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Computer Simulation of Solder Bridging Phenomena

Solder bridging is investigated under the assumption that liquid solder bridges are equilibrium capillary surfaces and that the principal factor that determines whether a bridge will freeze to form a permanent short is its configurational stability. A computational parametric bridge stability study is conducted to determine the response of bridging to the system volume, the distance between pads, the contact angle between the liquid metal and resist surface and the relevant physicochemical properties of the liquid metal.

1 Introduction

The mitigation of solder process pathologies such as solder bridging and wicking has always been an area of concern in the microelectronics industry. However, as ultrafine pitch technologies are slowly incorporated in an increasing number of applications, the need to reduce defect incidence has reached a higher degree of urgency. Historically, soldering processes have been adjusted to provide maximum manufacturing yield for the given technology that is being soldered. As various technologies experienced continual reduction in length scale as a result of advances in miniaturization, the associated soldering processes were adjusted to maximize yield. This approach was viable, in the sense that yields were maintained at acceptable levels, for several generations of increasingly finer length scale technologies. However, it was then intuitively obvious and ultimately confirmed by experience, that the reduction in length scale, most importantly some measure of the distance between adjacent pads, could not progress to arbitrarily small dimensions without creating formidable problems in soldering processes. Now, with the increased employment of ultra-fine pitch technologies on circuit cards, the number of soldering pathologies per joint formed, particularly solder bridging defects, is escalating dramatically. To understand the magnitude of the problem presented by soldering defects, one need only contemplate that there are some $10^{13}-10^{14}$ solder joints created worldwide per year, and that this annual figure has exhibited a steady growth history.

Solder bridging is presently the most prevalent of all soldering process pathologies. Bridging can occur in all types of soldering processes. A much under-emphasized fact when considering the solder bridging defect is that solder bridges are formed routinely and deliberately in many soldering processes. For example, in wave soldering, an entire region of circuitry may be bridged during, and for a short temporal interval following, the wave passage, but if the process is adjusted properly, an amount of solder is separated from the wave such that the deposited solder cannot exist in the bridged state. In the bar print process, entire rows of pads are intentionally bridged by a paste bar that becomes a continuous liquid metal bridge spanning the entire pad row during reflow. If the process is properly configured, the bridges that initially are present between adjacent pads are incapable of persisting in the steady state. An example in counterpoint is the bridge formed between opposing pads in the controlled-collapse or bump-type joint. In this context, the existence of the bridge in the steady state is clearly desirable. In all the above examples, the factor determining whether or not a bridge—regardless of how it is formed or the context in which it occurs—will exist in the steady liquid state is its *stability*. If a solder bridge is stable in the liquid state, it will ultimately freeze to form a solid metal connection.

The stability of a solder bridge as it typically occurs in microelectronics soldering is a dynamic problem. If we consider even the simplest bridging scenario, say a bridge created by a paste smear between adjacent surface mount pads, the evolution of the bridge shape through the entire soldering process is a very complex process. Typically, early in the reflow stage, there is first a phase transformation during which the solid constituents in the paste liquify. This phase transformation occurs simultaneously with segregation of the liquid metal from other liquid constituents in the paste. This is followed by a rapid shape metamorphosis to a configuration clearly dictated by predominance of capillary forces. Subsequently, flow of the bridge liquid occurs from the lower energy surface of the solder mask to the higher energy surfaces of the metal pads. The dynamics of the liquid redistribution during this flow, with an ultimate endstate of minimum system energy, are what determine whether the bridge will be stable or unstable. Observations in our laboratory of the flow phase suggest that the approach of the bridge meniscus to a static equilibrium occurs through a sequence of quasi-equilibrium steps, with the meniscus maintaining a shape typical of menisci whose shapes are dominantly influenced by surface tension forces. Thus, although dynamic forces, e.g., inertia forces, viscous forces, etc., clearly play a role in solder bridge stability, the above quasi-equilibrium behavior suggests that they exert only second-order effects and that solder bridge stability may be addressed by investigating the configurational or static stability of the bridge meniscus. This implies that the solder bridge be considered an equilibrium capillary surface (Finn, 1986). We note that the approach of the bridge meniscus to a static equilibrium does not necessarily imply a stable bridge, but admits the possibility of bridge instability following which the static equilibrium configuration of the system would be comprised of two separate liquid masses in equilibrium about the two solder pads previously bridged. As noted above, bridge instability, in most soldering process contexts, is a desirable event.

In this paper, we examine the phenomenon of solder bridging computationally using the Surface Evolver code (Brakke, 1992, 1995). The Evolver is a highly interactive (public domain) computer code designed for the study of surfaces. It evolves a surface towards its equilibrium configuration (equilibrium capillary surface) by minimizing total system free energy. The surface is represented as a simplicial complex of triangles, a representation of the surface that can be made either piecewise linear (default) or piecewise quadratic. The vertices of the triangles are points on the surface which are moved during surface

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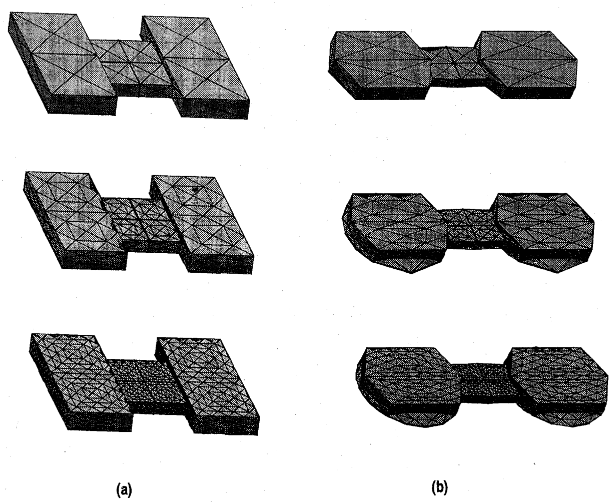

Fig. 1 **Initial liquid solder shapes for Surface Evolver at three levels of refinement. (*a*) Rectilinear pads, (*b*) circular pads. The resist surface surrounds the two pads and thus underlies the liquid bridge spanning the two pads.**

evolution using any of several variants of (energy) gradient descent. The discretization of the surface can be taken to an arbitrarily fine scale although there are obvious limitations imposed by computer memory and compute time. A criterion for the convergence of a particular surface to a minimum energy configuration is left to the subjectivity of the user; total surface energy values converged to twelve decimal places for a given level of discretization may be achieved in a reasonable amount of compute time for surfaces that are not particularly complex.

The advantages of using Evolver for solder bridging studies are several. It is clearly more economical than laboratory experiments, and, with a reasonably powerful computer, is faster than laboratory experiments. Computational simulations of bridging can be carried to arbitrarily small length scales, whereas laboratory experiments are very restricted in this aspect. All regions of the stability parameter space may be explored, e.g. the effect on bridge stability of the (1) physicochemical properties of the pad and mask surfaces as well as those of a particular solder alloy, (2) the geometry of the joint, e.g. pad dimensions, pad shape, and pad spacing, and (3) process parameters, such as solder deposition volume. Whereas a comprehensive study of the relevant regions of the parameter space described above is a formidable undertaking even with such a powerful tool as the Evolver, a comparable experimental investigation would be both prohibitively expensive and time consuming.

Eventually, in order to utilize the Evolver as an investigative tool for solder bridging, it will first be necessary to establish the validity of the computational bridge models by comparing the Evolver output from these models with experimental results for the same parameter settings. Experimental validation of the Evolver solder bridge models will be the subject of a future paper. Our ultimate goal will be to generate a map of the relevant regions of the solder bridge stability parameter space for use as design input to minimize bridging defects in current processes as well as to be used to design against bridging defects in the development of new circuitboard/module technologies and new soldering process technologies. This work is a first step in this direction.

2 The Computational Model

Model information is input to the Evolver in the form of an initial data file. This file contains the initial positions of the vertices, oriented connectivity information for the creation of surface edges and facets (triangular surface elements) from the initial vertices, system constraints (e.g., pinned contact lines, symmetry, etc.) and user-defined parameters (e.g., liquid volume, contact angle, etc.). Parameters can be changed at any point in the evolution of the surface. Edges and facets may be selectively or globally refined an arbitrary number of times. Edge refinement consists of putting a new vertex at the midpoint of the edge, thereby generating an additional edge. Facet refinement is accomplished by refining the three edges of the facet and then connecting the midpoints so formed; a refined facet thus decomposes into four facets. Refined elements inherit the constraints of the parent element. The initial shape of the surface as defined in the input data file is typically very unrealistic, i.e., the surface is far from an equilibrium capillary surface. The form of the initial shape is somewhat arbitrary, provided it does not introduce an artificial instability.

In the present work, liquid solder is placed on both pads; the initial pad volumes are then connected by a solder bridge. Figure 1 shows the initial distributions of liquid solder for both rectilinear and circular pads at several levels of refinement. The solder heights for the pads and bridge are chosen to give a volume in the desired range of investigation. The initial volume may be either incremented or decremented interactively during a stability study in which volume is a varied quantity. Typically, the volume is changed after a desired degree of energy convergence is achieved for a particular volume.

We assume that the two pad-bridge system has inherent four-fold symmetry (Fig. 2), and the data file is constructed to exploit the symmetry in order to obtain considerable savings in compute time. Approximately one-fourth the number of initial data points are used in the data file than are required in the complete model, with symmetry conditions imposed across the symmetry planes. The complete surface may be constructed from the evolved quarter surface using view transformations available in the Evolver. All complete surfaces exhibited in this paper have been constructed in this fashion. The imposition of symmetry has obvious implications with regard to the problem being modeled. Actual solder bridges will not possess perfect symmetry due to a variety of imperfections and nonuniformities in the real system, e.g. chemical inhomogeneities of wetted surfaces, nonuniformities in pad geometry and placement, etc. Furthermore, the stability conclusions arrived at here exclude, by construction, possible non-symmetric modes of instability.

The solder is assumed to fully wet the pads. The model imposes Dirichlet-equivalent boundary conditions on the surface along the perimeters of the pads where the assumption of contact line pinning is made. On the resist between pads, however, a Neumann-equivalent condition is imposed on the bridge portion of the surface, i.e. the static contact angle between liquid solder and resist is specified (the contact angle is related to the derivative of the surface at the contact line). Associated with the latter condition is the accompanying complexity of a free boundary, i.e. the location of the equilibrium contact line. Both

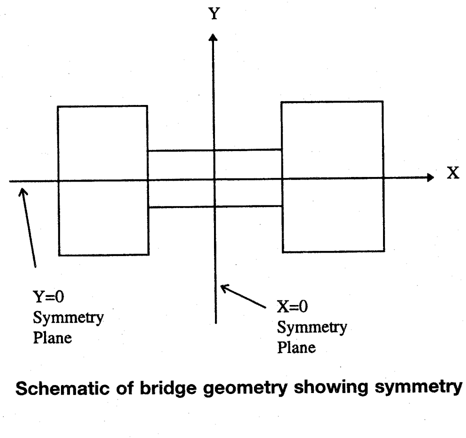

Fig. 2 **Schematic of bridge geometry showing symmetry planes**

of the above conditions are contained within the data file as constraints. The constraint of pinning along pad perimeters has its physicochemical origin in the discontinuous jump in interfacial energy between metal pad surfaces and the resist surface (deGennes, 1985) (the small difference in height between the pad surface and resist surface is neglected here).

We include the effects of gravity in the calculation of meniscus shape. Here, gravity is taken perpendicular to the plane of the pads and acts downward into the plane. The effects of gravity in microelectronics soldering are typically small because of the small length scales involved. Thus the Bond number, the square of the ratio of a physical length scale to the capillary length scale (thereby a measure of the relative importance of gravitational to surface tension forces), is typically small for equilibrium menisci formed in microelectronics applications. Our calculations here are done for relatively large pitch applications, primarily so that we may compare our results with data from a bridge simulation apparatus currently under design (Glovatsky, 1994). Once such comparisons can corroborate our bridge stability calculations, we can extend—with confidence—our bridge stability calculations to values of pitch commensurate with ultra fine pitch devices, i.e., to regions of parameter space which cannot be accessed with our experimental apparatus.

In addition to volume, the effects of other system properties on solder bridge stability can also be investigated rather conveniently using the Surface Evolver. By defining those system properties whose effects are to be studied as parameters in the data file, their values may be changed interactively during a parametric stability study. In this paper, we attempt to determine in some detail the effects of distance between pads and pad geometry on solder bridge stability, and, in somewhat less detail, the effects of the system properties of surface tension, contact angle of the liquid solder on the resist between pads, and liquid solder density.

3 Results and Discussion

Figures 3 and 4 show typical sequences of converged surfaces of stable bridges as a function of system volume between circular and rectilinear pads, respectively; all other system parameters are held constant. Both sequences show a neck developing in the center region of the bridge as the volume decreases. This is a common characteristic of bridges as they approach instability in the limit $V \rightarrow V_{\text{crit}}$ from above. When the critical volume is reached, the neck pinches and breaks, resulting in two stable menisci on the two pads. There appear to be distinguishing evolutionary features (which have been supported by preliminary experiments) between the surfaces associated with the curvilinear and rectilinear pads. Figure 3 shows that the bridges between circular pads develop a single saddle point and the surface itself is a well-defined saddle surface. Figure 4 shows that a bridge between rectilinear pads (aspect ratio 3:1) possesses a saddle point but exhibits a less well-defined saddle surface.

Figure 5 exhibits the total energy - system volume response with all other system parameters held constant. As the volume, a system load parameter, is decreased, the instability of the bridge is marked by a precipitous drop in system energy. The fact that a sharp energy decrease induced by a small change (which could be made infinitesimal) in system volume is accompanied by a radical change in system configuration is indicative of the fact that the system has undergone a bifurcation or catastrophe (Iooss and Joseph, 1990 and Gilmore, 1981) and bridge breaking is thus connected with such phenomena. The exact nature of this bifurcation is currently being investigated. The portions of the curves associated with volumes smaller than V_{crit} have been calculated by growing a discrete volume of liquid whose contact line is pinned on the perimeter of a pad of desired geometry. The process is begun for values of volume less than

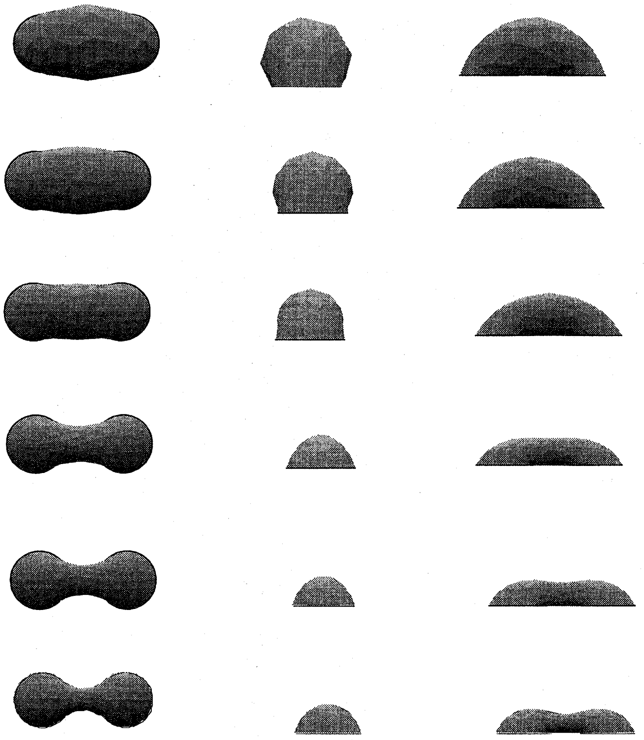

Fig. 3 Evolver output of a sequence of stable bridge surfaces for circular pad geometry

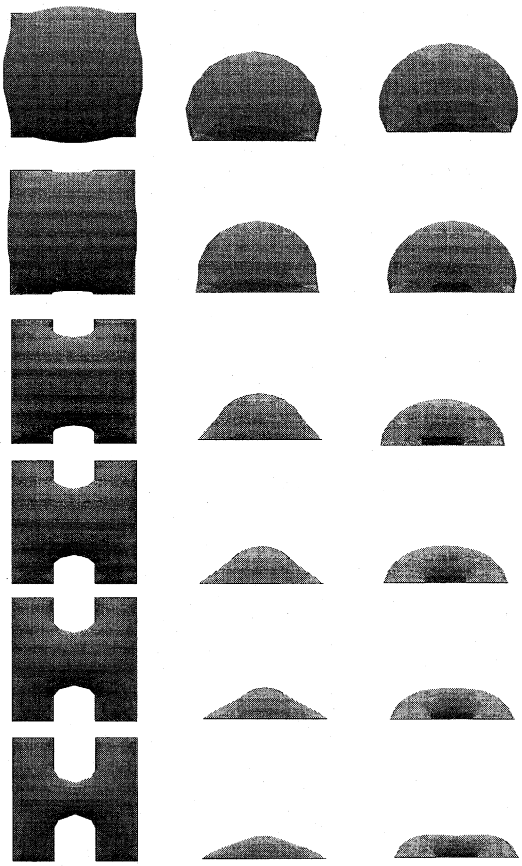

Fig. 4 Evolver output of a sequence of stable bridge surfaces for rectilinear pad geometry

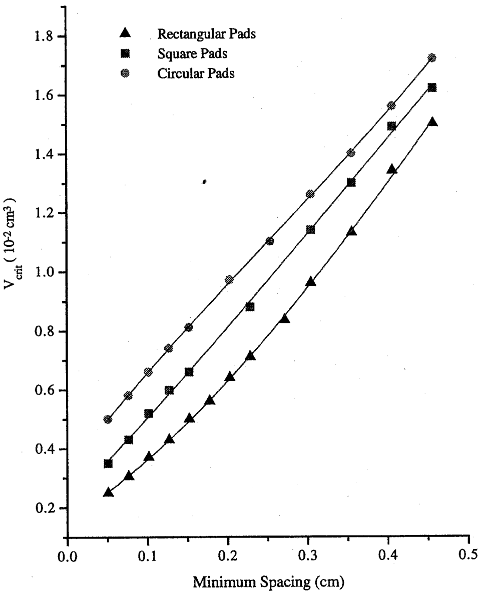

Fig. 5 Total system energy versus system volume for various pad geometries. Energy jumps occur at critical volumes, i.e., bridge instability where the system undergoes a catastrophe or bifurcation to a different configuration.

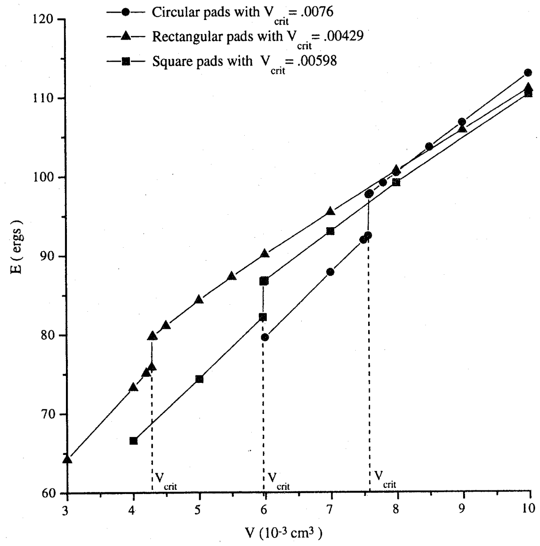

Fig. 6 Bridge stability curves of volume versus minimum spacing for various pad geometries. For any curve, the region above the curve corresponds to stable bridge configurations while the region below the curve corresponds to unstable configurations.

V_{crit} and a point on the energy-volume curve is obtained by multiplying both the volume and the converged value of energy by a factor of 2. The latter value is the energy of the symmetric *unbridged* system (We note here that preliminary experimental results suggest that symmetric instability is the preferred mode of bridge breaking.) We continue this calculation for larger volumes, and terminate the calculations at the point corresponding to V_{crit}. The difference in energies corresponding to the two curves for the same geometry at the critical volume is associated with the system catastrophe. We note that we have continued to calculate the energy-volume curve in this fashion, going past V_{crit} until the meniscus on the single pad just touches the midplane between pads, at which point the system undergoes another bifurcation and returns to the bridged state and in so doing, forms a hysteresis loop. As they are not particularly relevant to this paper, we do not show these calculations.

For the construction of stability diagrams for volume versus distance between pads, three different pad geometries were examined while holding the area of all pads approximately constant. Circular (0.249 cm. diameter), square (0.221 cm. × 0.221 cm.) and rectangular (0.381 cm. × 0.127 cm., 3:1 aspect ratio) pads were studied. We plot our results for two different measures of distance between pads, minimum spacing (shortest distance between points on the pad perimeters) and pitch (distance between geometric centers). The differences between the graphs are attributable to the simple geometric effect arising from the constant pad area constraint: for equal minimum spacings, the value of pitch for circular pads is largest, followed in order by values for square and rectangular pads. Values for minimum spacing for all geometries ranged between 0.038 and 0.127 centimeters. The values used for the static contact angle, liquid density and surface tension were 2.356 radians (135°), 13.7 g/cm^3 and 490 dynes/cm, respectively. As mentioned above, we are preparing to conduct laboratory bridge stability experiments in which mercury will be used to model liquid solder. For purposes of future comparison with experimental data, then, we have done our Evolver studies using the physicochemical properties of mercury. The Bond number, based on minimum spacing, ranged between 10^{-2}–10^{-1} in our study. Figures 6 and 7 show stability curves for the three pad geometries using minimum spacing and pitch, respectively, as measures of the distance between pads. For any of the three stability curves in each diagram, a point lying below the curve represents an unstable pairing of system volume and pad spacing; a point above the curve represents a stable system configuration. Thus, for example, Fig. 6 shows that a portion of the stable parameter space for rectangular pads lies in the unstable region of the square pad stability space while portions of the stable parameter space for both rectilinear geometries lie in the unstable regime of the circular pad geometry. For a given *minimum spacing*, then, it is the bridge between circular pads that is most unstable. Figure 7 shows the geometrical effect when the same stability data is plotted using pitch as a measure of distance between pads. In this case, bridges between rectangular pads of 3:1 aspect ratio are the most unstable of the three geometries. We mention that, as the aspect ratio of the rectangular pads is in-

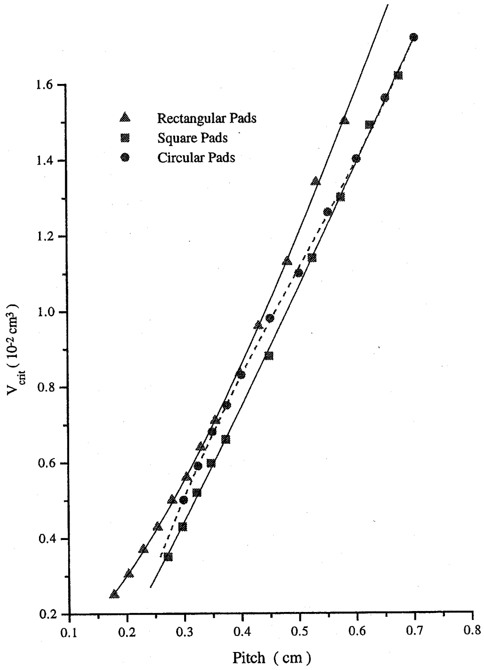

Fig. 7 Bridge stability curves of volume versus pitch for various pad geometries.

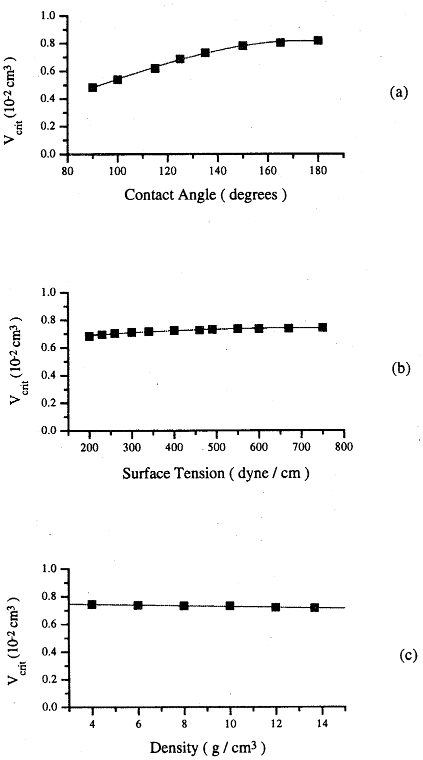

Fig. 8 (*a*) Bridge stability curve showing volume-contact angle response. (*b*) Bridge stability curve showing volume-surface tension response. (*c*) Bridge stability curve showing volume-density response.

creased while holding the area constant, the distance between the stability curve for the rectangular pads and curves for other geometries will increase. From a practical soldering perspective, Fig. 7 provides the following guidance: For a given pitch, the rectangular pad geometry, in the standard orientation of surface mount technology, will allow the maximum solder volume deposition such that, should a bridge inadvertently be formed between adjacent pads, it would be inherently unstable (to a capillary instability) and incapable of existing in the steady state. It also appears as though the rectangular pads retain their superiority, with respect to bridging resistance, over both circular and square pads as the pitch decreases. However, the relative superiority of rectangular pads as compared with other geometries appears to vary with pitch, but this may be an artifact of the difficulty with the Surface Evolver in maintaining precise levels of discretization of the surface for different points in the parameter space. For example, in our calculations for circular pads, the mean number of surface elements, after equilibrium was achieved, for the 11 data points was 335 with a standard deviation of 39 or roughly a 10 percent variation about the mean. The calculations performed here were done in the range of refinement where energy was relatively insensitive to additional refinement.

Figures 8(*a*–*c*) show the responses of critical volume with respect to contact angle, surface tension, and density for circular pad geometries. Figure 8*a* demonstrates the rather strong sensitivity of bridge stability to the contact angle of the liquid solder on the resist surface. This has the obvious implication for all soldering processes that bridging incidence can be reduced by maximizing the solder-resist contact angle. While different solder alloys will manifest different contact angles, it is clear that a resist surface engineered to maximize contact angle is very desirable. Figure 8(*b*) exhibits the insensitivity of bridge stability to changes in surface tension values in the range typical of liquid metals (Ida and Guthrie, 1991). The explanation of this response is connected with that for the rather flat response of bridge stability versus liquid solder density shown in Fig. 8(*c*). The ratios of gravitational potential energy to total energy for the density values of 4.0, 8.0 and 13.7 g/cm^3 are 1.2, 2.4 and 4.0 percent, respectively. Thus, gravity exerts a very small effect on the interfacial shape which is consequently dominated by surface energy effects. Because surface energies are dominant, the surface is approximately a minimal surface and its shape is consequently not significantly affected by changes in surface tension. By the same argument, density changes have no significant effect. If one regards the surface shape as determined by the Young-Laplace equation, then the above results may be explained in terms of the Bond number being small. Then, a zeroth-order approximation (for small Bond number) to the Young-Laplace equation contains neither the physical constants of density nor surface tension. However, if the density was to become (unrealistically) large or the surface tension to become (unrealistically) small, thereby invalidating the above arguments, one would expect the bridge stability to exhibit sensitivity to such property changes.

4 Conclusions

The phenomenon of solder bridging was studied computationally from the perspective of the stability of equilibrium capillary surfaces. The equilibrium shapes of bridges between adjacent solder pads were calculated using the Surface Evolver. Bridge stability curves of critical volume versus two measures of distance between pads, minimum spacing and pitch were calculated. The optimum geometry from the perspective of resistance to bridging depended on the measure of distance used. For fixed minimum spacing, circular pads were superior while for fixed pitch, rectangular pads were superior. The effects of the liquid solder-resist surface contact angle, solder surface tension and solder density on solder bridge stability were assessed. It was found that bridge stability exhibited sensitivity to contact angle, bridges being less stable for larger contact angles, while low sensitivity of stability on surface tension and density was established. Finally, the instability of bridges was shown to be connected with the phenomenon of bifurcation or catastrophe.

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References

Brakke, K., 1992, "The Surface Evolver," *Experimental Mathematics,* Vol. 1, pp. 141–165.

Brakke, K., 1995, *Surface Evolver Manual,* Version 1.98, The Geometry Center, University of Minnesota.

deGennes, P., 1985, "Wetting: Statics and Dynamics," *Reviews of Modern Physics,* Vol. 57, pp. 827–863.

Finn, R., 1986, *Equilibrium Capillary Surfaces.* New York: Springer-Verlag.

Gilmore, R., 1981, *Catastrophe Theory for Scientists and Engineers,* Wiley-Interscience, New York.

Glovatsky, A. Z., 1994, "*An Experimental Investigation of the Stability of Simulated Solder Bridges,*" M. S. thesis, Department of Mechanical Engineering, State University of New York, Binghamton, NY.

Ida and Guthrie, 1991, *The Properties of Liquid Metals,* Oxford, London.

Iooss, G., and Joseph, D., 1990, *Elementary Stability and Bifurcation Theory,* Springer-Verlag, New York.