Lead-free soldering and the issues of lifting of pad, fillet and fillet tearing

The physics of critical failure mechanisms

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Pad lifting and crack formation at the surface of solder fillets on plated through-hole joints were issues in the days when boards were processed at 'solder cutting solder' lines, common in the 1980s. The use of lead-free solder alloys has brought about a recurrence of this crack formation, called fillet-tearing. There appears to be no cure this time; changing process parameters hardly provides any improvement.

The problems occur primarily on boards with through-hole plated solder joints, since this joint construction is vulnerable to joint deformation during soldering. This may cause small permanent deformation effects during solder-joint formation depending on alloy composition. Cracks in the solder joint and separated fillets on plated through-hole solder joints are commonly considered cosmetic concerns, having no detrimental effect on reliability. A lifted pad, however, is sometimes considered a defect that may compromise joint reliability. Here, we describe the effect of thermal expansion during wave soldering on plated through-hole solder joints, particularly that part of the pad that is connected to a track. By using a mathematical model derived from a practical case, we will see that there is little need for concern, in most cases, regarding the reliability of a loose or lifted pad where this pad is connected to a track.

Result of differences in thermal expansion

Pad lifting, fillet lifting and fillet tearing are effects resulting in part from the differences in thermal expansion coefficients of the PCB base material, the epoxy/glass FR-4 laminate and the copper barrels and copper tracks on the PCB. During contact with the liquid alloy, there is a relatively large thermal expansion of the board material in the Z-direction. This expansion causes a deformation of the joint-pad, giving a conical shape to the pad. This is because epoxy has a much larger coefficient of expansion than the copper hole-wall metalization. Even after the joint has passed the wave, board expansion continues because much of the solidification heat has been transmitted to the adjacent board material.

After the board has left the solder bath, thermal migration from the wave to the connection ceases and the connection begins to cool to ambient. During this phase, the solidification heat will spread to the joint area, contributing to further temperature rise of all parts in or near the joint. Let us assume that the solder begins to emit its solidification heat at 217°C. Due to the heat transmitted to the joint during solidification and the good heat conductivity of the copper-hole barrel, the adjacent epoxy-glass material will also be close to, or at, 217°C at that point. Once all solidification energy has been emitted, the joint begins to ramp down to ambient.

When the joint begins to solidify, the board material cools down and returns to its original planar shape. This movement will introduce considerable stress to the surface of the solder joint, which is still very weak at this stage. This stress may cause pad lifting; or, if the adhesion between pad and board is at that point stronger than the solder, it can cause cracks in the solder surface, known as fillet tearing. Fillet lifting may also occur.

Since a concentration of joints, as in a connector, will provide a relatively higher heat emission to the adjacent board material, these areas are more vulnerable to fillet tearing and lifting. If the adhesive strength is still high enough during the cooling stage, the solder may become separated from the pad, causing fillet lifting. This often happens when lead contamination, originating from the solder-pad finish, is present in the solder fillet. Fillet tearing occurs while the base material is returning to ambient temperature. The shape of the fillets changes from wedge-shaped back to flat.

During solidification, the solder joint begins to harden from the top of the board towards the bottom, because the topside of the board has not been fully in contact with the liquid solder and thus has a lower temperature. Additionally, the solder on the underside of the board comes directly in contact with the atmosphere right after exiting the wave; this air naturally has a much lower temperature than the solder joint at that moment.

It's possible that the solder at the joint surface on the underside might form a solidified skin, while the solder inside the joint is still pasty or liquid. If, at this time, the joint or parts of the joint are moving, cracks can be generated in the skin. During the transformation of the soldered pad from wedge shaped to flat, the solder in the fillet is still weak, while relatively strong forces are acting on the fillet due to the forced change of the solder-spot flange connected to the solder fillet. If, at that point, the strength of the bond between the base material and the copper is strong enough, deformation of the solder fillet may cause cracks. Fillet tearing is a phenomenon associated with this mechanism. Nothing can be done under the given circumstances to prevent it from happening once the solder alloy and the layout are fixed.

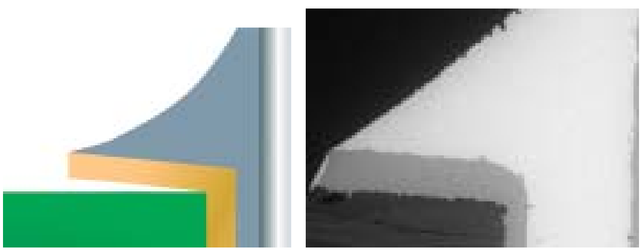
All of these problems have become commonplace with the use of lead-free alloys, which generally require higher process temperatures and also solidify at a higher temperature, typically 217°C. The higher the temperature, the more expansion will result and the more deformation will occur during soldering.

Mathematical model for fillet deformation

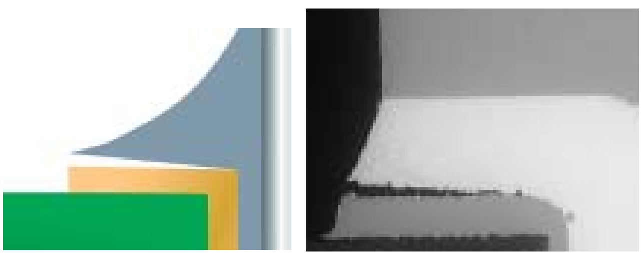
The actual case for this model is a PCB where two plated-through holes, of 0.9mm diameter on a 2.54mm pitch on a 1.6mm thick epoxy FR-4 board, have lifted pads or fillet lifting. The absolute pad size is not relevant for this model. The average measured pad wedge angle is 4°.

We assume that the two pads are connected by a track. This will be the worst-case scenario wherein the track suffers the greatest deformation. We also assume that the wedge angle during soldering will be 4° on both sides of the track relative to the copper barrel. For a pad connected to a track, the initial angle in the 'knee' was about 4°, but no permanent lifting after cooling took place in this case.

One could argue that deformation during soldering might cause pad lifting exceeding 4°. However, when a track



Pad lifting illustration and sample



Fillet lifting illustration and sample

connects these pads, it will reduce the deformation, providing strong resistance against deformation caused by the expanding epoxy board material. Thus, we use the 4°-lifting angle as basis for further calculations.

Literature

(1) Clyde F. Coombs, JR: Printed Circuits Handbook. McGraw-Hill, 1967
(2) Franz and Tappe: Electronic Engineering Magazine, October 1971, page 38
(3) Jeny. S. Hwang: Environment-friendly Electronics: Lead-free Technology. Electrochemical Publications
(4) J. Klein Wassink: Soldering in Electronics, Second Edition. Electrochemical Publications

The mechanical properties of the copper track during wave-soldering will not change much, due to the high melting temperature of copper (about 1083°C) against the relatively low process temperatures, which are normally below 270°C. Finally, we assume that the expanding epoxy creates a bow or arc-shaped deformation on the PCB surface between the copper hole barrels during wave soldering.
Using these assumptions from figure 1, we can make the following calculations:
The width of the epoxy-glass dam between the copper barrels is 2.54 – 0.9 = 1.64 mm. The length of the arc between the barrels can be calculated from figure 1, where α = 4°, 1.64 mm is the distance in-between the two barrels and R is the radius of the arc.
$R = 0.82/\sin \alpha$
Giving R = 11.755mm
The arc = $R \times \pi \times \alpha/90$
Giving the arc length = 1.64133mm
The difference between the original barrel distance of 1.64mm and the arc length of 1.64133mm is the elongation of the copper track Δl = 0.00133mm.
According to Hooke $\Delta l = (P \times l)/(E \times F)$. Knowing that the tensile strength is expressed as $\sigma = P / F$, we can convert to:
$\sigma = E \times \Delta l / l$
This formula can be used as long as the material is behaving within the elastic strain limit, which is for copper 122N/mm^2.
The modulus of elasticity (E) for copper is
E = 110GPa = 110 kN/mm
The tension in the copper track due to the elongation during the deformation as a result of the wave-soldering operation is thus:
$\sigma = E \times \Delta l/l =$
$110 \times 0.00133/1.64 =$
0.0892 kN/mm^2 = 89.2 N/mm^2
This value is well below the elastic strain limit, 122 N/mm^2. This means that the copper-track deformation was only an elastic deformation which will return to the original shape as the track has cooled down to the ambient. Therefore, the track will still adhere to the epoxy-base material after wave soldering, because there is no mechanism that will separate the track from it, if that part returns to its original shape. If pad lifting has occurred over 360° of the pad, the connected track might become partly loosened from the base material.
Let us assume that this can happen, and that the lifting angle at the pad/track connection is also 4°. Having a pad flange of 0.8mm as a common dimension, we can calculate that the theoretical lifting height is about 56µm, which is less than twice the track thickness. Even in this case there is no fear of a broken track, because at room temperature, the shear strength of a 1-ounce copper-clad track is stronger (1.13 ×) than the peel strength of the track. At solder temperature, this relationship factor of 1.13 will increase rapidly due to the reduction of the adhesive bond between the track and the glass epoxy at higher temperatures. Thus, even when there is a scenario where the track becomes partially separated, the track will still be connected to the pad. (Note: The peel strength of 1-ounce copper-clad is 8lbs/inch. The shear modulus of copper is 46GPa [1])
It might be possible that only those parts of the pad that are not connected to a track will suffer pad lifting, but this has no effect on the electrical connection between joint and track. In terms of reliability, it is a non-issue; pad lifting is not the same as track lifting. Only track lifting should influence joint-reliability issues; thus, pad lifting should not be considered a malignant defect. Thus far we have not found evidence of track lifting, but even if track lifting should occur, the electrical contact will still function properly, according to our calculations, based on material specifications.

Expansion of FR-4 epoxy-glass

The expansion-coefficient value for epoxy FR-4 in the Z-direction depends on temperature. We calculate with $\lambda = 80 \cdot 10^{-6}$ between 23°C and 103°C; $\lambda = 220 \cdot 10^{-6}$ between 103°C and 153°C; and $\lambda = 340 \cdot 10^{-6}$ between 153°C and 217°C (2). This will provide a total expansion, originating with an ambient temperature of 23°C and ramping to a soldering temperature of 217°C, of $1.6 \times (80 \times 80 + 50 \times 220 + 64 \times 340) \times 10^{-6} = 63 \times 10^{-3}$mm.
The λ for copper is $17 \cdot 10^{-6}$, giving an expansion of the copper barrel of $1.6 \times 17 \times 10^{-6} \times 194 = 5.3 \times 10^{-3}$mm
The difference in thermal expansion between the copper and the board is in this case about 58×10^{-3} mm. This gives a theoretical tension in the copper barrel of: $\sigma = E \times \Delta l/l$
σ = 110 kN/mm^2 × 58 × 10^{-3}/1.6 = 3988 N/mm^2
If the copper is really exposed to this tension, it will be far beyond 122N/mm^2, the value for copper where elastic deformation becomes permanent deformation. This means that the copper barrel and pad will be permanently deformed in soldering if the board material would be exposed to sufficient force during its expansion. This is a rare event because the metalization thickness is in most cases sufficient to prevent barrel cracking. Also, due to the relatively weak strength of the FR-4 at soldering temperature, the copper barrel would not be fully exposed to the calculated expansion. This theoretically calculated tension would therefore be far less in real life.
If we assume that the expansion will create a symmetric deformation on the bottom and top-side of the PCB, then we can calculate the theoretical wedge angle of the solder pads in the most extreme situation for the example. We must calculate the basic angle for an arc that has a height of 29×10^{-3} m and a basis of 1.64mm. From this we can calculate the arc radius R.
$R = (0.82^2 + 0.029^2) / 0.058 = 11.6067$mm
Also we can calculate $\tan \alpha = 0.82 / (11.6067 - 0.029) = 0.07082$
Given α = 4.05°
This theoretical calculated value correlates well with the measured values from practical examples where we found an average value for a of about 4°. So, it seems that in the case of pad lifting that the pad loses its contact with the base material when the pad lifting is at its maximum before the solder solidifies, according to this comparison of the practical and theoretical values.

Tolerable lifting without deformation

If we calculate the maximum allowable track deformation within the elasticity-boundary tension, it is possible to calculate the maximum pad lifting angle where, after wave soldering, the track will still adhere to the base material.
This deformation is expressed as $\Delta l = \sigma \times l/E$
Giving Δl = 122 N/mm^2 × 1.64mm/110 kN/mm^2 = 0.00182mm
Now knowing that the arc is 1.64 + 0.00182 = 1.64182mm and the basis is 1.64mm, the angle α

Terms

R = arc radius
α = pad lifting wedge angle
β = angle between solder fillet and pad
σ = tensile strength
E = elasticity modules
λ = expansion coefficient of material
Δl = length increase due to thermal expansion
l = length at ambient temperature

Definitions

Crack – A crack or micro-crack is a small tear-shaped recess or a gap in the solder surface that can be relatively deep relative to the width of the crack. Crack formation is often the result of pad movement during the soldering process. Micro-cracks can be caused by several mechanisms acting on the solder joint during solidification.
Fillet lifting – The wedge-shaped gap that can be present between the solder joint and the pad after soldering, when the PCB has returned to ambient temperature.
Fillet tearing – Usually small gaps, called cracks or micro-cracks, parallel to the PCB surface, be present at the surface of a solder fillet after soldering, when the PCB has returned to ambient temperature.
Pad – The mostly circular copper-clad part, which in the case of plated through-holes has a connection to the copper barrel, commonly on both sides of the PCB, forming the joint in connection to the mounted component lead and the solder. Most pads are connected to a track.

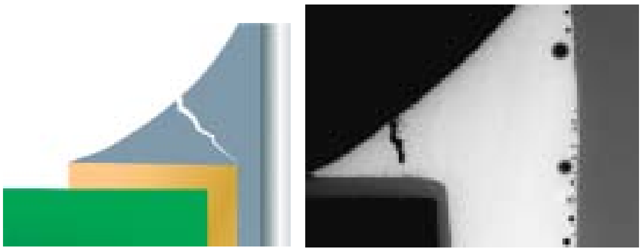
can be calculated. This angle is 4.673°. We can also calculate the expansion of the base material at this angle in the Z-direction, which is 0.067mm.

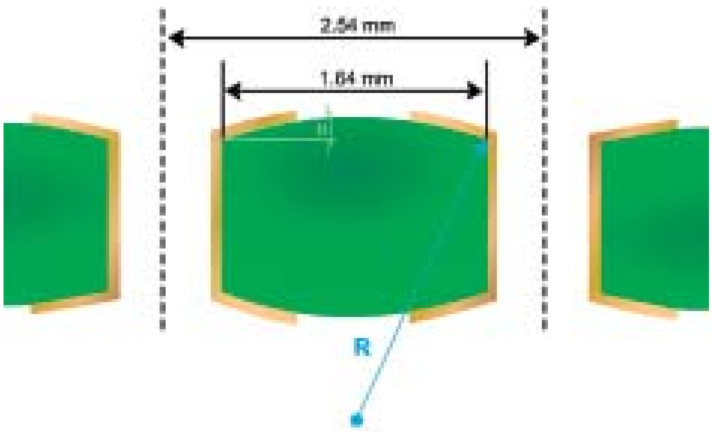
Allowable average PCB temperature

Knowing the allowable expansion of the base material FR-4 of 0.067mm, we can calculate the maximal allowable board-material temperature T = X + 153, where X can be found from the equation:
$1.6 \times (80 \times 80 + 50 \times 220 + X \times 340) \times 10^{-6} = 0.067\text{mm}$
$X = (67000/1.6 - (80 \times 80 + 50 \times 110)) / 340$. This gives X = 72, so T = 225°C
A conclusion from this calculation is that as long as the maximum average PCB temperature during wave soldering of these critical areas will be below 225°C, there is no need for concern that the tracks will lose their adhesion to the PCB material. Conversely, when this temperature is exceeded, it does not immediately create a damaged track, because in this model we did not calculate the effect of the resistance to the expansion deformation due to the coverage of the base material by the copper tracks. Resistance is a factor that diminishes the expansion of the base material, which also becomes weaker at higher temperatures and cannot completely transfer the severity of forces required for copper-track deformation. This is proven by the fact that the copper barrels in the holes normally resist and reduce the expansion of the base material at the holes. Due to this effect pads are deformed during soldering in the first place.
Another point might be the assumption that the deformation of the top and bottom sides is symmetrical. This assumption is based on the fact that the temperature in the area between the joints is homogenized by the latent heat that is emitted from the solidifying solder in the joints after the PCB has left the wave. The copper barrel filled with solder will heat the base material from the inside. This latent energy brings the temperature of the adjacent PCB areas next to the soldered joints to its maximum value. This retarded temperature rise is also due to the relatively poor heat conductivity of the epoxy-glass, which does not aid rapid heat transfer from the solder wave at the bottom side to the topside of the PCB.
In the event that a copper track between these joints on 1e (2.54 mm) is only present at one side of the PCB, the expansion of the base material will not be symmetrical. For the most extreme situation, we need a calculation wherein all expansion affects the one side without a copper track between the pads. In that case, the pad-lifting angle α can in theory go up to 8.09° for a pad not connected to a track.

Causes of fillet tearing

Next, we use the model with 8.09° pad lifting for the calculation of possible cracks in the solder fillet, where we assume that the flange of the pad has a length of 0.8mm. If the pad returns to its original flat shape, the edge of the pad has been displaced over 0.8mm × sin 8.09° = 113µm, going from the 8.09° wedge angle to the flat position.
This displacement results in an elongation of the fillet surface. The effect of this dislodgment on the crack dimensions also depends on the fillet angle β in relation to the solder pad. In theory, this elongation can then result in cracks with a maximum total gap width corresponding to the dimension of pad-edge displacement relative to the fillet angle β, given in the following formula:
Total elongation or width of fillet cracks = pad-edge displacement × sin β
Calculating with a common fillet angle β of about 45°, the maximum crack dimensions as a result of fillet lifting will be 113µm × sin 45° = 80µm
Another reason for possible crack formation in the solder fillet is due to the effect of about 4% volume reduction when liquid solder solidifies. If the last part of the solder solidification is at the fillet surface, a dent or a crack can be formed in the fillet surface as a result of that volume reduction.


Fillet tearing illustration and sample



Pad lifting at two adjacent holes

If some lead (Pb) from connector-lead finish has been dissolved in a joint, the integrity of those solder joints can be compromised by cracks. These cracks are initiated at the surface and propagate through the solder joint along transgranular or intergranular paths (3). There the effects of Pb contamination in lead-free solders are described. "It is postulated that a small amount of Pb precipitates tends to reside preferentially at the grain boundaries, causing early grain boundary fracture".
Finally, solder cracks can be formed due to the expansion mechanism, combined with an alloy that has a melting range instead of a melting point.

ZUSAMMENFASSUNG

Mit der Einführung der bleifreien Fertigung treten an den Lötstellen von Durchkontaktierungen wieder verstärkt Pin-Abheber (pad Lifting) und Risse (Cracks/Fillet Tearing) auf, denn diese Lötstellen sind empfindlich gegenüber Deformationen während der Prozedur. Wie es aussieht, sind Änderungen der Parameter im Lötprozess hier weitgehend wirkungslos. Der Autor geht akribisch der Frage nach, wieweit hier Einbußen an Qualität und Zuverlässigkeit der Baugruppen zu erwarten sind? Oder ob es sich bei geringem Ausmaß dieser Effekte – die von den thermischen Ausdehnungskoeffizienten der Materialien bestimmt sind – in erster Linie um eine Art von „kosmetischen" Unzulänglichkeiten handelt?

RÉSUMÉ

Avec l'introduction de la production sans plomb, on constate de nouveau une recrudescence des décollements (pad lifting) et de criques (cracks/Fillet Tearing) aux brasures des métallisations de trous, ces brasures étant sensibles aux déformations pendant la procédure. Il apparaît que dans ce cas, des modifications apportées aux paramètres du procédé de brasage sont en grande partie sans effet. L'auteur se penche sur la question quant à savoir dans quelle mesure on peut s'attendre à une perte de qualité et de fiabilité des modules. Ou encore s'il s'agit en premier lieu de simples imperfections lorsque ces effets, qui sont fonction des coefficients de dilatation thermiques des matériaux, ne sont que limités.

SOMMARIO

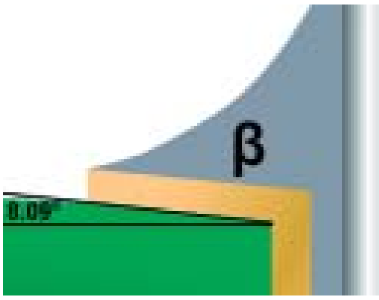
Con l'introduzione dei processi di produzione senza piombo, sui punti di saldatura dei contatti continui si verificano spesso dei sollevamenti dei pin (pad Lifting) e crepe (Cracks/Fillet Tearing), infatti, questi punti di saldatura sono molto sensibili alla deformazione durante il processo. Modifiche dei parametri nel processo di saldatura qui maggiormente non hanno alcun effetto, come già dimostrato. L'autore si pone con acribia la domanda in quanto siano attendibili delle perdite di qualità e affidabilità dei gruppi costruttivi? O se in una lieve entità di questi effetti – dovuti ai coefficienti di dilatazione termica dei materiali – potrebbe trattarsi in prima linea di una specie di inaccessibilità „cosmetica"?

Due to this range, the solder will have a pasty range during solidification. This is where the solder strength is very weak and where solid parts are mixed with solder that is still in a liquid state. The solder finally solidifies with a rough surface where micro-cracks can often be found.

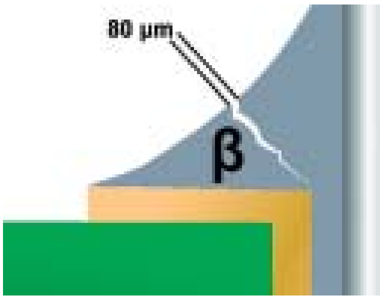
Effects on solder-joint strength

If we assume that the solder fillet on the top side of the PCB was filled to the upper hole edge and that the fillet on the solder (bottom) side has no contact with the solder pad, we have the worst scenario where the fillet does not really contribute to joint strength. In an ideal case, we must calculate the strength of a joint where the fillet has a sound connection to the pad, and the pad has a sound connection to the base material. This joint should then be compared with the worst-case model.

We will base our calculations on a joint with a common lead of 0.6mm diameter, which protrudes 1.5mm at the solder side, with a pad size of 2mm. The solder-fillet height for this layout can be found in the literature (4). This height is maximum 0.8mm. For the calculation of the added strength of this solder cone compared to the joint area inside the barrel, it is realistic to calculate with 1/3 of this fillet height. So, the additional strength of the sound fillet is 1/3 × 0.8 = 0.27mm lead part. The total with solder connected lead length is this 0.27mm plus the 1.6mm board thickness is 1.87mm. The relative reduction in joint strength due to a damaged pad connection can now be calculated. This is 0.27/1.87 = 0.144 or 14.4%. In most cases, this initial reduction in actual joint strength has no effect on the reliability of the assembly.



During soldering



After soldering

A short summary

As long as the maximum average PCB temperature during wave soldering on critical areas will be below 225°C, there is no need to be concerned that the tracks will lose their adhesion to the FR-4 base material. Only track lifting should be a concern affecting joint reliability; pad lifting should not be considered a defect. When a pad is connected to a track, full pad lifting over 360° is nearly impossible during wave soldering.

Supporting our calculations, we have not seen any practical evidence yet of full pad lifting during a (lead-free) wave-soldering process when a track is connected to a pad. Cracks in solder fillets, on plated through-hole joints, called fillet tearing, are a common effect with lead-free alloys which can have several causes. The initial reduction in joint strength on plated through-hole solder joints is, in the worst-case scenario (complete loss of strength of the cone at the solder side of the joint) about 14 %.

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