Education and training in
Electronic Design Realisation

Multilayer bonding – what's it all about?

written by Geoff Layhe

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Multilayer bonding – what's it all about?

In the last few years, more and more small to medium sized printed circuit manufacturers are coming to the conclusion that it's better to concentrate on high margin multilayers rather than single- or double-sided boards. At the same time advances in resin technology have taken some of the 'Black Art' out of multilayer manufacture. However, there is still something of a mystery attached to some aspects of building multilayers.

While it may be impossible to take all the mystery out of multilayers, in the following paper we will try to simplify the process of multilayer bonding, help to give an insight into what is happening during the bonding process and discuss what problems may arise and why.

1 Prepreg

At the heart of successful multilayer manufacture is an understanding of the function and use of prepreg. At its simplest level prepreg is the glue that holds layers together; but we ask more than that from prepreg. When bonded into a multilayer there must be enough flow to remove any air. However there must not be too much flow, otherwise the multilayer will be too thin and the expelled resin will stick donned stacks together, the finished thickness must be consistent within a press load and from press load to press load, the prepreg must encapsulate and adhere to copper and epoxy, it must have the same temperature rating as core laminate, and so on.

So what is this high tech glue and how is it used?

Prepreg consists of a single ply of woven glass cloth which is impregnated with a blended epoxy resin and then partly polymerised to a 'B-Stage', the final polymerisation or curing takes place during the bonding cycle.

The woven glass is made up of glass filaments approximately 6µm in diameter that are bundled together and twisted at a set number of turns per inch to give a yarn. The yarns are then woven together to give a glass cloth ready for impregnation.

The filament thickness, number of filaments in the yarn, the twist imparted in making the yarn and the number of threads in the warp and weft, all have an impact on the finished board. For instance, the prepreg chosen to manufacture a multilayer can have a direct and significant effect on the amount of inner layer movement experienced during bonding.

Manufacture of prepreg

Prepreg is made by processing a roll of woven glass cloth in a 'treater'. The glass cloth is drawn through a bath of epoxy resin, at the exit of the bath the glass cloth is pulled through a pair of nip rollers which can be adjusted to give the correct resin to glass ratio. The treated cloth is then drawn up through a heated tower during which time volatile solvents are flashed off and the partial polymerisation to B-stage occurs. The finished prepreg is cooled and is either rolled onto cores at the end of the treater or is panellised directly off the treater.

The critical areas of prepreg manufacture are:

- the thickness of the wet resin, set by the nip rollers
- the amount of polymerisation, set by the heat and speed of the treater
- the characteristics of the resin, determined by the resin blend

Any glass cloth can be treated, but four main styles are in use today – 1080, 2116, 2113 and 7628. 2125, whilst obsolescent, is also still seen. The thread counts, thickness and weight of the glass cloth are outlined in Table 1.

glass style	**ends** (per 5cm)	**cloth thickness** (mm)	**weight** (gsm[1])
1080	118 x 93	0.0584	49.16
2113	118 x 110	0.0711	80.7
2116	118 x 114	0.0089	109.18
2125	79 x 77	0.0991	87.82
7628	83 x 63	0.1778	203.43

Table 1: Thread counts, thickness and weight of common glass cloth materials

Prepregs for multilayer manufacture are usually chosen for their pressed thickness, but there are other important characteristics which must be considered, such as resin content, melt viscosity and gel time. Table 2 gives some typical values for the common prepreg styles.

style	**weight** (gsm)	**MMV** (Pa·s)	**gel** (s)	**resin flow** (%)	**resin content** (%)	**PPT** (mm)
1080	125	70	150	37	62	0.077
2113	173	70	150	28	55	0.099
2125	210	70	150	24	50	0.119
2116	196	70	150	28	55	0.113
7628	364	70	150	22	44	0.195

Table 2: Typical characteristics of common glass cloth materials

[1] gsm = grams per square metre. Typical paper for your printer will be in the range 80gsm–100gsm; card is usually 160gsm.

What do the figures[2] mean?

Resin content is the %age of resin by weight, this figure is important because it defines the amount of resin available for encapsulation and also determines the finished board thickness.

Gel time is a test value that gives an indication of how long the resin takes to 'gel' or start to solidify. The longer the gel time, the longer the resin is able to flow.

Resin flow is determined by weighing a set number of plies of 4 in. squares of prepreg, bonding them at a set pressure and time, cutting a disc of diameter 3.192 in. from the centre of the specimen, weighing it and calculating the % difference in weight. Since resin flow is purely a test value and doesn't necessarily indicate how a prepreg will behave in the press it is rarely used to define prepreg nowadays.

MMV = Minimum Melt Viscosity is probably the most important value. It is a measure of how 'runny' the prepreg is, and therefore of how easily air is expelled from the package.

PPT = Pressed Ply Thickness is the average thickness of plies of bonded prepreg.

Using the above information it is possible to decide which prepreg to use for which application.

1080

1080 has the highest resin content, the finest weave and has the lowest press ply thickness of the prepregs we are considering. It is therefore used in high layer count multilayers where the finished board thickness excludes the use of thicker prepregs. 1080 is usually the prepreg of choice where encapsulation of thick copper layers is required.

In general, 1080 next to the surface copper foil will give a smoother finish than standard 7628 prepreg, which has a coarse weave and a resin content of 44%. However, if too many plies of 1080 are used, this can lead to excessive flow.

2113

2113 is the next in terms of thickness, it has less flow and less resin content than 1080. 2113 is a more open weave. It tends to be less stable than the equivalent thickness prepregs because although the number of ends per 5 cm is almost equal in the warp and weft the thickness of the strands in the weft is twice that of the strands in the warp. This can lead to unpredictable movement of inner layers during bonding.

[2] If you have problems with converting some of the units, such as Pa·s, you may like to download the free converter at http://joshmadison.com/software/convert/.

2125

2125 is another prepreg which has a very uneven weave in that the strand size in the weft is almost half that of the warp, also the size of the filaments which go to make up the yarn is less in the warp direction , the thread count is also low and this gives rise to a very open-weave ‘runny’ prepreg.

2125 tends to give poor results for inner layer movement during bonding. This may be due to the fact that the dominant weave is in the warp, and it is the warp direction which is under tension during both weaving and treating. This built-up tension is released when the resin melts, allowing the prepreg to shrink in the warp, and there is little to restrain the movement because the weft is not strong.

2116

2116 is a very even prepreg both in terms of the thread count and the strand size, and the warp and weft are almost identical in terms of thread count, filament diameter and strand size.

2116 is a close-weave prepreg that gives excellent results for inner layer movement. Where finished board thickness permits, 2116 should be the prepreg of choice.

7628

7628 prepreg is the workhorse of the prepreg range. It is used in manufacturing rigid laminate and used extensively for 4-layer and for some 6-layer work, although its thickness usually precludes it from being used on higher layer counts. It is a stable prepreg and an excellent ‘filler’ to build up thickness. One consideration when using 7628 may be the surface finish – it may be necessary on some ‘fine-line’ work to face-off 7628 with a finer weave, although it is possible that a finer weave such as 1080 may actually nestle down in the 7628 cloth and *reinforce* the surface finish of 7628.

High resin prepregs

Control of manufacturing parameters such as melt viscosity now means that most of the above prepreg styles are also available with higher resin contents. This allows the use of fewer plies of prepreg in a multilayer build. For instance, a 4-layer can be fabricated with a 1.0mm core and just one ply of prepreg each side of the core.

Table 3 gives approximate pressed ply thickness for high resin prepregs:

prepreg style	1080	2125	2116	7628
thickness	0.105 mm	0.168 mm	0.145 mm	0.213 mm

Table 3: Approximate pressed ply thickness for high resin prepreg

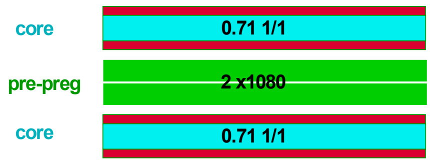
2 Multilayer builds

Leaving aside the above considerations, the choice of prepreg for a particular multilayer usually comes down to either thickness or cost. However, there are some basic rules which, if followed, will go some way to reducing problems.

- To help avoid bow and twist in a finished board, the build should always be symmetrical about the centreline, and all copper layers should be balanced. Symmetrical builds may not eliminate bow and twist because there are so many other causes, but unsymmetrical builds will definitely cause bow and twist that cannot be removed.
- Wherever possible the thickest cores allowed in the overall board thickness should be used.
- Unless high resin prepregs are used, it is best to have two layers of prepreg between cores.
- In order to ensure that the copper is fully encapsulated, the prepreg thickness should in general be twice the copper thickness being encapsulated.
- In general, the warp should be in the same direction for all prepreg and cores. However, there is an exception to this rule: a package of prepreg and core can be cross-plied, on condition that the forces in each direction can be equalised through the package.
  [This is usually found by trial and error and is not a widely used method because the consequences of getting it wrong are bowed boards which will never be flattened]

4-layer

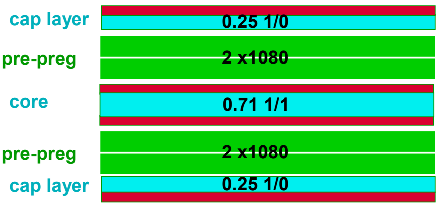
Originally 4-layer boards were constructed simply by bonding two double-sided laminates together. This method however is prone to bow and twist and, while the laminate costs are relatively cheap, processing costs are expensive and a tooling system is required for good registration at bonding.



4-layer two-piece construction

Cost factor 0.75

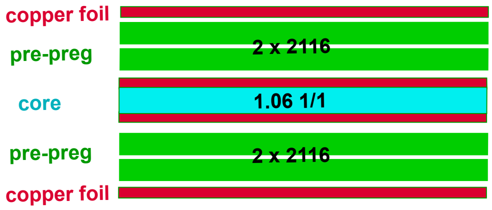
A natural follow on to this was the use of 'cap layers' where a central core of laminate was used for the two inner layers and a single sided laminate was bonded each side of this to form the outer layers. The laminate costs of this construction are higher than the double-sided construction but the processing costs are less, and the need for tooling pins is reduced.



4-layer cap construction

Cost factor 1.0

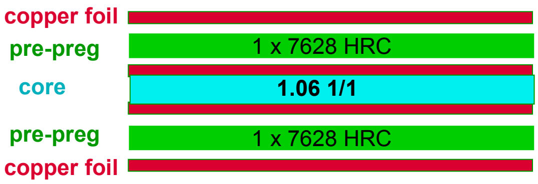
The next stage in the evolution of 4-layer manufacture was to do away with the resin on the capping layers and to use copper foil. This meant that the core could be thicker, giving less possibility of bow and twist, and also resulted in a reduction in material cost.



4-layer foil construction

Cost factor 0.66

A further reduction in cost can be achieved by using a single ply of high resin content prepreg each side of the core. This will typically give a material cost reduction of more than 50% over the capping layer build, and a reduction of almost 20% over a typical build using two layers of prepreg on each side of the core.

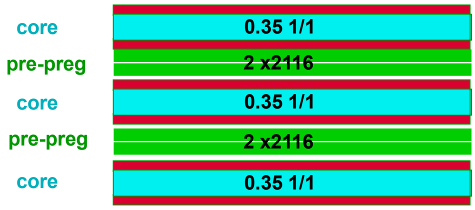


4-layer single-ply construction

Cost factor 0.55

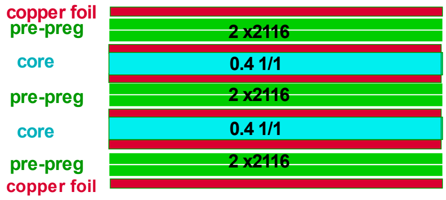
6-layer and above

The information on construction of 4-layers also holds true for 6-layer and above, a selection of possible builds for a 1.6 mm finished thickness and typical pricing is included for interest. The cost factors are for each layer type and are typical material costs only.



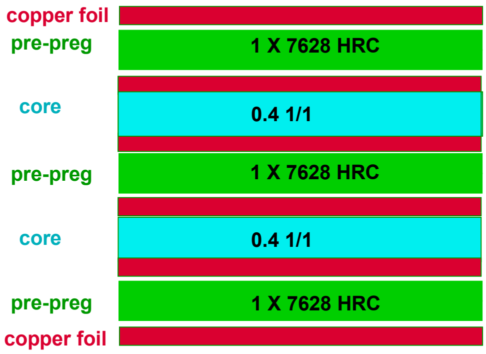
6-layer double-sided construction

Cost factor 1.0



6-layer foil construction

Cost factor 0.95



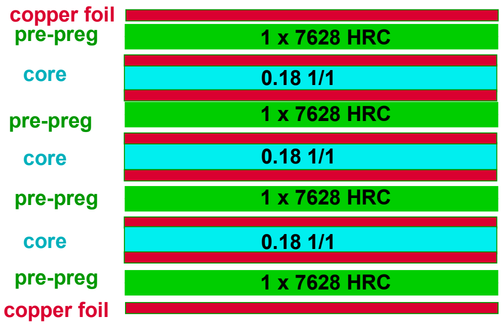
6-layer single-ply construction

Cost factor 0.77

8-layer

8-layer foil construction

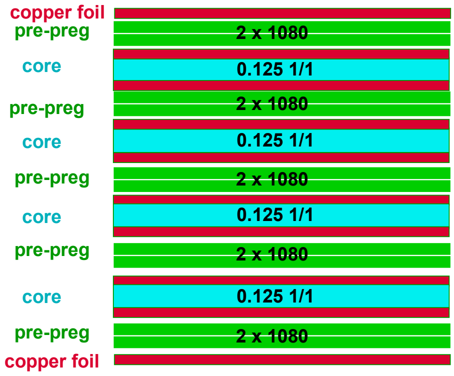
Cost factor 1.0



8-layer single-ply construction

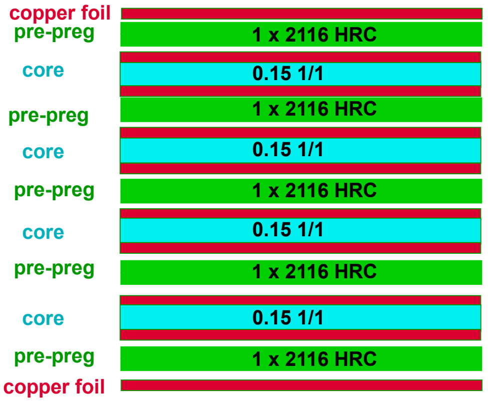
Cost factor 0.83

10-layer



10-layer foil construction

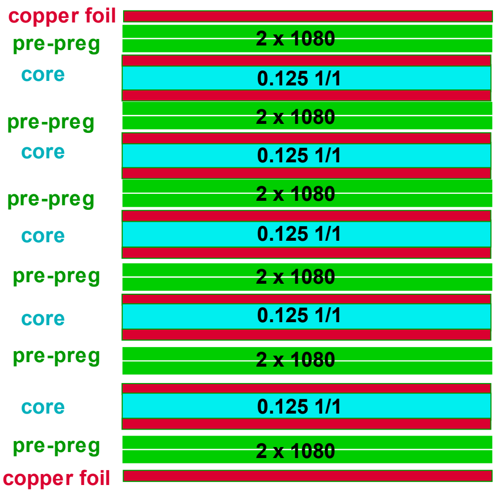
Cost factor 1.0



10-layer single-ply construction

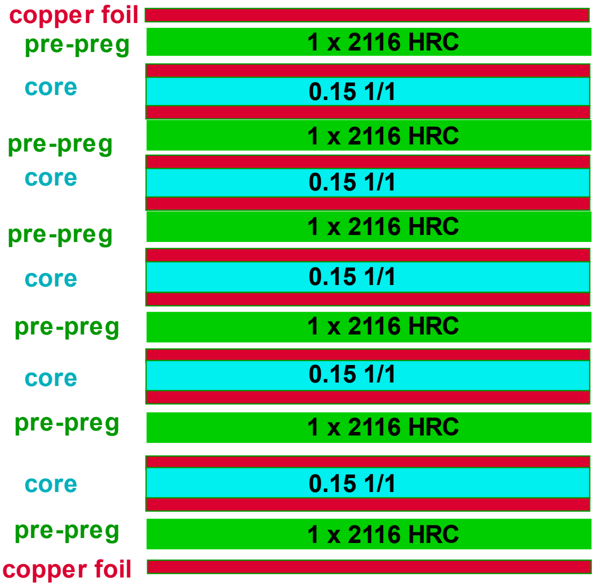
Cost factor 0.85

12-layer



12-layer foil construction

Cost factor 1.0



12-layer single ply construction

Cost factor 0.84

3 Registration

You've decided the construction of the multilayer, and chosen the best prepregs for the job. Now you have to print and etch the inner layers. This is where registration becomes an issue. In order to make sure the board functions as required, all the inner layers must be registered to themselves and to the outer layers.

There are a number of ways of doing this: to register the circuits on each side of an inner layer core the artworks are registered to themselves and tooling holes punched in the film. Corresponding tooling holes are punched or drilled in the core laminate and the artwork is pinned to the core, which has been coated with a photosensitive resist, and exposed. Tooling holes used for printing are also sometimes used for bonding.

Pinning the artworks and core for exposure is probably the most accurate method, but it isn't the only method. For four layers that don't have particularly tight features, it is possible to use the 'book method' of printing. In this method, targets (usually three) are added to the artworks to aid registration. The artworks are registered to themselves and then stuck along one edge so that they open like a book. The core can then be inserted into the book and printed.

Four-layer boards do not need to have tooling holes in order to register the layers, and so they can be 'free bonded' without the use of pins. The outers are usually registered to the inners by drilling through targets that are pre-printed on the inner layers. The targets can be found by trepanning down with a flat ended milling tool in the approximate area of the target until the right place is hit. However, that can be time consuming and inaccurate. The easiest way to find the target is to put a high temperature paper or polyimide self adhesive disc over the target before bonding, when the position of the target can be seen clearly.

For multilayers of six layers and above, it is necessary to register the inner core to themselves this is carried out by one of three methods – (a) eyelets, (b) pinned tooling or (c) welding the inner layers together prior to bonding. For all three methods, tooling holes need to be punched or drilled in the inner layers. Methods (a) and (b) usually have three or four holes in the inner, and the number and positioning of the holes can have an effect on the finished registration. Method (c) only requires two holes to register prior to welding the inners, and extra holes don't necessarily improve the registration.

Eyelets

Eyelets or rivets can be used successfully to register high layer counts and it is possible to manufacture 14 layers with good registration. To some manufacturers, one advantage of eyelets is the fact that the panel size can be altered to suit the board size and standard panels are not required.

In order to use eyelets, targets are added to the inner layer artwork and holes are punched or drilled through these targets in the cores after etch. Usually two holes per side are a minimum requirement for best results. Corresponding holes are punched or drilled in the prepreg and the stack is laid-up on a jig using some of the tooling holes, while eyelets are inserted in the other holes. The stack is then riveted together, using either a hand or foot press. Once the stack is held firmly, the rest of the eyelets can be inserted.

The choice of eyelet shape and size is important for registration of the finished product. The diameter must be correct for the size of tooling holes, and there should be no variation in eyelet diameter. If there is too much clearance between the hole and the eyelet, this will allow the core to move once the prepreg is molten.

The design of the top and bottom flange of the eyelet, as well as the thickness of the barrel, are important characteristics in choosing the right eyelet. This is because, when the eyelet is under pressure in the bonding cycle, it should deform in such a way that the cores are held evenly, and the barrel of the eyelet should not deform inwards and allow the cores to move.

The eyelet press should be in good condition to ensure consistent results. Any wear or damage to the pin or the anvil can lead to deformed eyelets and poor registration.

Pinned tooling

This is probably the most widely used tooling system,. Proprietary systems can be purchased which include not only post etch punches for cores but also X-ray systems which optimise drilling of tooling holes for the outer-layer drill and print operation.

All pinned tooling systems require tooling plates, tooled separator plates and standard panel. sizes.

Pinned tooling systems can be split into two types, edge systems and opposed slot tooling.

> In **edge** systems, tooling holes are used at one edge of a panel only. The disadvantage here is that registration may be fine at the pinned edge, where the laminate is held securely, but prepreg flow and laminate movement will increase away from the pinned edge so that at the furthest edge the registration will be worse. The larger the panel size, the more difficult it is to obtain good registration with this system.
>
> **Opposed slot** tooling systems usually have two or four tooling holes at opposite edges of the panel. The tooling holes are usually slotted to allow for laminate expansion during bonding, reducing the stress placed on the inner cores. Having opposed slots also means that movement at the centre of the panels is zero and total inner layer movement is halved at each edge of the panel.

The stack height that may be bonded is limited by the height of pins, which in turn may be limited by the thickness of the press plates. It is important that, when the prepreg resin is molten and the stack is being pressed, the pins are not pushed through the press plates and into the platens.

A major advantage of the pinned system is the fact that consistent results are achieved, which allows for accurate scaling of inner layer artwork.

Disadvantages of the pinned systems are the initial high cost. There may also be some 'bleed through' around the pins, which may get onto the surface of the board. The pins, tooling plates and any steel separator plates need to be regularly cleaned of resin.

Welding of inner layers

Welding of inner layers is a method that is gaining approval from high layer count manufacturers because of the accuracy that can be achieved.

In this method accurate registration is achieved by drilling or punching holes in two pre-registered targets in the same way as the eyelet method. The inner layer cores and prepreg are laid up on two pins on the bed of the spot welding machine. Whilst the package is held in register on the pins, a clamping head is lowered, and heating heads are applied to pre-set points around the panel edges. The heads are rapidly heated and this cures the prepreg in the area of the heads. The resulting cured prepreg studs now hold the package in register and the package can be lifted off the welding machine and transferred to the press.

The main advantage of this method is that once the package has been spot-welded it can be free-bonded in the same way as a 4-layer without pins. Other advantages are fast lay-up and accurate registration of high layer count multilayers.

A disadvantage is the cost of the equipment, although the cost is not as much as a complete pinned system.

A final design comment

Whichever tooling system is used the golden rule is 'There must always be copper around the tooling holes.' This reduces distortion of the inner layers around the tooling holes and improves registration of the bonded panel.

4 Multilayer presses

An essential piece of equipment for a multilayer manufacturer, and probably the only new piece of equipment required for a double-sided shop converting to multilayer, is the press. In its basic form the press is what melts and squashes the prepreg so that all the layers stick together. Only it's not quite that simple!

During the bonding process we expect the press to expel all the air from the package, to stick the prepreg and laminate together, to give a close tolerance on finished board thickness, to fully cure prepreg to give the maximum Tg value, not to cause undue laminate movement, not to induce undue stresses, and to produce flat panels. All done by heat and pressure and, on most occasions, a little vacuum.

To understand a little about how multilayers are laminated, let's first look at press types.

Presses can be divided into two categories: those that achieve pressure on the panel stack by hydraulic means, and those that use a heated gas and a vacuum (known as an 'autoclave'). The autoclave press has advantages over the hydraulic type, as well as a few disadvantages. However, there are far more hydraulic presses in operation in multilayer shops, so the following discussion will be limited to hydraulic presses.

The majority of hydraulic presses in operation today have a bottom platen that is driven upwards by a ram against a fixed top platen, with 'floating' platens in between. One floating platen gives a two-daylight (openings) press, two floating platens give three daylights, and so on.

Hydraulic presses can be further subdivided depending on the heating medium and the method of cooling. Heating may be carried out by electricity, steam, high-pressure water or hot oil; cooling is carried out either in the same platens that were used for heating, or in separate platens ('transfer press'). Electric and steam presses are usually cooled by water; oil heated presses are usually cooled by oil. An electric hot transfer press therefore is heated by electricity and has a separate cooling press cooled by water.

Most presses made in the last 15 years are vacuum-assisted, in that the platen area is enclosed in a vacuum chamber. This helps to remove air from the package and allows lower bonding pressures to be used, which can reduce laminate movement.

Heating

Whichever method of heating is used the same basic rules hold true: the temperature difference across a platen and between platens should be less than 2°C, heat input to the platens should be even and equal across all platens. Unequal heat input can lead to air entrapment, delamination and warpage. Temperature control needs to be equal across all platens.

Steam heated

The platens of steam-heated presses have internal conduits drilled in them through which the steam and cooling water flow. These are made by drilling holes in the platen and using blanking plugs to divert the flow of steam so that the platen is heated evenly. There are usually separate conduits for the steam and water.

An advantage of the steam-heated press is that a fast heat up rate is possible.

One disadvantage is that of possible oxidation and disintegration of blanking plugs in the conduits, the remains of which can then block the flow of steam to other areas, leading to uneven heating. If cooling is carried out in the same press, then it is usually necessary to alternately pass cooling water for a limited time followed by a purge of air, this has two functions, firstly it reduces the thermal shock to the package and secondly it prevents air locks.

Cooling water may be taken straight from the mains, but this gives a great heat shock to the bonded panels. It is best to use a closed-loop system, where the water is passed through a heat exchanger, or the water heated initially by some other means. The cooling may be more even using this method, but may also take longer.

It is important that the steam channels are kept clear to ensure even heating. It is equally important that the water flow is even through all the channels. One major cause of blockages is build-up of lime scale, especially in hard water areas. For this reason it is a good idea to use a water softener, or periodically clear the pipes and platen conduits of lime scale.

A good way to check that the cooling flow is even from one platen to another is to attach a thermocouple to the cooling pipes going from each platen It is then possible to monitor the cooling water temperature from each platen and act if there is an imbalance in any of the temperatures.

Electrically heated

Electrically heated presses have an advantage over steam-heated presses in that higher temperatures are achievable which allows the bonding of BT, polyimide and PTFE laminates

There are two main methods of electrically heating the platens: cartridge elements, or oil filled platens. Electrically heated presses are usually used as hot-start presses due to the cost of continually heating from cold.

The oil in oil filled platens is heated by cartridge type heater elements, and the temperature control tends to be closer than with cartridge heaters alone. Platens are constructed in such a manner that there is no possibility of a leak of hot oil.

The most common method of electric heating is to use cartridge elements buried inside the platens. It is important to ensure that there are enough elements to give even heat distribution over the whole platen.

No matter which method is used for heating, the most important consideration is temperature control.

On most electrically heated presses, the thermocouple sensors which indicate platen temperature are placed in the centre of the platen and therefore only indicate the temperature of one heating element. Should an adjacent element not be working, it might not be noticed.

If not already fitted, it is worthwhile installing meters to show how much power each heating element is pulling. It is then easy to see if any elements are not functioning properly.

The hysteresis of the controller should be set so that the platens do not cool down too much before the controller switches on the power.

Some points to check in the event of problems with heating are:

- Are all elements working correctly all the time?
- On a hot start press, is the heater response fast enough when the package is inserted?
- Do all the heaters respond the same when the package is inserted?
- Is the control set point set properly?
- Is the temperature control tolerance around the set point set correctly?

Don't assume that the temperature on the chart is the temperature of all parts of the stack or even of all parts of the platen.

Hot transfer

In the hot transfer press, the cured package is transferred from the hot press to a cooling press after the cure cycle. For best results the stack should be cooled below the glass transition in the hot press before the transfer, and the cooling press should also be heated to approximately 80ºC to reduce the thermal shock.

Benefits of hot transfer presses are a saving in energy and a saving in time, because the hot press is used only for initial bonding and curing, not for cooling.

Vacuum assist

Most modern hydraulic presses are fitted with a vacuum to assist in the removal of air from the package. A vacuum chamber is built around the platens: once the stacks are loaded into the platens, the platen area is sealed, usually by closing a sliding door, and the vacuum started. If the press is not fitted with a vacuum it is still possible to carry out vacuum bonding by using either a vacuum frame or vacuum bags.

When a vacuum is used it is important that it is used right at the start of the cycle.

The main advantage of using vacuum assist is that a lower bonding pressure can be used, leading to less stresses in the finished board. Finished boards also have better resistance to delamination and measling.

Pressure

The following table of pressures to be applied to any particular panel area is given as a guide, the actual pressure used will depend on such things as number of layers, resin content of prepreg, thickness of inner layer copper etc.

panel size	panel area	applied pressure
12" x 12"	144	250psi (17 bar)
18" x 12"	216	275psi (18.7 bar)
18" x 16"	288	300psi (20.4 bar)
18" x 20"	360	325psi (22 bar)
24" x 24"	576	400psi (27.2 bar)

Table 4: Guideline pressures for different panel sizes

It is important to calculate and set the required pressure correctly on the press.

On some presses the indicated pressure is the hydraulic pressure on the ram, in this case the pressure is calculated from:

$$\text{pressure} = \frac{\text{pressure to be applied to the stack} \times \text{area to be bonded}}{\text{cross-section area of ram}}$$

For example:

$$\text{area to be bonded} = 24" \times 24" = 576\,\text{sq. ins}$$

$$\text{pressure required} = 400\,\text{psi}$$

$$\text{diameter of ram} = 12"$$

$$\text{cross-section of ram} = \pi r^2 = 3.1416 \times 6 \times 6 = 113.1\,\text{sq. ins}$$

$$\text{pressure} = \frac{400 \times 576}{113.1} = 2{,}037\,\text{psi}$$

On some older presses, the indicated pressure is the load on the press, in which case the pressure is calculated from:

$$\text{pressure} = \text{pressure to be applied to the stack} \times \text{area to be bonded}$$

$$= 400 \times 576 = 230{,}400 \text{ psi}$$

The platens need to be parallel, so that pressure is evenly distributed across the whole stack to be bonded, otherwise the thickness of the bonded boards will vary across a board. Platens may become bowed and dished in the centre due to small area panels always being bonded This is especially true if the press has a ram at each corner of the platen rather than a central one. The result of this is a board which is thicker in the centre than the outside, and there may also be entrapped air in the centre of the panel. Platens may also not close parallel due to the guides on the outside of the platens sticking on the runners. This will lead to wedge shaped boards, or in the case of a stack of unpinned boards, to panels being forced out of the press.

A quick check to see if the platens are closing parallel can be carried out by closing the press with lead shot or an equivalent at each corner and in the centre of the platens. Once the press is opened, the lead shot can be removed and the thickness checked with a micrometer.

The parallelism test can also be carried out by bonding two or three sheets of a thin prepreg such as 1080, which are cut to just under the platen size, with oversize release film. The thickness of the resultant cured prepreg can then be measured at various points over the platens. This will give a more accurate picture of the state of the platens.

The usual quoted figure for parallelism is 'better than ±0.05mm over the whole platen': variations within this are usually taken up by the thermal lagging (kraft paper) in the stack.

Of course it's no use having parallel platens if the press plates or separators are not parallel. It is therefore important to check press plates and separators on a regular basis.

5 The press cycle

The following is based on FR4 laminate and prepreg being bonded, and a hot start cycle.

Probably the most misunderstood process in printed circuit manufacture is the press cycle used for bonding multilayers. It doesn't matter if you have the best laminate and prepreg in the world, the most up-to-date equipment, the best registration system ever invented – 'if you haven't got the press cycle right you ain't gonna make good multilayers'.

The term 'press cycle' covers the relationship of temperature, time and pressure. In the press cycle the objective is to remove air and volatiles, and stick the layers together to give a flat void-free board of the correct thickness.

The press cycle can be considered to be made up of three distinct parts (Figure 1): 1 Prepreg melt and flow; 2 Resin cure and 3 Cooling.

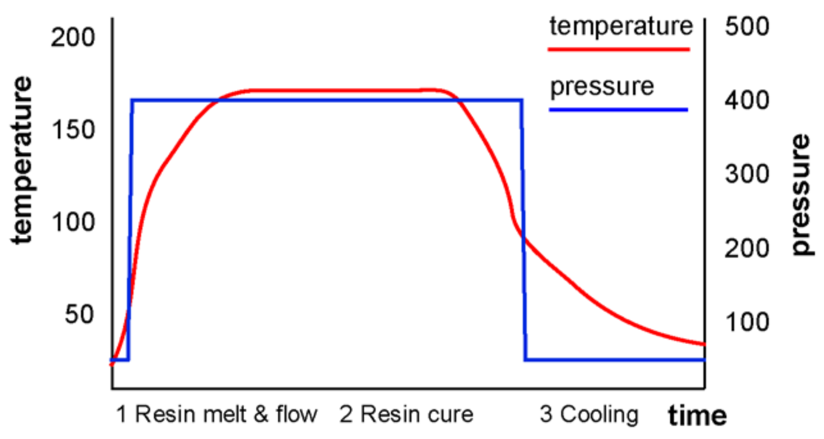


Figure 1: Typical press cycle

In the first section, as the press is heated, the resin in the prepreg melts and pressure is applied, to make the prepreg flow and encapsulate circuit features. In the second section the press is held at constant temperature and pressure and the now-solid resin hardens, and in the third section the fully cured resin cools under controlled conditions.

Each part of the press cycle is has an influence on the physical properties of the finished board.

1 Resin melt and flow

During the first stage of the cycle, the built-up multilayer stack is placed between the pre-heated platens of the press, the press is closed and the multilayer stack heats up. The resin melts at 60ºC and full pressure should be applied before the resin reaches this temp. The heat up rate as measured in the multilayer stack should be between 5ºC to 8ºC per minute.

The heat up rate is controlled by using a heat lagging material such as kraft paper. If it is chosen properly, the kraft paper evens out the heat flow into the stack so that there is as small a difference as possible in the heat rise between the boards in the centre of the stack and those on the outside,. For best results, kraft should be used once only. The weight of kraft paper commonly used is either 215 gsm[3] or 160 gsm. However, weight is not the sole criterion: when choosing kraft, the moisture content and density are also important. A moisture content of 3-5% and a density of around 540 g/cc give best results. With hot start presses a total weight of between 860 gsm and 1290 gsm each side of a stack is recommended.

The press should be loaded and closed as quickly as possible, in order to avoid the uneven heating that will happen when only one side of a stack is in contact with a heated platen. [Some presses have spring loaded 'stand-offs' built into the platens to avoid this happening]

[3] This area density unit stands for '**g**rams per **s**quare **m**etre'. The paper you buy for your printer is typically 80gsm, and card double that.

As the resin melts, it becomes less viscous ('more runny') until it reaches its minimum melt viscosity. This is the time and temperature at which it is at its most 'runny' and therefore it will flow and encapsulate the circuitry. The resin will become more viscous as it heats up after it has attained its minimum melt viscosity, until at about 140ºC it gels or sets. It follows that the important time for resin flow, registration, evacuation of air and other volatiles, and encapsulation is between 60ºC and 140ºC.

If the heat-up rate is too fast, there will be too much flow, resulting in thin boards and poor inner layer registration. If the heat-up rate is too slow, then the resin will start to cure before it reaches its minimum melt viscosity, resulting in thick boards, air entrapment and delamination.

Uneven heating across a platen will lead to the resin achieving its minimum melt viscosity at different times so that some areas will be at minimum viscosity while others may not have melted, this can lead to air entrapment and bowed boards.

A lot of information can be gained from observation of the resin 'flash' around the bonded board. The flash should be even all round the board. If it isn't this is an indication that the flow is not even, this may be due to either uneven heating across the platens, or the platens not being parallel. Too much flash indicates a fast heat rise; too little flash indicates a slow heat rise. (The optimum amount of flash depends on the resin system being used and is best determined from experience). A 'frothy' flash indicates moisture in the prepreg and may be accompanied by excess flow.

2 Resin cure

Once the resin has flowed and gelled, it requires continued heat and pressure to fully cure. The actual time and temperature required will depend on the resin, typical requirements for FR4 being 40 minutes at 160 ºC or 30 minutes at 170ºC. If the time and temperature are not sufficient to achieve full cure, then the glass transition temperature will be lower than expected. This can lead to excess laminate movement in the X, Y and Z directions the next time the board is heated to near the Tg, which will probably be at solder mask cure.

The degree of cure can be determined by thermal analysis methods by laminate manufacturers.

3 Cool down

The cool down may seem a simple operation but, as with the other parts of the press cycle, if the cool down isn't correct then there will be problems with the finished boards.

With hot start presses the stack is transferred to a separate press for cooling. The cool down rate should be similar to the heat up rate, at 5ºC to 8C per minute. Cooling should be even through the stack. If the outer boards in a stack cool too fast, those boards will be bowed; if the cooling press is not heated, the resultant thermal shock on the outer boards may cause bow.

It is acceptable to release the pressure once the cure has finished although some recommend keeping the pressure on until the stack has cooled below the Tg.

6 Multilayer lay-up

Figure 2 shows a lay-up for bonding 6-layer panels of which, for clarity, the outer panels only are shown.

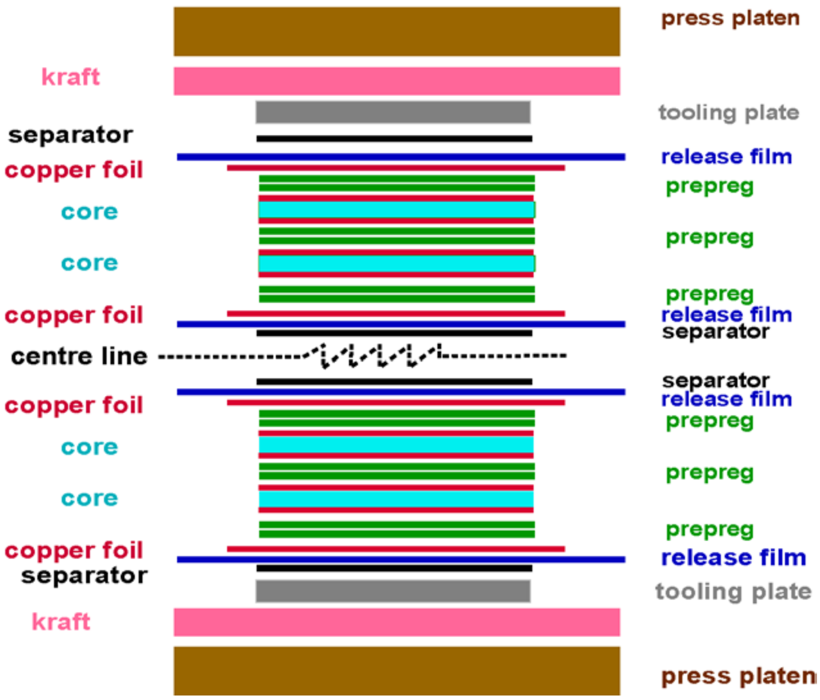


Figure 2: Typical multilayer build-up

Kraft paper

Kraft paper is used to regulate the heat input to the stack. Placing it between the platen and the press plate gives a slightly slower (approx 2°C/min) heat-up rate than if it were on the inside of the press plate. This can be advantageous when using a hot start press with platens set at 180ºC. One disadvantage of putting the kraft on the outside is the difficulty in handling, unless a tray is used. Putting the kraft on the inside means that the kraft must be tooled and an extra piece may be needed.

Release film

Release film is there mainly to contain the resin flow and stop the stack sticking together, and although this can be achieved by using oversize copper foil. release film does have other uses. It reduces the incidence of copper foil creases on larger multilayers due to thermal expansion differences between copper, separator plates and laminate. It does this by acting as a 'slippy' layer allowing the copper to slide rather than wrinkle.

It is also a good idea to use release film between the outer tooling plates and aluminium separators because of the difference in CTE.

Separator plates

Separator plates have three functions, firstly, they separate panels in a stack and give a smooth flat surface for the copper foil, thereby eliminating telegraphing of circuit features or defects from one board to the next.

Secondly, they help to even out pressure differentials due to repeated circuit feature, and thirdly they help to even out temperature differences due to circuit designs, for example, uneven copper distribution across a panel.

Separator plates are normally made from either steel or aluminium. Steel separators are usually about 1.6mm thick and have a smooth surface finish. Aluminium separators are either 0.3mm or 0.4mm thick.

There are numerous grades of steel and the one chosen for separators should be a hard grade with little or no residual stresses induced during manufacture. The surface should be hard enough to resist scratches.

Hardness values quoted for best results are > 40 Rockwell C. Thermal conductivity is of the order of 30W/m/K.

Grades of steel in common use are:-

AISI 3104 – a relatively cheap grade, this is soft and can give more telegraphing than other grades.

AISI 301 – has a harder skin and resists scratches, but the centre is softer, and this can lead to stresses being induced.

AISI 420 – a hard alloy (44–48 Rockwell C) whose CTE matches that of copper-clad laminate. This is probably the best grade for separator plates.

Steel separators are expensive initially and require any resin in them to be cleaned off.

Aluminium separators are inexpensive initially, they are used once or twice and then discarded, or used as drill entry, depending on their condition. They are available with or without a release coating , the release coating allows easier separation of the stack and can also reduce the incidence of copper foil creasing.

As with steel separators there are various grades available, and the grade chosen should be hard enough to resist telegraphing and should not wrinkle

The aluminium separators used are 3000 series aluminium/manganese/magnesium or aluminium/manganese/copper alloys. These alloys contain approximately 98.5% aluminium. The purer 1000 series, which contain 99.5% aluminium, tend to telegraph too easily and can distort during bonding.

Whichever type separators are used, it is important that they are not be mixed in a stack as this can lead to bowed boards.

Tooling plates

Tooling plates or press plates (sometimes known as caul plates) hold the bushes for the tooling pins if the pinned system is used. They even out the pressure and temperature entering the stack. They can be tooled for different panel sizes but the tool plate should not be too large for the panel being bonded. The thickness (which is usually 12mm) should be enough to accommodate the length of pin being used so that the press platens are not damaged by the pins on bonding. Grades of steel used are AISI 420 or AISI 4140.

7 Controlled impedance

> The topic of controlled impedance is one whose relevance you will not fully understand until you have studied our *Signal Integrity* module. Unfortunately, that is scheduled for later in the course. However, we feel that we must not avoid mentioning at this point a subject which has a major impact on manufacturing, especially as lamination and build-up offer the most appropriate context for this.
>
> The text in this section was written from the perspective of a manufacturer of controlled impedance boards, and is based on direct experience, rather than written from a design viewpoint.

As the need for faster computing speeds increases, this puts demands on the interconnections between components. In other words, the signal speed in the interconnection (track) needs to match the speed in the component. The circuit board must therefore be designed and made to exacting tolerances to ensure the signal speed is correct. We often use the term 'transmission line' instead of track to emphasize the high-frequency nature of a connection and the need for tight control in design and manufacture.

Impedance is a measure of the way a transmission line responds to the flow of a current. The factors that affect impedance in a transmission line as applied to a circuit board are the cross-sectional area (track width and track height), dielectric constant of the surrounding material (laminate; solder mask; air), separation from ground planes, and the proximity of other transmission lines.

There are many published formulae for calculating impedance. These differ depending on the source: the ones quoted in Appendix A, which originated at Motorola, have been used successfully to calculate impedance values, and have been found to correlate well with actual measured values using time domain reflectometry. They cover all five of the main track geometries, microstrip, buried microstrip, strip line, dual strip line and differential strip line.

If you would like to try other sources, impedance calculators of varying levels of sophistication can be found at:

http://www.chipcenter.com/onlinetools/signalintegrity.html
http://www.emclab.umr.edu/pcbtlc/
http://www.icd.com.au/board.html (referenced on the IPC web site)
http://www.polarinstruments.com
http://www.ultracad.com/calc.htm
http://www.zuken.com/solutions_board_interactive.asp

Or try a Google search for 'impedance calculator'! Of the calculators, probably the most sophisticated and up-to-date is that at the Polar Instruments web site: this will give good results in even complex situations. For general reading on the topic, you will find that UltraCAD's material is particularly friendly in its approach.

All the calculators estimate figures for characteristic impedance of a structure from three main parameters, the dielectric constant, dielectric spacing and track width:

The quoted **dielectric constant**[4] (ε_r) for FR4 is usually measured at a frequency of 1 MHz (much lower than operating frequencies) and is dependent on the ratio of resin to glass in the laminate. The ε_r of epoxy resin is 3.65, the ε_r of E-glass is 6.32: it follows that the ε_r of a laminate with a high glass/resin content will be higher than the ε_r of a laminate with a low glass/resin content.

The ε_r of a laminate at the top end of the thickness tolerance will be lower than a laminate at the bottom end. For example, for a 1.6mm laminate with a close tolerance of ±0.14mm according to BS EN 60249.5.2, the ε_r will be 4.66 at the top tolerance and 4.85 at the bottom tolerance. In practice, inserting a value of $\varepsilon_r = 4.7$ in the formulae in Appendix A has given good correlation between calculated and measured impedance values.

The **dielectric spacing** is usually taken as being measured from the closest part of the copper, and for this reason low profile copper is sometimes used for impedance boards. However, whilst this may give more repeatability, using low-profile copper will have little effect on the actual impedance value.

The **track width** is usually measured at the bottom of the track. In this case, because it is the cross-sectional *area* which is important, measurements should be taken at the centre of the track to give a closer approximation to the actual cross-sectional area. The track sidewall should be straight, with as little undercut and as small a foot as possible.

[4] If you can't remember what this means, go back to p.13 of *Board materials*.

Effect of variables on impedance value.

To show which variables have the most effect on the impedance value we can take a simple strip-line configuration, vary one element at a time, and calculate the resulting value.

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right]$$

ε_r	w	h	t	Z_0	Δ	
4.7	0.15 mm	0.5 mm	0.035mm (1oz)	50.18 Ω		
4.5				51.29 Ω	+1.10	±2.1%
4.9				49.15 Ω	-1.03	
±4.3%	0.175 mm			46.82 Ω	-3.36	±7.2%
	0.125 mm			54.01 Ω	+3.82	
	±16.7%	0.55 mm		52.82 Ω	+2.64	±5.5%
		0.45 mm		47.27 Ω	-2.92	
		±5%	0.025 mm	52.03 Ω	+1.85	±3.6%
			0.045 mm	48.45 Ω	-1.73	
			±28.6%			

Whichever formula and test method is used, you need to understand the effect of the design and process variables on the finished impedance. Where the track characteristics are critical, the EDR engineer should consult with the circuit designer to make sure that the designed features meet the end requirements.

8 Troubleshooting

This section is not intended as a comprehensive guide to multilayer problems, but it covers some of the common problems and their fixes. Although of most value to fabrication engineers, this sections will also give design professionals an insight into the potential problems experienced in bonding.

Problem	Cause	Cure
1 Panels pressing thin	Wrong core used	Use correct core
	Wrong prepreg used or ply missed out	Use correct prepreg
	Too much resin flow	See 3
	Too much pressure	Check applied pressure
2 Panels pressing thick	Wrong core used	Use correct core
	Wrong prepreg used or extra ply	Use correct prepreg
	Too little resin flow	See 4
	Too low pressure	Check applied pressure
3 Too little resin flow	Prepreg out of date	Check prepreg
	Low flow type prepreg used	
	Heat-up too slow	Remove some heat lagging
	Heaters not working	Check press heaters
	Stack height too high	Reduce stack height
	Initial press temp too low	Make sure press is at correct temp
4 Too much resin flow	Heat up too fast	Not enough or wrong type of heat lagging
	High moisture content in prepreg	Improve prepreg storage
	High resin content prepreg used	Change prepreg type
	Initial press temp too high	Make sure press is at correct initial temp
5 Uneven resin flow side-to-side	Platens not parallel	Check and adjust
	Some heaters not working	Check heaters
	Stack not central in press	Make sure stack is central

6 Creasing copper	Poor handling during lay-up Pressure too high during initial stages Low resin content in prepreg Expansion of separator does not match copper Tooling holes incorrect	Improve handling Use kiss pressure Use high resin content prepreg Use release film next to copper Check tooling
7 Delamination	Insufficient pressure Out of date prepreg Excessive moisture in laminate or prepreg Poor bond enhancement (oxide) treatment	Check pressure Improve storage conditions Bake cores before bonding Check oxide process
8 Poor registration	No copper around tooling holes No copper border around inner layer Tooling holes damaged Tooling pins/bushes damaged	Make sure there is copper around every tooling hole Add border to inner layers Improve tooling and handling Replace tooling pins/bushes
9 Bow and twist	Cool down too fast Cooling press too cold Uneven cooling Stack height too high Unsymmetrical build Uneven heating Mixed material separator plates	Slow cool down by increasing heat lagging or by heating cooling water Heat cooling press before transfer Check platens cool evenly Reduce stack height All builds must be symmetrical Check heaters Check heat lagging material gives consistent lagging across platen Separators must be same material throughout a stack

Always go back to basics when troubleshooting.

Never assume anything.

Check every feature of the press cycle. A lot of information can be gained by studying the prepreg flash. Is it even? Is there more flow on one side or corner? If it is uneven, then you may have an imbalance in heat up across the board (probably because of a platen heater problem), the thickness of the board will vary and you may have a warp and twist problem. Or the press plates may not be parallel.

Is the prepreg flash equal throughout the stack? If not, you have not got the lagging right or a platen may not be heating correctly. The thickness of the boards will vary through the stack and you may have a problem with bowing.

Is the prepreg flash 'frothy' or 'milky'? If so the pre preg may have been stored in a humid atmosphere and you may have air entrapment in the board.

A quick check to see if the prepreg flow is even is to lay up two sheets of prepreg on either side of a core, draw a series of concentric circles with a marker pen on the outer prepregs and bond in the usual way with foil as the outer layer. As the resin flows, so will the ink from the pen. If the heat-up and pressure are correct, then the circles will be deformed uniformly. Using this method it is possible to identify defective platens without using expensive temperature measuring equipment. Try this at different places in a stack.

By checking the temperature of the cooling water pipes at the exit of the platens, it is possible to determine if there are any blockages in the cooling channels (all pipes should be at a similar temperature).

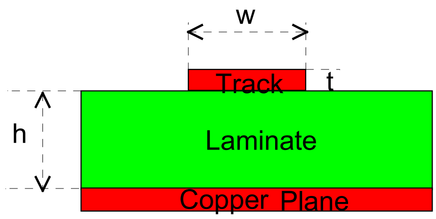
Multilayer manufacture will never be trouble-free but, by understanding the process and paying attention to detail, some of the difficulties can be removed.

Acknowledgement

The course team are very grateful to Geoff Layhe of Lamar UK Ltd for permission to use material published under the same title by Lamar Technical Service. Geoff may be contacted at glayhe@lamar-uk.co.uk, and we would encourage you to visit the company web site at www.lamar-uk.co.uk.

Appendix A: Some impedance formulae

Microstrip



One track is on the surface of a board and the corresponding ground plane is either buried in a multilayer or is on the other side of the board.

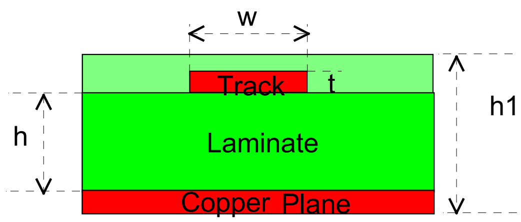
The formula for this is

$$Z_0 = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left[\frac{5.98h}{0.8w + t}\right]$$

where:

Z0	=	impedance
εr	=	Dielectric constant of laminate
w	=	track width
t	=	track thickness
h	=	dielectric separation
ln	=	natural log

Buried microstrip



The formula for this is

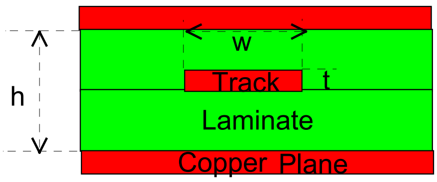
$$Z_0 = \frac{87}{\sqrt{\varepsilon_{r1} + 1.41}} \ln\left[\frac{5.98h1}{0.8w + t}\right]$$

where:

εr1	=	$\varepsilon_r(1 - e^{-\frac{1.55h1}{h}})$
Z0	=	impedance
εr	=	dielectric constant of laminate
w	=	track width
t	=	track thickness
h	=	dielectric separation
ln	=	natural log

h1 = total dielectric thickness

Strip line

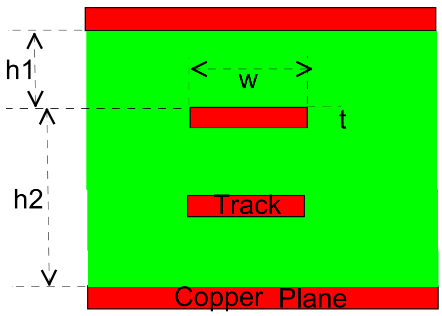


The formula for this is $$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right]$$

where:

Z0	=	impedance
εr	=	dielectric constant of laminate
w	=	track width
t	=	track thickness
h	=	dielectric separation
ln	=	natural log

Dual strip line

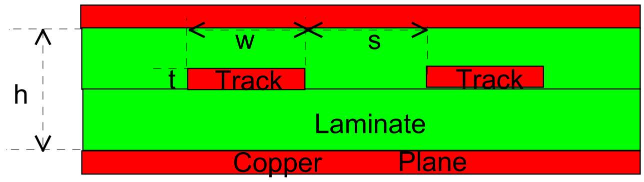


The formula for this is $$Z_0 = \frac{2 \cdot F1 \cdot F2}{(F1 + F2)}$$

where: $F1 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right]$ $F2 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right]$

Z0	=	impedance
εr	=	dielectric constant of laminate
w	=	track width
t	=	track thickness
h1	=	dielectric separation
h2	=	dielectric separation
ln	=	natural log

Differential strip line



The formula for this is $$Z_{diff} = 2 \cdot Z_0[1-(0.347e^{(2.92/h)})]$$

Where $$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right]$$

εr	=	dielectric constant of laminate
w	=	track width
t	=	track thickness
h	=	dielectric separation
ln	=	natural log
s	=	conductor spacing
e	=	a constant 2.7813