

Printed circuit boards-Properties of laminates

Process compatibility

For our products we are looking to use laminates that have the correct electrical, mechanical and thermal properties, but also sufficient chemical resistance (primarily to withstand the fabrication and assembly processes), humidity resistance (for an extended life) and fire retardance (to meet commercial and legal requirements).

These parameters are affected by the manufacturing method, structure and materials. For example:

The thickness of the individual layers, the makeup of the reinforcement in each layer, and the overall thickness of the board, all affect its mechanical characteristics

The resin type and formulation affect the laminate's electrical characteristics and its chemical resistance and fire resistance.

A specification sheet for a laminate is an extended document! Good examples of the genre are the BS EN 60249 specifications for generic FR-2 and FR-4 materials. These specify:

Electrical properties

resistance of foil

SIR1 and volume resistivity after damp heat testing

SIR and volume resistivity at maximum rated temperature

dielectric constant and dissipation factor after damp heat testing

corrosion at surface and edge.

1 Surface Insulation Resistance is a measure of the unwanted conductivity across the surface. How this is often measured is described in the context of flux in How joints are made

Non-electrical properties of the clad sheet

surface finish (allowable level of imperfections)

thickness tolerance (doesn't apply to the outer 25 mm of the sheet)

bow and twist (related to thickness and panel dimension)

peel strength of the copper foil bond (initial and after simulated processing).

Non-electrical properties of the laminate after removal of the copper

appearance of the base material

flexural strength

flammability

water absorption.

There are also requirements for packaging and marking, and recommendations for choosing which acceptance tests will be carried out by the purchaser of the material.

At this point, if you have time, we would recommend you to take a look at typical specifications, and see the extent to which they contain comparable information. One suitable site which lists a range of laminate materials is <http://www.isola.co.uk/>: look under 'Products'.

There are minor variations between test specifications from different institutions, but a very convenient source, and one we often make reference to, is the IPC-TM-650 Test Methods Manual. All the tests in that manual can be downloaded without charge (though as separate .PDF files) from <http://www.ipc.org/>.

In the remainder of this part and the next, we are reviewing these properties in generic terms, looking in more detail at design, test and application aspects, but specifically focussing on FR-2 and FR-4 laminates. A wider range of materials will be discussed in the final part of the unit More about board materials.

Physical and mechanical characteristics

Figure 1 is an attempt to pull together the important physical and mechanical issues for a board design, looking at all aspects other than the thermal and electrical characteristics, which are considered separately.

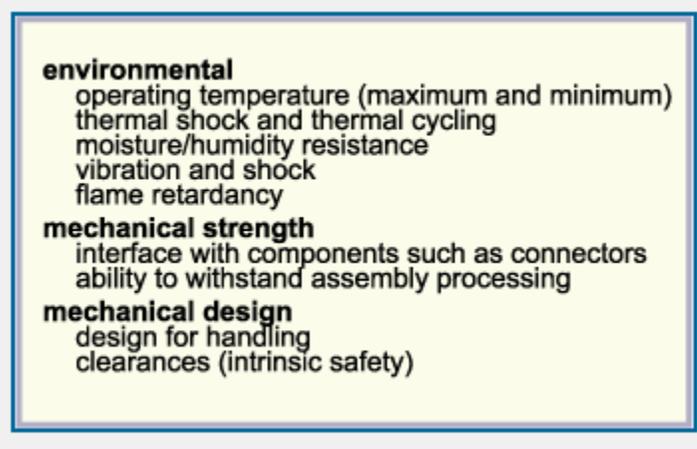


Figure 1: Physical issues for PCB design

Operating temperature

Table 1 indicates typical maximum temperatures quoted. Note that, as in this case for FR-4, a distinction may be drawn between the maximum operating temperature for adequate electrical function and a slightly higher temperature for acceptable mechanical performance.

operating temperature °C		
material	electrical parameters	mechanical parameters
FR-2	105	105
FR-4	130	140

Table 1: Maximum operating temperatures of common laminate materials

Glass transition temperature

As the temperature of a laminate passes through its glass transition temperature (T_g , sometimes referred to as 'T sub g'), molecular bonds begin to weaken, and the resin changes from a 'glassy' state to a more random 'rubbery' state. The transition is fully reversible– as with water turning to ice and back again – and the only permanent change that will take place is if the 'rubbery' material is allowed to distort, and then 'sets' in this position when cooled.

The 'phase transition' phenomenon, which is seen in a wide range of materials, both thermoset and thermoplastic, is accompanied by changes in both dimensional

stability and a range of properties. Exceeding T_g is typically accompanied by substantial increases in CTE, reduction in flexural strength and changes in electrical properties, and for this reason T_g is often regarded as being synonymous with maximum operating temperature.

Amorphous and crystalline polymers

T_g is a measure of how well a laminate resin system resists softening from heat, but is just the temperature at which molecular bonds begin to weaken enough to cause a change in physical properties: this is not the same as saying that the resin reaches any kind of melting point during its glass transition. After all, resins retain some stiffness even above their T_g , whereas a molten material will not resist deformation to any significant extent.

To understand the difference between glass transition and melting, we need to recall that some polymers are crystalline and others classified as 'amorphous'. If you find difficulties here, then look up the topic in Polymer basics.

Crystalline polymers melt when the polymer chains are released from their crystal structures and become a disordered liquid. On the other hand, amorphous polymers do not have a single temperature at which the crystalline structure 'collapses'. Instead, the polymer chains can move more easily as the temperature increases, but they are never released totally from their micro-molecular structure.

Whilst one might expect a clear distinction between the two types of polymer, the position is complicated by the fact that even crystalline polymers have some amorphous proportion which might make up 40–70% of the polymer sample. Whilst the crystalline portion can undergo melting, the amorphous portion can only undergo glass transition, which is why many real polymers have both a glass transition temperature and a melting temperature!

Confused? Just remember that almost all materials currently used are thermoset materials, and as such have amorphous structures, so that the change in characteristics that takes place is gradual, over a range of temperatures.

Differential Scanning Calorimetry (DSC)

The original way of determining glass transition temperature makes use of the fact that any phase change is accompanied by either generation or absorption of heat. [This is the same phenomenon which gave rise to the plateau in the cooling curves used to generate the phase diagram of solder, and which we shall meet again in condensation soldering] The method of differential scanning calorimetry (DSC) is well-loved of polymer scientists and is carried out in an apparatus shown schematically in Figure 2.

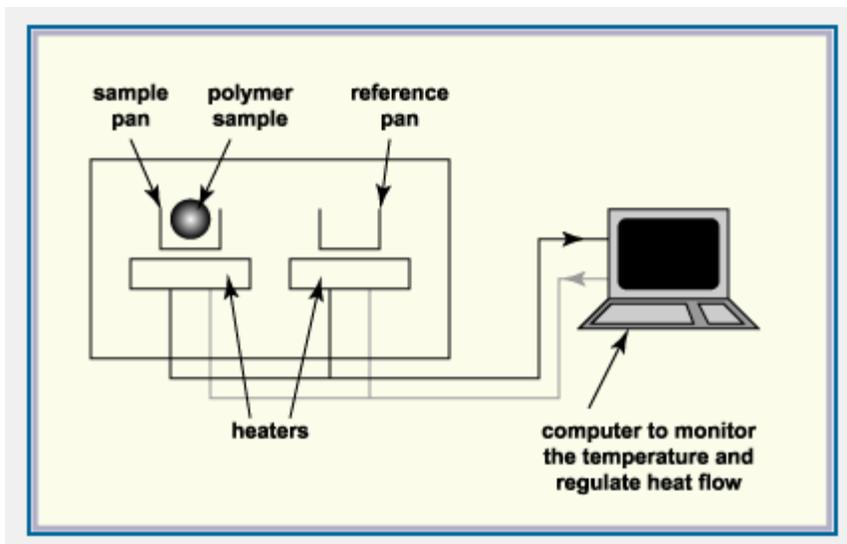


Figure 2: DSC equipment schematic

A sample of polymer, and an identical but empty reference vessel, are both heated to achieve a constant rate of rise of temperature. If the polymer in the sample pan neither generates nor absorbs heat, then the heaters under both sample pan and reference pan will require the same power in order to heat them to the same temperature. However, if the polymer sample either gives out or absorbs heat, the amount of heat to be supplied by the feedback control system, consisting of thermocouple controller and heaters, will automatically regulate the heat flow at a different level.

The equipment plots the difference in heat output for the two heaters against the temperature achieved. If the material is just heating up, then the rate of heat flow will be constant, and determined by the specific heat of the sample. When there are

changes in state, as for example when the polymer crystallises or reaches its glass transition temperature, then there is either a dip or an increase in the plot. A permanent change in increase represents a permanent change in state. To learn more about this, why not take a look at the website run by the Department of Polymer Science at the University of Southern Mississippi at <http://www.psrc.usm.edu/macrog/dsc.htm>, where there is a nice explanation of some of the other things that DSC can do.

Thermal Mechanical Analysis (TMA)

DSC is an indirect method of measuring glass transition temperature; thermal mechanical analysis (TMA) is a more direct method of determining the temperature at which the glass transition of a material makes a difference to the rate at which its dimensions change. The method is particularly appropriate for the dielectric materials used in printed boards, because it is easy to apply to changes in laminate thickness, and it is this Z-axis expansion that is particularly important in determining the reliability of a board structure.

The sample, with a quartz rod resting on its surface, is placed in a small heating chamber. As the chamber is heated, the material begins to expand, moving the quartz rod along with it. At the other end of the quartz rod is an extremely sensitive gauge that can measure movement, so that any change in dimension can be plotted against temperature. Quartz is chosen because it has a low CTE, and transfers the majority of the expansion from sample to gauge.

The actual measurement of the movement may employ different types of transducer, depending on the style of equipment:

high resolution linear optical encoders measure movement by means of the diffraction pattern of light through two gratings, one moveable and one stationary

a moveable-core linear variable differential transformer (LVDT) has an output proportional to the linear displacement of the core caused by changes in sample dimensions.

Another way of observing mechanical changes in a material is to look at the way in which it transmits force. The so-called dynamic mechanical analysis (DMA) technique clamps the sample between a force generator and detector which is placed inside a heated chamber. As the material goes through glass transition, its ability to transmit force changes.

IPC-TM-650 Method 2.4.24.3 uses TMA to measure the dimensional change with temperature. Around the glass transition temperature there is a change in slope of the dimension-temperature curve, and the value of T_g can be estimated by the intersection of the tangents to the two slopes (Figure 3).

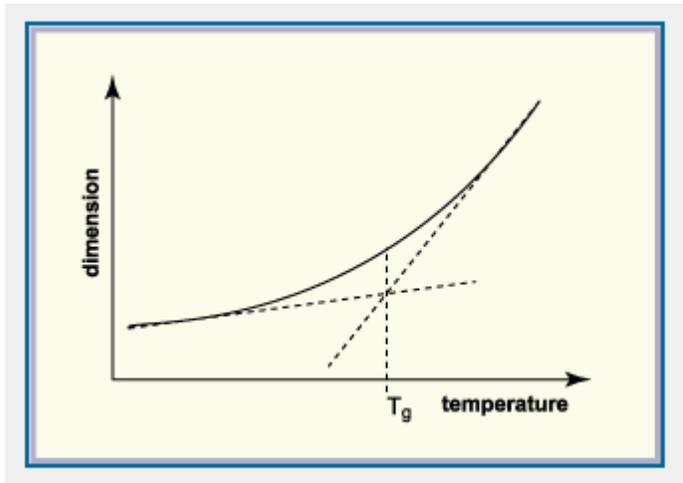


Figure 3: Laminate glass transition temperature

Note that the IPC test method specifies that:

metallic clad laminate shall be tested without the cladding

specimens taken from multilayer boards shall have no internal metal layers, if possible

exterior metallic cladding shall be removed by etching using standard industry practices.

In other words, be aware that measurements must be applied to the laminate itself, and not be overly affected by the presence of the copper foils, which have a different rate of expansion, and no discontinuity in CTE.

CTE

As explained in Coefficient of Thermal Expansion why materials change dimensions in response to changes in temperature, and we have just seen that polymeric materials which exhibit glass transition have different values of CTE depending on whether the measurement is taken above or below T_g . For reinforced materials, there will also be differences along the different axes, as a result of the reinforcement being in the plane of the laminate (the X/Y plane).

Typically, laminates have similar CTE in X and Y directions, corresponding to the warp and weft directions of the woven material. However, this results from

conventional weaves having broadly similar constructions in both directions, and is not necessarily the case. However, in the Z axis (through the thickness of the material) there is no constraint on TCE as a result of the reinforcement. As a result, the Z-axis CTE may increase substantially above Tg, and the expansion and contraction that occur with changes in temperature can lead to deformation in the through-holes and stress on the surface pads. Over time, thermal cycling can fatigue the through-hole and cause failure by separation of the conductor from the hole wall or cracking of the conductor within the barrel. This is the reason why attention is paid to creating a plated layer of sufficient ductility.

The CTE is a function of the materials used and the volume percentage of these materials. The key factors, particularly in Z-axis expansion, are the performance of the resin system, and the resin content of the laminate, as resin systems have relatively high CTE compared to reinforcements. Using more fillers will depress CTE; 'resin-rich' systems will tend towards higher values.

We shall be saying more in later units about the impact of Z-axis expansion on through-hole reliability, but be aware that expansion in the plane of the laminate also becomes important when large components are attached to the surface: differences in CTE between board and component can compromise the reliability of the bond.

A topic we will return to in Technology Awareness is that of controlling CTE in the X/Y plane in order to improve the reliability of certain structures. One way of lowering the CTE, and making it more compatible with silicon and ceramic materials, is to change the foil from copper (CTE ~ 17 ppm/ $^{\circ}$ C) to a material of lower CTE. The most common replacement foil is a sandwich construction with copper outside and invar inside. Invar is a 36% nickel-iron alloy whose CTE is less than $1.3 \times 10^{-6}/^{\circ}$ C over the range 20–100 $^{\circ}$ C, and very low over the range –100 $^{\circ}$ C to +200 $^{\circ}$ C. Invar is commonly used in applications such as CRT shadow masks, and was the forerunner of a family of controlled expansion nickel-iron alloys used in bimetallic strips and thermostats. For more details, search for "invar" at <http://www.azom.com>. Having a copper surface makes the material compatible with normal PCB processing – the thickness of the skin on standard CIC foils is either 12.5% or 20% of the overall thickness.

Balancing Tg and CTE

Although the value of the glass transition temperature is a measure of the stability of a material when heated, it is not necessarily a guarantee of better performance above T_g . In theory at least, the properties of a high- T_g resin may change much more rapidly above T_g than one with a low T_g , and the lower T_g material may even exhibit superior properties at high temperature (Figure 4).

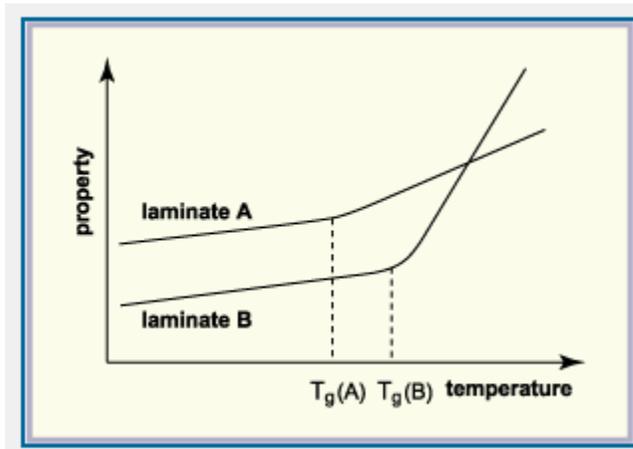


Figure 4: Theoretical independence of properties and T_g

In practice, materials with a higher T_g are generally favoured for laminates because they maintain their dimensional stability over a wider temperature range, and the total expansion due to temperature up to solder reflow temperature is lower for a high T_g material (Figure 5).

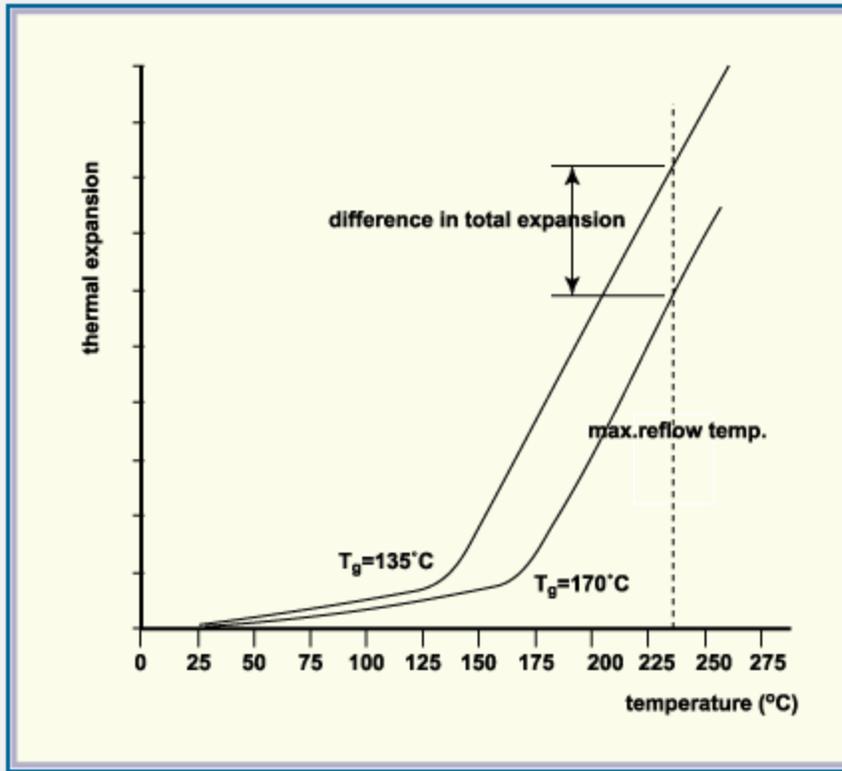


Figure 5: Total expansion for materials of different T_g

This reduced total expansion has a significant benefit in reducing the strains associated with the copper barrel of a through-hole or via. Reduced strain results in reduced pad lifting, reducing copper barrel cracking, and reduced inner-layer foil cracking.

The increased T_g has other benefits:

for the fabrication process, there is less epoxy smear during the drilling process, giving a more reliable result for less de-smearing

for both applying HASL and soldering during assembly, there is an improved resistance to measing damage due to solder shock.

For most laminates, the glass transition temperature is influenced mainly by the chemical structure of the resin: difunctional epoxy exhibits a T_g of 125–135°C; polyimide 250–260°C. With epoxies, there is a substantial spread in T_g between different materials (Figure 6), the value depending on the degree of cross-linking, so that it can be increased by using a multifunctional chemistry. However, the glass

transition temperature of phenolic resins is related to the cure temperature, and can be elevated by baking.

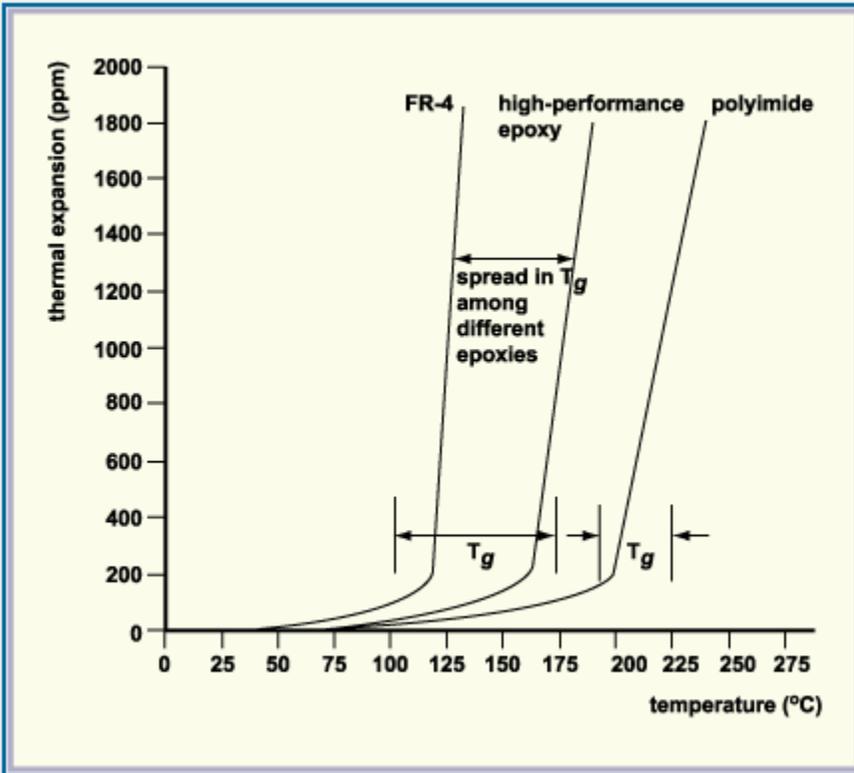


Figure 6: Glass transition temperature for different resin types

Other environmental issues

We have concentrated primarily on the glass transition temperature, because this is so often used almost as a shorthand way of indicating the quality of the material. Of course this simplification has limitations, and we will find that other materials, although they have a high glass transition temperature, are not so satisfactory as epoxies from the point of view of fabrication.

What happens to a laminate at high temperatures will be considered in the next part of this unit. However, from the perspective of environmental resistance, we also need to consider what happens to a laminate material when it is exposed to:

thermal shock and thermal cycling

moisture/humidity

vibration and shock.

Thermal shock and thermal cycling are both related to temperature change, the term 'shock' being used for rapid changes and 'thermal cycling' for the slower, more gradual changes that are typical of life. For the purposes of testing², thermal cycling generally takes place in an air environment, with rates of change restricted to 5°C/minute, whereas thermal shock uses a rapid change of environment, and is often associated with liquid immersion in order to speed the transition.

2 The specification for change of temperature testing, BS EN 60068-2-14, describes three tests of increasing severity: Test Nb has a specified rate of change of 1, 3 or 5°C/minute; Test Na moves the part from one environment to another in 2–3 minutes; Test Nc involves liquid immersion. Advice for designers as to the applicability of particular severities of test is found in BS EN 60068-2-33. Note that care has to be taken that condensed moisture should not affect the results or impart additional stresses to the unit under test.

Over the normal operating range, most laminate materials will survive thermal excursions with little damage. However, when they are built into assemblies, associated solder joints may fail, particularly if changes in temperature are associated with warping of the board. As we will see later, this warping is generally caused by a lack of balance in the structure of the board, and as such is greatly influenced by design.

The resistance of a board to humidity and moisture is dictated primarily by the resin content, although moisture will be transmitted along the fibres of a reinforcement, particularly if the reinforcement is not completely wetted by the resin. This is one reason why great care is taken over surface preparation of glass fibres.

Laminates will typically shed gross droplets of liquid, but will absorb some moisture into their structure when exposed either to liquid or water vapour in the atmosphere. Typical polymeric materials will absorb around 1% by weight of moisture, a figure which can be verified easily by weighing before and after exposure. Whether or not this has an adverse impact on the reliability of the structure will depend on the ionic content of the resin – as we will see in later units, ions plus moisture plus volts can lead to electromigration. Some resins will also

expand when they have absorbed moisture, potentially affecting the integrity of the board, but this is not usually a problem.

Finally, the ability of the board to withstand vibration and shock is mostly a design issue that is affected by the weight and distribution of the added components and the support provided by the enclosure.

Mechanical requirements

In the previous part we have already discussed machinability from the point of view of punching as against drilling, and seen how paper-based materials are more suitable for punching than are those containing woven strands of glass. Ease of punching can be improved by carrying out the operation on a warmed laminate, but care still has to be taken to specify a punchable grade where this is the intended method of profiling or creating holes.

The presence of woven strands of glass can also impact on the drilling process, both deflecting small diameter drills (reducing the allowable stack height) and reducing bit life through abrasion. The optical characteristics of the glass fibre also make it difficult to adopt the alternative approach of laser-drilling vias. Nevertheless, woven glass continues to be the most commonly specified reinforcement, because it combines reasonable ease of processing with adequate robustness and low cost.

An important characteristic for metals is the stress/strain ratio referred to as the modulus of elasticity or Young's Modulus. [If you have forgotten what this means, look at Mechanical properties of metals]. Laminates too will have a Young's Modulus, but are less likely than metals to be exposed to direct compression or tension. However, laminates will get flexed, so the most appropriate measure of the robustness of a material is its flexural strength.

Flexural strength

The generic ASTM flexural strength test shown in Figure 7 measures the load which a beam of material will withstand without fracture when supported at the ends and

loaded at the centre. The test piece is under compressive stress at its top surface and tensile stress at its under-surface, with a neutral axis along the mid-section of the beam.

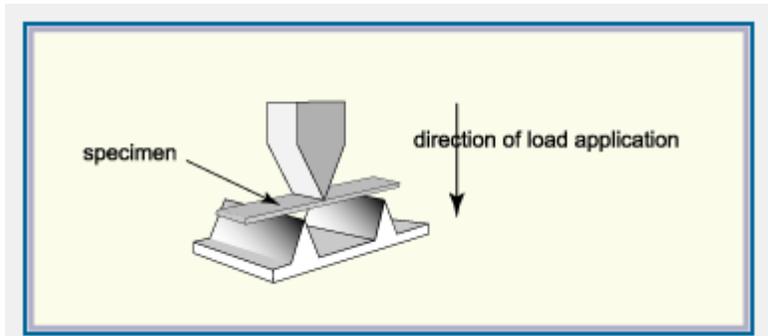


Figure 7: Flexural strength test

For materials that do not break, the flexural strength is usually reported as the load at which 5% deformation/strain of the outer surface occurs.

If you bend a piece of laminate, you will find that it springs back exactly to its original state only for relatively small deflections. When greater loads are applied, and then removed, some permanent bending in the laminate will be observed. At higher strains still, the stress/strain curve may also show a reduced slope, similar to yielding in a metal, corresponding to fracture and delamination effects on a microscopic scale within the bulk of the laminate.

The test for the flexural strength of boards is defined by IPC-TM-650, Test 2.4.4, which is based on the generic ASTM-D-790 test. The standard specifies the nominal thickness and dimensions of the specimen, the span between supports, and the rate at which load is applied, and provides a formula for deriving the flexural strength. Be aware, however, that the IPC test is to destructive fracture, and provides no indication of the level of stress that leads to a permanent deformation of the laminate.

Typical values for flexural strength are given in Table 2. You will notice a slight difference between the lengthwise and crosswise values, which is another example of anisotropy. Reinforced composites of any kind will have maximum strength and stiffness in the direction of the alignment of the reinforcement. When half the strands are laid at right angles to the other half, the resulting strengths in either direction are less than those of the parallel alignment. Fortunately, most laminates

are made with 'balanced' fabrics, with equal yarn distribution in warp and weft directions. The differences reported will probably be due to minor differences in the weave.

Table 2: Flexural strength: typical 'minimum average' figures

material	lengthwise	crosswise
FR-2	83 MPa	72 MPa
FR-4	414 MPa	345 MPa

Both flexural strength and flexural modulus will be functions of temperature, with their values reducing with increased temperature, even below glass transition. It is important therefore that the board does not deform either under operation at elevated temperatures or during the more severe conditions of solder assembly, and this is why one IPC test (IPC-TM-650, Test 2.4.4.1) measures flexural strength at elevated temperature.³

³ IPC-TM-650, Test 2.4.4.1 suggests test temperatures that are comparatively close to the maximum working temperature, as shown in the following table:

resin type	thickness	test temperature
difunctional, tetrafunctional epoxies	all	125°C
hot strength retention epoxies high temperature epoxies	up to 1.6 mm 1.6 mm and over	190°C 170°C
BT-epoxies; modified epoxies	all	170°C
polyimide (T _g >250°C)	all	204°C
polyimides (T _g ≤250°C)	all	170°C
cyanate esters	all	204°C

Stiffness

Board thicknesses are normally in the range 0.8–1.6mm, over three-quarters of products being in that range. However, there is a trend towards thinner boards. As boards become thinner, so the inherent stiffness of the laminate becomes more important.

Thin, flexible laminates are not easy to handle during fabrication. At assembly, there are particular difficulties at component placement, reflow and wave soldering, and for depaneling, as well as continuing difficulties when the assembly is mounted into its enclosure. Certainly the board may have to be supported in order to stay flat during both wave and reflow soldering:

during wave soldering, a board that is warped may not receive an even coat of solder or, worse, solder may flood over the centre of the board

in reflow soldering, a board may retain its bowed shape after components have reflowed and the solder joints subsequently solidified, causing strains on the components if the board is flattened in order to fit it into an enclosure

These are issues we shall meet again when we consider soldering processes and the reliability of chip ceramic capacitors.

The three-point bending method used for flexural strength tests can also be used to determine the flexural modulus (resistance to bending) of the beam (E_f), from the ratio of the stress difference to the corresponding strain difference at two discrete points, normally corresponding to strains of 0.5% and 2%.

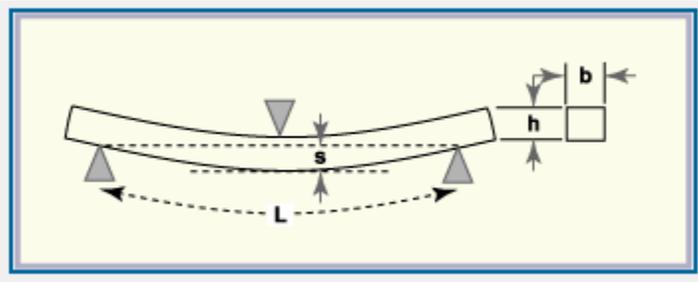


Figure 8: Flexural modulus measurement

Referring to Figure 8, the flexural stress σ_f (in MPa) is calculated from the equation:

$$\sigma_f = \frac{3FL}{2bh^2}$$

Where

F = load applied at centre of beam (N)

L = distance between support points (mm)

b = width of beam (mm)

h = thickness of beam (mm)

The flexural strain ϵ_f is derived from the equation:

$$s = \frac{\varepsilon_f L^2}{6h}$$

Where

s = deflection at centre of beam (mm)

L = distance between support points (mm)

h = thickness of beam (mm)

The flexural modulus can then be calculated from the deflections s1 and s2 that correspond to two different values of stress, using the equation:

$$E_f = \frac{\sigma_{f2} - \sigma_{f1}}{\varepsilon_{f2} - \varepsilon_{f1}}$$

Where

sf1 = flexural stress measured at deflection s1

sf2 = flexural stress measured at deflection s2

Note that these equations hold exactly only for linear stress/strain behaviour. For most plastics, they are accurate only for small deflections, which is why the two strains suggested are 0.5% and 2%.

Intuition, supported by calculation, will show that the flexural modulus for a board depends on the properties both of the laminate and the foil. The detailed calculations are complex, but an approximation for many mechanical properties of composites can be calculated using the 'Rule of Mixtures'. Here the property of the composite is estimated as resulting from the responses of each component, weighted by the volume fraction of the component in the composite. For example,

this gives a reasonable estimate of properties parallel to the fibres in a material. For more details see http://islnotes.cps.msu.edu/trp/back/est_rule.html and following pages.

The practical implication is that getting a stiff, thin laminate is not easy, unless we can use exotic materials, and our design has to allow for some flexing of the substrate.

Bow and twist

As the discussion above has indicated, a key concept to bear in mind in relation to board flatness is that the laminate is not a stable material! The base laminate as supplied may have a fairly tight flatness tolerance, but by the time you have built up a number of layers made of materials with differing TCEs, and which flow and shrink during heat treatment, there are many opportunities for non-flatness.

The specifications distinguish between two types of deviation from flatness that are illustrated in Figure 9:

Bow, which is characterised by a cylindrical curvature of the board, so that all four corners are in the same plane, but the centre is raised.

Twist, which is deformation parallel to a diagonal, so that only three of the four corners of a rectangular sheet lie in the same plane.

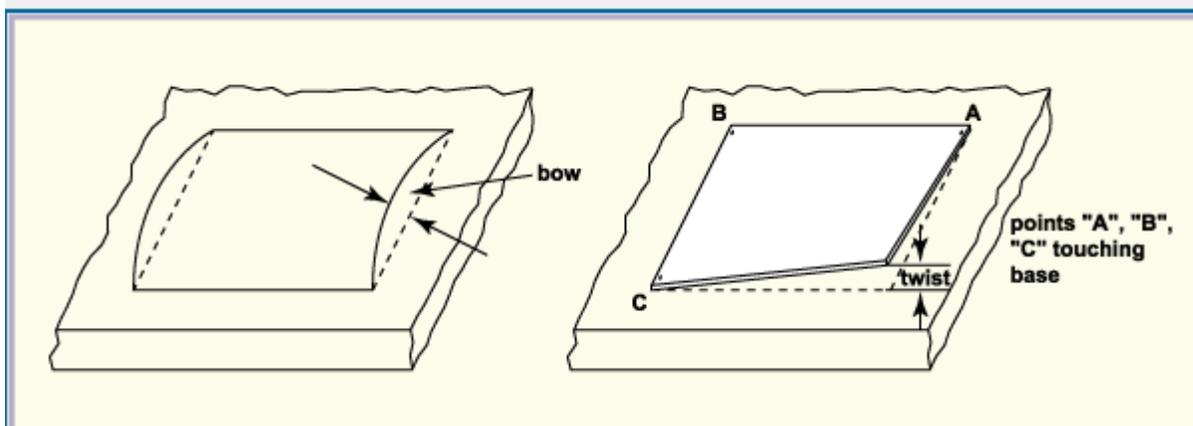


Figure 9: Bow (left) and twist (right)

Not only does excess distortion affect the fit of the final board in its enclosure, but warped boards create substantial difficulties for the assembler.

Electrical characteristics

The important electrical properties of a PCB track (or 'trace') are summarised in Figure 10. In this section we shall be considering first the DC properties of an interconnect and then its reactive components, which are important at high frequencies.

resistance	leading to conductor heating and power loss	dependent on conductor thickness and track width
capacitance	producing signal delay	dependent on laminate thickness and track width
inductance		dependent on track length
coupling	leading to noisy or incorrect circuit function	dependent on length and proximity of coupled tracks

Figure 10: Properties of a track on a PCB

Bulk effects

The resistance of tracks varies in proportion to their length and inversely to their cross-sectional area. The track resistance R is given by the formula:

$$R = \frac{\rho \cdot L}{A}$$

where

ρ = the volume resistivity of the conductor

(approximately $1.72 \times 10^{-6} \text{ W}\cdot\text{cm}$)

L = the length of the conductor

A = the cross-sectional area of the conductor

This formula gives a reasonable estimate for the resistance of a wide track, but few narrow tracks have vertical sides. A better estimate of the shape is given by Figure 11, which shows a trapezoidal cross-section, where the undercut on each side is approximately half the thickness of the track.

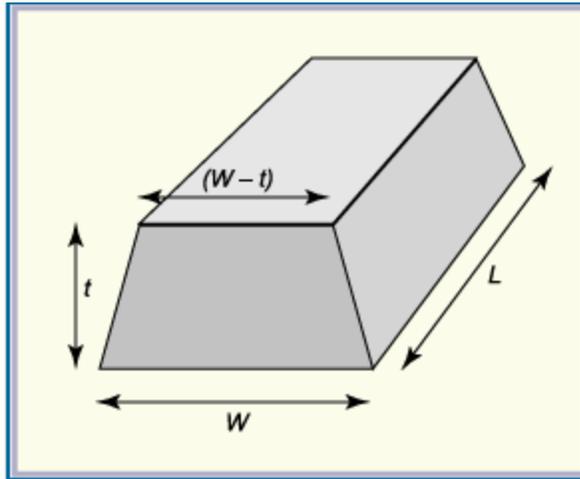


Figure 11: Trapezoidal cross-section of a track on a PCB

Using this approximation, the area of the cross-section of the track can be estimated using the formula:

$$A = [(w-t) \times t] + \frac{t^2}{2}$$

The thickness of the copper of course is the actual thickness of foil, together with any plating, allowing for the thickness tolerance on both plating and initial foil. Copper also has a substantial positive temperature co-efficient of resistance which may need to be taken into consideration if there is substantial track heating. For more information on calculating DC line resistance, see http://www.merix.com/resourcecetr/tech/dc_line.doc

Whilst for digital signals even the thinnest tracks that can be manufactured consistently and economically are more than adequate to carry the signal current, on high dissipation boards current-carrying capacity has to be considered. This is especially important with multilayer boards, which have higher track concentrations, and where tracks on inner layers cannot radiate heat direct to the air.

The current-carrying capacity of a track depends on its width and the thickness of the copper foil from which it was etched, and on the permissible heat rise, which is a complex function of materials, construction, operating temperature range and intended use. Figure 12 is a typical set of curves that shows how the steady state temperature rise in a 70 μm thick copper foil is related to current and track width.

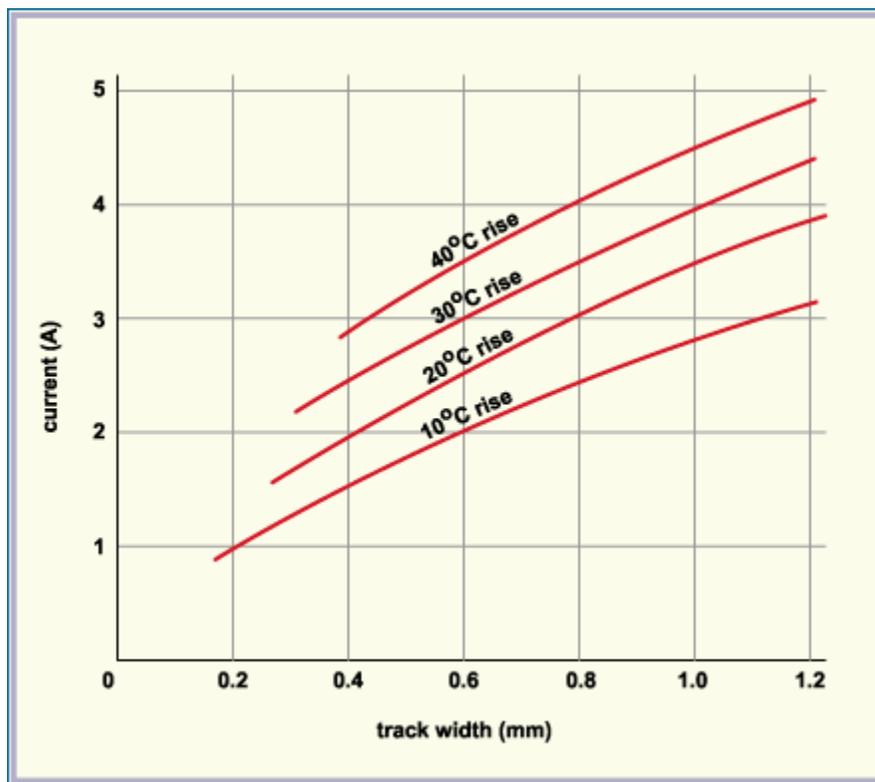


Figure 12: Heat rise in a 70 μm copper foil as a function of current and track width

IPC-2221 contains a fuller set of such curves, which may be used to calculate the recommended track width for any current. Obviously, in assessing what track temperature rise is allowable, the designer has to take into account the maximum operating temperature of the laminate and the worst case internal temperature of the equipment. The ways in which the full chart can be used, and a copy of the charts themselves is available at the UltraCAD website at http://www.ultracadm.com/using_ipc_temp_charts.pdf

The charts rely on graphical interpolation, which is not terribly convenient, so you may like to try one or more of the many calculators that are aimed to help the designer relate current, conductor width, and conductor thickness:

Doug Brooks: <http://www.ultracad.com/calc.htm>

George Patrick: <http://www.aracnet.com/cgi-usr/gpatrick/trace.pl>

Brad Suppanz:

<http://www.geocities.com/CapeCanaveral/Lab/9643/TraceWidth.htm>

The first of these is a download; the others are Javascript calculators that can be run from your browser; all are based on IPC-2221.

Whilst the graphs seem fairly clear in their recommendations, practical experience has indicated that the results they yield are far from accurate. Fortunately conservative, they prove to be based on very old experiments indeed, even before the days of multilayer, so that their extension for use with internal layers was based on pure hypothesis! Nevertheless, they are still the official IPC position. Until, that is, when the new standards, more closely aligned to experiment results, are released. Information on this has been provided for EDR students by Coretec, and it may be accessed at this link.

But what do you do in a high-power application, when the calculator suggests that, to avoid over-heating and possible damage, a wider track should be used than can be fitted into the space available? The main alternatives are either to select a laminate with a thick copper foil or to increase the track thickness locally by selective plating. In some high-current cases, it may be advantageous to fit bus-bars as components: bear in mind that resistive heating is associated with voltage drop, and this may also impact on circuit performance.

Ground and power connections are usually planes, complete layers of copper connected either to ground or supply voltage. This minimises both the resistance and the inductance of the connection, although the plane is less than perfect because it is pierced with multiple holes. One problem area is getting high currents into a plane: designers must have a sufficient total cross-sectional area of copper in

contact with the connector pin(s), and this depends on their number and diameter, as well as the foil parameters.

Contact resistance points on the board, such as an edge connector, may be coated with thicker gold to provide a low resistance connection which can be made and broken during life. This coating is totally different from the electroless nickel with gold flash used for soldering, that we will discuss in later parts of this unit. It typically consists of electrolytically-deposited hard nickel covered with 1-3 μm of hard gold, so that the design has to allow for electrical connection to be made to these areas during the plating operation. The practicalities of this are beyond the scope of this module, and you should consult your board fabricator.

But a PCB is more than just copper! The remainder of this section gives information about the electrical properties of the laminate, in terms of surface resistivity, dielectric strength and breakdown, dielectric constant and dissipation factor. These last two parameters are of particular consequence for high-frequency operation.

Surface leakage/tracking

The surface resistivity of a board depends on the material, the condition of the surface, and the relative humidity of the surroundings: typical values for glass-epoxy laminates at 60–70% RH are 10^{-13} to 10^{-14} W/sq.⁴

4 For an explanation of this unit, see Conductors and insulators.

The effect of humidity on surface resistance of glass-epoxy was measured, starting with 97.5% RH at 40°C and decreasing the humidity to 64%. The results, shown in Figure 13, indicate that the surface resistivity decreases logarithmically with an increase in humidity at approximately the rate of one decade per 20% humidity change: roughness and contamination also reduce the surface resistivity very markedly.

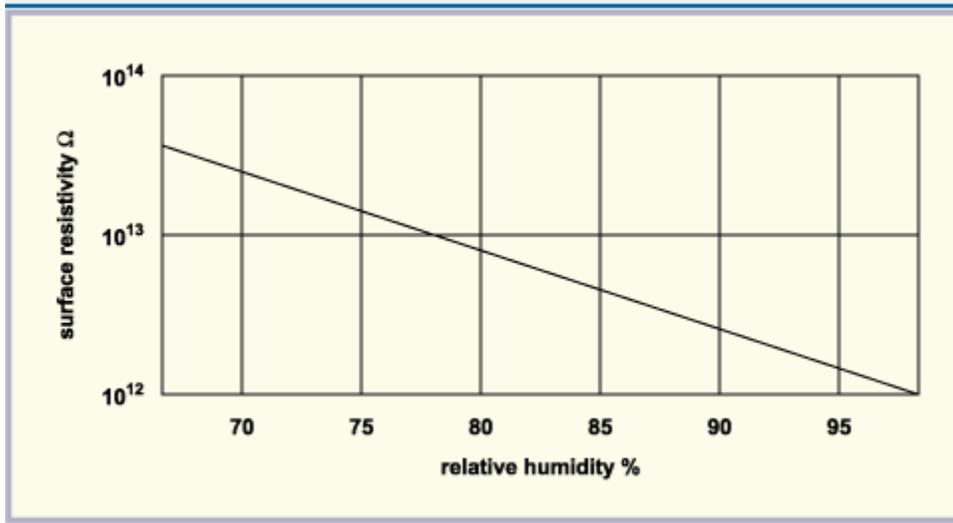


Figure 13: Surface resistivity vs. relative humidity

However, provided that the surfaces are clean, solder mask coatings enhance surface resistivity both in dry and humid conditions, and also reduce any tendency towards electromigration of the conductor material.

Dielectric strength and breakdown

These are measures of the ability of an insulation material to resist the passage of a disruptive discharge produced by an electric stress: dielectric strength is measured through the laminate, with values quoted per unit of laminate thickness; dielectric breakdown is measured between two electrodes inserted in the laminate on set centres perpendicular to the laminations. The test results will vary with the material thickness, the form and size of electrodes, the time for which the voltage is applied, the frequency and wave shape of the voltage, the surrounding medium, and the temperature.

The applied voltages are high, and all tests are run under oil to prevent breakdown occurring through the surrounding air. In the short-time tests, the applied voltage is increased at a uniform rate of 0.5 kV/s; in the step-by-step test, the initial voltage is 50% of the short-time breakdown voltage, and the voltage is increased at 1 minute intervals in increments according to a predetermined schedule.

he test values for dielectric strength vary with the thickness of the material, the form and size of electrodes, the time of application of the voltage, the temperature, the frequency and wave shape of the voltage, and the surrounding medium. In Table 3, the test figures are given in the SI unit, which are volts per metre of laminate thickness – in this case MV, because laminates don't come metres thick!

Perhaps a friendlier way of looking at these figures⁵ is in the original volts per mil (thousandth of an inch), where $19 \text{ MV}\cdot\text{m}^{-1} = 500 \text{ V/mil}$.

⁵ In much of the PCB industry, measurements are quoted in Imperial System units, 'mil' being the US term for 0.001in, the distance referred to in the UK as 'thou'.

Table 3: Dielectric strength data (step-by-step test)

Material	$\text{MV}\cdot\text{m}^{-1}$
FR-2	29
FR-4	20

Dielectric breakdown testing measures the disruptive discharge between two electrodes inserted in the laminate on 25 mm centres. Both short-time and step-by-step tests (Table 4) are performed perpendicular to the laminations, and measured under oil.

Material	kV
FR-2	15
FR-4	40

Table 4: Dielectric breakdown data

'Electrical clearance' refers to the minimum distance separating isolated electrical conductors. Recommendations for this are given in Table 5. The distance is a function of the voltage between them, the environment in which the assembly is to be used, and whether the surfaces are conformally coated:

Table 5: Some recommendations for conductor spacing

DC (peak AC) voltage between conductors	minimum spacing (sea level to 3 km)	minimum spacing (above 3 km)	minimum spacing
	uncoated board		conformal coating
50 V	0.63 mm	0.63 mm	0.38 mm
500 V	2.54 mm	12.7 mm	1.51 mm
>500 V	0.051 mm/V	0.127 mm/V	0.03 mm/V

Dielectric constant and dissipation factor

The dielectric constant (or 'permittivity') is a measure of the ability of an insulating material to store electrostatic energy. It is a dimensionless quantity, whose value is the ratio of the capacitance of a capacitor with a given dielectric to the capacitance of the same capacitor with air as a dielectric. As Table 6 shows, common laminates have dielectric constants in the range 4.0–5.0. These values are calculated from the

capacitance as read on a capacitance bridge, the thickness of the specimen, and the area of the electrodes.

Table 6: Dielectric constant

Material	permittivity (at 1MHz)
FR-2	4.5
FR-4	4.6

Note that these measurements are averages over the electrode area, and there will be local variations because of the presence of the reinforcement, more noticeably with woven reinforcements than with non-woven types. For this reason, specifications for laminates that are designed for high-frequency use will often put limits on the value spread in dielectric constant.

In an insulating material, the dissipation factor is the ratio of the total power loss in the material to the product of the voltage and current in a capacitor in which the material is a dielectric. As with permittivity, dissipation factor varies with changes in temperature and humidity, and also depends on frequency (Table 7). Measurements should therefore always be taken under standard test conditions.

Table 7: Permittivity and dissipation factor of a typical FR-4 laminate

frequency	dielectric constant	dissipation factor	frequency	dielectric constant	dissipation factor
100 Hz	4.80	0.009	10 MHz	4.55	0.022
1 kHz	4.75	0.012	100 MHz	4.50	0.024
10 kHz	4.70	0.015	1 GHz	4.45	0.025
100 kHz	4.65	0.018	10 GHz	4.40	0.025
1 MHz	4.60	0.020			

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Source: http://www.ami.ac.uk/courses/topics/0140_pl/index.html