Moisture Measurements in PCBs and Impact of Design on Desorption Behaviour

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Abstract
High levels of residual moisture in PCBs are problematic and can result in delamination during soldering and rework. Moisture accumulates during storage and industry practice recommends specific levels of baking to avoid delamination. This paper will discuss the use of capacitance measurements to follow the absorption and desorption behaviour of moisture. The PCB design used in this work, focused on the issue of baking out moisture trapped between copper planes. The PCB was designed with different densities of plated through holes and drilled holes in external copper planes, with capacitance sensors located on the inner layers. For trapped volumes between copper planes, the distance between holes proved to be critical in affecting the desorption rate. For fully saturated PCBs, the desorption time at elevated temperatures was observed to be in the order of hundreds of hours. Finite difference diffusion modelling was carried out for moisture desorption behaviour for plated through holes and drilled holes in copper planes. A meshed copper plane was also modelled evaluating its effectiveness for assisting moisture removal and decreasing bake times. Results also showed, that in certain circumstances, regions of the PCB under copper planes initially increase in moisture during baking.

Introduction
Delamination during soldering can occur due to high levels of moisture within a PCB, which rapidly expands during soldering and rework operations. This delamination may not always be visible as a raised or discoloured surface. Whilst techniques such as pulsed thermography [1] and acoustic microscopy can be used to detect delamination and prevent delaminated boards from entering service, it is preferable to avoid delamination completely through suitable board storage, design and pre-baking.

Moisture enters the PCB when the partial pressure of the moisture in the atmosphere is greater externally to that inside the PCB. The random thermal agitation of the water molecules causes them to diffuse to regions of lower moisture concentration further into the PCB. The diffusion of moisture in PCBs has previously been modelled using various techniques [2-4] and Weide-Zaage et al [5] have considered different arrangements of internal copper layers.

To prevent delamination in the soldering phase, IPC guidelines suggest keeping the moisture content to less than 0.1% by weight for high (260°C) temperature soldering and less than 0.2% for low temperature (230°C) soldering [6]. Moisture content can be experimentally assessed through mass measurements of the PCB, although the percentage change in mass will be dependent on the amount of copper on the board. Prior work investigating moisture uptake in PCB's has identified capacitance measurements as being capable of detecting changes in moisture content [7]. Capacitance measurements are able to detect moisture content changes, as they are dependent on the permittivity (which is dependent on moisture) of the material between the electrodes. Whilst mass measurements reflect the average moisture condition of a board, capacitance sensors can be positioned to measure the moisture content locally. Moisture uptake and removal at three bake temperatures was also modelled and fitting of the data yielded diffusion coefficients for the FR-4 composite material [8]. These coefficients have been used here to model the diffusion of moisture into PCBs with features similar to that experimentally investigated.

Experimental
A test board has been designed with capacitors situated on inner layers between external copper planes (Figure 1). The board had four sections, each comprising a grid of 3 by 3 capacitors (20 mm by 20 mm in size), with different plated and non-plated hole densities. The different hole densities corresponded to centre-to-centre spacings of 4, 5.6 and 8 mm, as well as a section with uninterrupted copper planes. Versions of this board were built, with either plated through holes (PTH) or non-PTHs. The boards were of 4 layer design using 7628 prepreg (pre-impregnated composite fibres) either side of a 1 mm copper clad core. The 7628 prepreg had a resin content of 51±3%, fibre thickness of 0.173 mm and fabric count (warp x fill) of 17.3×12.2 per cm. The capacitance was measured across the central layers, which were 1 mm apart. PTHs were 0.4 mm drilled size with a land diameter of 0.8 mm. The clearance distance to the copper plane was a further 0.2 mm. Non-PTHs were drilled at 0.8 mm diameter to maintain a constant clearance to the copper plane. The design of the grid capacitors is shown in Figure 2, the grids consisting of 0.2 mm tracks on a pitch of 0.8 mm with 25 openings (2.4 x 2.4 mm) available for holes.

The test boards were initially soaked in an 85% RH/85°C environment for two months. Subsequently, the boards were divided into three groups in order to investigate moisture removal at bake temperatures of 80, 110 and 125°C. The boards were periodically removed from the ovens and allowed to cool for 45 minutes; the capacitance values were then measured

before returning the boards to their respective ovens. The capacitance was measured at a frequency of 100 kHz using an Agilent 4263B LCR meter.
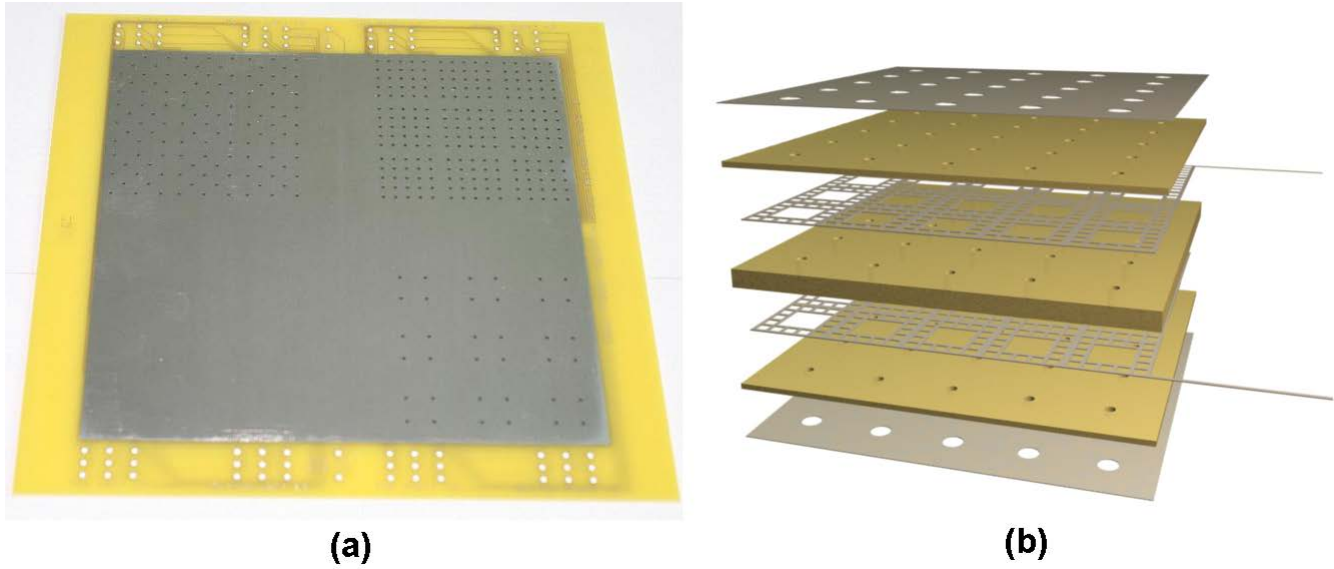

Figure 1 (a) Test board showing plated and non-plated through holes at different densities and (b) illustration of the internal grid capacitors
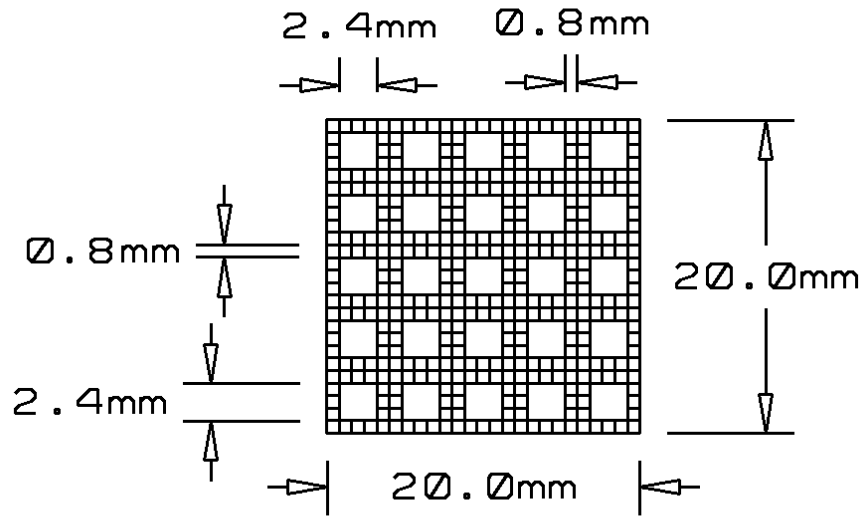

Figure 2 Dimensioned capacitor design

Theory
To model the effect of copper planes and various PCB features, a finite difference modelling approach has been used to solve the diffusion equation:

$$\frac{\partial \rho(\underline{r}, t)}{\partial t} = D \nabla^2 \rho(\underline{r}, t)$$

Where D is the diffusion coefficient and ρ is the moisture concentration. For non-varying temperatures and a diffusion coefficient that is independent of moisture concentration, we can use a relative approach to the moisture concentration allowing the moisture content to vary from 0% (dry) to 100% (saturated). The moisture at the boundary is set to 0% to simulate baking and 100% to simulate soaking of the modelled PCB. At symmetry planes and copper planes, the differential of the moisture content is set to zero such that no moisture can flow. The time step used in the model was sufficiently small for model stability and to get accurate results. The meshing of the model was restricted to rectangular elements such that the hole features are approximated using square elements. The finite difference model has been described in more detail elsewhere [8].

Results

The capacitance values measured during the test are shown as a percentage decrease from the start of the bake in Figure 3.
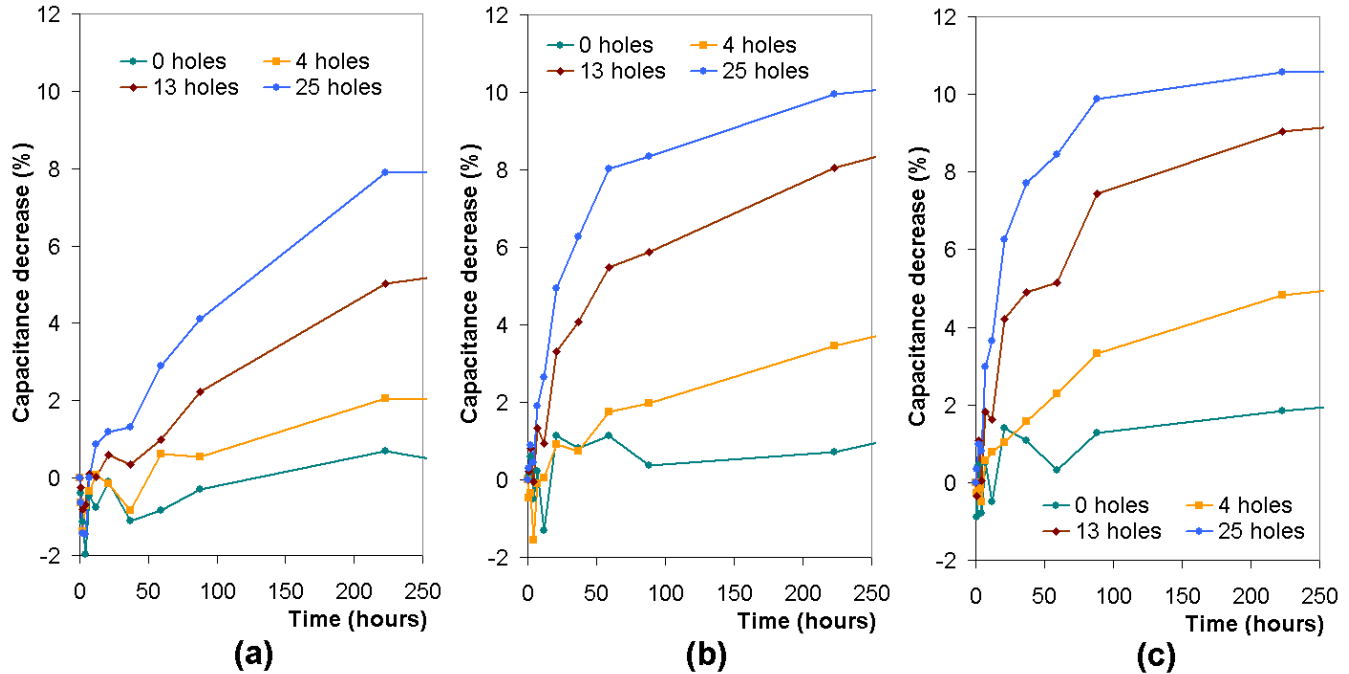

Figure 3 Effect of non-PTH hole density on average capacitance (of the 9 capacitors) decrease for the test boards baked at (a) 80°C, (b) 110°C and (c) 125°C.

The average capacitance decreases more quickly for higher hole densities, both due to the increase in surface area from which moisture can escape and the lower average distance of the moisture to the surface. The higher temperatures increase the diffusion rate in accordance with the Arrhenius equation and thus we see that shorter bake times would be required to reduce the moisture content to below a suitable level. The average capacitance measured for the different hole densities of PTH is compared with those for non-PTH for the 125°C bake condition in Figure 4. It was found that capacitance decreases faster for boards with non-PTH, indicating that such boards would require a shorter bake time to ensure moisture levels fall below a certain value compared to PTH boards of the same hole density. PTH boards have a smaller exposed surface area than non-PTH boards, and the moisture cannot escape so easily from the plated through holes.
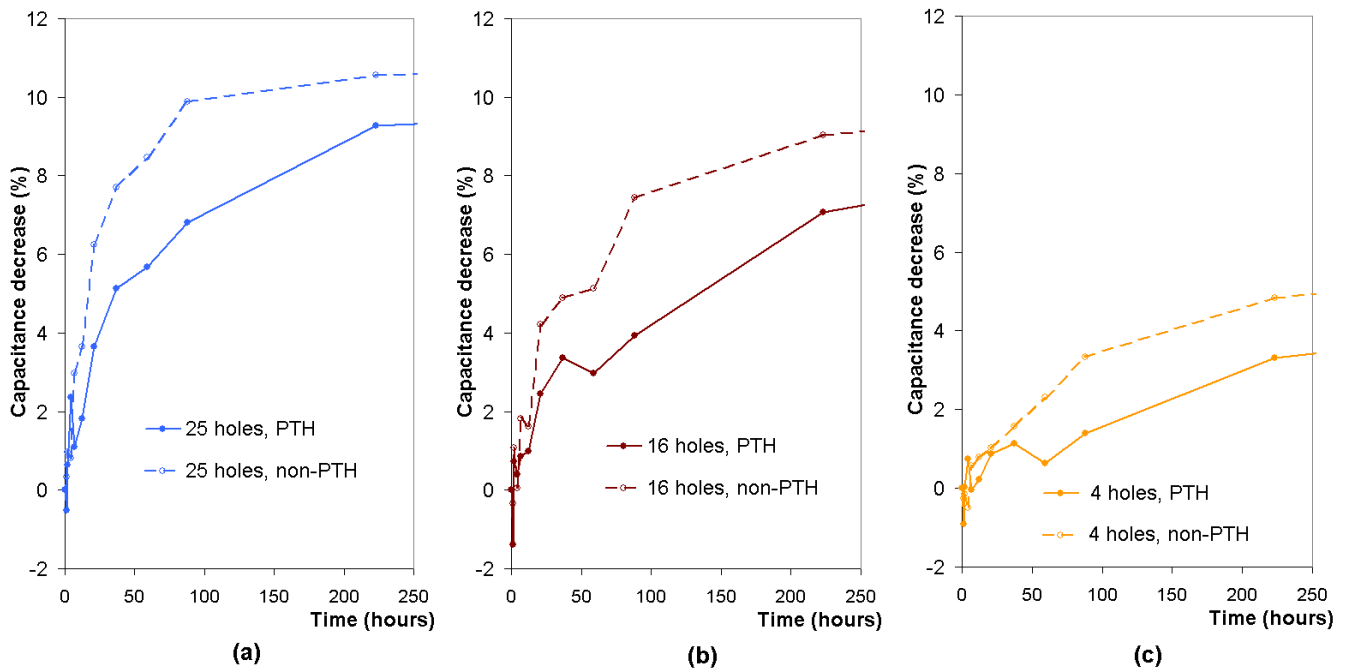
Figure 4 Comparison of PTH and non-PTH on the capacitance decrease with bake time at 125°C for three hole densities corresponding to (a) 25 holes in capacitor, (b) 13 holes in capacitor and (c) 4 holes in each capacitor.

Modelling PTH and non-PTH in copper planes

The different moisture desorption capability of PTH and non-PTH boards during a baking process was compared using a simplified model. This model consisted of a PCB with a 0.4 mm hole repeated infinitely in both x and y directions and with a pitch of 4 mm (see Figure 5). The non-PTH to copper plane clearance was set to 0.4 mm, whilst for the PTH the land diameter and clearance to copper plane were set to 0.8 mm and 0.2 mm respectively. Since not all boards have copper planes on the surface, an extra model was created to represent copper planes on inner layers only (Figure 5c).
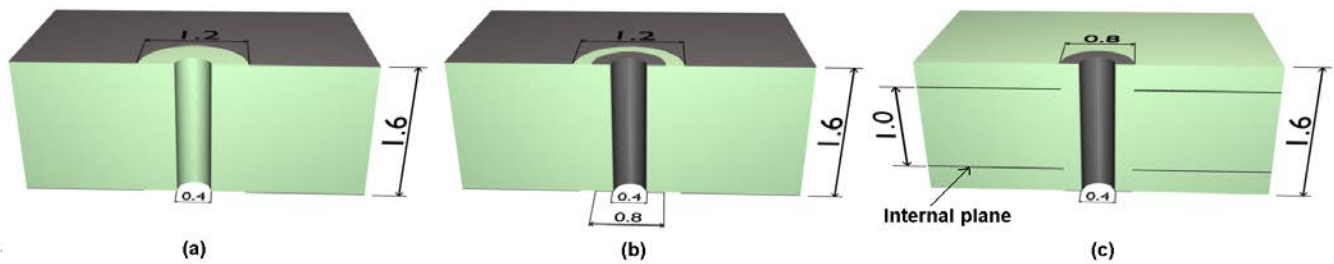

Figure 5 Cross section of through holes for (a) non-PTH with copper plane on outer layers, (b) PTH with copper plane on outer layers and (c) PTH with internal copper planes (dimensions in mm).

The model boards shown in Figure 5 were subjected to simulated baking. A diffusion coefficient of 33 $\mu m^2 s^{-1}$ was used, equivalent to baking FR-4 material at 125°C [8]. The moisture profile over the cross section after 1, 12, 24, 48, 100 and 150 hours for the three models is shown in Figure 6 with a dark blue colour representing saturated and light yellow as dry.
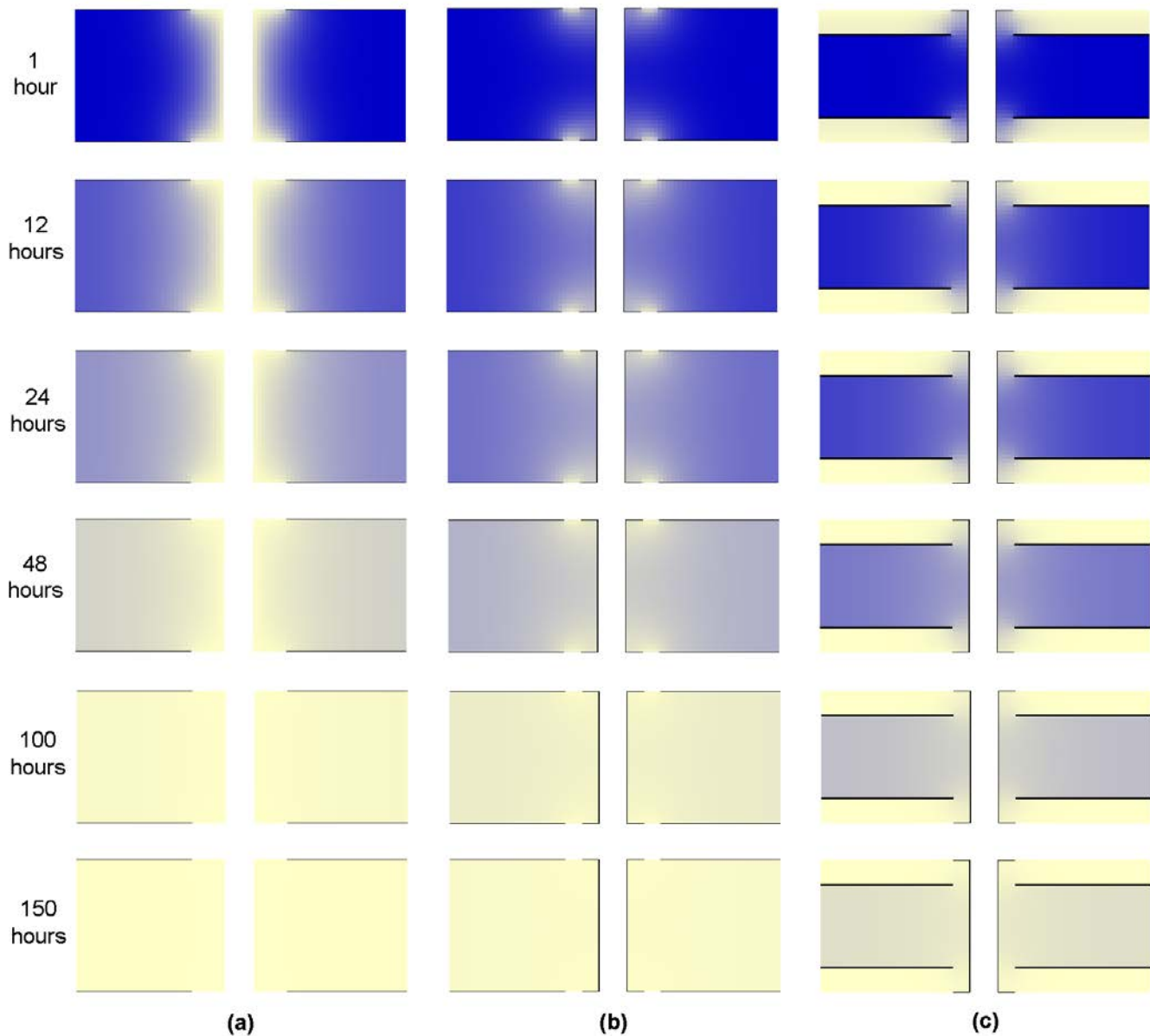
Figure 6 Modelled moisture profile over hole cross section after 1, 12, 24, 48, 100 and 150 hours for (a) non-PTH with copper plane on outer layers, (b) PTH with copper plane on outer layers and (c) PTH with internal copper planes

The moisture exits the non-PTH PCB model much more quickly because moisture can escape more easily from the greater open surface area which is 1.26 mm^2 for the PTH and 4.02 mm^2 for the non-PTH. For a PTH board, the rate of moisture loss is much slower, because moisture must diffuse a greater distance to find a surface free from copper before it can exit the board. The mean moisture content of the central 1 mm core of a PTH and non-PTH PCB is plotted in Figure 7. It takes 17 hours to halve the internal moisture within the 4 mm pitch non-PTH board; the time increases to 27 hours for the PCB with PTH holes. For the board with internal copper planes (Figure 5c), the moisture rapidly exits from the external layers above the copper planes, but takes 49 hours to halve the moisture level between the copper planes. This is mainly due to the decrease in area from which the moisture can escape as the gap within the copper planes is smaller (the clearance distance is still 0.2 mm between PTH and copper plane, but as the copper plane open area now has a smaller radius due to no land, the gap area has decreased by 40%, 0.63 to 0.38mm²). This is illustrated in Figure 8.
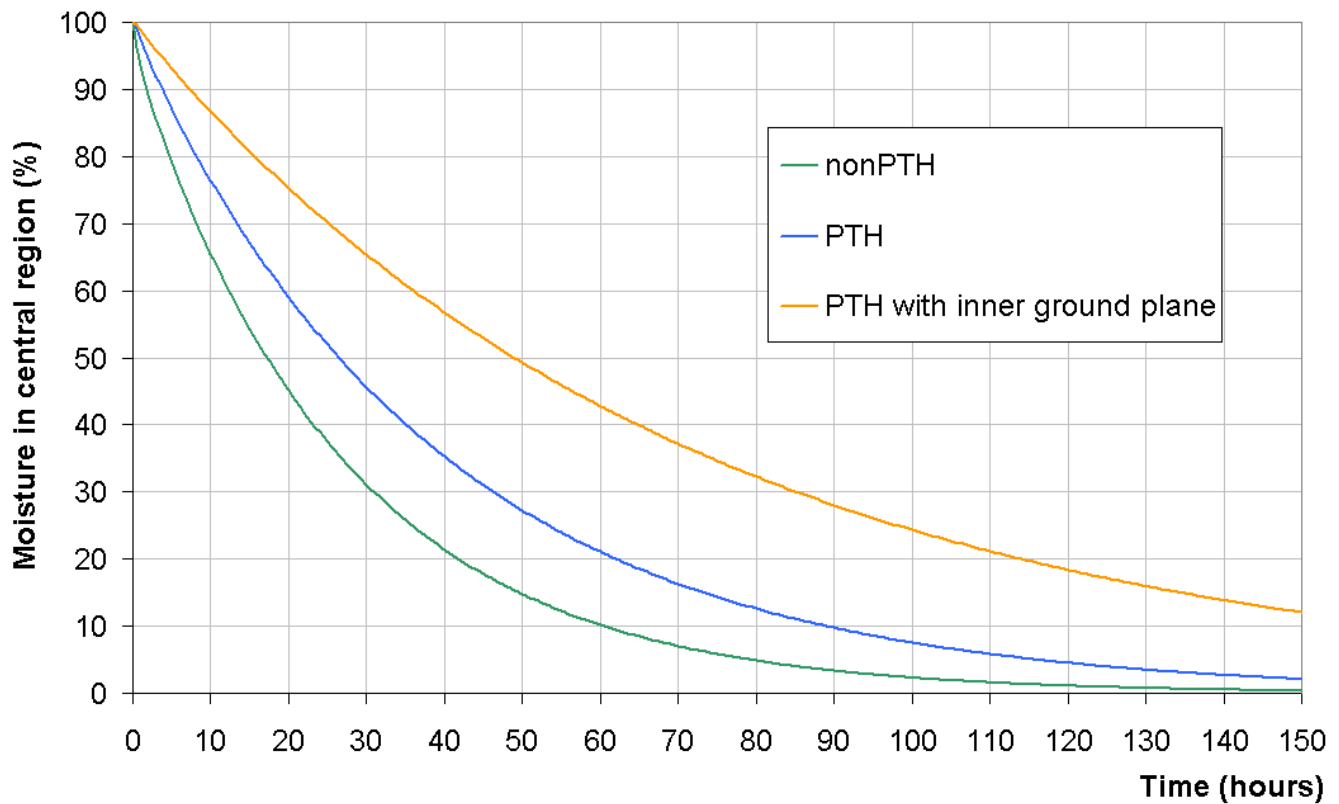
Figure 7 Modelled effect of bake time on the mean moisture content in the central region (1 mm off the copper plane) in boards PTH and non-PTH boards.
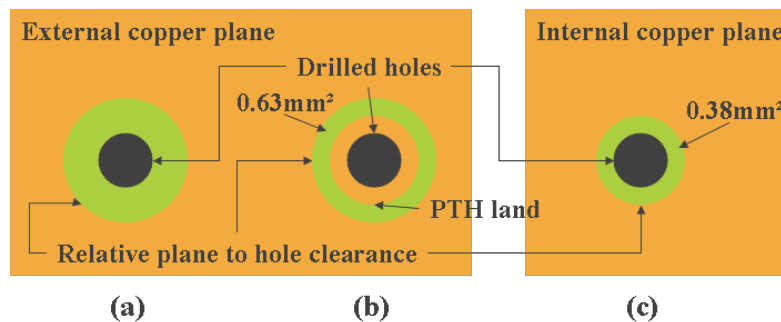

Figure 8 Diagram showing relative plane to hole clearances (open areas for moisture diffusion) for (left) non-PTH with copper plane on outer layers, (centre) PTH with copper plane on outer layers and (right) PTH with internal copper planes

Whilst there is a difference in the bake times for PTH and non-PTH, this difference is relatively small compared to the effect of the hole density, which has been reported elsewhere [8] and can also be appreciated by considering the hole density in a meshed copper plane.

Modelling desorption in meshed copper planes

Meshed copper planes can provide improved bonding between adjacent epoxy layers, thus increasing strength and also provide a shorter route for moisture to diffuse more quickly into and out of the board. However, meshed copper planes may degrade electrical performance. A model was created to illustrate the effectiveness of meshing a copper plane on the surface of a double-sided PCB, (see Figure 9). The PCB was initially set to be saturated with moisture, the external surface was set to be dry, and moisture was allowed to escape with a diffusion coefficient of 33 $\mu m^2 s^{-1}$ (to simulate baking FR-4 material at 125°C). Figure 10 displays the moisture profile at a depth of 0.6 mm after 6, 15, 25 and 45 hours. As expected the moisture content decreases as it diffuses out of the board.
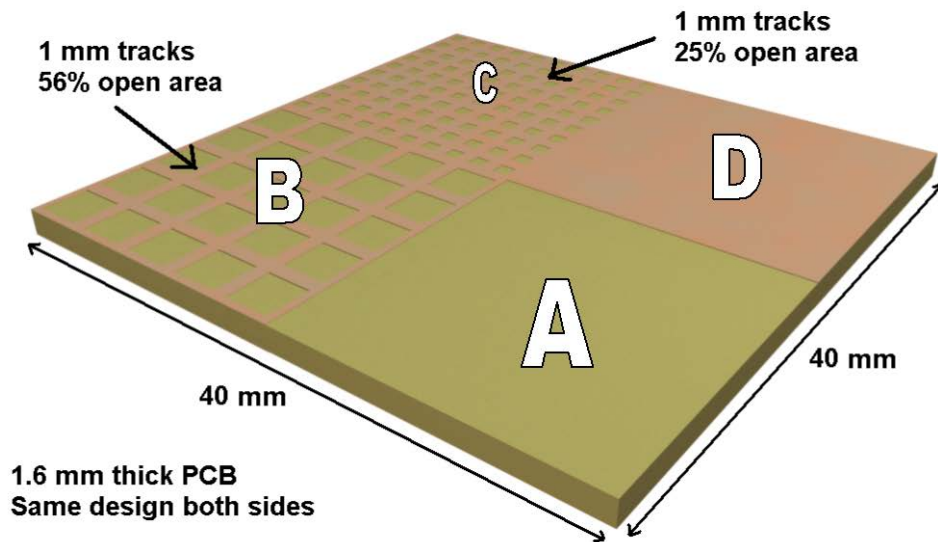
Figure 9 Model used to illustrate the effect of meshed copper planes consisting of areas with (A) no meshing, (B) 56 % open area, (C) 25% open area and (D) solid copper plane.
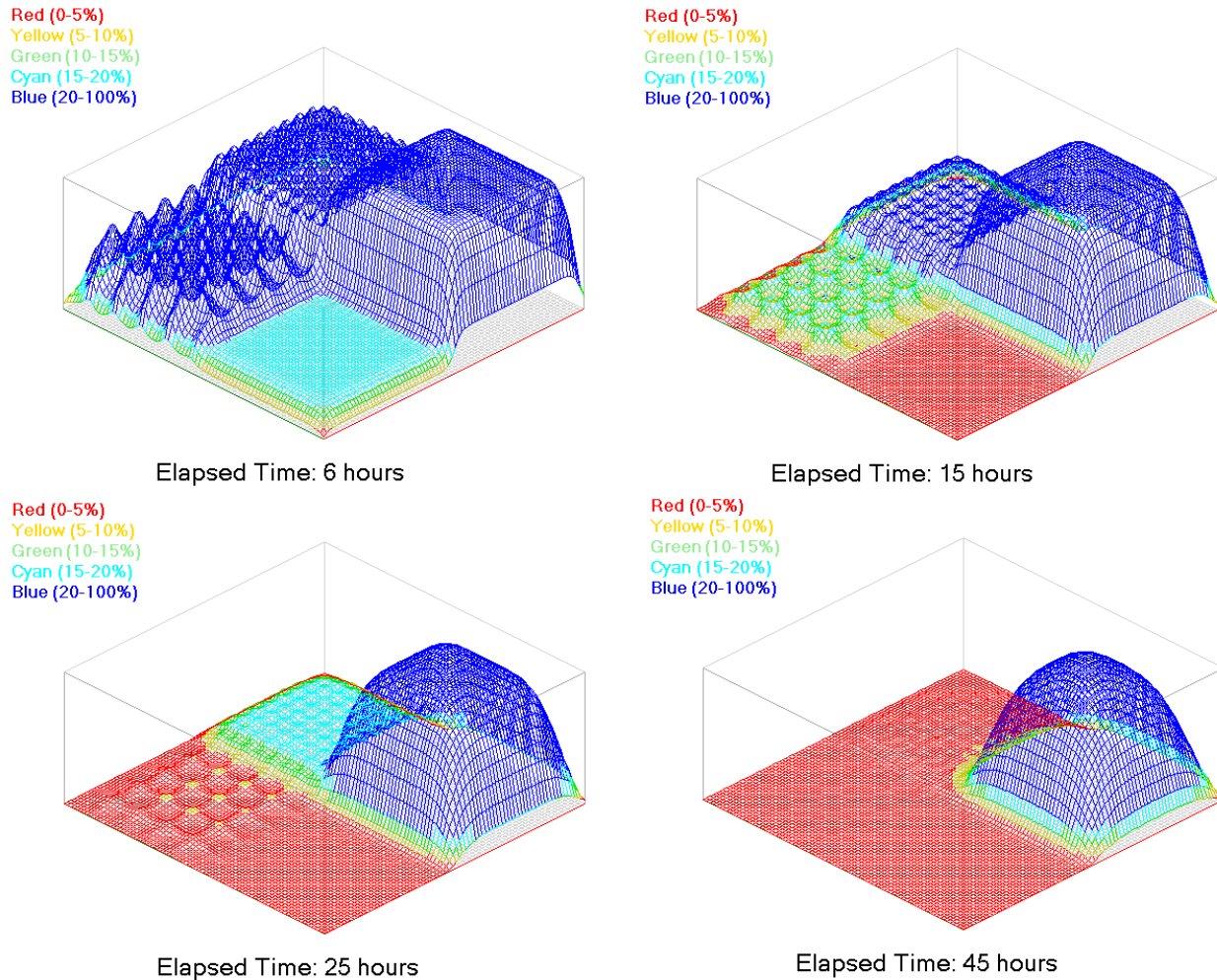

Figure 10 Contour plot showing the percentage of initial moisture inside the PCB at a depth of 0.6 mm after 6, 15, 25 and 45 hours of baking at 125°C.

For the open area (A), the moisture was reduced to less than 20% of the initial moisture content in 6 hours. For the mesh with 56% open area (B), this increases to 15 hours and for the mesh with 25% open area (C) this increased further to 25 hours. After 45 hours the meshed region with 25% open area (C) had decreased to below 5% of the initial moisture content. The area with no meshing (D) still has considerable moisture content and a further 14 days are required to reduce this to 20% of the initial moisture content. Again, this illustrates that once moisture has diffused underneath continuous copper planes, baking is unlikely to be effective in removing it. To investigate the effect of mesh pitch and the track width, a single open area with tracks model was repeated infinitely in the x and y directions by using symmetry planes for a 1.6 mm thick double sided PCB with mesh pitches from 0.4 mm to 6.4 mm. The time required to decrease the mean moisture content to half the initial value has been plotted in Figure 11. For different mesh pitches, the bake time increases as the track width increases due to the decrease in the open surface area from which moisture can escape. The bake time is also seen to increase as the pitch increases because moisture must travel a longer horizontal distance before it can escape through one of the open areas in the mesh.
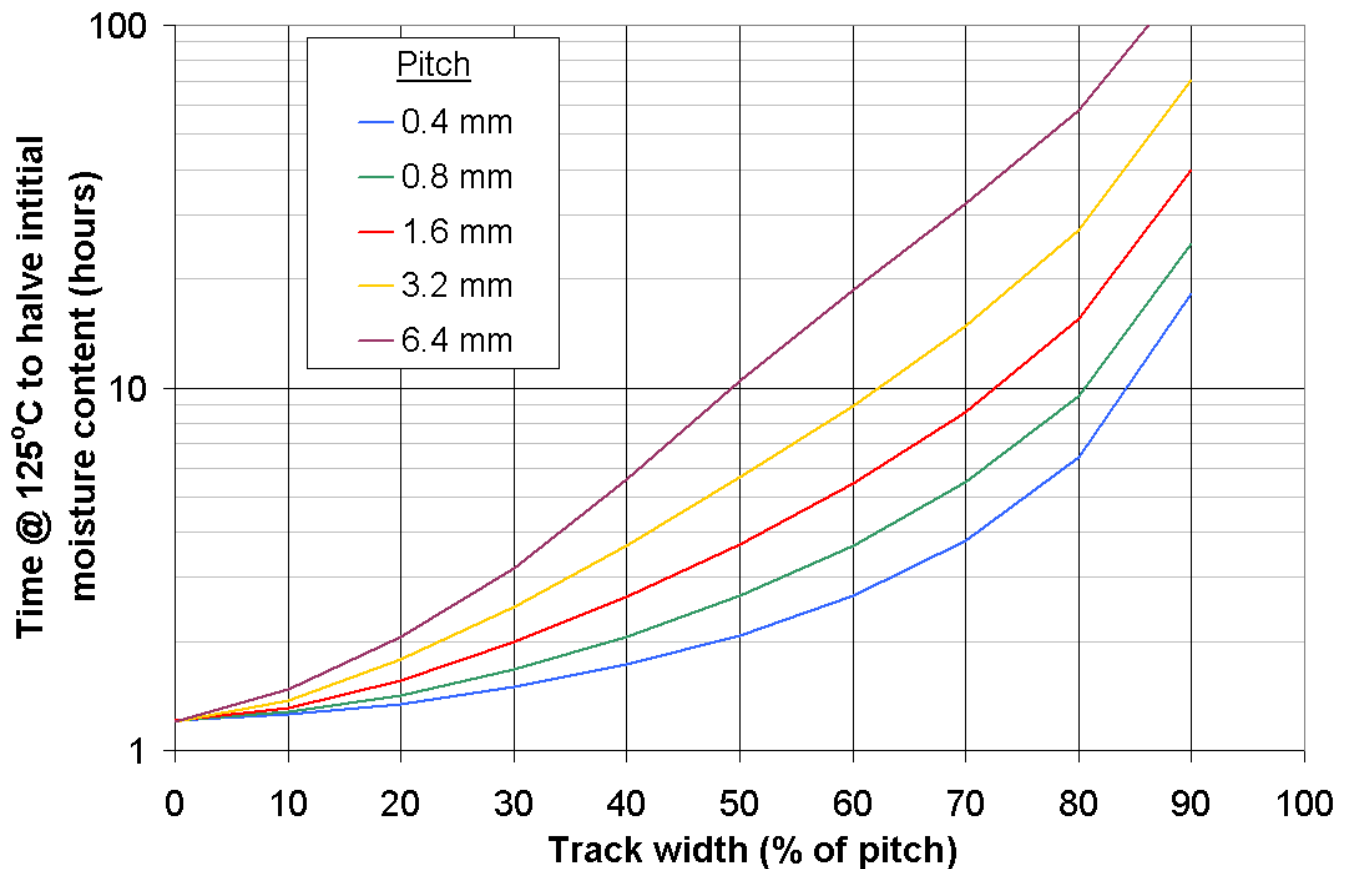

Figure 11 Effect of track width as percentage of mesh pitch on the time required to reduce mean moisture content to 50% of the initial value for a 1.6 mm thick FR4 PCB.

Discussion

Baking is generally be used to remove moisture from PCBs. However, for PCBs with large uninterrupted copper planes, the local moisture concentration can initially rise during baking and can potentially increase the risk of delamination. To illustrate this point, we model a 20 mm square, 1.6 mm thick FR-4 PCB, with solid copper planes 12 mm square, on the top and bottom surfaces as shown in Figure 12. In this case, a diffusion coefficient of 0.25 $\mu m^2 s^{-1}$ was used to simulate a baking at 20°C [8]. Moisture from the atmosphere enters the PCB over a 120-day period (this, for example, could represent the time a board is held in storage). Whilst moisture near the edge of the copper plane is almost saturated, the moisture at the centre of the copper plane is still <5% of this. This PCB is then baked at 125°C and the subsequent moisture diffusion is followed (Figure 12).
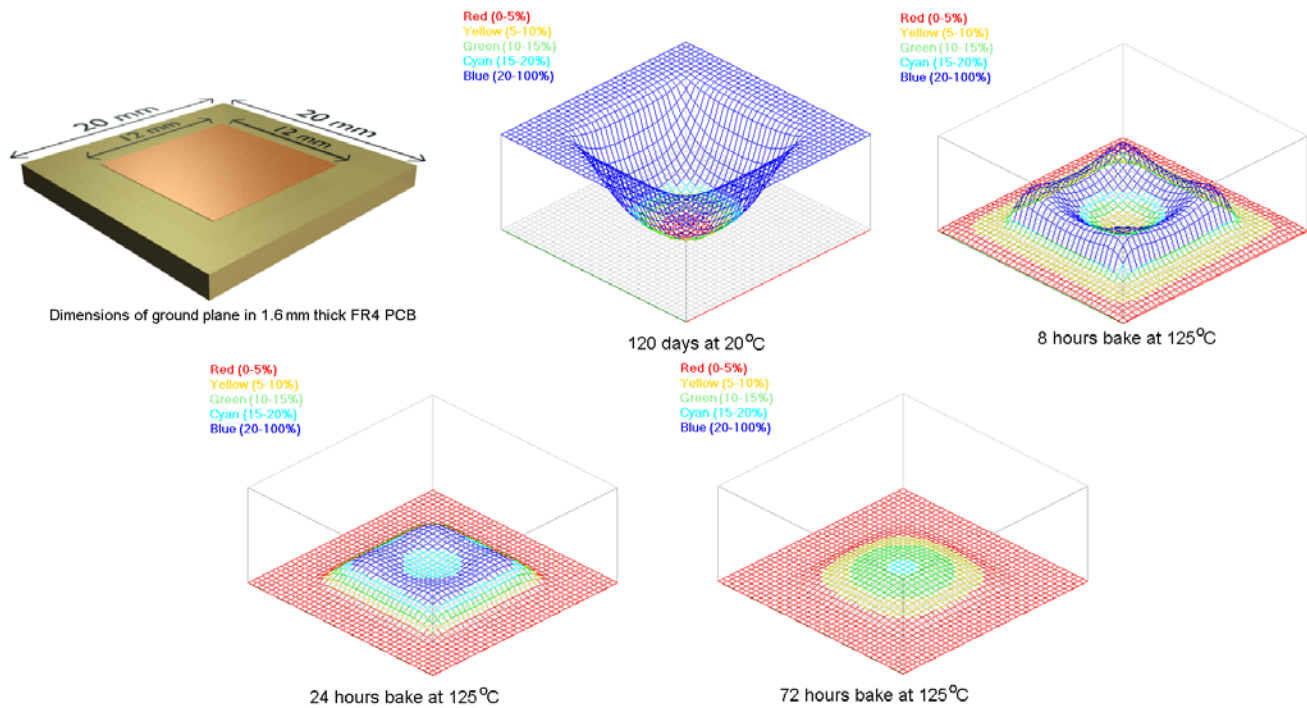
Figure 12 Illustration of modelled surface copper plane, moisture profile after 120 days at 20°C, and moisture profile after baking at 125°C for 8, 24 and 72 hours.

Whilst the moisture readily comes out at the edges of the copper plane, further inside the moisture is still diffusing towards the centre of the copper plane, but now at a much faster rate than it entered the PCB, due to the much greater diffusion coefficient at the higher bake temperature. The moisture at the centre therefore increases, reaching moisture content corresponding to 19.6% of the 20°C saturation condition after 40 hours as shown by Figure 13 before decreasing.
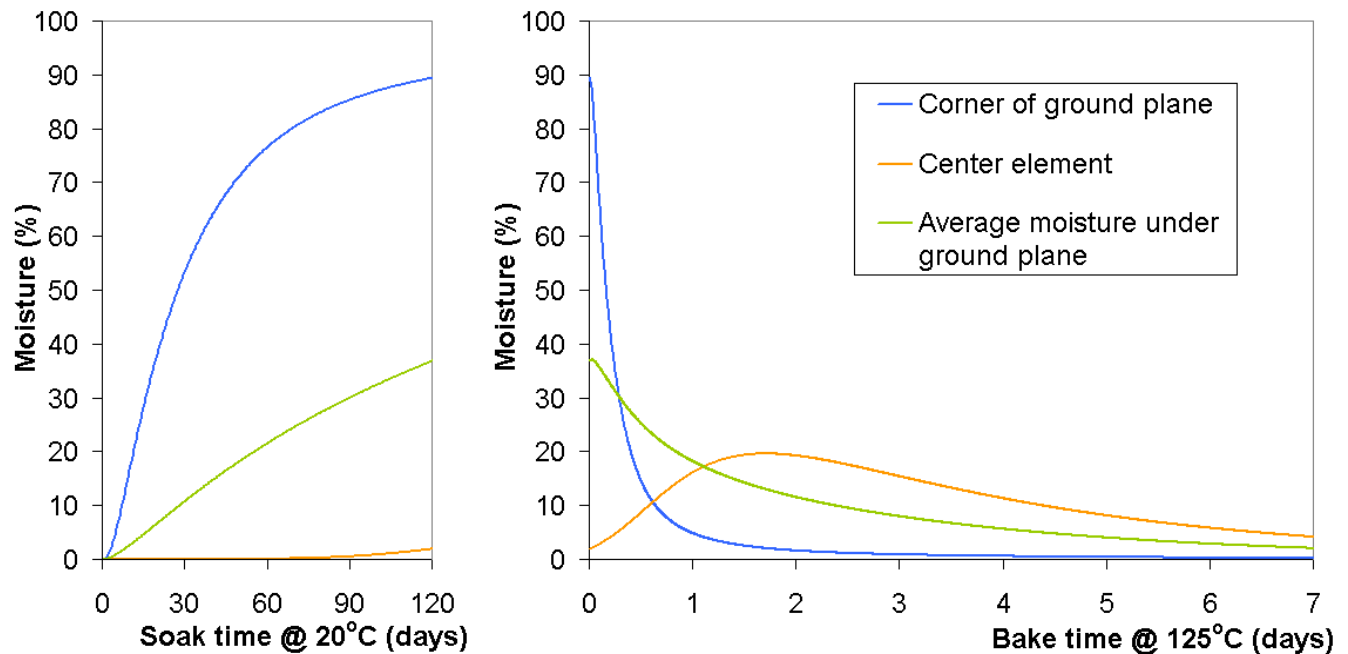

Figure 13 Average moisture content under copper plane, moisture content at centre and at the corner of the copper planes throughout the soak and bake of the 12 mm square copper plane model.

The saturation moisture concentration in air at 10°C is 0.009 kg m^{-3} whilst at 30°C this becomes 0.030 kg m^{-3}. The moisture concentration also varies linearly with the humidity up to the saturation concentration. Therefore, the amount of moisture

that can diffuse into a PCB will be largely dependent on the storage conditions, with cooler and dryer storage conditions being preferred. Under constant humidity conditions, the moisture from the ambient will in time extend into the PCB with the final saturation concentration being dependent on the PCB moisture uptake capability.

Conclusions

Copper planes have a significant effect on moisture desorption and hence consideration to their design should be given to bake out requirements. Increasing the bake time, whilst removing more moisture and reducing the delamination risk, can have detrimental effects to the solderability and mechanical properties of the PCB, such that a compromise in bake time should be sought. In many cases, when moisture has diffused under copper planes, it is not feasible to remove the moisture. Hence preventative measures are required to stop moisture entering the PCB in the first place.

The removal of moisture may not be straight forward, as was shown for two equal 12 mm square copper planes where in the central region the moisture initially increased during bake out, as the moisture initially equilibrates before diffusing out of the board. If such moisture increases are into a delamination prone region, it is conceivable that baking may in some cases have an unwanted effect of increasing delamination risk.

Modelling has shown that meshed copper planes can significantly reduce bake out times, with a clear functional dependence on the open area of the mesh.

Acknowledgements

References

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