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CAPILLARY FLOW SOLDER WETTABILITY TEST

by

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Abstract

A test procedure was developed to assess the capillary flow wettability of solders inside of a confined geometry. The test geometry was comprised of two parallel plates with a controlled gap of constant thickness (0.008 cm, 0.018 cm, 0.025 cm, and 0.038 cm). Capillary flow was assessed by: (1) the meniscus or capillary rise of the solder within the gap, (2) the extent of void formation in the gap, and (3) the time-dependence of the risen solder film. Tests were performed with the lead-free solders 95Sn-5Sb, 96.5Sn-3.5Ag, and 91.84Sn-3.33Ag-4.83Bi. The capillary rise of the lead-free solders was less than that observed with the 63Sn-37Pb control. Reducing the solder surface tension and contact angle improved capillary flow. Void formation by the non-lead solders increased as the gap became smaller. Generally, the extent of voiding was determined primarily by the gap size rather than the wettability parameters (contact angle or surface tension) of the individual alloys.

Introduction

Numerous test techniques have been developed to evaluate the wettability (or solderability) of a particular substrate/solder/flux system[1, 2, 3, 4]. Some procedures are performed on generic substrate geometries (thin coupons, wires, etc.) in closely controlled laboratory experiments, while others are conducted on actual package features (resistor leads, chip terminations, circuit boards, etc.). In the former case, the meniscometer/wetting balance technique[4] has provided valuable laboratory data on the wettability of alternative, lead-free solders, particularly with respect to the consideration of such alloys for prototype circuit board assembly trials[5]. On the other hand, wettability tests on electronic devices and substrates have been used to determine the acceptability criteria of such items for later assembly into products[6,7].

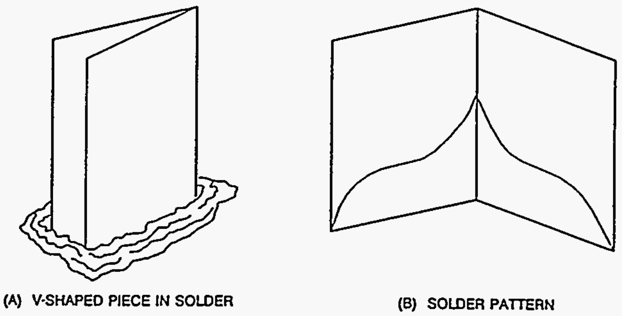
(A) V-SHAPED PIECE IN SOLDER
(B) SOLDER PATTERN

Fig. 1 "Open book" sample configuration of the test developed by Wolverton and Ables[8].

Like the meniscometer/wetting balance method, a majority of wettability tests evaluate solder wetting on an "open" substrate configuration (horizontal or vertical surfaces). In the case of "confined geometries" such as holes or lineal gaps, factors such as capillary action and the movement of flux volatiles become important in the wetting process. Solderability testing has addressed the confined test configuration primarily from the product viewpoint through the rotary dip test for through-hole circuit boards[1]. In the simplest format of the rotary dip test, a through-hole circuit board is swung onto a solder bath, allowing the matrix of holes to fill with solder. The quantitative metric is the number of holes that are filled with solder. Recently, a laboratory test procedure was developed by Wolverton and Ables which measured the capillary rise of solder in an "open book" configuration (Fig. 1)[8]. This technique provided a more refined measurement scale from which to assess capillary wetting. However, correlating the time-dependent meniscus rise against gap thickness, or determining the effects of flux volatiles on capillary wetting, are not readily assessed by this technique.

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The need for an alternative, "confined geometry", wettability test was identified from studies of the T-peel mechanical strength of lead-free solders performed at Sandia Laboratories[9]. It was observed that during the sample fabrication process, the lead-free solders did not fill the specimen gap geometry as readily as did the traditional tin-lead solder. In addition, excessive void formation was observed in the specimens. Therefore, a test methodology was sought to provide a *quantitative* determination of: (1) the extent of flux volatiles in the joint; (2) capillary flow as a function of gap; and (3) the time dependence of capillary flow by the solder meniscus within the gap.

Theoretically, the meniscus rise of a liquid between two parallel plates can be computed (at equilibrium) by the force balance between the vertical component of the solder surface tension and the weight of the liquid column:

$$p\, g\, h\, x = 2\, G(lf) \cos A \qquad (1)$$

where h is the capillary rise distance above the liquid surface; G(lf) is the surface tension; A is the contact angle; p is the liquid density; g is the acceleration due to gravity; and x is the gap distance[10]. The wetting force is G(lf) cosA, multiplied by two for the contribution of both sides of the gap, and pgxh is the weight of the solder column. The expression for the meniscus height, h, is given by:

$$h = \frac{2\, G(lf) \cos A}{p\, g\, x} \qquad (2)$$

The quantitative metric for capillary flow will be the parameter, h. It is noted in equation (2) that the meniscus height increases as the value of {G(lf) cosA} increases and as the gap distance decreases. Equation (2) assumes that the capillary profile is one of a spherical cap. Suitable corrective terms can be added to equation (2) which take account of larger, non-spherical cap profiles[11]; however, the general functional dependence on surface tension and contact angle remain unchanged.

The present study examined the capacity for several lead-free solders to fill a vertically oriented gap between two parallel copper plates. The extent of capillary rise, along with the propensity for void formation within the gap were quantitatively assessed. The time dependent properties of solder rise within the gap, will be described in a later report.

Experimental Procedures

The samples used in the evaluation were made from rolled plates of oxygen-free, high conductivity (OFHC) copper plates measuring 2.54 x 5.08 x 0.051 cm (Fig. 2). The surfaces were used in the as-received condition; plates were rejected for excessive surface damage or curvature. Copper spacers were resistance welded onto one of each pair of plates. The spacers were of such thicknesses as to provide one of the following gap widths: 0.008, 0.018, 0.025, or 0.038 cm. Next, the plate pairs were etched for 30 sec in a 1:1 volume solution of HCl plus water, rinsed, and subsequently dried in dry nitrogen. The outer surfaces (i.e., those which would not form the walls of the gap) were masked with temperature resistant tape. The surfaces that did form the gap interior were coated with an RMA flux. and then immediately joined together by the spot welding process.

The solder alloys and their respective solidus, liquidus, and test temperatures were: (1) 63Sn-37Pb (wt.%),T_s=183°C, T_l=183°C, 260°C (baseline); (2) 96.5Sn-3.5Ag, T_s=221°C, T_l=221°C, 260°C; (3) 95.5Sn-4.0Cu-0.5Ag, T_s=216°C, T_l=222°C, 267°C; (4) 95Sn-5Sb, T_s=232°C, T_l=240°C, 280°C; and (5) 91.84Sn-3.33Ag-4.83Bi,T_s=212°C, T_l=212°C, 260°C. The solder alloys were designated by the following respective abbreviations: Sn-Pb, Sn-Ag, Sn-Cu-Ag, Sn-Sb, and Sn-Ag-Bi. All tests were performed under ambient atmosphere conditions.

Testing of the assembled specimens was performed by attaching each sample to a wetting balance apparatus. The sample was immersed 1.0 mm into the solder bath, where it remained for 60 sec. This interval eliminated the

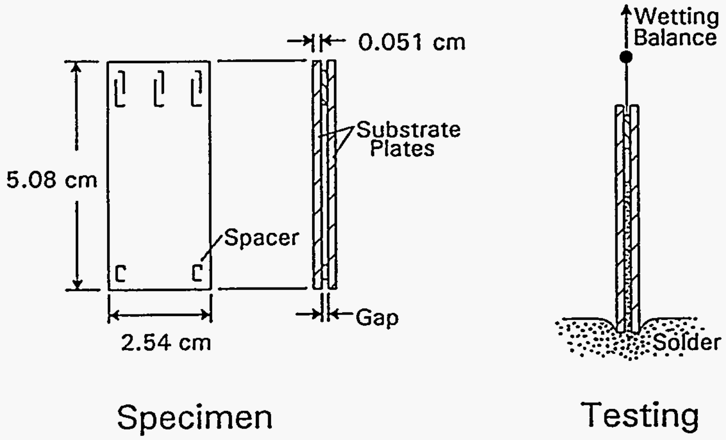

Fig. 2 Test sample configuration.

effects of transient behaviors at the initial phase of wetting, while maximizing the extent of capillary flow. Upon completion of the 60 sec hold period, the samples were removed from the bath. The drainage of solder from the gaps was not observed. Five specimens were tested per solder alloy.

Measurement of the capillary rise and void content was performed on x-ray photographs of each specimen. The extent of capillary flow and the location of voids were clearly delineated. Capillary rise was measured from digital images made of the x-ray photographs (taking account of the 1.0 mm immersion depth). Those digital images were further analyzed to determine the percent of the projected gap area which contained voids, using commercially available image analysis software. The data were represented as the mean of five data and a scatter term of plus-or-minus one standard deviation.

Results and Discussion

Capillary Rise

Shown in Fig. 3 is the capillary (meniscus) rise distance as a function of gap width for each of the tested solders. The capillary rise of the Sn-Pb solder exhibited a strong dependence on the gap size, increasing as the gap width became smaller as predicted by equation (2). The Sn-Pb data shown in Fig. 3 were compared with theoretical values computed from equation (2), using G(lf) and cosA values taken from previously conducted, meniscometer/wetting balance tests[5]. For the gap sizes of 0.008, 0.025, and 0.038 cm, the computed heights (with experimental values from Fig. 3 shown in parentheses) were 10.9 cm (5.1 cm), 3.5 cm (2.8±0.4cm), and 2.3 cm (1.9±0.1 cm), respectively. The size of the test sample (5.08 cm) restricted the meniscus rise in the 0.008 cm gap to that dimension. In each of the other gap sizes, the experimental heights were slightly less than the theoretical values. This difference was not caused by the presence of voids within the gap. In fact, the effect of void formation would be exactly the opposite, causing the capillary rise to be greater, due to an effective reduction in the weight of the solder column.

The analysis was next extended to the lead-free solders. The meniscus rise of the Sn-Ag-Bi lead-free solder also showed the expected dependence on gap. In the case of the Sn-Ag solder, however, only the capillary rise between 0.025 cm and 0.038 cm gaps exhibited an appreciable change. There was no significant trends observed for the other solders. As for the Sn-Pb solder, theoretical heights were computed, using equation (2) and previously acquired wettability data. Shown in Table 1 are the calculated values, including those for the Sn-Pb baseline solder. It is clear from a comparison between the theoretical calculations and the experimental results that the capillary rise distances of the lead-free solders were discrepant in two aspects: (1) The meniscus rise values fell short of the theoretical values and (2), the capillary height of the lead-free solders did not exhibit a strong dependence on gap width.

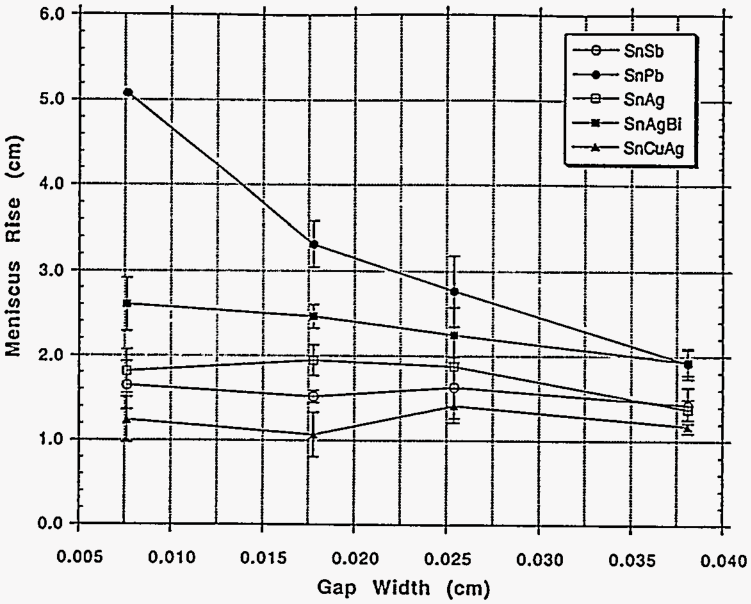

Fig. 3 Capillary (meniscus) rise as a function of gap size.

Table 1 Theoretical Capillary Rise Heights.

Solder (wt.%) / Temp. (°C)	Capillary Rise (cm) Gap Size (cm) 0.008	 0.025	 0.038
Sn-Ag / 260	12.9	4.1	2.7
Sn-Sb / 280	12.1	3.9	2.6
Sn-Ag-Bi / 260	12.2	3.9	2.6
Sn-Pb / 260	10.9	3.5	2.3

It was at first hypothesized that the differences between the experimental and theoretical results from the lead-free solders were due to an inadequate temperature rise in the copper plates, resulting in premature solidification of the head of the solder column. Therefore, the following analysis was performed. Since the Sn-Ag-Bi solder should have achieved a theoretical capillary rise comparable to that of the Sn-Pb at the 0.008 cm gap, it was surmised that the experimental height of only 2.7 cm reflected the "temperature boundary". Since the temperature gradient is independent of gap size, and according to Table 1, the Sn-Ag-Bi solder should be able to achieve a theoretical height of 2.6 cm at a gap of 0.038 cm, then the solder should, at least, rise to that value, 2.6 cm. The experimental height was only 1.4 cm for that gap. A similar analysis was performed, and result observed, for the Sn-Ag alloy. Moreover, the Sn-Cu-Ag data should have duplicated the Sn-Ag results, given similar liquidus and working temperatures; yet, the experimental values of the Sn-Cu-Ag alloy were significantly lower than those of the Sn-Ag solder. In conclusion, although temperature gradient effects cannot be completely dismissed as having some role in the wetting behavior, the above analyses suggest that capillary flow "artifacts" had a significant impact the experimental meniscus height data.

As noted above, the test data showed that the magnitudes of the capillary rise of the all of the solders were less than those predicted by theory. A further evaluation of the experimental data was performed in an attempt to determine whether the solder wettability properties (contact angle and surface tension) were determining factors on the meniscus rise. Equation (2) indicates a positive, linear relationship between the height, h, and the generalized material parameter, [G(lf)cosA]/ρg. When a linear regression analysis was performed between h and [G(lf)cosA]/ρg for each of the gaps, a satisfactory correlation (as represented by the square of the correlation coefficient, R^2) was observed; however, the correlation was negative. In order to further delineate the source of the negative correlation, capillary height data were examined with respect the surface tension, G(lf), and the contact angle, A. Those results for the 0.018 cm gap are shown in Figs. 4 and 5, respectively. Similar trends were observed for the other gap sizes. The capillary rise increased as the surface tension term decreased; this trend would appear to be contrary to equation (2). The meniscus rise increased as the contact angle decreased as would be predicted by the theoretical expression. Therefore, the increase of the meniscus rise with G(lf) was the source of the unexpected trend as compared with equation (2).

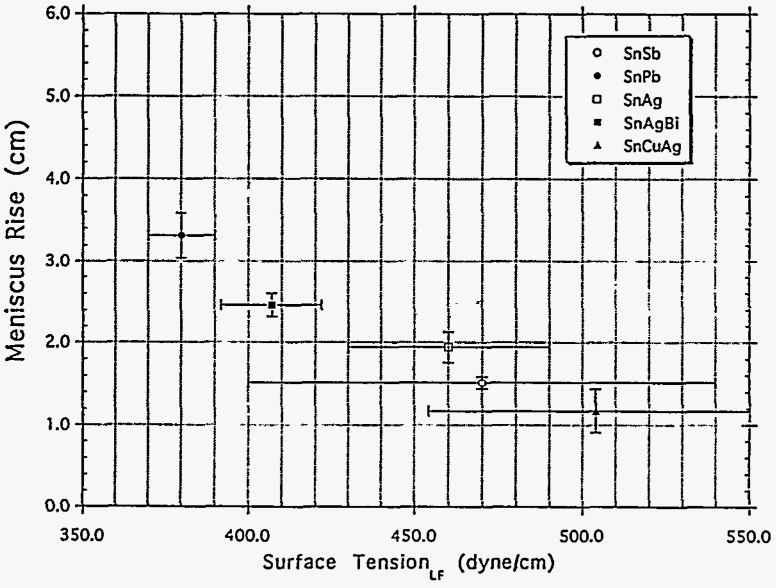

Fig. 4 Meniscus rise versus surface tension, G(lf), for a 0.018 cm gap.

The experimental data presented above substantiates qualitative observations that show: solder wettability improves as its surface tension decreases. In fact, decreasing solder surface tensions is one of the beneficial effects of a flux coating. The physical source of the seemingly contradictory dependence of capillary rise on surface tension, lies with geometric factors in the wetting process (Fig. 6). In order for wetting to reach the equilibrium configuration as described by equation (2), the meniscus surface must achieve the equilibrium contact angle, A (Fig. 6a). However, should the gap geometry be too small to accommodate the surface profile required of the surface tension, G(lf), then the contact angle, A', will exceed the equilibrium value (Fig. 6b). Therefore, the extent of capillary rise is reduced in accordance with equation (2).

In summary, the discrepancy between the experimental capillary behavior of the lead-free solders and the theory as represented by equation (2) was caused by the geometric constraint of the gap which did not allow the contact angle to achieve the equilibrium value (as measured in the non-confined configuration of the meniscometer/wetting balance technique). Only with those gaps in which the width does not prevent the solder meniscus from reaching a profile determined by the surface tension, will equation (2) aptly describe the extent of capillary flow. It was noted earlier that even at the largest gap of 0.038 cm, equation (2) did not adequately represent the experimental data. Since the selected gap range was comparable to geometries encountered in traditional circuit board product, it is apparent that the capillary flow properties of alternative, lead-free solders will not be predicted by equation (2); rather, minimizing the contact angle and G(lf) will be the required objectives. Moreover, quantitative evaluations for comparison purposes will necessitate empirical data from tests such as that described in this report.

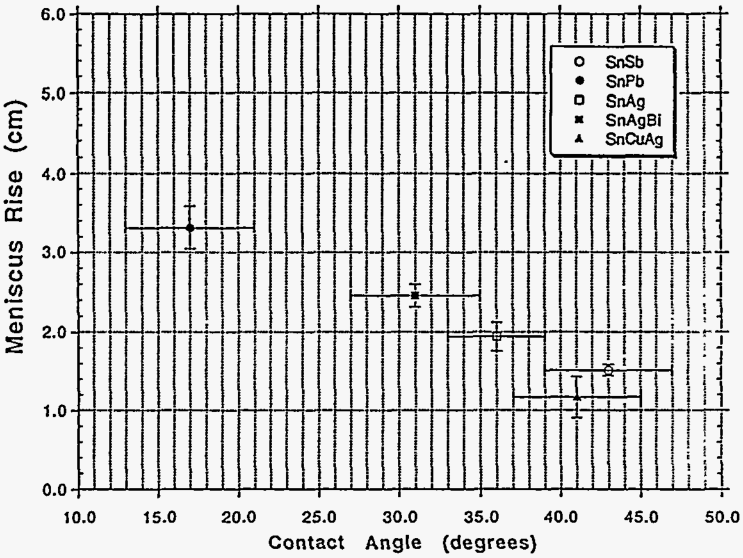

Fig. 5 Meniscus rise versus contact angle, A, for a gap of 0.018 cm.

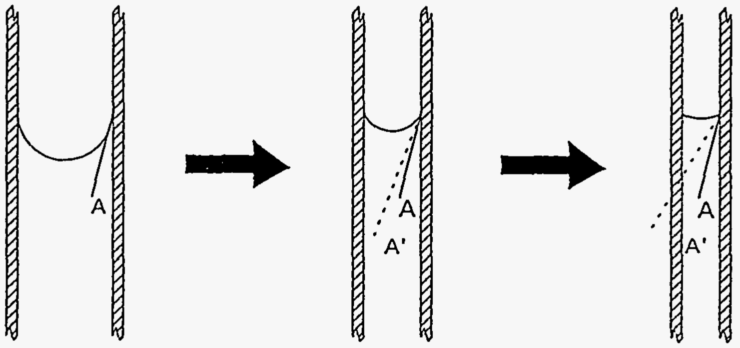

Fig. 6 Schematic diagram of solder wetting a gap. (a) Low G(lf) that allows for an equilibrium contact angle, A, to be achieved. (b) Combination of the confined geometry and G(lf) causes the contact angle, A', to be greater than A.

Void Formation

Shown in Fig. 7 is a graph depicting the percentage of voids as a function of gap width for each of the solders. As anticipated, the percentage of voids within the gap increased as the gap became smaller. This trend reflected the increased difficulty with which flux volatiles escaped the gap region. Void formation exhibited very little solder alloy dependence at the largest gap of 0.038 cm, being in the range of 1% to 3%. However, as the gap grew smaller, the extent of void formation became sensitive to the solder composition. In the case of the Sn-Pb (baseline) and Sn-Ag alloys, voiding grew to over 11% of the area at a gap of 0.008 cm. Void formation remained relatively low for the Sn-Sb solder (<4.0%), until tests with the 0.008 cm gap also produced approximately 11% voids in the solder column. The increases in voiding were less severe with the Sn-Ag-Bi and Sn-Cu-Ag solders, rising to values of between 5% and 6% in both cases.

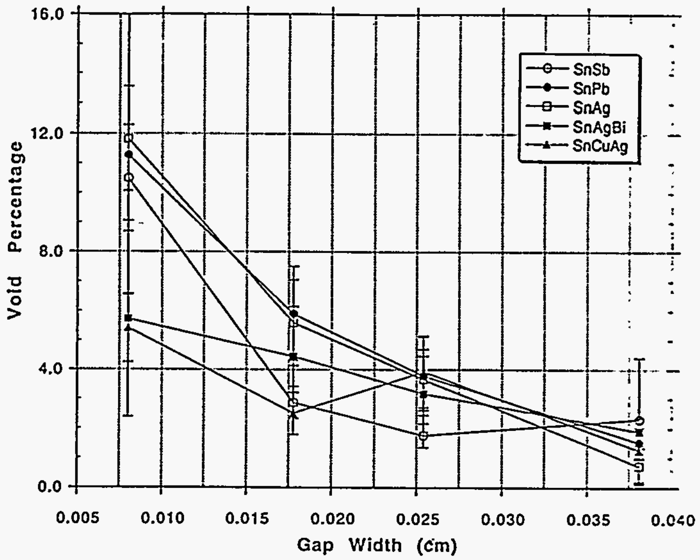

Fig. 7 Percentage of voids as a function of gap width.

The data was further analyzed to determine whether the wetting properties of the solders had an impact on the propensity for voids in the solder column. Shown in Fig. 8 is a plot of the void percentage as a function of the solder contact angle (A). A correlation coefficient (R) was determined by linear regression analysis. A value of R^2 equal to 0.63 (negative correlation) was computed, reflecting an acceptable correlation. However, the coefficients worsened for the larger gaps and the smallest gap width. Next, the void percentages were plotted against the surface tension parameter G(lf). An example is provided by the 0.018 cm thick gap results that are

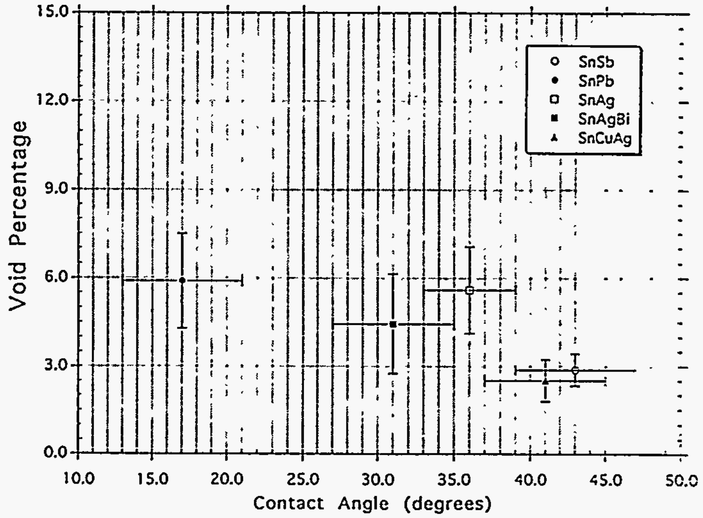

Fig. 8 Void percentage as a function of contact angle, A. The gap was 0.018 cm.

shown in Fig. 9. This particular data set exhibited a "fair" R^2 value of 0.54 (negative correlation). Again, for either the smaller and larger gaps, the coefficient values quickly deteriorated, showing no correlation between surface tension and the void content of the solder column.

The above analyses indicate that the extent of void formation within the gap could not be consistently correlated to the wettability properties of the solder alloys. The correlation was good at a gap of 0.018 cm, but then worsened for larger and smaller gap widths. Moreover, the 0.018 cm gap data indicates void formation and capillary flow have opposing trends; that is, optimizing solder wetting performance by minimizing the contact angle, A, and the surface tension, G(lf), will increase the tendency for voids to form in the joint. However, in those cases where the gap dimension is smaller or larger than the 0.018 cm value (or a suitable window thereabouts), gap geometry has a stronger impact on void formation than would the wetting properties of the solder, eliminating this apparent conflicting trend.

In summary, the void formation results show that solder wettability properties will not provide a consistent predictor of void propensity. The geometry of the confined joint (as well as the flux material) can significantly affect void formation, necessitating the use of experimental evaluations to document this phenomenon.

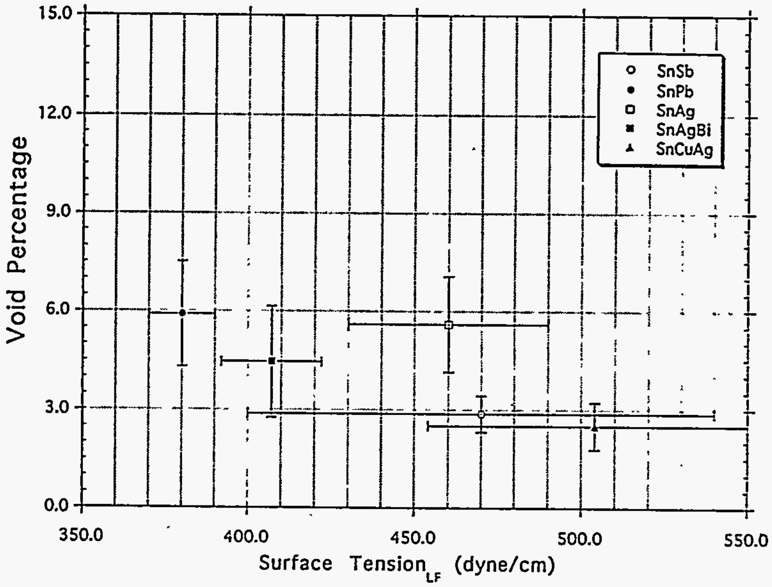

Fig. 9 Void percentage as a function of surface tension, G(lf). The gap was 0.018 cm.

Summary

1. An experimental technique was developed to evaluate the capillary wetting characteristics of alternative, lead-free solders between two parallel plates. Quantitative measurements of capillary flow and void formation were performed.

2. The extent of capillary rise by the lead-free and baseline Sn-Pb solders was less than predicted by the theoretical equation for the parallel plate gap. The lead-free solders exhibited a reduced sensitivity to gap width than was observed with the baseline Sn-Pb solder.

3. Contrary to capillary flow theory, the extent of capillary rise was optimized for those solders with the lower

solder surface tension, G(lf). This behavior was caused by the confined geometry of the gap, which prevented the solder film from achieving its equilibrium contact angle on the gap walls.

4. Void formation was 1% to 12% of the solder column for the given range of gap widths. Voiding increased as the gap size was decreased. The sensitivity of void formation to solder alloy became increasingly significant as the gap size diminished.

5. The impact which the wettability parameters of the alternative solders had on void formation, appeared to be restricted to only a very limited gap range. Beyond that window, the gap geometry (and flux composition) were the dominant factors.

Acknowledgments

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