A Hydrostatic Model of Solder Fillets

Agreement with experimental results establishes a method for designing soldered connector terminals by calculation

BY T. Y. CHU

ABSTRACT. A model to predict the shape of fillets formed between a terminal pin and a plated-through-hole is presented. The model is based on the hydrostatic balance of surface tension and pressure (i.e., the weight of the molten solder). The model is exact for the axisymmetrical fillets formed by a round pin and a plated-through-hole. For the case of a square wire wrap terminal, an approximated form of the model is used. Instead of requiring detailed force balance on a differential scale, an overall force balance concept is used. In both cases there is good agreement between calculation and experiment. Results of calculations based on the model are used in the selection of proper preform sizes for reflow soldering operations. The fillet height obtained in the calculation is also useful in the proper design of wire wrap terminals.

Introduction

It was once stated that soldering is the foundation of the electronics industry. There is certainly more truth than exaggeration in the statement. However, despite its wide use and long history as a metal joining technique, soldering until today remains as much an art as a science. For example, although there are some general characteristics that can be used to describe a good solder joint or fillet, there is no precise definition of a good solder fillet. With the increasing application of mass soldering methods for manufacturing large numbers of identical parts, it becomes desirable to have a precise definition of a good solder fillet. Such information will not only be useful in quality control and component design, it also contributes to the understanding of the basics of the soldering technique. An analytical model based on the balance of surface tension and pressure forces is formulated to predict fillet shapes. The paper deals mainly with the fillet formed by a pin and the land area of a plated-through-hole. The model can also be adopted to other geometries.

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The Basic Axisymmetric Model

One of the most common types of solder joint in electronics is that formed by a pin and the land areas of a plated-through-hole (PTH). The pin could be a terminal or the lead wire of a component. A plated-through-hole is a hole drilled through the depth of a circuit board, the surface of the hole is plated to make interconnection between the top and the bottom circuits. The plated-through-hole usually has land areas on the top and the bottom of the circuit board. In the case of a multi-layer board, which is essentially a lamination of several double-sided boards, the plated-through-hole may also be connected to some inner layers. A top view of a multi-layer board (MLB) with soldered connector terminals is shown in Fig. 1. The shiny parts at the base are the solder fillets. The black holes between the rows of pins are the plated-through-holes. The shiny rings are the land areas. In soldering these terminals, each pin is first provided with a donut-shaped preform, heat is then applied to melt the solder and form the joint. Figure 2 shows schematically the reflow soldering process.

Force Balance Consideration

Figure 3 is a schematic of the fillet formed by a round pin and a plated-through-hole. The equation that describes the fillet shape is derived by forming a force balance on a segment of the interface between the molten solder and the surrounding fluid as shown in Fig. 3. Attention will be focused on the upper fillet curve, $Z_T(r)$. The total upward force due to the surface tension on the axisymmetric interface segment between r and r+dr is

$$\sigma_{SF} \cdot \left[2\pi r \sin(2\pi-\theta) \right] \Big|_{r} - \sigma_{SF} \left[2\pi r \sin(\pi-\theta) \right] \Big|_{r+dr}$$

where

σ_{SF} is the surface tension of the molten solder. The total downward force due to the pressure difference $(P_F - P_S)$ across the segment is

$$(P_F - P_S) \cdot 2\pi r dr$$

where P_F and P_S are the pressure in the fluid and the solder respectively. At static equilibrium the upward and downward forces are equal, thus,

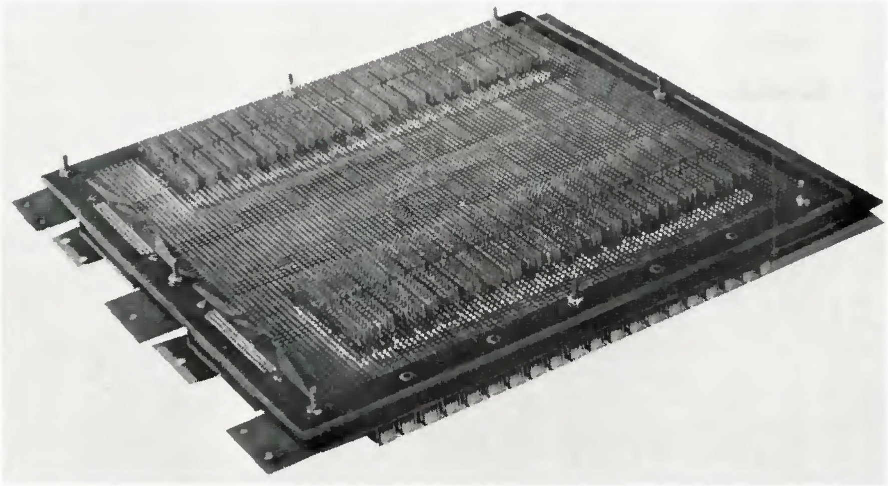

Fig. 1 — A multi-layer board with soldered connector terminals

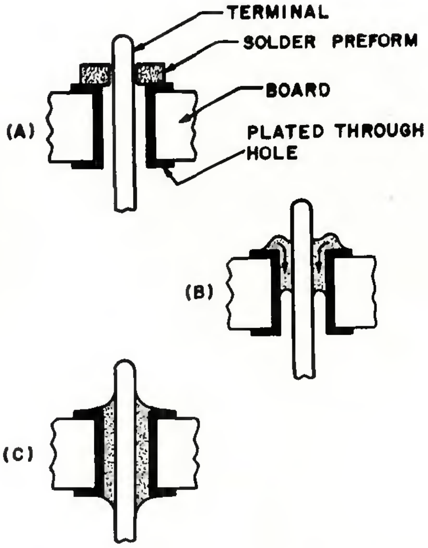

Fig. 2 — A schematic of the reflow soldering process

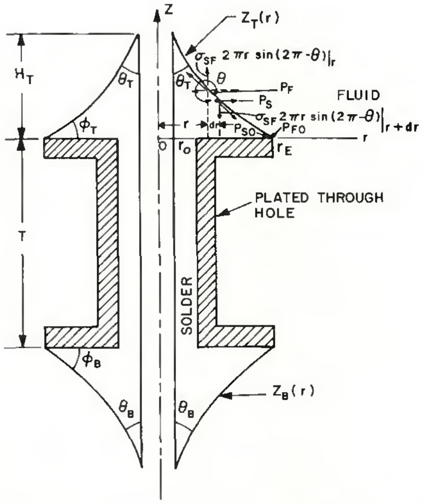

Fig. 3 — Force balance diagram of a solder fillet

$$\sigma_{SF}\cdot 2\pi r\sin\theta|_{r+dr} - \sigma_{SF}\cdot 2\pi r\sin\theta|_r = 2\pi r(P_F - P_S)\,dr$$

$$P_F - P_S = \frac{\sigma_{SF}}{r}\frac{d}{dr}(r\sin\theta) \qquad (1)$$

The above equation can be expressed in terms of Z and r by using the relation:

$$\sin\theta = (dZ/dr)[1+(dZ/dr)^2]^{-1/2}$$

Making the substitution, the pressure difference can then be written as:

$$\Delta P = \sigma_{SF}\{(1/r)(dZ/dr)[1+(dZ/dr)^2]^{-1/2} + (d^2Z/dr^2)[1+(d/Z/dr)^2]^{-3/2}\} \qquad (2)$$

The expression in the square brackets are principal radii of curvature of the interface. Thus,

$$\Delta P = \sigma_{SF}\ [(1/R_1) + (1/R_2)] \qquad (3)$$

This is the Young-Laplace equation of surface tension (Ref. 1). Pressures can be expressed in terms of Z and the fluid densities. Let the pressure at Z = O in the solder and in the fluid respectively be P_{SO} and P_{FO}. The pressure difference, ΔP becomes

$$\Delta P = P_F - P_S = P_{FO} + \rho_F gZ - (P_{SO} + \rho_S gZ)$$

where ρ_F and ρ_S are the densities of the surrounding fluid and the solder respectively and g is the gravitational acceleration.

Finally, the equation for the top fillet shape is obtained:

$$Z_T = (\sigma_{SF}/\Delta\rho g)\{(1/r)(dZ_T/dr)[1+(dZ_T/dr)^2]^{-1/2} + (d^2Z_T/dr)[1+(dZ_T/dr)^2]^{-1} - \alpha\} \qquad (4)$$

$$= (\sigma_{SF}/\Delta\rho g)\{[(1/R_1) + (1/R_2)]_{ZT} - \alpha\} \qquad (4.a)$$

$$= (\sigma_{SF}/\Delta\rho g)\{(1+r)\ [d(r\sin\theta)/dr|_{ZT}] - \alpha\} \qquad (4.b)$$

where

$$\alpha = (1/\sigma_{SF})(P_{SO} - P_{FO})$$

$$\Delta\rho = \rho_S - \rho_F$$

Similarly, for the bottom fillet, one finds

$$-Z_B = (\sigma_{SF}/\Delta\rho g)\{(1/r)(dZ_B/dr)[1+(dZ_B/dr)^2]^{-1/2} + (d^2Z_B/dr^2)[1+(dZ_B/dr)^2]^{-3/2} + \alpha \qquad (5)$$

$$= (\sigma_{SF}/\Delta\rho g)\{[(1/R_1)+(1/R_2)]_{ZB} + \alpha\} \qquad (5a)$$

$$= (\sigma_{SF}/\Delta\rho g)\{(1/r)[d(r\sin\ )/dr|_{ZB}] + \alpha\} \qquad (5b)$$

Equations (4) and (5), related through parameter α, are the working equations for the present calculation. Physically, α indicated the fact that the two fillets are not independent. They interact through the plated-through-hole.

An overall force balance can be obtained by adding equations (4.b) and (5.b) and integrating once between the pin surface, r_o and the edge of the land area, r_E:

$$\int_{r_O}^{r_E} 2\pi(Z_T - Z_B)\Delta\rho g r\,dr = \sigma_{SF}\left\{2\pi r\sin\theta\,\Big|\,Z_T{}_{r_O}^{r_E} + 2\pi r\sin\theta\,\Big|\,Z_B{}_{r_O}^{r_E}\right\}$$

In terms of $\theta_T, \theta_B, \theta_T$ and θ_B as defined in Fig. 3, one has

$$\int_{r_O}^{r_E} 2\pi(Z_T - Z_B)\Delta\rho g r\,dr$$

$$= 2\pi r_O\sigma_{SF}(\cos\theta_T - \cos\theta_B) + 2\pi r_E\sigma_{SF}(\sin\phi_B - \sin\phi_T) \qquad (6)$$

The integral on the left-hand side of the equation is essentially the weight of the solder. The expression on the right is the total force in the vertical direction due to the surface tension forces acting along the solder-pin and solder-land contact line. Therefore, equation (6) represents the overall balance of the weight of the solder and the surface tension forces. Equation (6) can also be derived by taking the fillet system as a free body and performing an overall force balance.

Equations (4) and (5) are second order ordinary differential equations connected by a parameter α. To completely specify the fillet shapes, five constraints are needed. It has been observed that the fillets always stop at the edge of the land area. This condition gives two constraints, one at the edge of the top land area and one at the edge of the bottom land area. The fixed volume of solder provided for each joint is the third constraint. Two more constraints are needed.

With two free end conditions, it is possible to have a range of fillet configurations which all satisfy the overall force balance. To choose the most stable fillet shape, one must consider the energy of the system.

Energy Consideration

For a system at a state of stable equilibrium, the total free energy is minimum (Ref. 2). There are two contributions to the change of free energy in an isothermal capillary system, the interfacial energy and the gravitational potential energy. The gravitational energy varies due to change of elevations. The interfacial energy varies due to area changes of various interfaces; there are three contributions, the solder-fluid interface (SF), the solder-pin interface (SP) and the fluid-pin interface (FP). The interfacial energy can therefore be expreseed as:

$$\sigma_i A_i = \sigma_{SF} A_{SF} + \sigma_{FP} A_{FP} \qquad (7)$$

The σ's are surface tensions or surface energies per unit area (Ref. 4). A's are the interfacial areas. The σ's are related through the equilibrium contact angle θ_c which is the angle formed by a small drop on a horizontal surface (Refs. 2,3):

$$\cos \theta_c (\sigma_{FP} - \sigma_{SP}) / \sigma_{SF}$$

The total free energy of the solder-fluid-pin system can thus be written as

$$G = \text{Potential Energy} + \sigma_1 A_1 \qquad (8)$$

From the energy point of view, a variational problem minimizing the total free energy with a constant volume constraint can be formulated. Similar problems have been formulated for a single fluid-fluid interface. It is found that for minimum free energy the angle between the interface and the vertical boundary is equal to the equilibrium contact angle, θ_c, formed by a small drop on a horizontal surface (Refs. 2,3). However, it is not immediately obvious that the same result would be applicable to the present two fluid-fluid interface system interacting through a constant volume constraint. A variational problem for the present system was formulated, and although the detail derivation is not presented here, it was shown that the minimum energy solution requires both the bottom and the top fillet to meet the plate (pin) at the equilibrium contact angle, θ_c.

Referring to Fig. 3,

$$\theta_T = \theta_B = \theta_c \, .$$

Together with the previous three conditions, the ideal fillet is completely described.

Empirical Consideration

It has been observed that when a drop is placed on a plane surface which is subsequently tilted, the contact angle on the downhill edge increases and the contact angle on the uphill edge decreases. The two angles are referred to respectively, as advancing and receding angles. This phenomenon is called contact angle hysteresis. The exact cause of contact angle hysteresis is not well understood. However, its occurrence is found to be related to surface roughness and contamination; for pure fluids on clean surfaces no hysteresis is observed (Ref. 6).

For soldering processes, surface roughness and contamination are always present and contact angle hysteresis always occurs. The contact angle for the top fillet is always smaller than the equilibrium contact angle and the contact angle for the bottom fillet is always bigger than the equilibrium contact angle. To realistically predict fillet shapes, this empirical observation should be incorporated into the theory.

Consider a solder preform at the top of the plated-through-hole. When it melts, the solder, pin, hole system has a free energy much higher than the equilibrium value. Thus, the driving potential toward the equilibrium shape is very large. However, this driving potential becomes smaller and smaller as the system approaches the equilibrium shape. Finally, this potential becomes so small the systems will not be able to overcome the surface roughness and contamination effects. At this point, the system stops changing.

An "operationally ideal" solder fillet can be defined from the above discussions. The fillet shapes obey the overall force balance equation, equations (4) and (5). The solder should stop at the edge of the land area. The upper fillet should have a contact angle smaller than the equilibrium contact angle. The total free energy of the fillet system should approach the minimum energy condition within a close limit. A value of 0.5% of the total energy change is taken arbitrarily as the limit in the following discussion. Therefore, there is a range of "operationally ideal" fillets.

Methods of Solution

The governing equations (4) and (5) are rewritten as two systems of two linear ordinary differential equations. A Runge-Kutta forward integration scheme available from the IBM scientific subroutine package is used to numerically integrate the equations.

For the ideal fillet calculation, the following constraints are used:

1. Prescribed fillet volume V_{FL}. This is the total volume of solder available from the preform less the volume of solder in the plated-through-hole.
2. The fillets stop at the edge of the land area, referring to Fig. 3:
 at $r = r_E$, $Z_T = 0$
 at $r = r_E$, $Z_B = -T$
3. Minimum free energy determines that

$$\theta_T = \theta_c$$
$$\theta_B = \theta_c$$

The value of free energy, ΔG, is also calculated according to equation (8), or more explicitly,

$$\Delta G = \int_{r_0}^{r_E} f(r, Z_r, Z_B, Z'_T, Z'_B) 2\pi r \, dr,$$

where f is defined in the derivation of the variational problem minimizing the total free energy with constant volume constraint.

To find the range of "operationally ideal" fillets the last set of constraints is relaxed. A receding angle $\theta_T = \theta_R$ is prescribed. Any fillet with ΔG within 0.5% of ΔG_{min} is considered to be "operationally ideal."

Equations (4) and (5) together with the constraints are two-point boundary-value problems. A shooting method using a Newton-Raphson scheme to correct initial guesses is employed to solve the equations.

Results of the Axisymmetric Model

Calculations have been made of fillets formed by a 21 mil pin in an 11 mil deep, 60 mil diameter PTH and 110 mil land areas; this geometry corresponds to an actual circuit currently in production. Since only pressure is involved in the calculations, the diameter of the plated-through-hole has no direct bearing on the final equilibrium shapes.

The constants used in the calculation are as follows:

- Surface tension of solder — 490 dyne/cm
- Density of solder — 8.04 g/cm^3
- Equilibrium contact angle — 12 deg
- Receding contact angle, — 2 deg

The equilibrium contact angle is used in the free energy calculation. The receding contact angle is the angle between the top fillet and the pin. The choice of the value of the receding angle is somewhat arbitrary; however, it is found that the final shape of the fillets is not greatly influenced by the choice of this value or the value of the equilibrium contact angle.

Figure 4(a) shows the equilibrium

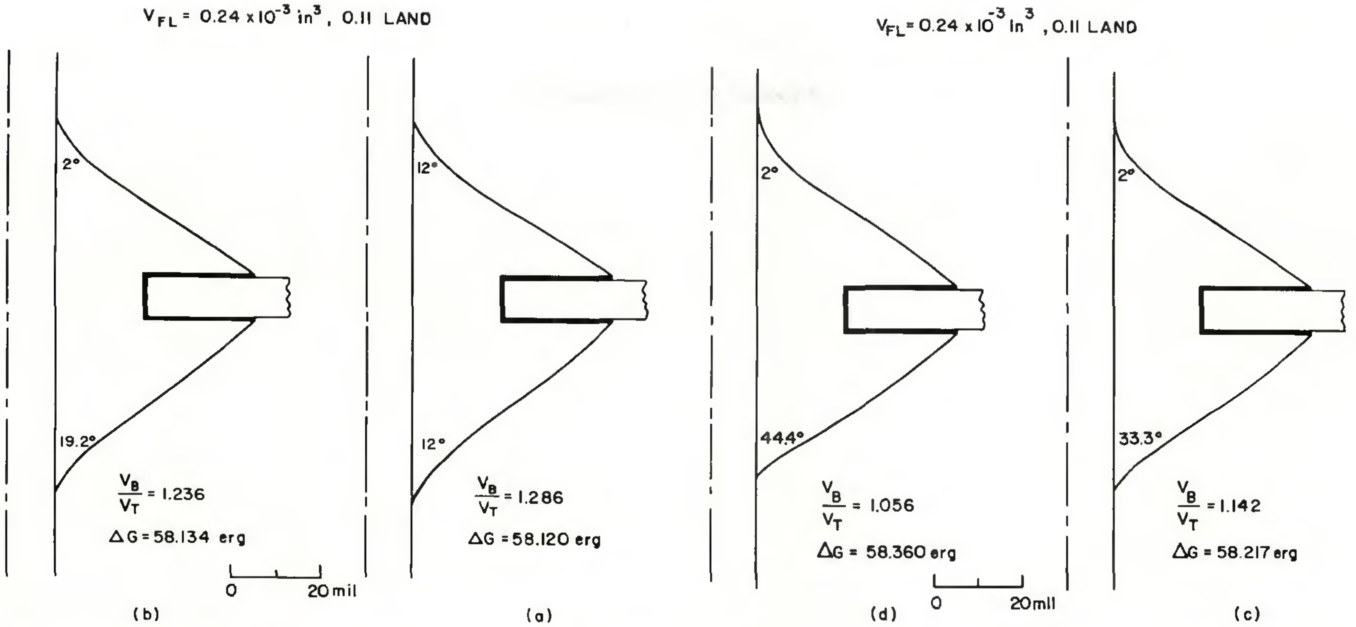

Fig. 4 — (a-d) Example of axisymmetrical fillets with V_{FL} = 0.24 x 10^{-3} in.³

(ideal) fillet shape for the chosen geometry. The fillet volume, V_{FL}, is 0.24×10^{-3} in³. The fillet volume is the total volume of solder less the volume of solder in the plated-through-hole; it is the appropriate parameter since for a fixed V_{FL} the fillet shapes will remain the same for any size of plated-through-hole. Figures 4(b), 4(c), and 4(d) are near equilibrium (operationally ideal) shapes. The shapes do not show any drastic departure from the equilibrium shape except that the bottom contact angle is bigger.

Figure 5 shows a free energy versus θ_B plot. The total free energy change for the volume of solder to the final equilibrium shape is estimated to be 50 ergs, thus, the 0.5% limit is 0.25 ergs above the minimum energy. The limit corresponds to a bottom contact angle of 45 deg. As can be seen in Fig. 5, the top contact angle, θ_T, has very little influence on the ΔG versus θ_B curve. The initial free energy of the solder, pin, PTH, system is calculated according to equation (8). Therefore, the effective land area or the plated-through-hole diameter does influence this initial free energy. Thus, the "operational ideal" fillet shapes are influenced indirectly by the size of the plated-through-hole. In estimating the free energy changes, the initial shape of the molten solder is assumed to be spherical.

Figure 6 is the ideal fillet for the same geometry with a fillet volume of 0.12×10^{-3} in³. The effect of reducing fillet volume is to make the fillet more concave. Figure 6(b), (c), (d), shows the operationally ideal fillets. It should be noted that for all ideal fillet shapes the bottom fillet is always bigger than the top fillet by 20 to 35%. The volume ratio, V_B/V_T, is shown in the figures.

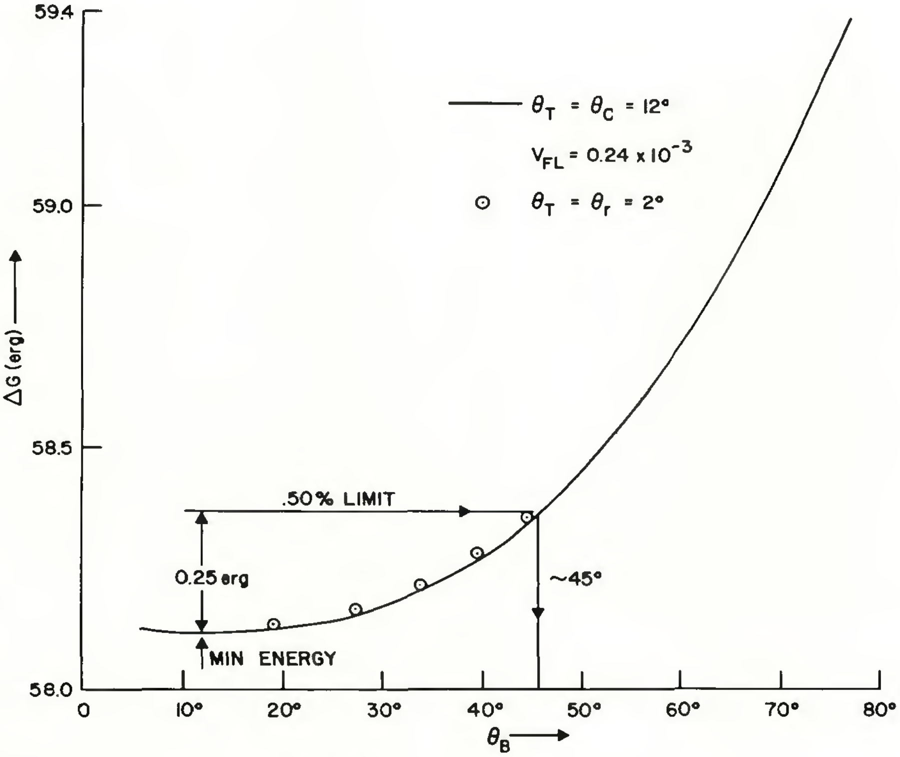

Fig. 5 — Free energy versus θ_B plot, V_{FL} = 0.24 x 10^{-3} in.³

An alternate way of estimating the total energy change is to assume the initial molten solder to be the same shape as the preform. Using this estimation, the total energy change for the case described in Fig. 4 would be 78 erg with a preform of 40 mil ID, 90 mil OD and 47 mil in thickness. A fillet shape with energy within 1.5% of the minimum energy would have a bottom contact angle of about 75 deg. Figure 7 shows the calculated shape and a comparison with experiment. The agreement is quite good.

Unless detailed chemical and physical conditions of each interface can be precisely prescribed, the limit to which the "operationally ideal" fillet approaches the ideal fillet cannot be specified. Therefore, the limit discussed here is more a parameter than an absolute limit.

Thus far discussion has been limited to the case where V_{FL} is prescribed. This is the usual case when solder preforms are used. However,

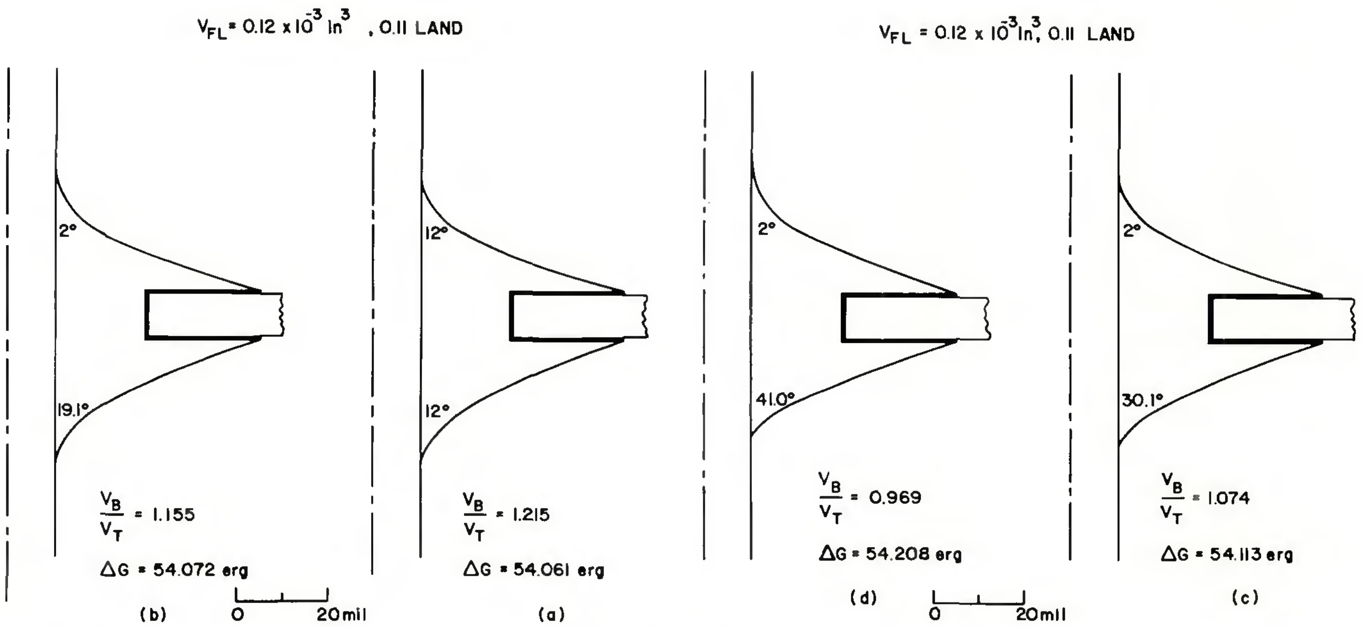

Fig. 6 — (a-d) Example of axisymmetrical fillets with V_{FL} = 0.12 x 10^{-3} in.^{3}

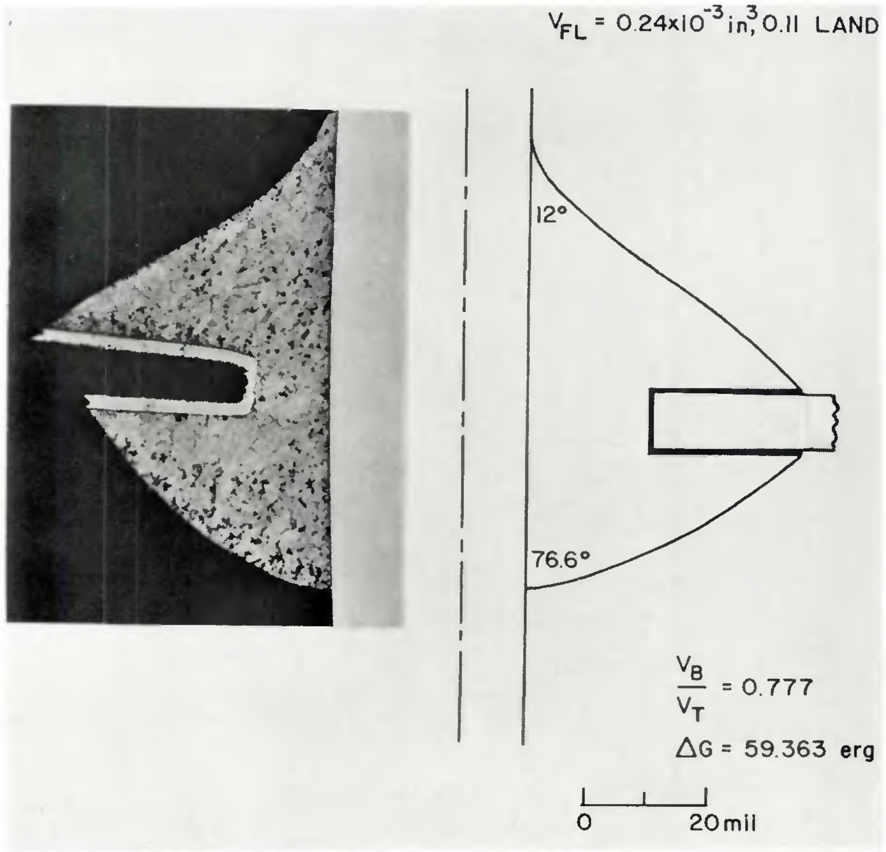

Fig. 7 — Comparison of calculated and experimentally obtained fillet shapes, axisymmetrical fillets

for wave soldering, conditions are slightly different. When the circuit is immersed in the solder wave, the pressure inside of the forming fillet is prescribed. Referring to Fig. 8a, for example, if the circuit is just immersed in the wave, the pressure at the top land area is atmospheric. For this case, α is zero in equations (4) and (5); this condition replaces the prescribed volume constraint.

Figure 9 shows the fillet shape corresponding to wave soldering of the chosen geometry; the fillet volume, V_{FL} (= 0.0917 $\times$ 10^{-3} in.^{3}), is part of the solution. In fact, it is possible to change the fillet volume by varying the pressure inside the fillet while it is being formed. As shown in Fig. 8b, if the circuit is forced into the wave, the pressure at the top land area is increased. The resulting fillet will be bigger. The fillet shown in Fig. 6a corresponds to a depression of about 1/8 in. Since the interface will adjust its shape to the surrounding pressure, a ⅛ in. depression will not correspond to a ⅛ in. rise of the top fillet.

Working Model for Wire Wrap Terminals

For many applications, wire wrap connections are made to terminal pins after soldering. To insure a good wire wrap connection, the wire wrap terminals are square rather than round. Therefore, the above developed axisymmetric model cannot be directly applied. However, it is important in wire wrap terminal design to have a knowledge of the expected fillet shapes, especially the height of the fillets, because the wire wrap portion of the terminal must not be coated with any significant amount of solder if subsequent high reliability wire-wraps are to be made to the terminals.

Fillet Equations

For some applications, the fillet geometry is translationally symmetrical, instead of rotationally symmetrical. For example, in the "Tee Joint" between two perpendicular plates, the resulting fillet is two-dimensional. In this case $1/R_1$ in equations (4) and (5) is zero. The fillet equations become

$$Z_T = (\sigma_{SF} / \Delta\rho g)[(1/R) - \alpha] \quad (9)$$

$$-Z_B = (\sigma_{SF} / \Delta\rho g)[(1/R) + \alpha] \quad (10)$$

$$(1/R)=(d^2Z/dr^2)\,[1+(dZ/dr)^2]^{-3/2} \qquad (11)$$

For the case of a wire wrap terminal and a plated-through-hole, one has a square pin with a round land area. It is obvious that near the pin the fillet is close to two-dimensional since the square pin presents a flat surface to the solder. The fillet becomes axisymmetric near the edges of the round land area. It is not immediately clear how the fillet profile should be represented as a whole. The profile is probably best described by joining a two-dimensional profile with an axisymmetric profile at some point between the pin and the edge of the land area. However, computation would be greatly simplified if the entire fillet could be arpproximated either by an axisymmetric or a two-dimensional profile. Calculations were made of the fillet shapes using both models. Figure 10 shows a comparison between the axisymmetric and the two-dimensional approximation. It is clear that the two-dimensional approximation describes adequately the fillet shapes for the square pin near the land as well as at the pin. Therefore, the two-dimensional equations are chosen for the square pin calculation.

The success of the two-dimensional approximation can be explained by observing the effect of R_1, eq. (3). In an axisymmetric approximation, the effect of radii of curvature will be largest near the pin where R_1 is small. However, R_1 is actually infinite at the flat surface of the square wire wrap pin. Large errors would be introduced near the pin with the axisymmetric approximation. Near the edge of the land area, the effect of R_1 becomes smaller; the error due to the two-dimensional calculation is thus smaller.

Constraints and Boundary Conditions

Equations (9) and (10 are used to generate the fillet profiles. To completely describe the set of two second order differential equations with a parameter α, again five constraints are needed. Three of the constraints are obvious physical constraints as before:

1. The fillet volume (V_{FL}) is prescribed by the preform size and the plated-through-hole geometry. The solder volume is calculated by assuming the fillet surface to be a surface of revolution generated by the

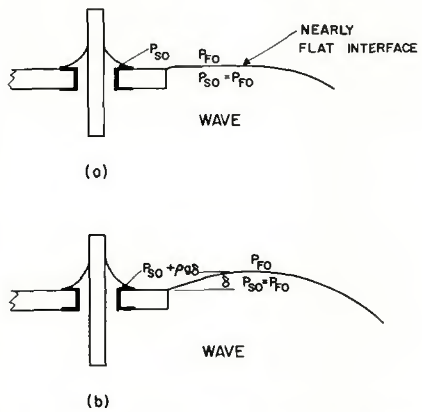

Fig. 8 — (a,b) Pressure control in wave soldering

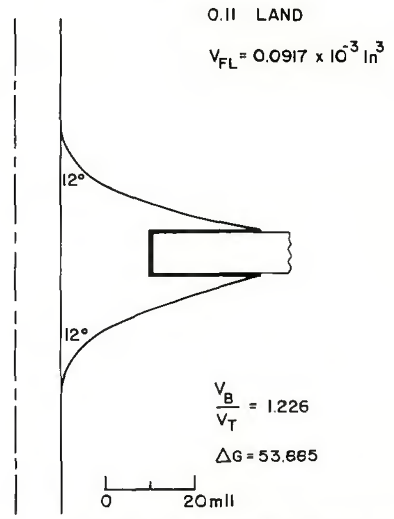

Fig. 9 — Fillet shape corresponding to wave soldering

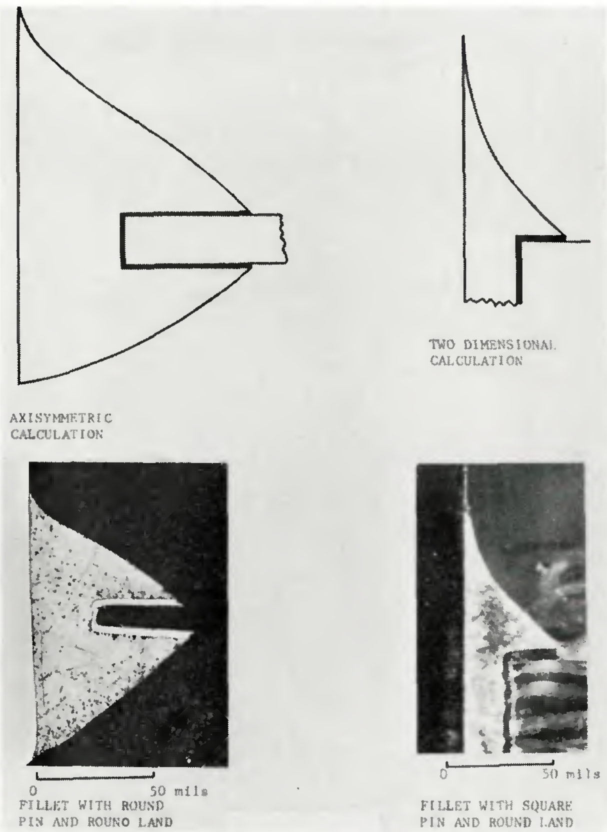

Fig. 10 — A comparison between the axisymmetric and two-dimensional approximation

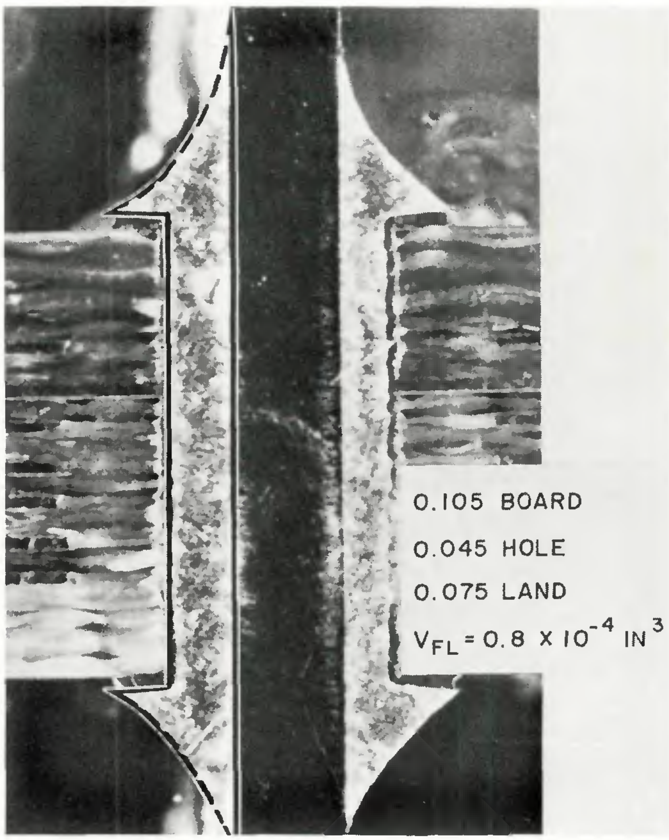

Fig. 11 — Comparison of calculated and experimentally obtained fillet shapes formed between a square pin and a plated-through-hole

curves obtained from equations (9) and (10). The volume is calculated as if the pins were round with diameter equal to width of the square pin. Since V_{FL} is calculated as if the pins were round, the actual fillet volume corresponding to a square pin is slightly smaller. The two volumes differ by the amount equal to the volume difference between a square cylinder and a circular cylinder of length equal to the sum of the top and the bottom fillet lengths.

2. At $r = r_E$, $Z_T = 0$, Fig. 3.
3. At $r = r_E$, $Z_B = -T$, Fig. 3.

The above two constraints state that the fillets stop at the edge of the land area. An additional constraint is provided by observing that the top contact angle (θ_T in Fig. 3) is always very small; a receding angle can be prescribed.

4. $\theta_T = \theta_R < \theta_C$, where θ_C is the equilibrium contact angle.

The fifth constraint comes from an overall force balance consideration. Although the cross-sectional profile of the fillet is well-described by the two-dimensional equation, the overall shape of the fillet is essentially axisymmetric. The present model assumes the fillet to be a body of revolution generated by the two-dimensional profiles except near the corner of the pin where the surface is interrupted; however, unlike the axisymmetric case, this body of revolution does not automatically satisfy the overall force balance in three dimensions as described by equation (6). Therefore, only profiles that satisfy this condition are chosen. This becomes the fifth constraint and is written exactly as equation (6).

Equations (9) and (10) are solved numerically for an arbitrary top fillet height H_T (Fig. 3) under the first four constraints. Again a shooting method using a Newton-Raphson scheme to correct initial guesses is employed to solve the equations. For an arbitrary H_T the overall force balance constraint, equation (6), is generally not satisifed. Let the difference between the two sides of equation (6) be ΔF. A second order least square fit of ΔF versus H_T for the five points closest to $\Delta F = 0$ is obtained. The solution is found for the H_T corresponding $\Delta F = 0$.

The above development of the working model is similar in spirit to the integral method of solving boundary layer problems (Ref. 1). In the integral method, an approximated velocity profile is assumed. The profile satisfies all the boundary conditions and the overall force balance. A detailed force balance on a differential is, however, not required.

To test the validity of the model, a set of profiles is calculated to compare with fillets obtained experimentally. The board is 0.095 in. thick with 45 mil plated-through-holes and 75 mil land areas. The pins are 25 mils square. The dimensions are measured directly from plotted cross-sections. The preforms used are 40 mils ID, 90 mils OD and 35 mils thick; the volume of each preform is 1.79×10^{-4} in.^{3}. The corresponding fillet volume, V_{FL}, is 0.8×10^{-4} in.^{3} A receding angle of 1 deg is assumed. Figure 11 shows the comparison between experiment and calculation. The dotted line shows the calculated profile; the photograph is the actual cross section. The agreement between calculation and experiment is excellent.

In the axisymmetric model an additional minimum free energy constraint is imposed. If this constraint is used instead of the force balance constraint, a different set of profiles is obtained. Figure 12 shows the two solutions. The difference is rather small. Except under ideal conditions, the minimum energy solution is not realized in practice. Therefore, the force balance constraint rather than the minimum energy constraint is used in the present calculation.

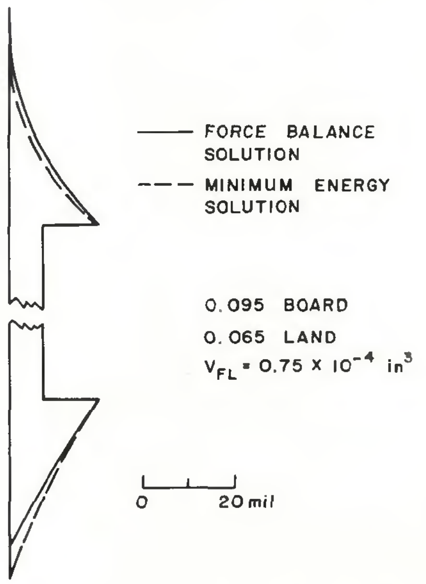

Fig. 12 — Comparison between fillet shapes obtained using the overall force balance constraint and the minimum energy constraint

Results of the Wire Wrap Pin Model

The developed model is used to calculate the fillet shapes formed between wire wrap terminals and the

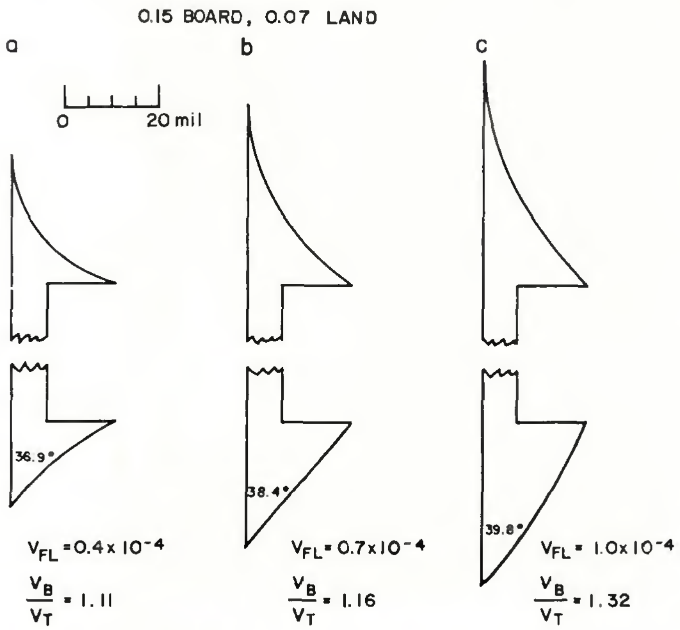

Fig. 13 — Fillet shapes as a function of fillet volume

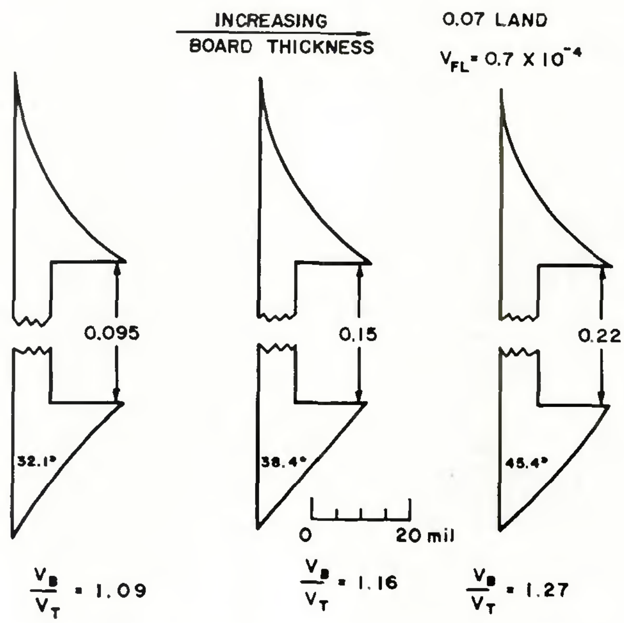

Fig. 14 — Fillet shapes as a function of board thickness

PTH's of various multilayer boards. Fillets for various land areas and board thicknesses have been examined. The wire wrap terminals are 25 mils square. A receding angle of 1 deg is used in the calculations.

Since geometry varies for different applications, only a few typical calculations are presented. Figure 13 shows the fillet profile for a 0.15 in. thick board with 70 mil land area with different amounts of solder. Fillet profiles for 0.095 in., 0.15 in. and 0.22 in. thick boards are presented in Fig. 14 for land areas of 70 mils with the same solder fillet volumes (V_{FL}) of 0.07 $\times$ 10^{-4} in^3. From the profiles presented, a general trend for the fillet shapes is established. When the amount of solder used is small, fillets of the commonly desired shape can be obtained; both the top and the bottom fillet profiles are concave, Figure 13a. For the same board with increasing solder volume, the top fillets stay concave while the bottom fillets become fuller. Finally, the bottom fillet becomes convex. Figures 13a, b, and c show this general trend. If the fillet volume is held fixed, the trend is toward fuller bottom fillets with increasing board thickness. Figures 14a, b, and c show the trend. For a V_{FL} of 0.7 $\times$ 10^{-4} $in.^3$ the bottom fillet changes from concave to nearly straight to convex as the board thickness varies from 0.095 in. to 0.15 in. then to 0.22 in. It is also useful to note that with excessive amounts of solder, most of the excess goes to the bottom fillet; the top fillet stays relatively constant. The dashed line profile in Fig. 15 corresponds to a fillet volume of 1.0 $\times$ 10^{-4} $in.^3$; the solid line corresponds to a fillet volume of 1.9 $\times$ 10^{-4} in^3. With a change of V_{FL} by nearly a factor of two the top fillet volume increases by 31%, the bottom fillet increases by about 140%.

The above observed trend can be understood by examining the Young-Laplace equation for two dimensions. The equation is:

$$\Delta P = \sigma_{SF} \quad (1/R) \qquad (3.a)$$

For the solder interface configuration under consideration, a concave interface corresponds to a negative pressure inside of the solder as compared to the surrounding fluid pressure; a convex interface corresponds to a positive pressure. With good wetting, the top fillet takes a concave shape to create a negative pressure with respect to the atmosphere to support the solder column. Let the negative pressure be:

$$-|\Delta P_T(r)|.$$

If the solder column height is H(r), the pressure difference at the bottom interface would be

$$\Delta P_B = -|\Delta P_T| + \Delta\rho g \cdot H(r)$$

This value could either be positive or negative depending on H(r). For small H(r), ΔP_B is negative; the bottom fillet is concave. For large H(r), ΔP_B is positive; the bottom fillet is convex. Large H(r) corresponds to large V_{FL} and/or large board thickness. Therefore, a convex bottom fillet is not necessarily a sign of bad wetting, only a convex top fillet is a definite sign of bad wetting.

The effect of increasing land area can be estimated by noting that the distance between the pin and the edge of the land area becomes larger with increasing land area; therefore, the curvature of the top fillet becomes gentler. According to equation (3.a), the corresponding negative pressure would also be smaller in magnitude. Therefore, the bottom fillets are more likely to become convex with increasing land area.

Although convex fillet does not necessarily mean bad wetting, from a quality control point of view it is still advantageous to design for concave fillets. If a fillet volume expected to produce concave fillets produces a convex fillet instead, then there is a definite indication of bad wetting.

By making a series of calculations, one can obtain the exact solder volume beyond which a convex fillet will occur. This volume will be called the critical fillet volume. The critical volume as a function of board thickness for the 70 mil land is shown in Fig. 16. Conditions above the critical volume line result in convex bottom fillets, below the line the bottom fillets are concave. The "45 deg Cone

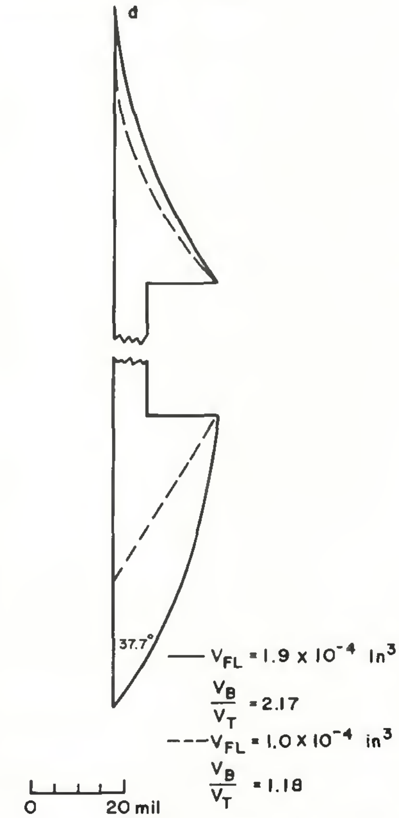

Fig. 15 — Effect of increasing fillet volume on fillet shapes

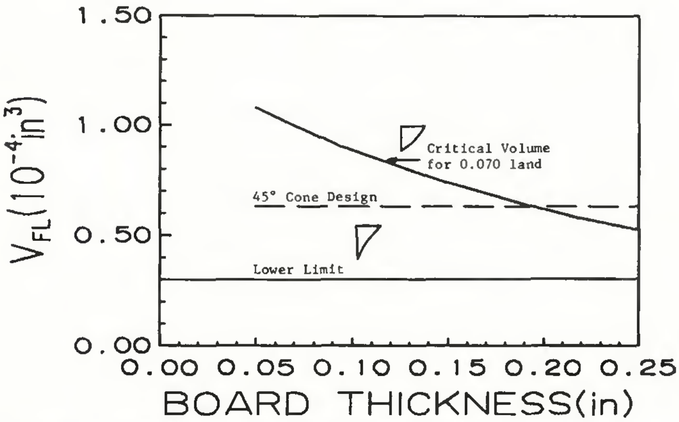

Fig. 16 — Critical volume as a function of board thickness

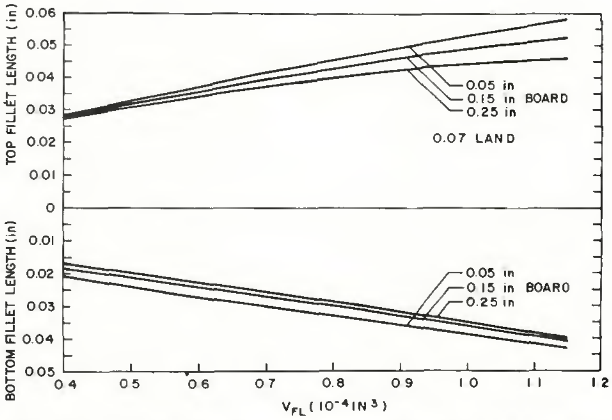

Fig. 17 — Fillet length as functions of fillet volume and board thickness

Design" shows a commonly used design criteria. The volume of solder required is obtained by assuming the fillet to be a truncated 45 deg cone with a base of the size of the land area. The estimate is acceptable up to a board thickness of about 0.195 in., above which the estimate will give convex fillets.

So far, the discussion has concentrated on the upper limit of V_{FL} for a concave fillet. There exists also a practical lower limit. As V_{FL} decreased, the angle between the top fillet and the land, ϕ_T, in Fig. 3, becomes smaller and smaller; it cannot be smaller than zero. By extrapolating a curve of V_{FL} versus ϕ_T to $\phi_T = 0$, a lower limit of V_{FL} is obtained. Since the top fillet shape stays fairly constant for varying board thickness, the lower limits of V_{FL} are essentially constant for a particular land area. The lower limits of V_{FL} are essentially constant for a particular land area. The lower limit of V_{FL} for 70 mil land is estimated to be 0.3×10^{-4} in^3. Any fillet volume between the lower limit and the critical volume line will result in concave fillets. Any fillet volume below the lower limit will probably result in incomplete coverage of the land area. Based on the above calculations, proper preforms can be chosen for various board thicknesses.

Figure 17 shows the expected fillet length for different fillet volumes and board thicknesses for 70 mil land areas. Only a few board thicknesses are shown, linear interpolation between the lines will give results within 0.3 mils of actual calculated values. These curves are useful in determining the length of the bare terminal available for subsequent wire wrapping.

Concluding Remarks

A hydrostatic model of solder fillets based on the surface tension theory is developed in this paper. The model is used to calculate fillet shapes formed between a terminal and the land areas of a plated-through-hole. Exact solutions can be found for the axisymmetrical fillets formed by a round pin and a plated-through-hole. For the case of a square wire wrap terminal an approximated form of the model based on an overall force balance concept is developed. In both cases the results show good agreement with experiments.

In general, the fillet on the top land area remains relatively constant with increasing board thickness whereas the bottom fillet tends to become fuller with increasing board thickness as a result of increasing hydrostatic head. The results obtained are useful in the selection of proper preform sizes for reflow soldering operations as well as in the design of wire wrap terminals.

Although the paper deals mainly with fillets formed by a pin and a plated-through-hole, the model can also be used for other geometries. For example, the two dimensional form of the model can be used to calculate fillets formed by a terminal wire laying on a flat land area. Such calculations will be useful in the design of connector boards for flat flexible cable termination. The axisymmetric model can be used to predict the shape of the solder meniscus in a plated-through-hole after fusing. A PTH with excessive amount of solder will be plugged by solder after fusing. The fillet model can be used to determine the maximum solder plating thickness beyond which hole plugging would result after fusing.

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