Estimation of Liquidus Temperature when SnAgCu BGA/CSP Components are Soldered with SnPb Paste

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Abstract

Recently, the soldering of lead-free components with SnPb paste, or lead-free backward compatibility, is becoming a hot topic. One of the major challenges in backward compatibility assembly is the development of a right reflow profile for the soldering of SnAgCu Ball Grid Array (BGA)/Chip Scale Package (CSP) components with SnPb paste. If the SnAgCu reflow profile is used, the reflow temperature may be too high for other SnPb components in the same board during assembly according to the component rating per IPC/JEDEC J-STD-020C. In addition, the flux in SnPb solder paste may not function properly in such a high reflow temperature. On the other hand, if the SnPb reflow profile is used, SnAgCu solder ball may only partially melt. The incomplete mixing of the solder paste with the BGA/CSP ball raises serious reliability concern. Therefore, it is important to know the minimum reflow peak temperature that is able to achieve complete mixing of SnPb paste with lead-free components. This paper presents a method to estimate the liquidus temperature of mixed compositions when SnAgCu BGA/CSP components are soldered with SnPb paste. The liquidus temperature is the minimum reflow peak temperature able to achieve complete mixing of SnPb paste with lead-free components. It will be shown that the liquidus temperature depends on the Pb ratio in the mixed composition and the liquidus temperature is below 217°C, which is the liquidus temperature of SnAg3.0Cu0.5 solder. The liquidus temperatures of several experimental studies in literature are estimated and it is found that the estimated temperatures are consistent with experimental results. A user interface is designed using Visual Basic for Application in the Microsoft Excel environment to facilitate the estimation of the liquidus temperature. It is expected that the estimation of the mixed compositions liquidus temperature will be able to guide process engineers to develop a right reflow profile in backward compatibility assembly.

Introduction

In response to Europe's Restriction of Hazardous Substances (RoHS) and other countries' lead-free directives, the electronics industry is moving toward lead-free soldering. However, some products, such as servers, are exempt from the RoHS directive beyond 2010. Additionally products such as medical equipment, and military and aerospace products are not required to be lead-free. These products will continue to be built with conventional tin-lead (SnPb) solder paste because the reliability of lead-free solder joints for these high reliability applications is still unknown. Since many component manufacturers are migrating to lead-free production, components such as memory modules are no longer available in SnPb finish. Therefore, soldering of lead-free components with SnPb paste, which is called backward compatibility, must be studied.

One of the major challenges in backward compatibility assembly is the development of the right reflow profile for the soldering of SnAgCu Ball Grid Array (BGA)/Chip Scale Package (CSP) components with SnPb paste. A schematic of the BGA/CSP backward compatibility assembly is shown in Figure 1. If the SnAgCu reflow profile (peak temperature of 230 to 250°C) is used, the full mixing of the SnPb paste and the SnAgCu ball will be achieved as shown in Figure 2. But the reflow temperature may be too high for other SnPb components in the same board during assembly according to the component rating per IPC/JEDEC J-STD-020C. In addition, the flux in SnPb solder paste may not function properly at such a high reflow temperature. On the other hand, if the SnPb reflow profile is used, the SnAgCu solder ball will only partially melt and won't be self-aligned as shown in Figure 3. The incomplete mixing of the solder and no self-alignment of the BGA/CSP ball raise serious reliability concerns.

Studies [1-4] show that the reliability of solder interconnections degraded significantly when the SnAgCu ball is only partially mixed with the SnPb paste. Gregorich & Holmes [1] reported that the reliability of backward compatibility assembly when the mixed assembly was reflowed at peak temperature of 200°C was much poorer than that of the control SnAgCu ball with SnAgCu paste in both the accelerated temperature cycling test from -40°C to +125°C and the mechanical shock test. The poor reliability is believed to be due to the inhomogeneous microstructure resulting from partial mixing of Pb. The reliability of backward compatibility assembly improves as the reflow temperature increased to 225°C. Hillman, et al. [2] evaluated the reliability of a BGA package assembled using a peak reflow temperature of 215°C with the duration of time above 200°C at 40 seconds. They observed partial mixing of Pb in the joint microstructure. The reliability of the solder joint was very poor as the solder joint failed at only 137 cycles in temperature cycling from -55°C to +125°C with dwell times of 11 minutes at each extreme and a ramp rate of 10°C/minute maximum per IPC-9701 guidelines. Hua, et al. [3-4] reported similar results showing that incomplete mixing lead to unacceptable solder joints. Therefore, it is critical to achieve

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complete mixing of SnPb paste with SnAgCu ball in BGA/CSP backward compatibility assembly.

The degree of mixing in backward compatibility assembly is expected to be a function of the reflow peak temperature and time above liquidus. Grossmann, et al. [5] observed that the SnAgCu ball was only partially mixed with SnPb paste at the reflow peak temperature of 210°C; and the SnAgCu ball was totally dissolved when the reflow peak temperature exceeded 217°C, which is the liquidus temperature of Sn3.0Ag0.5Cu alloy. They also found that a homogeneous reaction of the SnPb paste with the SnAgCu ball with a minimum formation of voids was achieved at the peak reflow temperature of about 230°C. Zbrzezny, et al. [6] investigated various reflow profiles and concluded that complete mixing of the solders was achieved when the reflow peak temperature reached 218-222°C.

Most of these studies believed that full mixing is achieved only when the reflow peak temperature exceeds 217°C [4-6], however, a full mixing of the SnPb paste with the SnAgCu ball can be achieved when the peak reflow temperature is below 217°C. For example, Nandagopal, et al. [7-8] observed that a full mixing of the SnPb paste and the SnAgCu ball was accomplished at a peak reflow temperature of 210°C for about 15 to 25 seconds. They used the Differential Scanning Calorimeter (DSC) to characterize the time required to achieve full mixing. Handwerker [9] indicated that full mixing occurred at 207°C for sufficient time for a Sn3.9Ag0.6Cu solder ball constituting 75% of the final solder. Snugovsky, et al. [10] described the mixing process using a SnPb phase diagram. From the study, they concluded that a complete mixture may be achieved at a temperature lower than 217°C and that the temperature depends on solder ball composition, ball/solder paste ratio, dwell time, and component size.

Although a considerable amount of work [1-12] has been done so far on the backward compatibility assembly and its reliability, the minimum temperature able to achieve the full mixing is still unknown. The key in backward compatibility assembly is to develop a reflow profile with the peak temperature high enough to be able to achieve full mixing of the SnPb paste and the SnAgCu ball, and the peak temperature low enough (prefer below 220°C) so that SnPb components won't be damaged. Therefore, it is critical to know the minimum reflow peak temperature that is capable of achieving a complete mixing of SnPb paste with lead-free components.

This paper presents an approach to estimate the mixed composition liquidus temperature when SnAgCu BGA/CSP components are soldered with SnPb paste. The mixed composition liquidus temperature is the minimum reflow peak temperature able to achieve complete mixing of SnPb paste with lead-free components. First, the calculation of mixed composition is described. Then the estimation of the liquidus temperature of the mixed composition is presented. The liquidus temperatures of different BGA/CSP component pitch levels are estimated. The liquidus temperatures of several experimental studies in published literatures are estimated as well, and it is found that the estimated liquidus temperatures are consistent with published experimental results. Finally, the paper describes a user interface designed to facilitate the estimation of liquidus temperature.

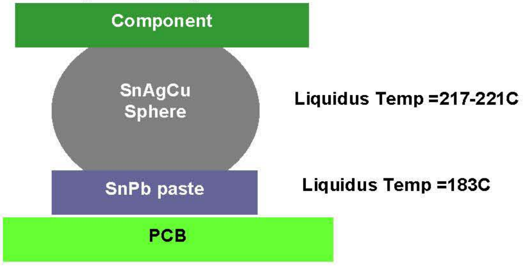

Figure 1. A schematic of BGA/CSP Backward Compatibility

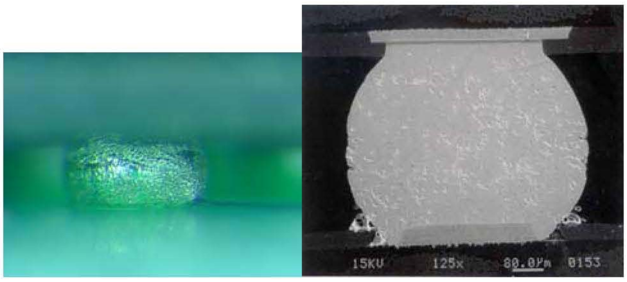

Figure 2. Full mixing achieved when the SnAgCu reflow profile is used

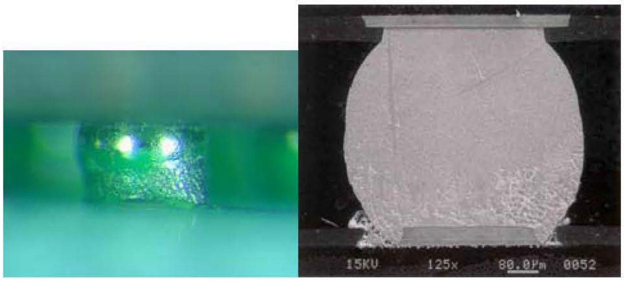

Figure 3. Partial mixing when the SnPb reflow profile is used

Mixed Composition Calculation

There are four alloying elements in the mixed composition when SnAgCu BGA/CSP components are soldered with SnPb paste: Sn, Ag, Cu, and Pb. The percentage of each metal element in the mixed composition can be calculated

$$W_{Pb} = \frac{f_{Pb} \times V_{Paste} \times f_m \times d_{SnPb}}{V_{Paste} \times f_m \times d_{SnPb} + V_{Ball} \times d_{SnAgCu}} \qquad (1)$$

$$W_{Ag} = \frac{f_{Ag} \times V_{Ball} \times d_{SnAgCu}}{V_{Paste} \times f_m \times d_{SnPb} + V_{Ball} \times d_{SnAgCu}} \qquad (2)$$

$$W_{Cu} = \frac{f_{Cu} \times V_{Ball} \times d_{SnAgCu}}{V_{Paste} \times f_m \times d_{SnPb} + V_{Ball} \times d_{SnAgCu}} \qquad (3)$$

$$W_{Sn} = 100 - W_{Pb} - W_{Ag} - W_{Cu} \qquad (4)$$

where W_{Pb}, W_{Ag}, W_{Cu}, and W_{Sn} are the weight percentage of Pb, Ag, Cu, and Sn in the mixed compositions, respectively; f_{Pb} is the percentage of Pb in weight in SnPb solder paste; f_{Ag} and f_{Cu} are the weight percentage of Ag and Cu in SnAgCu alloy; f_m is the volume percentage of metal content in SnPb solder paste; d_{SnPb} and d_{SnAgCu} are the density of SnPb and SnAgCu alloys. V_{paste} is the SnPb solder paste volume, which can be calculated

$$V_{paste} = \begin{cases} L^2 H(TR) & \text{for square aperature} \\ \pi\left(\frac{D}{2}\right)^2 H(TR) & \text{for round aperture} \end{cases} \tag{5}$$

where L is stencil aperture length for square aperture, H is stencil thickness, D is stencil aperture diameter for round aperture, and TR is the transfer ratio, which is defined as the ratio of the volume of solder paste deposited to the volume of the aperture.

V_{ball} is the volume of a solder ball in the BGA/CSP component. If the ball diameter, D, is given, the ball volume can be calculated

$$V_{ball} = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 \tag{6}$$

If the sphere is reflowed and the ball height, H, and radius, R, are given, the ball volume can be calculated

$$V_{ball} = \frac{2}{3}\pi R^3 - \pi R^3\left[\frac{1}{3}\left(\frac{H-R}{R}\right)^3 - \left(\frac{H-R}{R}\right)\right] \tag{7}$$

For eutectic SnPb solder paste, f_{Pb} is 37 and typical value of f_m is 0.5 (or 50%). For Sn3.0Ag0.5Cu solder alloy, f_{Ag} =3.0 and f_{Cu} =0.5. The density of eutectic Sn37Pb, d_{SnPb}, is 8. 4g/cm^3 and the density of Sn4.0Ag05, d_{SnAgCu}, is 7.394g/cm^3 [14].

For example, a 1 mm pitch Xilinx fine-pitch BGA (FG676) package with a 0.61 mm (24 mil) Sn3Ag0.5Cu ball diameter is assembled with Sn37Pb paste. The solder paste is printed using a 0.127mm (5 mil) stencil with a 0.457 mm (18 mil) diameter round aperture. The SnPb paste has 50% metal content in volume. Assume a 90% transfer ratio. Using Equation 6, we can calculate that the volume of the Sn3Ag0.5Cu ball is 0.118mm^3 (7235 mil^3). Using Equation 5, we can calculate the volume of SnPb paste is 0.0188mm^3 (1125 mil^3). Using Equations 1 to 4, we can get the final mixed alloy composition:

$$W_{Pb} = \frac{37 \times 0.0188 \times 0.5 \times 8.4}{0.0188 \times 0.5 \times 8.4 + 0.118 \times 7.394} = 3.07$$

$$W_{Ag} = \frac{3.0 \times 0.118 \times 7.394}{0.0188 \times 0.5 \times 8.4 + 0.118 \times 7.394} = 2.75$$

$$W_{Cu} = \frac{0.5 \times 0.118 \times 7.394}{0.0188 \times 0.5 \times 8.4 + 0.118 \times 7.394} = 0.46$$

$$W_{Sn} = 100 - 3.07 - 2.75 - 0.46 = 93.7$$

Therefore, the mixed composition is 93.7% Sn, 3.1% Pb, 2.8% Ag, and 0.5% Cu, all in weight.

Estimation of Mixed Composition Liquidus Temperature

After we know the mixed compositions, the next question becomes what is the liquidus temperature of mixed composition Sn3.1Pb2.8Ag0.5Cu. The phase diagram of common binary and ternary systems that are relevant to solders can be obtained from the National Institute of Standards and Technology (NIST) webpage (available at http://www.metallurgy.nist.gov/phase/solder/solder.html). But the phase diagram of the complex quaternary SnPbAgCu is currently not available. The phase equilibria can be calculated from thermodynamic databases using the CALPHAD method [15]. Thermodynamic calculation is a very useful tool in obtaining phase diagram information, but it requires reliable thermodynamic databases and specialized knowledge. In this paper, the liquidus temperature of ternary and quaternary systems is estimated using the simple linearization of the binary liquidus lines. The linearization method has been successfully used by the National Institute of Standards and Technology (NIST) since the National Center for Manufacturing Sciences (NCMS) lead-free study [16]. Thus, the liquidus temperature of the quaternary SnPbAgCu system, a typical alloy system in backward compatibility assembly, can be calculated

$$T_l = 232°\text{C} - 3.1W_{Ag} - 7.9W_{Cu} - 1.3W_{Pb} \tag{8}$$

with limits: $W_{Ag} < 3.5$; $W_{Cu} < 0.7$; $W_{Pb} < 38$; where T_l is the liquidus temperature of Sn-rich solder alloys; 232 is the liquidus temperature of Sn; W_{Ag}, W_{Cu}, and W_{Pb} are the percentage in weight of Ag, Cu, and Pb, respectively. The coefficients before these alloy elements are the slope of the binary liquidus lines. For example, 1.3 is the slope of SnPb binary liquidus lines when Pb is less than 38% in weight; 7.9 is the slope of SnCu binary liquidus lines when Cu is less than 0.7% in weight; and so on. It should be emphasized that the limitation of the simple linearization is $W_{Ag} < 3.5$, $W_{Cu} < 0.7$, and $W_{Pb} < 38$. It should also be noted that Equation 8 is an approximation.

Based on Equation 8, the liquidus temperature of Sn3.0Ag0.5Cu,

$$T_l = 232°\text{C} - 3.1 \times 3.0 - 7.9 \times 0.5 - 1.3 \times 0 = 219°C$$

If Ag content is over 3.5% and less than 4% wt, Ag_3Sn is primary phase. In this case, Equation 8 is not valid. A simple fix is to add 5°C to Equation 8. Thus, the liquidus temperature of Sn3.8Ag0.7Cu is

$$T_l = 232°\text{C} - 3.1 \times 3.8 - 7.9 \times 0.7 - 1.3 \times 0 + 5 = 220°C$$

Currently the reflow profiles in backward compatibility assembly are developed through costly trial-and-error method. It is expected that the estimation of the mixed compositions liquidus temperature will be able to guide process engineers to develop the right reflow profile in backward compatibility assembly.

Table 1 summarizes the final joint compositions and liquidus temperature with Sn3Ag0.5Cu (SAC305) ball and Sn37Pb paste for typical BGA/CSP component pitch levels. The aperture size, shape, stencil thickness and ball diameter are based on Solectron's guideline for no-clean paste. The transfer ratio is assumed based on experiences. It shows that the final liquidus temperature is lower than 217°C, the liquidus temperature of SAC305. The liquidus temperature can be as low as 203°C. As the pitch level decreases (except 0.5 mm pitch), the weight percentage of Pb increases and the liquidus temperature decreases. Equations 1 to 4 imply that the liquidus temperature depends on the ratio of BGA ball volume and solder paste volume.

Table 1. Final Joint Compositions and Liquidus Temperature with Sn3.0Ag0.5Cu Ball and Sn37Pb Paste

Pitch (mm)	1.27	1.0	0.8	0.65	0.5
Aperture size in mm (mil)	0.533 (21)	0.457 (18)	0.406 (16)	0.356 (14)	0.279 (11)
Aperture shape	Round	Square	Square	Square	Square
Stencil thickness in mm (mil)	0.152 (6)	0.127 (5)	0.127 (5)	0.127 (5)	1.02 (4)
Transfer ratio (%)	100	90	85	80	70
Ball diameter (mil)	28	22	14	10	10
% of Pb	3.4	4.8	11.1	17.0	11.7
% of Ag	2.7	2.6	2.1	1.6	2.1
% of Cu	0.5	0.4	0.3	0.3	0.3
Estimated liquidus temp. (°C)	216	214	208	203	208

Equation 8 shows that a higher Pb percentage in the mixed compositions can reduce the mixed composition liquidus temperature. The higher Pb percentage can be achieved by printing more SnPb solder paste or reducing the SnAgCu solder ball. But it is unclear what effect of high Pb content in mixed compositions on the backward compatibility reliability. Zhu, et al. [17] studied the effect of Pb contamination on the lead-free solder joint microstructure and observed a Pb-rich phase formed in the bulk solder when the lead-free solder contains Pb impurity. Zeng [18] discussed the influence of the Pb-rich phase on solder joint reliability. The Pb-rich phase may be the weakest region in the bulk solder, and the crack may propagate along the Pb-rich phase interface during reliability testing [17, 18]. Bath, et al. [11] found that the reliability of backward compatibility assembly in accelerated temperature cycling (ATC) from 0°C to 100°C with 40 minute a cycle, even when the full mixing was achieved, was poorer than that of both SnAgCu ball/SnAgCu paste and SnPb ball/SnPb paste. But Bandagopal, et al. [7] found that the reliability of backward compatibility assembly in both ATC from 0°C to 100°C and -40°C to 125°C was better than the SnPb assembly when the full mixing was achieved. Furthermore, the reliability data of SnPb BGA ball soldered with SnAgCu paste (or forward compatibility), where high Pb content is in the mixed compositions, was better or equal to that of SnPb ball/SnPb paste control assemblies [19]. Therefore, no conclusion can be drawn yet regarding what effect of Pb content has on the backward compatibility reliability.

To assess the method, we estimated the liquidus temperatures from published experimental studies and compared the estimated liquidus temperature with published experimental results. The estimated temperatures and the published experimental results are summarized in Table 2. If the reflow peak temperature used is higher than the estimated liquidus temperature, full mixing is expected. Otherwise, partial mixing is expected. Overall, Table 2 shows that the estimated liquidus temperatures are consistent with reported experimental results. There are small variances between the estimated temperature and the reported results of studies in references 7 and 11. This could be due to the inaccuracy transfer ratio assumptions. Since only a few studies have reflow peak temperatures close to the estimated liquidus temperature, further experimental study is needed to validate the accuracy of the estimation method.

Table 2. Comparison of the estimated Liquidus Temperature and the Reported Experimental Results

Reference	Estimated liquidus temperature	Peak reflow temperature used	Experimental results
Gregorich & Holmes [1]	209°C	200°C	Partial mixing
		225°C	Full mixing
Hillman, et al. [2]	219°C	215°C	Partial mixing
Grossmann, et al. [5]	216°C	210°C	Partial mixing
		217°C	Full mixing
Nandagopal, et al. [7]	212°C	210°C	Full mixing
		227°C	Full mixing
Bath, et al. [11]	218°C	205°C	Partial mixing
		214°C	Full mixing

User Interface Development

To facilitate the estimation of the mixed composition liquidus temperature, a user interface was developed using Visual Basic for Application in the Microsoft Excel environment. Focus has been on designing an easy-to-understand user interface. One major feature with the user interface is that the input data, control menu and the results are presented on the same page. Another feature is that default data from typical assembly guidelines will be shown when a user selects a package pitch level. The user is also allowed to manipulate all input data. The input parameters include package pitch, package solder ball type, stencil dimensions, and solder paste compositions. The output data include mixed compositions, solder paste volume, and the estimated liquidus temperature. Figure 4 shows the interface for the BGA/CSP component user form.

Summary

A method to estimate the mixed composition liquidus temperature when lead-free components are soldered with tin-lead solder paste was presented. The estimated liquidus temperatures of published experimental studies are consistent with reported experimental results.

The liquidus temperature of backward compatibility assembly is lower than that of SnAgCu alloy. The temperature depends on the ratio of Pb in the mixed compositions. The ratio of Pb is influenced by the BGA ball volume, ball solder alloy types, and solder paste volume. Generally speaking, the smaller the pitch level of BGA/CSP components, the higher weight percentage of Pb, thus the lower the liquidus temperature. But the effect of high Pb content on the reliability of backward compatibility assemblies is still unclear.

A user interface for the liquidus temperature estimation was designed using Visual Basic for Application in the Microsoft Excel environment.

It is expected that the estimation of the mixed compositions liquidus temperature will be able to guide process engineers to develop the right reflow profile in backward compatibility assembly.

Future experimental study is needed to confirm the accuracy of the estimation method for liquidus temperature of mixed compositions.

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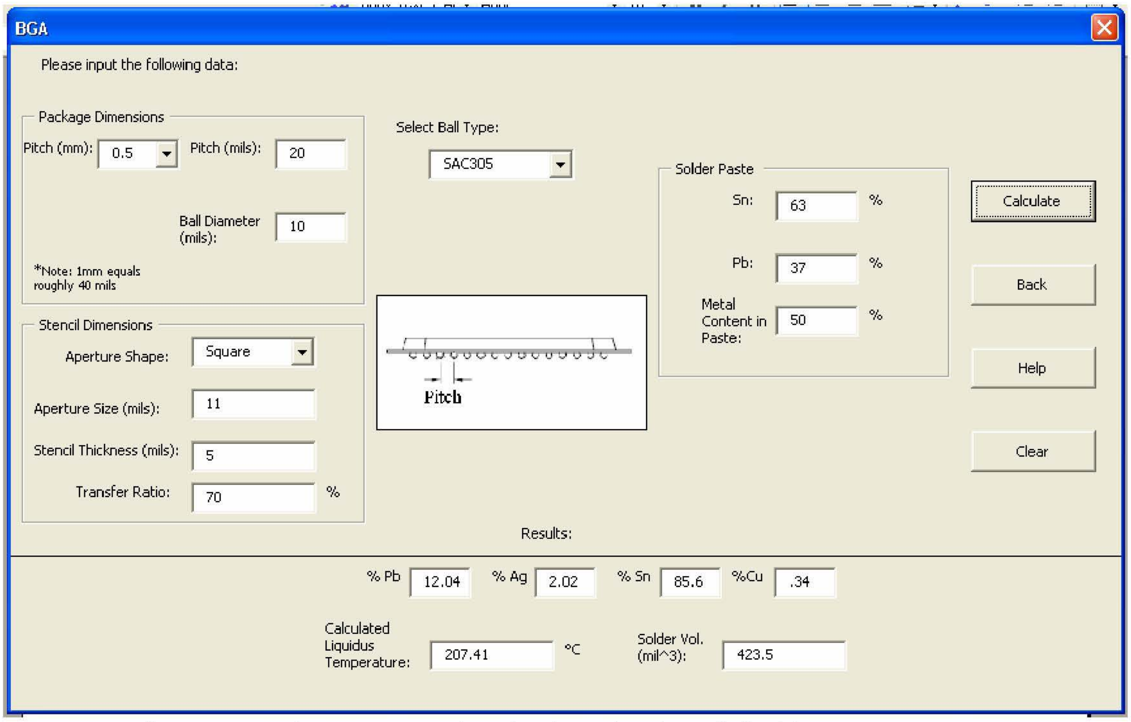

BGA

Please input the following data:

Package Dimensions

Pitch (mm): 0.5

Pitch (mils): 20

Ball Diameter (mils): 10

*Note: 1mm equals roughly 40 mils

Stencil Dimensions

Aperture Shape: Square

Aperture Size (mils): 11

Stencil Thickness (mils): 5

Transfer Ratio: 70 %

Select Ball Type: SAC305

Solder Paste

Sn: 63 %

Pb: 37 %

Metal Content in Paste: 50 %

Results:

% Pb 12.04 % Ag 2.02 % Sn 85.6 %Cu .34

Calculated Liquidus Temperature: 207.41 °C

Solder Vol. (mil^3): 423.5

Figure 4. BGA/CSP User Interface for the Estimation of Liquidus Temperature

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