

Printed circuit boards-Basic board materials

Introduction

Under this title we are considering the main materials of which a printed circuit board is made. Whole books have been written about the choices available, but to give too much information immediately would confuse! We are therefore restricting our focus to the main laminates that you will encounter in commercial and professional electronics, two materials which share an FR- designation, in that they are Fire Retardant:

FR-4 laminates are constructed on multiple plies of epoxy-resin impregnated woven glass cloth. FR-4 is the most widely used material in the printed circuit board industry because its properties satisfy the electrical and mechanical and thermal needs of most applications, and its performance can also be adequate for high-technology requirements. FR-4 is used in aerospace, communications, computers and peripherals, industrial controls, and automotive applications. Actually translucent, FR-4 is normally thought of as green in colour, the colour coming from the solder mask on the finished board.

FR-2 laminates are composed of multiple plies of cellulose ('Kraft') paper that have been impregnated with a flame-retardant phenolic resin. FR-2 laminate is less expensive than FR-4, and the cost difference becomes even greater for the finished board, because holes and profile can be created by punching. FR-2 is typically used in applications where tight dimensional stability is not required, such as in radios, calculators, toys, and television games. FR-2 is an opaque brown in colour.

For both materials, we will be looking at a conductive foil of copper: virtually every circuit board uses this material, although there will be differences in the final surface finish.

The board consists of resin, reinforcement, copper foil, and of course a lamination process. Although broadly similar to the manufacture of multilayer boards, the production of base laminate is generally carried out by specialists, who supply board fabrication houses with process blanks. 'Rolling your own' laminate is a possibility, but one that few will consider – there are already quite enough variables in the process!

The basic process

The overall process¹ is outlined in Figure 1: whilst this is for making FR-4, the configuration of the process for making FR-2 only varies in its use of a horizontal curing oven.

1 There are some good illustrations of the materials and process involved in laminate manufacture starting at <http://www.ilnorplex.com/manufact.htm>

Figure 1: The laminate manufacturing process in outline

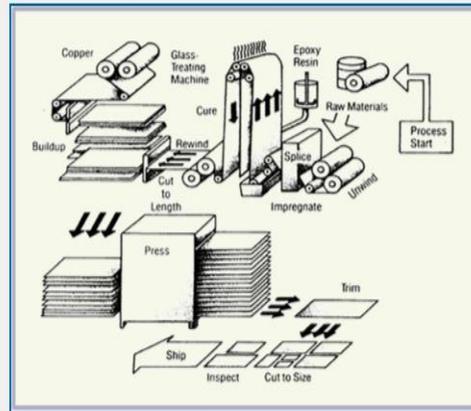
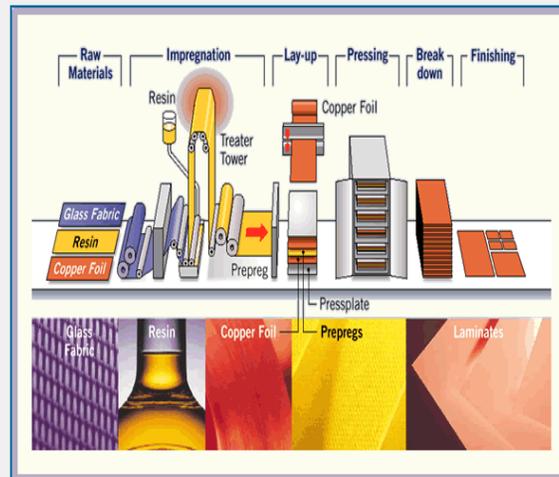


Figure 1: The laminate manufacturing process in outline

Schematic of process and materials used in laminate production



Schematic of process and materials used in laminate production

For both laminate types, the reinforcement is impregnated with 'varnish', a low-viscosity mixed resin system ready to be presented to the treater. As the materials are thermosets, some preliminary polymerisation is often produced by ageing. Important factors with varnish are:

the time that it takes to gel²

its viscosity, which must be maintained throughout the run.

2 There is a finite period of time during which the resin remains fluid enough to flow freely, after which its average molecular weight advances to the point at which we say it has 'gelled'

With FR-2, varnish is applied to the paper, on one or both sides; for FR-4, the glass cloth is dipped in varnish; for both the next stage is to evaporate the solvent, and partially cure the resin. The objective is to generate a sheet that is not tacky but is still in the B stage.

The dried impregnated fabric, which can range from very flexible to very rigid, is cut, stacked and pressed. 'Books' of laminates are pre-built with the right number of layers to give the correct final laminate thickness after pressing. Copper foil is applied to one side, and the composite is sandwiched between stainless steel press plates. As with multilayer lamination, the number of laminate books in a single press 'opening' will depend on the physical dimensions of the opening, the capacity of the hydraulic system, and the thermal profile needed. A typical cycle is 35 bar/175°C for 1 hour, but pressures can range as high as 200 bar, with temperatures to 300°C.

Punched or drilled?

Whilst most of our attention in this module is on materials such as FR-4, intended for professional applications, in fact over half of the area of laminate sold worldwide is for materials which can be punched, most of which are still paper-based. Punching allows all the holes, slots and other shapes to be produced in one or two press strokes, using a tool with multiple punches ('perforators'). The process is similar to metal stamping, using punches and matching die openings: every perforating punch must have a hole below it so that the pierced slug can pass through and be collected as waste. With printed circuit boards, however, much tighter clearance is needed between perforator and die opening in order to produce a clean hole that is free of fibres.

Again as with metal stamping, you will come across three different die types:

'Pierce' dies, which create just holes and slots

'Compound blank and pierce' dies which both pierce and blank a part in a single operation

Progressive dies, where several stages of piercing are completed by a final stage which blanks the part.

A critical factor in producing punched parts is the alignment of the perforator with the die blocks: misalignment results in punch breakage. Punch and die sets are expensive, and their detailed design and clearances depends on the exact properties of the laminate being punched.

The laminating resin

Some of the key properties of a material that will determine which laminating resin is chosen are:

operating temperature

coefficient of thermal expansion

dielectric constant

water absorption

thermal conductivity

flexibility

For the first part of this unit, we are deliberately looking at just two resins, but these are different in performance as well as chemical structure. Key differences between the two are their maximum continuous working temperature and insulation resistance.

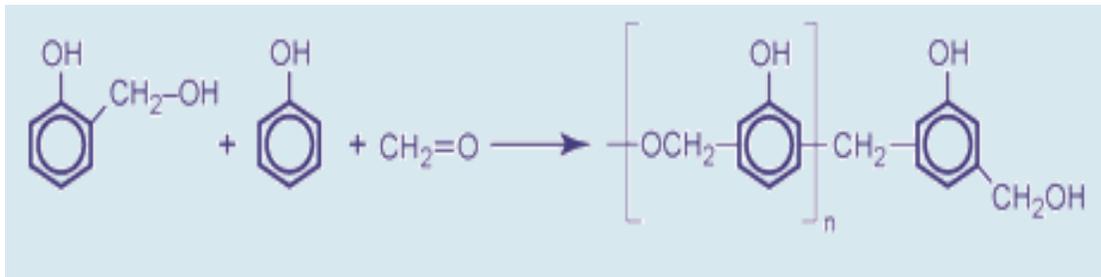
For a laminate the maximum continuous working temperature is around the value of the glass transition temperature of the impregnation resin. For FR-2, this is typically 105°C; for FR-4, in the range 130–140°C. Whilst these temperatures are not the maximum temperatures which the laminate will survive in the short-term, of these two laminates only FR-4 will withstand reflow soldering conditions for one/two cycles, and even FR-4 would degrade after repeated exposure.

Phenolics also have a low insulation resistance. Coupled with their greater water absorption and sensitivity of electrical properties to humid environments than epoxies, the use of phenolics has generally been restricted to lower-cost paper-based applications.

Phenolics

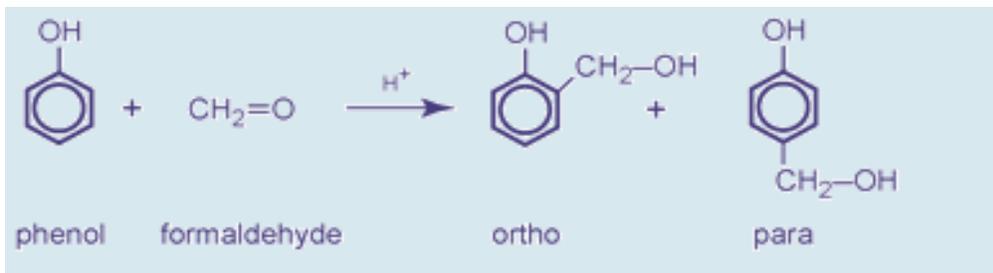
Developed by Baekeland and Thuslow in the early 1900s, the products formed by the condensation of phenols with formaldehyde were sold as Bakelite and Novolac. Phenol-formaldehyde resins (phenolics) were the first thermosets to be used for electrical laminates because they are easy to process and have good resistance to heat and chemicals.

Two types of reaction occur between phenol and formaldehyde, depending on the conditions. In the presence of a base and excess formaldehyde, the reaction is:

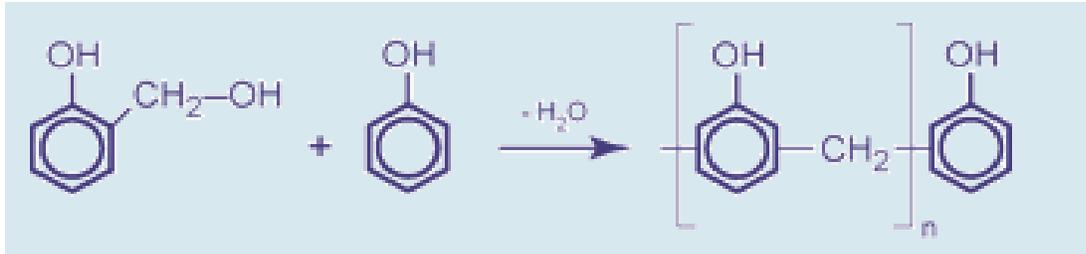


This produces a 'resole' resin, which will cross-link further by eliminating water to produce a highly cross-linked system. This is a 'one-step' phenolic.

With an acid catalyst, however, the links can form in either of two positions on the phenol group:



Since linking can occur at two different positions, branching occurs as polymerisation proceeds, represented symbolically as:



The resulting 'novolac resin' prepolymer has values of n in the range 6–12, but requires the addition of a curing agent (and thus a second stage) in order to cure fully. This 'two-step' phenolic commonly uses a 'resole' resin as a curing agent.

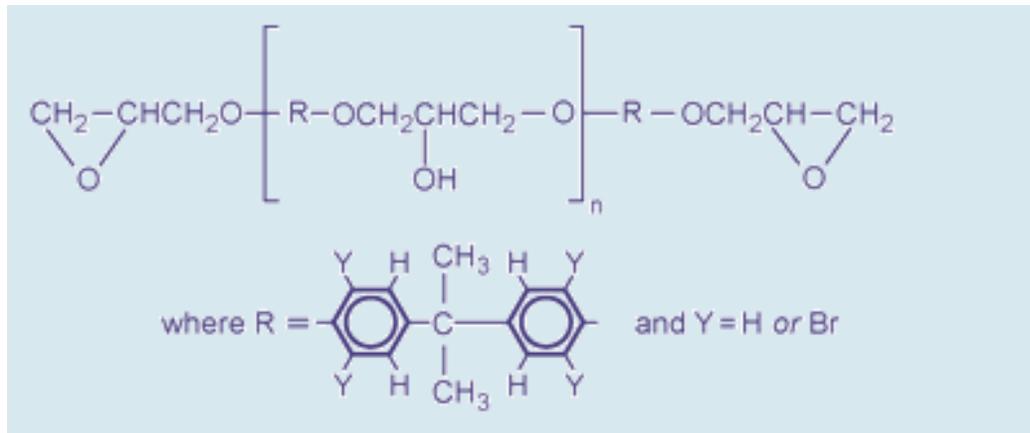
The resins used for lamination are primarily one-step resoles, though novolacs are added to improve water resistance, and other chemical changes made to reduce brittleness. Most of the resin systems used are highly plasticised, so that the laminate will punch at room temperature, or at least with a minimum amount of heating. As with any resin compound, inorganic fillers are added to improve characteristics while at the same time reducing the cost of the resin.

From this discussion you can see that there is the potential for FR-2 laminates to vary very considerably between suppliers, seeking to give the desired performance at lowest cost. Most of the suppliers will be in the Far East, as phenolic account for only a relatively small percentage of laminate volume in the USA and Europe.

Epoxies

Even more than with FR-2, there can be considerable variation in the resins used in making FR-4 laminates. Most of them are epoxies and modified epoxies, but this term covers a wide range of materials.

The simplest version shown below, the result of the reaction of epichlorohydrin with bisphenol A, is difunctional – if you don't remember what 'functionality' means then look at Polymer basics.



In order to make the resin flame retardant, a substantial proportion of tetrabromobisphenol A is incorporated.

Epoxy resins are inherently high flow materials, and are very fluid when melted. The problem is typically overcome by using a two-step or 'kiss' cycle, where the prepreg is heated and partially cured at low pressure before full pressure is applied.

The additional cost of doing this, as against a single laminating cycle, has however led to the development of products that have a high melt viscosity, often accomplished by using high molecular weight additives.

These high molecular weight epoxies are referred to as 'phenoxies', and viscosity control is achieved by appropriate choice of both the molecular weight of the additive and its concentration. Adding phenoxies degrades Tg and flammability, but improves bond strength and usually leads to a more controllable final product.

As with phenolics, inert fillers are used to modify the properties of the compounded polymer, and these are usually silane treated to provide a good bond to the resin. One property likely to require modification when resins are used to make thin laminates, is the transmission of ultraviolet light. 'UV blockers' prevent interference between patterns being exposed on opposite sides of inner layers, and are commonly added to most laminates.

Difunctional resins have adequate properties for many applications, especially in simple two-sided circuit boards. However, they have shortcomings as regards low glass transition temperature, with excessive Z-axis expansion and poor resistance to chemicals and moisture. Typically these resins can be improved by adding more cross-linking and this is often done by adding epoxy novalacs. Whilst these increase the level of cross-linking and give higher Tg products, with better chemical and

moisture resistance, care has to be taken less the materials have lower flammability resistance and become more brittle.

Despite recent sections, we are not trying to turn you into chemists! What we are seeking to do is to reinforce the fact that, although masquerading under single names, FR-2 and FR-4 are not just commodities whose detailed characteristics can be relied upon, but ones where there are substantial variations in specifications, performance and cost.

The reinforcement

Kraft paper

The original laminates used for punching, FR-1, FR-2 and FR-3, are all based on cellulose-based paper. This is made using wood pulp fibre, and is not bleached. It often goes under the name of Kraft paper (German for 'strength'). The FR-2 laminate, most commonly single-sided, is made with Kraft paper saturated with a plasticised phenolic resin. A 1.57 mm typical FR-2 laminate comprises four layers of cellulose paper/resin and one layer of adhesive-coated copper foil.

You will know from other life experiences that wet papers aren't very strong, so few are impregnated with the vertical treatment equipment that was illustrated in Figure 1. Instead a horizontal treater is used, as shown schematically in Figure 2.

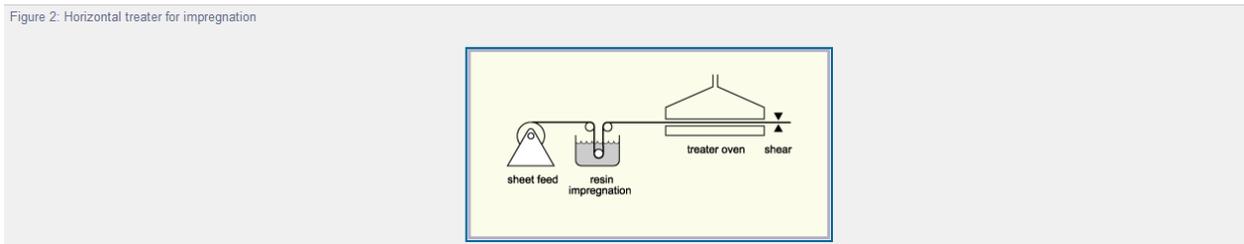


Figure 2: Horizontal treater for impregnation

Glass fibre

As with resins, glass fibre is a very variable material as regards quality, performance and cost. However, all fibres start with the mixing and melting of raw materials to form molten glass, the formation of filaments by extrusion, the application of a surface coating (sizing), and winding and twisting into yarn. From that point, the material may be chopped into strands, or, as in the case of FR-4, woven into cloth.

As you will have expected, silicon dioxide in the form of sand is a major component of most glasses. A number of different glass compositions are used for laminates, of which E-glass is the main runner. This contains 52–56% silica, 12–16% alumina, 5–10% borax, 15–25% lime, and variable amounts of other materials.

Continuous glass fibre is produced by extruding molten glass through tiny holes located in a forward-projecting extension to the glass furnace.(Figure 3).

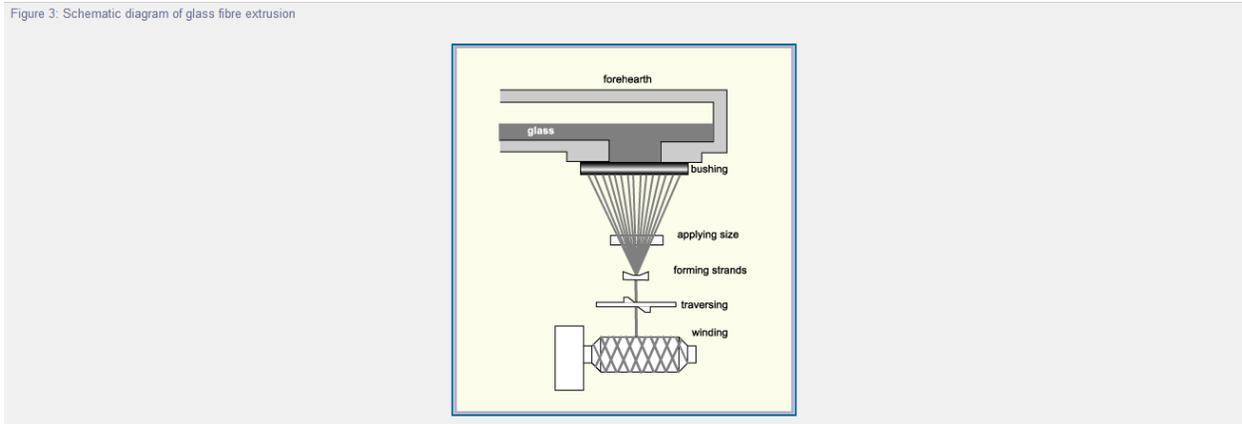


Figure 3: Schematic diagram of glass fibre extrusion

The individual fibres are then 'sized', applying a starch-oil emulsion coating that helps protect against abrasion and prevent surface defects causing filament fracture. The fibres can then be chopped to produce 'staple yarn', but in Figure 3 are shown twisted into strands, and wound onto bobbins. The strands produced may also be grouped together in twisted 'plies'.

Any detailed consideration of yarn is beyond the scope of this module, but you should be aware that there are two systems, one in use in the USA and the other the SI system, both designating the type of glass, the type of filament, the filament diameter, the number of strands, the number of plies, and the direction of twist.

Yarn is then woven into glass cloth 'fabric'. Whilst other weave constructions are possible, most glass cloth used in electronics is 'plain weave': one warp yarn passes over and under one fill yarn, and vice versa.



Section through resist, track and laminate, showing the woven structure of the reinforcement

Each fabric style is associated with a style number, which defines:

the yarn(s) used

the 'count' (the number of strands per unit length) both in 'warp' (along the length of the fabric in the feed direction) and in 'fill' (cross-wise or 'weft') directions

the nominal thickness of the fabric

its weight per unit area.

Table 1 shows the SI system parameters for some common fabric styles:

Table 1: Parameters of some common fabric styles

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style	count (end/5cm)		yarn		nominal thickness (mm)	weight (g/m ²)
	warp	fill	warp	fill		
106	110	110	5 5.5 1x0	5 2.75 1x0	0.033	24.4
1080	118	93	5 11 1x0	5 11 1x0	0.053	46.8
2112	79	77	7 22 1x0	7 22 1x0	0.81	69.2
2113	118	110	7 22 1x0	5 11 1x0	0.079	77.3
2125	79	77	7 22 1x0	9 33 1x0	0.091	86.1
2116	118	114	7 22 1x0	7 22 1x0	0.094	104.0
7628	87	63	9 68 1x0	9 68 1x0	0.173	204.4

After weaving, and before laminating, a 'heat cleaning' process is used to remove the size, and a glass-to-resin 'coupling agent', is then applied to the surface. The purpose of this is to enhance the adhesion between resin and reinforcement. The most commonly used materials are 'silanes'⁴ : one end of the molecule bonds to the glass surface, whilst the other is free, and has an organic structure which is designed to be compatible with the resin.

⁴ Equivalents of many simple organic materials can be made with a silicon atom replacing a carbon atom. Silane itself, SiH₄, is the equivalent of methane, CH₄, but silane coupling agents have many different forms, typically with both -OH and organic groups replacing the hydrogen atoms

The glass fibre gives the laminate most of its strength, so resin content should be kept to a minimum. However, sufficient resin has to be used to fill all the spaces between the fibres, as voids lead to unreliability. The amount of resin needed will depend on the weave pattern and count, on the filament diameter and twist, and on the way lay-up is carried out. With coarse plain weaves laid up by hand, 36–38% of resin may be needed, whereas types with less twist in the yarn may give a strong board with only 25% resin.

Typically prepreg materials for multilayer manufacture will be relatively 'rich' in resin. However, whilst this makes the process less critical, it also creates difficulties in getting accurate values of dielectric thickness, because the resin squeezes outwards during lamination.

The foil

Copper is by far the most common base material used to provide on-board connection between components. Its resistivity is low, second only to silver, a much more expensive metal. Copper is easy to plate, resistant to ionic migration, and forms a stable oxide which bonds well to resin for multilayer applications. Plated copper is also a ductile material, when plated properly, so that it can make reliable through-hole interconnects, even though changes in temperature cause considerable relative expansion and contraction between copper and laminate.

The most widely used type of copper foil is produced (Figure 4) by plating onto a cylindrical drum cathode that rotates partially submerged in the plating solution, and stripping it off to produce a continuous strip of foil whose thickness is set by the current density and the rotational speed of the drum. A uniform consistent layer is produced by making the anode conform to the curvature of the cathode, to produce an even current distribution.

Figure 4: Schematic for the foil manufacture process

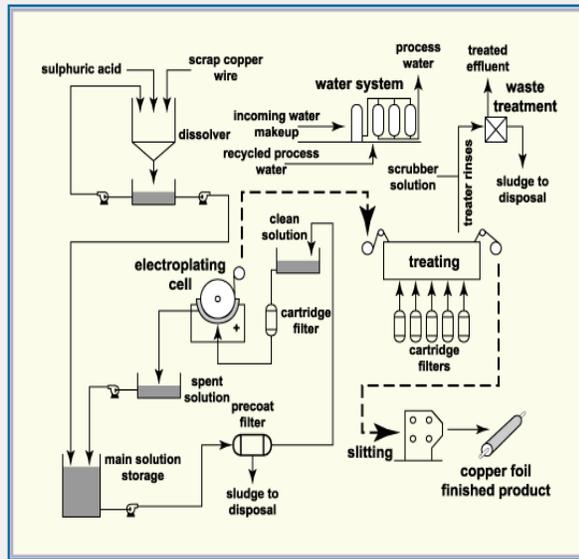


Figure 4: Schematic for the foil manufacture process

One side of the electrodeposited foil is shiny, mirroring the polished surface of the drum: the other has a rougher finish, sometimes even with nodules of copper. The roughness helps the foil bond to the impregnation resin, and the foil surface is usually treated to enhance its adhesion further. A typical treatment combines a 0.2–0.4 μm oxide-containing layer with a 0.05–0.1 μm brass, zinc or nickel thermal barrier to prevent bond degradation and a 10 nm chromium-based passivation layer to prevent oxidisation during storage and lamination. Thin (<10 nm) organic silane coatings are also used to improve adhesion.

The mechanical properties and roughness of the foil are controlled by the plating solutions, and by the surface preparation of anode and cathode. By modifying the process to change the initial grain structure, foil can be made with an increased elongation at high temperatures. This 'High Temperature Elongation' (HTE) foil was developed in the early 1980s to withstand the stresses during expansion which otherwise tend to fracture the copper layer within through-hole plated boards.

For applications that involve flexing, rolled copper foil is used. This has two shiny surfaces, and depends on surface treatment for adhesion. The ductility of the foil can be further enhanced by annealing, which changes the grain structure of the copper. Rolled foil also has improved electrical properties at high frequencies.

Copper foil thicknesses have historically been described in terms of weight per unit area in ounces per square foot, but there is a trend towards specifying thickness in microns. The most common materials are '1 oz' (nominally 35 μm thick), '½ oz' (18 μm) and '¼ oz' (9 μm), with '2 oz' (70 μm) used for high-current applications. Current permitting, there is a general trend towards thinner materials, as these are able to give enhanced trace definition.

Laminate construction

The actual lamination process is conceptually similar for both FR-2 and FR-4, but most users will get involved with the detail only for the latter material. This is because FR-2 laminate is purchased in the state in which it will be used, and never converted into multilayer assemblies, as FR-4 often is. If you want an FR-2 laminate that is #.# mm thick, with specific weights of copper on one or both sides, then that is what you order, and the fine detail is of less importance, except insofar as it affects cost and factors such as machineability. In practice, the board fabricator will tend to make the purchasing decision as to the specific grade required by the process.

On the other hand, FR-4 is much more custom-made, especially where used in multilayer constructions for high-speed circuits, where the dielectric thickness becomes crucial. A range of standard prepreg materials is available, the thickness depending on the glass fibre diameter and the weave used to form the cloth. Table 1 has already listed the characteristics of the most common prepreps.

Microscopic holes in the finished layer, known as 'pin holes', could create a short circuit between layers in the board if copper entered the hole. In order to avoid this, a minimum of two prepreps are usually bonded together, whether to form a basic laminate or between layers in a multilayer structure. For thicker boards, many more layers of coarser material are used: for example, a typical 1.60 mm FR-4 board uses 8 layers of (7628) glass fibre material.

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Source: http://www.ami.ac.uk/courses/topics/0232_bbm/index.html