there is a special surface extended from capillary tip for both capillary type B and C. It will easily adhere to that surface and then cause the molten solder to skew after being jet from both capillaries. The skew behavior is the major effect of low jetting accuracy or low performance of jetting.

In addition, for the solder ball jetting process, the solder will solidify during flow through the capillary tip and flying. The solidification rate of molten solder ball which jet from capillary type A may smaller than the molten solder ball which jet from the other two capillary types. Because there is no energy lost from adhering force between the molten solder and the special extended surface from capillary tip. Also the wettability of molten solder performed by capillary type A is better than molten solder wettability performed by capillary type B and type C and then it cause surface of solder joint from capillary type A is smooth (Figure 15).

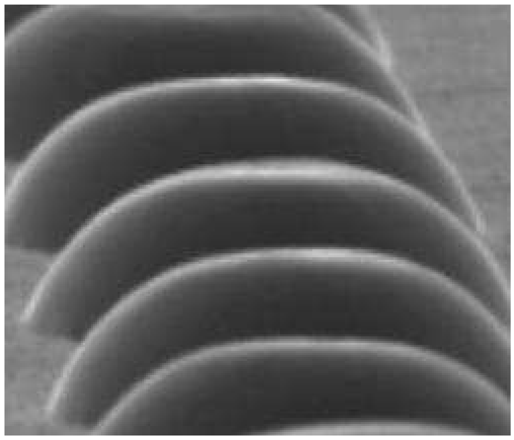


Figure 15. Solder joint surface performed by capillary type A.

On the other hand, energy lost from liquid adhering force behavior at the contact surface between molten solder and special capillary tip surface cause higher solidification rate on molten solder ball. It makes poor wettability and then it causes poor solder joint surface (Figure 16, 17).

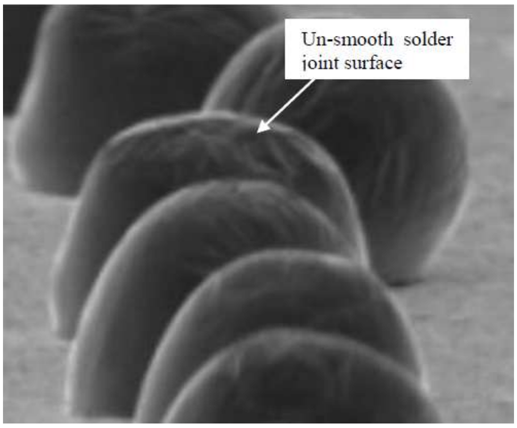


Figure 16. Solder joint surface performed by capillary type B

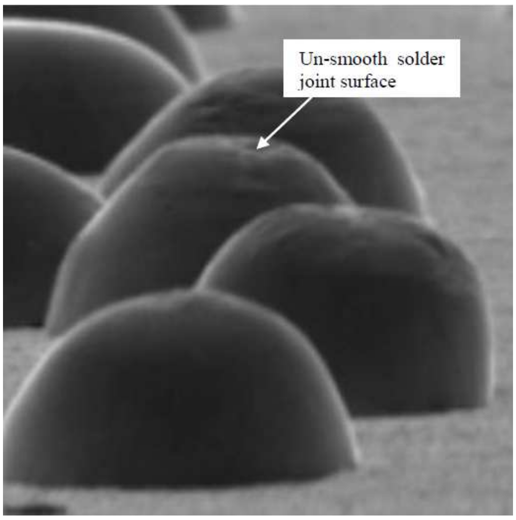


Figure 17. Solder joint surface performed by capillary type B

However, the effects of adhering force behavior and the solidification phenomenon of molten solder ball in this process was not focus in this study. The future studying of molten solder flow through capillary including of heat transfer behavior, fluid flow mechanism, adhering physics force and as well as melting and solidification of the solder ball in laser solder ball jetting process may give more understanding the phenomenon of the process. In this study was focus on jetting comparison between difference types of capillary tip geometry.

4. Conclusion

In this paper was to observe molten solder ball jetting phenomenon by using high-speed camera to photograph the solder ball. The semi-auto camera was used to study jetting accuracy of three difference types of capillary categorized by tip geometry. Capillary type A is the sharp edging tip, capillary type B is chamfer-edging tip, and capillary type C is fillet-edging tip. The results of studying show that:

1. The solder ball was not melted completely when it started moving out from capillary tip; its temperature kept increasing after it was ejected from capillary tube and reaching the completely melted point, the “glowing” point, when the solder ball was totally ejected completely from capillary tube. The molten solder ball shape still is in spherical form while it was flying.

2. The solder joint position error distribution both X-direction and Y-direction that performed by capillary type A is small than the jetting position error from the capillary type B and type C.

3. By using one-way ANOVA testing method, the solder ball jetting accuracy in

both X-direction and Y-direction that performed by capillary type A without special contact surface at capillary tip are significant better than the jetting accuracy performed by the capillary with chamfer and fillet at the capillary tip with P-value of 0.000.

4. The solder joint surface that performed by using capillary type A to jet molten solder ball is smoother than solder joint surface quality that performed by the other two capillary types. The liquid adhering on contact surface between molten solder ball and the capillary tip may cause solder jetting skew phenomenon. And also solidification rate of the molten solder ball during flow through capillary tip and flying may cause difference solder joint surface quality.

5. Capillary tip geometry has effects to molten solder ball jetting qualities including of jetting position error or jetting accuracy and as well as solder joint quality.

In addition, the details of solder ball jetting process behavior including of heat transfer during jetting process, fluid flow behavior, physics of adhering force and also melting and solidification of the solder ball still need to study in the future for more understanding.

5. Acknowledgment

The authors would like to show deep gratitude to the scholarship of The Nation Electronics and Computer Technology Center (NECTEC), Industry/ University Cooperative Research Center (I/U CRC) in HDD Component, Khon Kaen University and Seagate Technology (Thailand) Co., Ltd for providing financial support of this work.

6. References

(1) Wallace DB, Hayes DJ. Solder Jet Technology Update. Proceedings of the 1997 International Symposium on Microelectronics; 1997 Oct 14-16; Oklahoma, USA.

(2) Zakel E, Titerle L, Oppert T, Blankenhorn RG. Laser solder attach for optoelectronics packages. [Internet]. 2008 [cited 2008 Mar 07]. Available from: http://pactech.com/files/21%20 ICEP%202002%20Japan%20Paper%201 4 _03.pdf

(3) Li FQ, Wanga C, Zhao Z, Hub P, Liub D. Heat transfer analysis of molten droplet solder bumping for electronics interconnection. Proceedings of the High Density Microsystem Design and Packaging and Component Failure Analysis Conference; 2004 June 30 –July 3; Shanghai, China.

(4) Tian YH, Wang C, Liu D. Thermo-mechanical Behaviour of PBGA package during laser and hot reflow soldering. Model Simul Mater Sc. 2004; 12(2): 235–43.

(5) Zhao Z, Wang C, Li M, Wang L. Nd-YAG laser surface treatment of copper to improve the wettability of Sn3.5 solder on copper. Surf Coat Tech. 2000; 200(7): 2181–6.

(6) Tian DW, Wang CQ, Tian YH, Chen HT. Prediction of micro pitch motion of a microsensor component during laser soldering interconnection process.

Proceedings of the 7th International Conference on Electronics Packaging Technology; 2006 Aug 26 -30; Shanghai: China.

(7) Liu W, Wang C, Tian YH, Kong L. Sagging Phenomenon of Micro Solder Joint Fabricated by Laser Reflow Process. Proceedings of the Electronic Packaging Technology; 2007 Aug 14 - 17; Shanghai: China.

(8) Tian YH, Wang C, Chen Y. Characteristics of laser reflow bumping of Sn3.5Ag and Sn3.5Ag0.5Cu lead-free solder balls. J Math Sci Technol. 2008; 24(2): 220-6.

(9) Tian DW, Wang CQ, Hang C J. Three-dimensional modeling of solder droplet impact onto a groove. J Phys D App Phys. 2008; 41(24): 245-503.

(10) Rayleight L. On the instability of jets. Proc London Math Soc. 1878; s1-10(1): 4-13 doi:10.1112/plms/s1-10.1.4.

(11) Weber C. On the breakdown of a fluid jet. Z. Angrew Math Mech. 1931; 11: 136–154.

(12) Wallace DB. Capillary instability of a jet liquid metal**.** J Fluid Eng. 1993; 115 (3): 529-32.

(13) Essien M, Sackinger PA, Peebles HC. Computational modeling of on-demand solder delivery for fluxless MCM packaging application. Proceedings of the 1996 International Symposium on Microelectronics; 1996 Oct 8-10; Oklahoma, USA.

(14) Wu HC, Hwang WS, Lin HJ. Development of a three-dimensional simulation system for micro-inkjet and its experimental verification. Mater Sci Eng. 2004; 373(2):268–78.

(15) Bhardwaj R, Longtin JP, Attinger D. A numerical investigation on the influence of liquid properties and interfacial heat transfer during microdroplet deposition onto a glass substrate. Int J Heat Mass Tran. 2007; 50: 2912-23.

(16) Zakel E, Titerle L, Oppert T, Blankenhorn RG. Laser solder attach for optoelectronics packages [Internet]. 2008 [cited 2008 Mar 7]. Available from: http://pactech.com/files/21%20ICEP%202002%20Japan%20Paper%2014_03.pdf

(17) Oppert T, Teutsch T, Zakel E, Azdasht G. Single and multiple laser solder ball placement and reflow for wafer level CSP [Internet]. 2008 [cited 2008 Mar 6]. Available from: http://pactech. com/files/21%20ICEP%202002%20Japan%20Paper%2014_03.pdf

(18) Strandjord A, Teutsch T, Schffler A. Bumping for WLCSP using solder ball attach on electrolesses NiAu UBM [Internet]. 2008 [cited 2008 Mar 6]. Available from: http://pactech.com/files/62%20Pac%20Tech%20arcsis%20Gardanne%20 12 _2008.pdf

(19) Oppert T. Micro ball placement for wafer level CSP. Abstracts of the Deutsches IMAPS-Seminar; 2007 Feb; Illmenau, Germany.

(20) Oppert T. Contact-less laser solder jetting for fine pitch flip chip bumps.

Abstracts of the IMAPS Flip Chip Technology Workshop; 2002 Jun 24-26; Four Seasons Hotel Austin, Texas.

(21) Packaging Technology. Laser solder ball jet system SB^2-jet [Internet]. 2008 [cited 2008 Jul 12]. Available from: http://www.pactech.de/index.php

(22) Elert G. Temperature of a hot object red [Internet]. 2009 {cited 2009 Mar 7]. Available from: http://physics.uwo.ca