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Study of stencil printing parameters for ball grid array formation at smaller pitch

Shrikant G. Kulkarni, Varsha A. Chaware, Girish J. Phatak*
Centre for Materials for Electronics Technology (C-MET),
Off Pashan road, Panchawati, Pune
*Corresponding author: gjp@cmet.gov.in

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Abstract

In the new packaging paradigm, the area array interconnections realized through Ball Grid Array have become a necessity. For being the most simple and production oriented process, the stencil printing method is being re-investigated for the formation of Ball Grid Array (BGA). This process is known to pose difficulties in forming BGA at small pitches. We have investigated the stencil printing process. This paper investigates the stencil printing process with the aim of forming uniform BGA at a pitch of 2× (pad size). For present study, the target was to obtain hemispherical BGA on 0.76 × 0.76 mm square pads. The printing parameters *viz.* squeegee pressure, squeegee speed, snap off and aspect ratio have been studied over wide range of values by selecting two relatively thin (0.2 mm) and thick (0.4 mm) stencils. A maximum print volume of 0.26 mm^3 was obtained using a 1.0 mm aperture for 0.4 mm stencil, at zero snap off, low squeegee speed and high squeegee pressure. It is noticed that these results can be generalized for the BGA preparation of any size barring the issue of stencil stiffness. BGA were prepared at the optimized stencil printing conditions on LTCC substrates having 0.76 × 0.76 mm Ag/Pd pads using 90Pb/10Sn Type-IV solder paste. The optimized printing condition produced an average print volume of 0.256 mm^3 and uniform hemispherical BGA with bump height of 0.37 ± 0.01 mm after reflow.

1 Introduction

Even after many decades of its existence, the drive for miniaturization of electronics is continuing relentlessly. Recently, the onus of miniaturization has shifted on packaging in general and interconnection technologies in particular, due to the limitations of device scaling. With the rising pin counts projected to reach in the range of 5000–100000 Ball Grid Array (BGA) has emerged as an important enabling technology for high density area array interconnects due to their better high frequency performance, small foot print packages, smaller weight and low cost [The International Technology Roadmap for Semiconductors, 2010]. The need for such high density interconnections with highest process reliability, has now forced a re-look at the BGA formation processes.

Several methods are used for the BGA preparation. The BGA are prepared by attachment of solder spheres to the substrates pads, or prepared in-situ after reflow of the deposited solder paste or films on the pads. These films are formed by using one of the following methods, such as, vacuum evaporation, electroplating, solder jet printing and stencil printing [Annala *et al.* 1997]. Amongst these, the stencil printing process is the most simple and cheaper process. It is most important advantage is that it is already in use in the industry, causing better availability of quality machines and a large pool of trained personnel. The technique is ideal for large area deposition, has capability of handling high volumes and offers short cycle time. This technique does face some drawbacks, such as, bridging, non-uniformity in thickness and volume and weaker repeatability [Gong *et al*. 2003]. Solder bump height, pitch and co-planarity are amongst important factors to that need to be controlled while considering stencil printing deposition [Kelkar *et al*. 2000]. Such difficulties usually limit the BGA to more relaxed pitches. Obtaining BGA with a pitch of 2× (pad size) or lower, is, therefore, considered difficult. Further, the stencil printing process is sensitive to the environment, operator skills, consistency of the instrument as well as the paste and printing parameters. Minimizing the effect of such parameters and preparing uniform BGA at limiting pitch sizes in order to obtain high density solder bumps is an important task in the stencil printed BGA [Rajkumar *et al*. 2000; Ming-Hsien *et al*. 2008]. The above discussed merits of BGA preparation by stencil printing are attractive enough to expend efforts on addressing such outstanding issues. There would be enormous cost advantages if these issues could be tackled in an industrial environment, successfully and reliably.

There are several parameters that determine the success of stencil printing process for BGA formation, which are discussed below:

1. *Aspect Ratio:* The difficulty in preparing solder bumps by stencil printing stems from the issue of aspect ratio of the stencil aperture. Following quick, thumb rule calculations should make the picture clear. If one has to prepare hemispherical solder bumps of diameter 'd' (μm) and radius 'r' (μm) on a pad with side 'd' (μm) using a paste having solder volume fraction of 'v_r' (ratio) a stencil with aperture having side 'd', then the height of the stencil printed solder can be calculated as:

$$h\ (\mu m) = (\pi r/6v_r) \tag{1}$$

where, 'h' (micron) is the height of printed solder paste. The aspect ratio for the said aperture can then be given as:

$$\begin{aligned}\text{Aspect Ratio} &= 2r/h = 2r/(\pi r/6v_r) \\ &= 12v_r/\pi = 3.82v_r\end{aligned} \tag{2}$$

Thus, we arrive at an aspect ratio value which is a dependent on the solder volume fraction, and which is 3.82 times of the solder volume fraction in the paste, for all bump sizes. Usually the volume fraction of the solder content in the paste is around 50%. For such pastes, the necessary aspect ratio is about 1.9, which is very low and not adequate for proper transfer of solder paste.

The generalized calculations for solder print height can be carried out by following the steps given below [Li & Thompson 2000]

$$V(\mu m^3) = \pi\left[\frac{H}{6} + h\frac{d^2}{8}\right] \tag{3}$$

where 'V' is the volume of the solid section of the part of solder sphere with height 'H' (μm) expected to be formed on the pads. The volume of solder paste required to be dispensed on pads can be given as:

$$v_p\ (\mu m^3) = V/v_r \tag{4}$$

and the height of the printed solder volume for a given pad size can be found by equating the print volume to v_p, giving:

$$h\ (\mu m) = v_p/a_a \tag{5}$$

where, a_a is the area of aperture in $(\mu m)^2$.

It may be noted that the above calculations need to be tempered by various practical factors, such as, using nearest higher available value of stencil thickness to 'h', (which deteriorates the aspect ratio further) method of stencil fabrication, implying roughness of the aperture walls, cross sectional shape of the aperture walls and many more, which have a bearing on the actual transfer of solder paste to the pads.

It is known that stencil printing through an aperture with aspect ratio below 1.5 is not possible due to the tackiness of the solder paste [Kay *et al*. 2005]. Normally, the increase in aperture size should suffice to circumvent this difficulty. However, the combination of squeegee pressure and hardness of squeegee puts a practical upper limit on the aperture dimensions. It is reported that when a polymer squeegee is used for larger apertures, squeegee tends to scoop the top portion of solder paste that it has pushed into aperture [Soldering guidelines and SMD footprint design, 2004]. We have also reported such behaviour for an aperture with aspect ratio of 7 [Wadekar *et al*. 2005]. This effect is also reported by Jianbiao *et al*., who have derived an upper limit of aspect ratio as 2.87 above which scooping of paste dominates [Pan & Tonkay, 1999]. Such removal of solder paste due to squeegee is most likely to deposit non-uniform solder quantity across the printing area. The solder quantity will then depend upon the aperture size and its position on the stencil, as the squeegee deformation would not be uniform across its length. Another effect that may put an upper limit on the aperture size is the pad pitch, as discussed below.

2. *Pad Pitch:* With relaxed pitch, it is possible to increase the aperture size and obtain required print volume without bridging after reflow. However, for a pitch of 2× (pad size), there are practical limitations on the aperture size in view of bridging.

3. *Stencil quality:* The quality of the walls of the aperture has a bearing on the printed solder volume. Apart from improving the smoothness, printing with high aspect ratio is one of the ways of minimizing its effect.

4. *Paste properties:* Consistency in the paste viscosity and tackiness is an important issue in obtaining consistent results of printed volume, and thus, the bump size.

It is clear from the above discussion that the available window in terms of aspect ratio and pitch for obtaining stencil printed solder bumps is far too limited and mostly fall in the area of uncertainty, wherein the results cannot be guaranteed. There is a need to study the effect of every other process parameter in order to obtain relatively large solder print quantity through small aspect ratio aperture, consistently and repeatedly. Fortunately, it is possible to manipulate the print volume through various printing parameters, such as, squeegee pressure, snap off and squeegee speed once the pitch, aspect ratio and aperture sizes are finalized. However, this calls for a detailed study of printing parameters at limiting aperture values.

There are several reports about the study of stencil printing parameters for solder paste printing, applied mainly to the Surface Mount Technology (SMT) requirements [Pan & Tonkay, 1999; Manessis *et al*. 1998; Tsung-Nan Tsai, 2008; Barajas *et al*. 2008; Pan *et al*. 2004]. However, there are limited reports regarding study of printing parameters for BGA application. Pan & Tonkay, [1999] have reported a study of stencil printing parameters using apertures with different aspect ratio. The paper is mainly concerned about the effect of printing speed and aperture shape on the transfer ratio of the stencil and does not present detailed study of the selected printing parameters and also misses out the study of snap off. In contrast, Lau & Chang, [2000] studied all the relevant printing parameters, such as, paste type, squeegee pressure, snap off, aperture shape and aspect ratio and used the Taguchi method for parameter optimization. However, this study is restricted to only two values of each parameter, and is focused on maximizing the print volume. It is seen that maximization of the print volume from stencils with restricted aspect ratio and over pads having 2× (pad size) pitch and obtain uniform solder bumps still requires a detailed study of the relevant parameters. There is an attempt to study the theoretical aspects of printing parameters, such as, squeegee pressure, print angle, squeegee hardness and paste viscosity, and, a relation between paste transfer ratio and aspect ratio is suggested [Pan & Tonkay, 1999].

In this paper we have studied the effect of printing parameters, such as, squeegee pressure, squeegee speed, snap off and aspect ratio with an aim of achieving the required print volume at a pitch of 2× (pad size), so as to form uniform solder bumps over the large area. As outlined above, the window of aperture size and aspect ratio for the present study is vastly constrained and practically lies within the range of uncertainty wherein the success of the endeavour depends upon finding the right window of printing parameters. Unwittingly, this study also helps in understanding the effect of thick, stiff stencils and provides a possible generalized solution to the problem. This paper also introduces direct solder print volume measurements, which most of the earlier reports lack, except for the report by Hsu-Nan Yen *et al.,* [2006].

2 Experimental

For the present study, the targeted solder bump diameter was 0.76 mm, to be formed on square pads of 0.76 × 0.76 mm size having a pitch of 1.52 mm. Two types of substrates were used for printing. The blank 96% alumina substrates of 1″ × 1″ size were used when the experiments were limited to the study the shape and volume of the printed solder paste patterns, while fired Low Temperature Co-fired Ceramic (LTCC) substrates having a 15 × 15 array conducting, solderable pads of Ag-Pd paste were used to obtain solder bumps after reflow. For the printing experiments two stencils with different thickness and aperture sizes were used. Table 1 presents the details of the stencils and their sizes used in the present study.

The choice of stencil thickness and their patterns was based upon the window of aspect ratio and aperture sizes that are available for obtaining the targeted solder bumps. The consideration behind higher thickness was to improve solder bump volume with thickness, while the thinner stencil was used to obtain better aspect ratio. These stencils were fabricated by LASER cutting process (M/s Kristeel Shinwa Industries Ltd., Mumbai, India). The LASER cutting insured aperture size accuracy, tapered walls and facilitate paste release [Kloeser *et al.* 2002]. The printing experiments were carried out using Type IV (−400/+635) Pb90/Sn10 (IND 259, Indium Corporation, U.S.A) solder paste of particle size in the range of 20–38 µm. A semi-automatic screen and stencil printer (DEK J1761 RS) with a 60 Shore polyurethane squeegee[1] was used for the printing. The polyurethane squeegee was selected as it helps rolling of the paste during printing, in turn improving the print quality [Liu *et al.* 2006].

The printing parameters that were studied include squeegee pressure at 1.6, 5.4 and 8.4 kgf with small variation of ±0.2 kgf interval in the respective ranges, squeegee speed varied in the range 20 to 200 mm.sec^{-1} with interval of 40 mm.sec^{-1}, and snap off[2], which was varied over the range of 0 to 0.9 mm. For all experiments other than those studying aspect ratio, the printing was done through 1.0 mm aperture of the 0.4 mm thick stencil, giving an aspect ratio of 2.5. A stereo microscope (OLYMPUS SXZ12) with digital photographic attachment was used for optical observations and photo-recording. The printed volume measurements and 3D imaging of the printed solder bumps were carried out using LASER triangulation gauge of thickness measurement unit (Tallysurf CLI 2000, Talyor Hobson, U.K.). The solder reflow was carried out using a 4 zone solder reflow oven (Falcon 5C, Sikama Inc, U.S.A.). The BGA obtained were examined using stereo microscope and scanned for shape, dimensions and volume using the above mentioned 3D metrology.

[1]Squeegee is used to spread paste evenly across the back of a stencil making a solder bum on the printed surface.

[2]Gap between bottom of screen and top of substrate.

Table 1. Details of stencils, apertures and aspect ratio used in this study.

Sr. No.	Stencil thickness (mm)	Shape	Aspect ratio (mm)			
Aperture size (mm)			0.7	0.8	0.9	1.0
1	0.2	Square	3.5	–	–	–
2	0.4	Square	–	2.0	2.25	2.5

3 Results and discussion

In stencil printing, it is difficult to obtain a clear picture about the effect of individual printing parameters due to their close interdependence. Varying the printing parameters in a wide range is one possible way. This generates large experimental data that can, potentially, generate a good understanding about such interdependence. In the following, we present the dependence of print volume on squeegee pressure, squeegee speed, snap off and aspect ratio.

The squeegee pressure is an important parameter that decides shear stress over the paste. Figure 1 presents the dependence of the printed solder paste volume on squeegee pressure for the 0.2 and 0.4 mm stencils at zero snap off at a constant squeegee speed of 100 mm.s^{-1}. It is seen that the print volume for 0.2 mm stencil is lower than that for the 0.4 mm stencil, which is expected. However, it is seen that the printed solder volume is far lower than the theoretically expected volume of 0.4 mm^3 for the 0.4 mm stencil, while it is comparable to the expected volume of 0.1 mm^3 for the 0.2 mm stencil. This difference signifies the role played by the

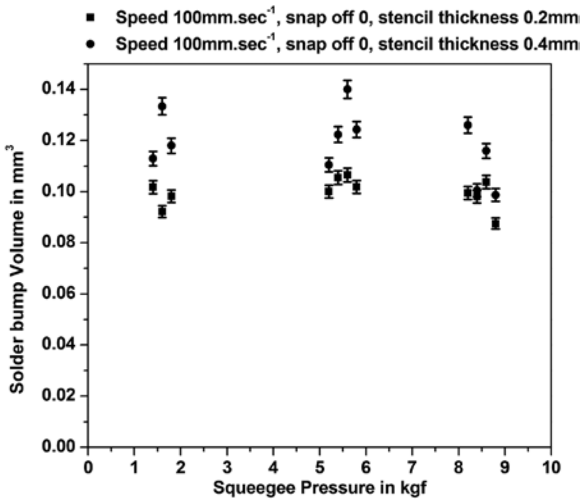

Figure 1. Dependence of solder print volume on squeegee pressure for the 0.2 and 0.4 mm thick stencils at constant squeegee of speed 100 mm.s^{-1}, zero snap off.

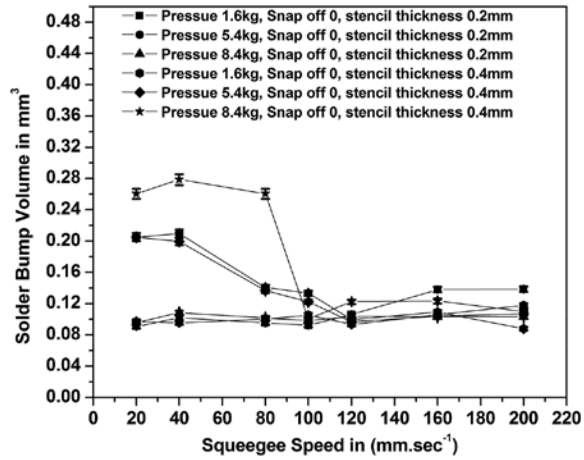

Figure 2. Dependence of solder print volume on squeegee speed for 0.2 and 0.4 mm thick stencils at zero snap off and at three different pressures of 1.6, 5.4 and 8.4 kgf.

relatively lower aspect ratio for 0.4 mm thick stencil. Normally, the higher squeegee pressure is expected to reduce viscosity of the paste due to higher shear. The results, however, indicate that there is no significant dependence on squeegee pressure for both the stencils, except for some reduction in print volume for 0.2 mm stencil at highest squeegee pressure. For 0.4 mm thick stencil, such observation indicates that this change in viscosity is not enough to overcome the effect of lower aspect ratio and other printing parameters. For 0.2 mm stencil the aspect ratio is sufficiently large. However, the print volume is already close to the maximum volume at low pressure to have any significant increase in print volume with pressure. At far higher squeegee pressure, there is a possibility of scooping and removal of the top portion of the printed paste, causing reduction in the printed volume [Mannan *et al*. 1994].

Squeegee speed is factor that decides dwell time over the pattern during stroke, which, in turn decides the aperture filling during the stroke. Here, the squeegee speed was studied at three different pressures with zero and a non-zero snap off. Figure 2 presents the dependence of printed volume on squeegee speed for zero snap off and at different squeegee pressures for the 0.2 mm and 0.4 mm thick stencils. Normally, the increasing squeegee speed is expected to increase the print volume due to lower viscosity caused by increased shear stress, while at the same time the dwell time is reduced [Pan & Tonkay, 1999; Tarr, 2007]. Thus, there are two opposite effects acting simultaneously. We found that these two effect cause peaking of printed volume with increasing speed. It is also seen that the increase in squeegee pressure, that causes increased shear, shifts of this peak towards the higher speed end. For the 0.2 mm thick stencil that has better aspect ratio, the peak is found to be around 180 mm.s^{-1} at 1.6 kgf pressure, which may be shifting towards higher speed range beyond the measured limits at higher pressure. The higher aspect ratio reduces the need of higher shear and lower viscosity [Durairaj *et al*. 2002].

On the other hand, the 0.4 mm thick stencil that has smaller aspect ratio, shows peaking of the print volume at much lower speed due to the need to exert higher hydrodynamic pressure for printing. From Figure 2 it can be observed that the peak for the 0.4 mm thick stencil shifts towards higher speed quite prominently at the squeegee pressure of 8.4 kgf.

Figure 3 presents the dependence of printed volume on squeegee speed at non-zero (0.3 mm) snap-off and at different squeegee pressures. A similar effect of reduced viscosity due to higher shear when squeegee speed increases and at the same time reduced dwell time, can be clearly observed. For the 0.2 mm thick stencil, however, such effect of snap off is not prominent at 5.4 and 8.4 kgf squeegee pressures, probably due to bending of the stencil that ultimately produces results similar to zero snap off. At 1.6 kgf

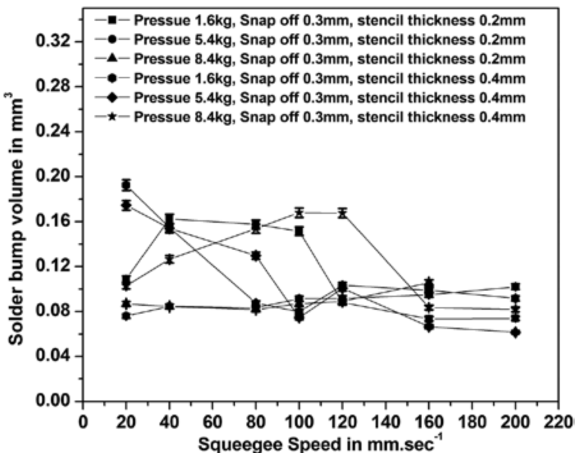

Figure 3. Dependence of solder print volume on squeegee speed for the 0.2 and 0.4 mm thick stencils at 0.3 mm snap off and at three different squeegee pressures of 1.6, 5.4 and 8.4 kgf.

pressure for this stencil, one can observe peak printing volume at much lower pressure and total volume much higher that theoretically expected. For the 0.4 mm thick stencil, however, the stencil stiffness does not allow much bending at any squeegee pressure, causing defined observation of peak print volume at all the pressures, though the whole range is seen shifting towards lower speeds, which is expected.

Increase in snap off is expected to increase the print volume as the effective thickness increases. However, there would be a limit beyond which further increase in snap off would reduce the print volume [Pan & Tonkay, 1999]. Figure 4 presents

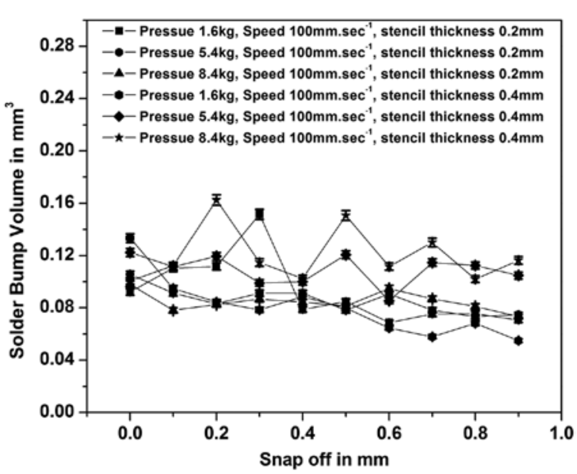

Figure 4. Dependence of solder print volume on snap off for the 0.2 and 0.4 mm thick stencils at a constant squeegee speed of 100 mm.sec^{-1} and at three different pressures of 1.5, 5.4 and 8.4 kgf.

effect of snap off on the print volume in case of 0.2 mm and 0.4 mm thick stencil. The results have been recorded at a print speed of 100 mm.s^{-1} and at varying squeegee pressure. With increasing squeegee pressure, the snap off value at which the print volume would be maximum, is expected to shift towards the higher side due to the bending of the stencil. This kind of behavior is clearly observed for the 0.2 mm thick stencil in Figure 4.

The effect of stencil bending is not expected for the 0.4 mm thick stencil. It is seen that the peak print volume for this stencil is at 1.6 kgf squeegee pressure and zero snap off, because insufficient paste shear is inadequate to push the paste up to the substrate at higher snap offs. The result at 5.4 and 8.4 kgf are similar, showing peak print volume in the similar range as there is hardly any bending of the squeegee at both the squeegee pressures. The falling part of the curves beyond the peak shows high variation, which may be due to the overlapping effect of various physical properties of the solder paste, such as, viscosity, tackiness and thixotropy and the local stencil conditions. In such cases the volume of dispensed solder paste was found dependent on quantity stuck to either wall of aperture or substrate during the printing process. Overall, the volume of solder paste dispensed was observed to be independent of snap off.

Aspect ratio plays a crucial role in stencil printing; the volume of solder paste dispensed on substrate is dependent on the ratio of aperture opening to its thickness. In this study, the apertures with openings 0f 0.8, 0.9 and 1.0 mm prepared on the 0.4 mm thick stencil provided an opportunity to study aspect ratio between 2 and 2.5. The dependence of print volume on aspect ratio is presented in Figure 5. These experiments were carried out at a squeegee pressure of 5.4 kgf, squeegee speed of 100 mm.s^{-1} and zero snap off. The trend seen in Figure 5 is as expected. The print volume of the paste does increase with aspect ratio. However, the maximum print volume obtained is much lower than that expected theoretically. Clearly, at the normal printing conditions it is not possible to transfer all the solder volume deposited in the aperture with an aspect ratio of 2.5. Higher aspect ratio is not possible for the 0.4 mm thick stencil due to pitch limitations.

It is clear from the above discussion that for obtaining solder bumps with a pitch of 2× (pad size) is constrained mainly due the aspect ratio, which cannot be increased much beyond

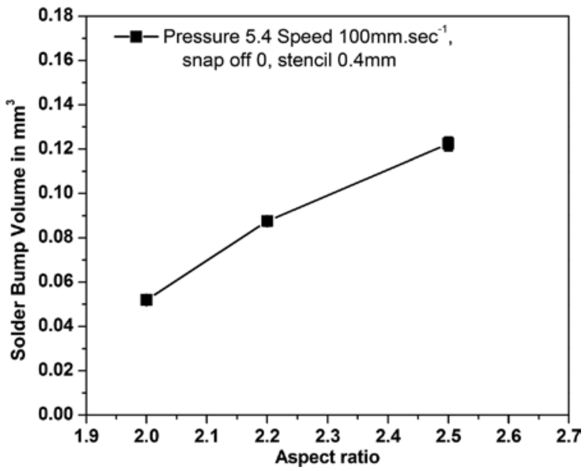

Figure 5. Dependence of solder print volume on aspect ratio for the 0.4 mm thick stencil, recorded at a squeegee pressure of 5.4 kgf, squeegee speed of 100 mm.sec^{-1} and zero snap off.

approximately 2.5 for any bump size due to scooping issues. Additionally, as the above results for 0.2 mm thick stencil with an aspect ratio of 3.5 clearly indicate, such an attempt need not provide the best possible print volumes. Thus, it becomes essential to work with non-standard, limiting printing conditions and relatively (relative to the targeted bump or pad size) thick stencils. In fact, the relation of the useful stencil thickness with the pad size, for a pitch of 2× (pad size), may be always close to 1.75 (ratio of pad size to stencil thickness) as has been found here. The optimized conditions at which highest print volume is obtained, also may work for all bump sizes, except for the issue of reduced stiffness when smaller size bumps are attempted. In such cases, non-zero snap off may provide better results than zero snap off as seen here.

The printing conditions at which the best print volume of ~0.26 mm^3 is obtained are summarized in Table 2.

Table 2. Printing parameters for reflow experiment.

Sr. No.	Printing parameter	Optimized value
1.	Squeegee pressure	8.4 kgf
2.	Squeegee speed	40 mm.sec^{-1}
3.	Snap off	0 mm
4.	Aspect ratio	2.5
5.	Stencil thickness	0.4 mm
6.	Substrate	Fired LTCC with Ag/Pd pads

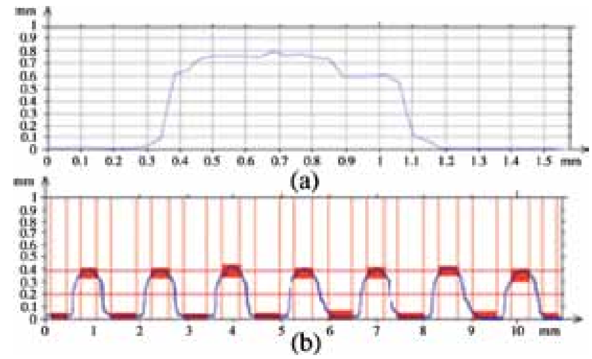

Figure 6. Representative Line scan profiles of 90Pb/10Sn solder print and bumps, obtained by printing on LTCC substrates at the optimized printing condition (**a**) line scan of a solder print before reflow, and, (**b**) line scan of eight solder bump in one row after reflow.

Solder bumps were prepared on printed and fired Ag-Pd conducting pads of 0.76 × 0.76 mm dimensions with a pitch of 1.52 mm, by first printing the solder paste at the optimized conditions, followed by its reflow at 320°C peak temperature with usual solder reflow profile across the reflow oven zones. The solder bumps thus produced, were hemispherical in shape and quite uniform across the test substrate of 1″ × 1″ size. Sample measurements of the printed volume indicated average print volume of 0.26 mm^3 before reflow. The bump height was measured across the sample at different positions after reflow. The average bump height was found to be 0.37 ± 0.01 mm across the sample. Good uniformity in the bump size may be noticed. Figure 6 presents sample thinness profiles of printed pads before reflow and that for of solder bumps acquired using the LASER gauge, while Figure 7 presents optical images of the BGA test sample.

4 Conclusions

Stencil printing is amongst the simplest methods that can be used for BGA formation, which

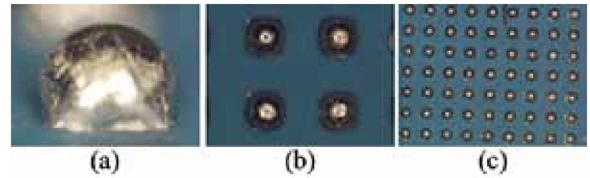

Figure 7. Optical pictures of the solder bumps at prepared optimized printing conditions (**a**) side view of a single bump, and, (**b**) and (**c**) top view of the solder bump array.

suffers from the difficulty of having to work with relaxed pitch. The results presented here indicate that it is necessary to work with relatively thick stencils at an aspect ratio that is below the recommended range, for clean, consistent printing in order to form uniform BGA at a pitch of 2× (pad size). This is achieved by employing printing conditions, such as, aspect ratio, squeegee speed and squeegee pressure, that tend to be at the extreme values. Using such optimized printing conditions, uniform hemispherical bumps of 0.76 mm diameter and ~0.37 mm height on 0.76 × 0.76 mm pads with 1.52 mm pitch could be formed with below 1% variation in bump height. The results suggest that it may be possible to form BGA of different sizes with a pitch of 2× (pad size) uniformly by generalizing these results. Thus, such BGA could be formed using a stencil of thickness in the range of (1/1.75) times pad size and having an aperture of aspect ratio around 2.5, at the similar printing conditions. It may be noted that the present results have been obtained using thick and stiff stencil. Therefore, the optimized printing parameters may change at very low bump sizes as the stiffness of the stencil would reduce. Further study is necessary to confirm these conclusions.

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Girish J. Phatak received his Ph.D degree in Microelectronics from the Department of Electrical Engineering, Indian Institute of Technology, Bombay, Mumbai, in 1993. He is currently Scientist at Centre for Materials for Electronics Technology (C-MET) at Pune. He has worked in the area of electronic devices, thin films, Si technology and hybrid microcircuit (HMC) materials. His current research interests include LTCC process, materials devices and applications in the wide area of Electronic Packaging. He has published over 37 papers in international journals and presented several papers in national and international conferences. He is currently a member of IEEE and life member of MRSI, and ISSS.

Shrikant G. Kulkarni, received his Ph.D. degree in Physics from Savitribai Phule Pune University (SPPU), Pune in 2015. He is Senior Research Fellow (SRF) in Centre for Materials for Electronics Technology (C-MET), Pune.

Since 2006 he joined in Electronic Packaging group. His initial work is in field of thick film materials and mainly in Low Temperature Co-fired Ceramics (LTCC) compatible materials and LTCC device fabrication. He has expertise in screen printing techniques and thick film paste development. He extensively worked in BGA development using stencil printing process.

His current research interests in materials for non-conventional energy sources and storage devices and its integration in LTCC structures as well as non co-planar micro fluidic devices fabrication in LTCC. He has published 19 papers in National/International conference and research papers in peer reviewed journals.

Varsha A. Chaware received her Ph.D degree in Electronic Science from Savitribai Phule Pune University in 2015. She is currently Research Associate at Center For Materials for Electronics Technology (C-MET) Pune. She has worked on the LTCC fabrication process and development of LTCC compatible dielectric materials. Her current research includes development of materials for integration of passive components in LTCC.