The T-lam System

T-guide for Manufacturability

Part II: Design Guidelines for Manufacturability with Thermagon T-lam Materials

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T-guide for Manufacturability

Part II: Design Guidelines for Manufacturability with Thermagon T-lam Materials

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The “T-guide for Manufacturability” (Design Guidelines Part II) provides details for designing T-lam Insulated Metal Printed Circuit Board (IMpcb) for Manufacturability, and for addressing the associated manufacturing controls and evaluation issues. Since the manufacturing, performance and reliability issues are not independent; the “T-guide for Performance” (Design Guidelines Part I) should be included as an integral part of all manufacturing considerations. Manufacturability should be interpreted in the broadest terms, and should include designing to insure the specified performance, product consistency, quality, reliability, and costs effectiveness.

The IMpcb manufacturing issues are similar to those for standard FR4 in many respects, although there are a number of special considerations associated with the metal base plate, thicker copper foil, special dielectric isolation, and typically higher power levels. The T-preg dielectric material is quite flexible, relative to other competitive thermal materials, which gives T-lam significant advantages over both standard and thermal materials. The IMpcb is well suited for both SMD and Chip & Wire assembly. Chip & Wire substrates may require the selection of specific surface finish, plating or special surface preparation for specific processes and applications.

The higher thermal conductivity of the T-preg, not only increases maximum device power dissipation and track and via currents, but it can greatly increases the current rating of the leads and connectors. The improved T-lam power dissipation often eliminates costly and awkward thermal and mechanical hardware, and can significantly reduce the product size. This in turn reduces the total product or system manufacturing cost, and as such any comparative cost analysis should not be limited to the power substrate or board.

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1.0 Basic Architecture

The T-lam system provides a broad range of IMpcb boards and substrates by laminating layers of various materials. They can include a metal base, T-preg, FR4 prepreg, copper foil, T-preg DSL, FR4 DSL, FR4 core and metal core. Figure 1 shows the basic materials that are used in some IMpcb examples.

1.1 Single-Sided T-lam IMpcb with Base Plate (See Figure 2)

The most common T-lam is the Single-Sided Board (SSB) or Substrate, built with a metal base plate that is laminated to a layer of T-preg and a layer of copper foil. The circuit pattern is etched into the copper foil to provide electrical routing, and mounting pads for semiconductor devices, connectors and other components. The T-preg dielectric provides excellent heat transfer from the foil and components to the base plate, while maintaining excellent electrical isolation. The base plate gives the single-sided substrate mechanical integrity, and distributes and transfers the heat to a heat sink, mounting surface or directly to the ambient air. The Single-Sided T-lam can be used with surface mount and chip & wire components, and provides much lower thermal resistance than FR4 PWB. The T-lam provides lower cost than ceramic substrates, and allows much larger areas than ceramic substrates.

1.2 Double-Sided Laminate T-lam (See Figure 3)

The Double Sided Laminate or Layer (DSL) is a layer of T-preg laminated between two layers of copper foil. The circuit pattern can be etched in both copper layers, and Plated-Through Vias (PTH) are commonly used to make electrical connections between the layers, and the vias can be used to enhance heat transfer between the layers. The DSL panels are normally used for construction of more complex multilayer IMpcb, although small DSL boards can be used independently where mechanical strength and flatness are not constraints.

1.3 Multilayer T-lam IMpcb (See examples in Figure 4 and 5)

The T-lam system is especially suited for multilayer construction. The Multilayer IMpcb is constructed by laminating one or more DSL and metal base plate or core with T-preg layers which provides adhesion, dielectric isolation and low thermal resistance. The T-lam system provides flexible layers, which make the multilayer exceptionally durable in temperature cycling, power cycling and mechanical vibration & flexing. This reliability feature is unique for this type of high thermally conductive multilayer.

1.4 Hybrid Multilayer IMpcb with both T-preg and FR4 (See example in Figure 6)

The T-lam materials can also be used to produce Hybrid Multilayer IMpcb, where select T-preg layers are replaced with lower cost FR4, in layers where good thermal conductivity or special dielectric properties are not required. The FR4 can provide mechanical integrity, and can sometimes be used in place of the metal base plate or a thick copper core. Hybrid systems without a metal base plate often depend on a thick copper foil ground plane to distribute the heat across the PCB, and are generally not mounted on a heat sink.

2.0 Base Plate

The IMpcb substrate is normally built on a metal base plate. Aluminum is typically used for good thermal conductivity, best TCE match to the dielectric, lower cost, lighter weight and fabrication ease. Copper is sometimes used for better thermal conductivity, better mechanical strength, better TCE match to thick copper foil, and compatibility with soldering and plating processes. In most applications, the thermal advantages of the copper base plate are insignificant, because the thermal resistance of the base plate is small relative to the thermal resistance of the dielectric layer and the components.

2.1 Aluminum and Copper Alloys for Punching, V-Scoring and Routing

The standard base plates are aluminum or copper alloys. The specific alloys and hardness recommended for products are dependent on the thickness, layout and the singulation technique. Singulation is defined here as the separating of the panel into individual substrates or boards. The recommended alloys are shown below. Details for the associated singulation techniques are followed by key physical, electrical and thermal properties of the aluminum and copper.

Standard Aluminum Base Plates:

Thickness in Inches	Alloys for Punching	Alloy for Routing, Shearing & V-Scoring
0.020	1100-H14	6061-T6
0.031	5052-H14	6061-T6
0.040	5052-H34	6061-T6
0.062	5052-H34	6061-T6
0.080	5052-H34	6061-T6
0.125	5052-H38	6061-T6
0.250	5052-H38	6061-T6

Standard Copper Base Plates

Thickness in Inches	Alloy for Punch, Rout Shear & V-Score
0.020	C11000
0.031	C11000
0.040	C11000
0.062	C11000
0.080	C11000

2.2 Properties of Aluminum and Copper Base Plates

The following thermal, electrical and mechanical properties are similar for the recommended aluminum and copper alloys, and the typical values shown below will be sufficient for most calculations. More precise numbers are available for the specific alloys on request.

Properties of Standard Base Plates @ 20 C:	Aluminum	Copper
Thermal Conductivity (W/mK)	190.0	390.0
Electrical Resistance (micro ohm-cm)	2.7	1.7
Thermal Coefficient of Expansion (ppm/C)	24.0	17.0
Modulus of Elasticity (10E+06 psi)	10.0	17.0
Density (grams/cubic cm)	2.7	8.9

2.3 Special Base Plate Materials:

The T-preg materials are exceptionally well suited for a broad range of special materials, because their flexibility accommodates a broad range of base plate TCE and thickness. Special materials may be used for mechanical strength, TCE or chemical properties, but such materials typically sacrifice thermal performance or add cost. Examples of a few alternate base materials are steel, nickel, copper/Invar/copper and copper/moly/copper.

2.4 Anodized Aluminum Base Plates

Aluminum base plates with the backside anodized are an available option. Anodization can minimize scratching and visual defects that are created during substrate or assembly processing and handling. The anodization will slightly increase thermal resistance and cost, but these increases are very small, and may be acceptable where aesthetics is important to an end product. Anodization is typically Type 2 black or clear, but other colors are usually available through the fabricator.

2.5 Singulation by Stamping, Scoring and Routing

The choice of the singulation technique is important for unit and tooling cost, sample lead-time, quality and precision, and sometimes for material utilization.

2.5.1 Milling or CNC Routing is often used for prototypes or very low volume custom products. It requires no tooling and can provide complex shapes and details, but the cost is usually too high for production. When routing is used, holes for mounting or alignment are usually drilled in panel form, which can be done quickly and precisely, and at a lower cost. Routing leaves a flat substrate, but convex shaping can be obtained with a secondary operation, if required.

2.5.2 Scoring is often used in applications where square corners are acceptable. Scoring is performed by cutting V-grooves between the individual substrate on both sides of the panel, and then breaking out the individual substrates. Although radius corners can be routed, radius corners are generally not economical beyond prototypes. As with routing, holes are usually drilled in panel form. Scoring is used for high volume production, and requires no tooling. There is no lost material between parts, which often makes it cost competitive at high volumes. The edge of the scored substrate is not as cosmetically clean as routed or stamped substrates, and may require secondary finishing operations for some applications.

2.5.3 Punching is used for high volume production, because it usually provides the lowest unit cost when tooled. Punching can provide complex shapes and holes in a single operation. Punching does require expensive tooling and lost material between parts, and does have some limitations on fine detailing and tolerances. The punching tools must be recessed in the circuit area, so that the tool only contacts the top surface of the substrate in the foil free border. The width of that border area is typically equal to the thickness of the base plate. Punching typically creates a burr on the upper or dielectric side of the substrate, but it can be removed with a secondary operation if no burr is allowed. The type of punching tool can significantly influence tooling and units cost. The primary types of tools are 1) single punch with manual index, 2) single turret punch, and 3) multiple punch.

The Single Punch with manual index is the lowest cost tool, and is often made as a soft tool using steel to produce initial stamped parts and to qualify the tool design. This initial tool is then replaced by a hard steel or tungsten carbide tool, for high volume production. The soft T-preg dielectric can often be punched with a hardened steel tool in high volume production, eliminating the need for the more expensive tungsten carbide tooling required by many competitive thermal materials.

Turret Punches utilize a single cavity tool, but with high speed automatic indexing. This can reduce the unit cost at high volume. Tools for Turret Punches are generally used for many more hits, and are typically made of tungsten carbide for longer tool life. The tungsten carbide tool is more expensive than a steel tool, but the automatic indexing reduces the unit cost.

Multiple Unit Punches or Multiple Cavity Punches are another way to increase the rate and reduce the unit cost. The tooling is more complex, but reduces the number of hits per cavity. Therefore, it is often possible to build high volume multicavity tools with steel, rather than the higher cost tungsten carbide tool. This option can be even more attractive with the lower abrasiveness T-preg materials.

The T-preg material is especially suited for punching, because the ceramic filler content of the dielectric is much lower than in most metal-based thermal substrates. In addition, the unique T-preg filler can act as a lubricant, in contrast to the abrasive alumina used in most competitive products. This gives much longer tool life and less tool sharpening with the T-lam materials. Note; some manufacturers highly thermal conductive materials require the tool to be sharpened every 1,000 hits.

Punched parts are typically produced with the base plate burr up, or towards the foil side. This allows optimum seating of the substrate base plate to a heat sink, and a small topside burr can generally be designed around. If the application requires no burr, it can be removed in a secondary operation. The maximum burr for the different singulation techniques is given in section 2.7.

2.6 Substrate Camber and Flatness

The flatness varies with substrate layers and thickness, and with the technique selected to singulate the substrates. If the base plate or laminated FR4 layer is sufficiently thick and rigid for a given substrate size, and the foil is not excessively thick or irregular, then the flatness shown below can be achieved with the specific singulation techniques. Copper base plates can provide quite flat surfaces over larger areas, because the TCE of the base plate matches the foil, and the copper base is stronger than the aluminum for a given thickness.

2.6.1 Routing and Scoring can achieve +/- 0.001” per inch camber, and often less than +/- 0.001” per inch flatness across large substrates.

2.6.2 Punching can achieve +/- 0.002” per inch, and often less than +/- 0.002” per inch flatness across larger substrates. Punching can shape or bend the substrate surface to provide better thermal contact when mounted to a heat sink or other surfaces. In high power modules, where thermal contact is critical, the bottom surface of the base plate is often formed convex, typically by 0.001” to 0.003” per inch. Again, the exceptionally flexible T-preg allows more convex forming than other high thermally conductive dielectrics.

2.7 Panelization and Substrate Tolerances

The T-lam is laminated in 24”x18” nominal panels. The usable panel area depends on substrate size, singulation technique and base plate thickness (t). The basic guidelines for panel borders, substrate spacing, substrate dimensional tolerance and maximum burrs are shown below based on the recommended aluminum alloys. Copper base plate guidelines are similar, but insufficient statistical data is available to quantify specific differences. Very small or very large substrates may also deviate from these general guidelines.

Punching	Routing, CNC	V-Scoring, both sides	Punching Single	Multiple
Minimum Panel Border	0.500”	0.500”	0.500”	0.500”
Minimum Substrate to Substrates	1t	0.000”	2t	2.5t
Typical Substrate L & W Tolerance	+/-0.002”	+/-0.010”	+/-0.005”	+/-0.005
Maximum Burrs	0.002”	0.002”	0.007”	0.007”

2.8 Corners, Holes and Base Plate Ground Connections

Substrate corners are punched or routed, and scored substrate either have no radii, or the radii are routed or punched in a secondary operation. The minimum radii for the different singulation techniques are shown below.

Mounting holes and alignment holes can be drilled or punched. Punched holes are the lowest cost, but do require a more complex stamping tool. Drilled holes are done preferably in panel form to minimize handling, and to utilize high speed and high precision standard PCB equipment. A small number of alignment holes are required in all panels for standard processing. In general, post singulation hole drilling is less precise and more expensive.

	Drilled,	Routed	V-Scored	Punched
Corner Radius, Outside (Min.)		0.000”	0.000”	0.7t
Corner Radius, Inside (Min.)		0.7t		0.7t
Bridge, Edge to Hole (Min.)		0.5t	0.5t	1.5t
Hole Diameter (Min.)	0.2t			1.0t
Hole Diameter (tol.)	+/-0.002”			+/-0.005”
Hole Location, hole to holes (tol.)	0.001”			0.001”
Hole Location, hole to edge (tol.)		0.005”	0.010”	0.001”

Some applications require Ground Connections from the circuitry to the base plate. Generally, this is a special operation, and a cost to be avoided where possible. If a ground connection is need, there are a number of standard approaches to select from:

a) Milling or drilling shallow flat bottomed hole into the top of the base plate can allow aluminum wire bonds from the base plate to the circuitry. Although this may be a simple and lower cost technique, it is only applicable to chip & wire products with aluminum wire bond capability.
b) A more general approach is to drill a small hole for a press-fit pin, which can be inserted down into the base plate, and soldered to the copper circuitry with the components. The individual pin insertion will increase costs, and should be automated in high volume products. Often stand-offs or other hardware at mounting holes can be used for the ground connection, and serve a dual function.
c) Drilled and plated holes are also possible, but require a number of special preparation steps and operations. This approach is easier with copper base plates, which can be plated directly.

Although there are other options for base plate ground connections, they are not standard processes, at this time. Many products can utilize existing leads of connectors to provide the ground connection off the substrate. The current requirement for the ground connection can vary with product and function. For example, the connection may be a low current connection for a ground shield, or it may be required for a high current fault. Note; some fault current connections are controlled by regulator agency rules.

3.0 Dielectric Layer

3.1 General Considerations

The T-preg dielectric is normally selected for performance, and the thermal, electrical and reliability advantages can be found in the Thermagon "T-guide for Performance".   Although the T-preg can be effective at reducing system cost or even substrate cost at higher power levels, this is often dependent on reducing the substrate size, or limiting the number of T-preg layers to those required specifically for the performance advantages.

3.2 T-preg Thermal Dielectric

The standard 0.008" thick T-preg layer provides low thermal resistance and high dielectric strength for most applications. Special high voltage AC or DC applications may require thicker dielectric layers, which will increase both thermal resistance and cost. Lower voltage applications can use thinner layers to provide even lower thermal resistance. Manufacturing costs may increase for very thin T-preg layers.

The T-preg has excellent flow properties during lamination, and therefore can accommodate the irregularities of the DSL layers with thick copper foil patterns by flowing into low areas and filling vias. In designs where this feature is used, it is important to increase the T-preg thickness to provide the necessary reservoir of material, and to avoid thin or depleted areas. When laminating pre-etched DSL into a multilayer, it is usually best to select a T-preg thickness of about four times the thickness of the etched foil, but this requirement will vary with layout pattern and associated layers. If the final thicknesses are specified in the procurement specification and drawing, then Thermagon or the fabricator will select the beginning T-preg thickness to reach the finished specification.

In the final lamination of multi-layer boards, it should be noted that the T-preg in the DSL is pre-cured and the separating T-preg is uncured. Therefore, the bottom and top surface of the multilayer will be flat, and the DSL will flex and bend to conform, and the separating T-preg will flow to accommodate the thickness variations in the pre-etched DSL.

The T-preg dielectric has been promoted for it's flexibility as an advantage with thicker copper foil and copper base plates, but the T-preg softness can be a disadvantage with very fine lines and many layers. Therefore, minimize T-preg thickness and number of T-preg layers with complex boards having very fine lines and spaces. It is suggested that when using very fine lines and spaces, that you consult the factory for specific recommendations, and that you confirm dimensional stability with engineering samples. Note; these limitations do not apply to most products.

As mentioned, the T-preg dielectric is very flexible and is typically laminated to a base plate or an FR4 layer for mechanical integrity.   The minimum thickness of the base plate or FR4 layer will depend on the size, and the required flatness and the required structure. In principle, if there are no flatness and structural requirements, a flexible DSL or multilayer could be used as an independent board. In fact, some production products have no base plate or FR4, and use an internal copper foil plane for support.

3.3 FR4 and Special Dielectrics

The T-lam system is compatible with most laminating dielectric materials including FR4, FR5, polyimide, etc. Hybrid combinations of T-preg and FR4 can capitalize on the advantages of each material, while using lower cost materials where the special T-preg performance is not needed. See example in Figure 6.

4.0 Copper Foil

4.1 Material Selection and Properties

The metallization or foil layers are used for electrical routing, heat conduction and distribution, and for pads to solder, epoxy, and wire bond components and connectors. As with standard printed circuit boards, the foil material is IPC Class 2 electro-deposited (ED) copper, and is available in six (6) standard weights, ½ oz., 1oz., 2oz., 3oz., 4oz. and 6 oz. The thickness and resistivity of the standard weight copper foils are shown below.

Weight	Thickness	Resistivity @ 20 C	Resistivity @ 130 C
0.5 oz	0.0007”	0.956 mohm/sq.	1.367 mohm/sq.
1.0 oz	0.0014”	0.479 mohm/sq.	0.686 mohm/sq.
2.0 oz	0.0028”	0.239 mohm/sq.	0.343 mohm/sq.
3.0 oz	0.0042”	0.160 mohm/sq.	0.229 mohm/sq.
4.0 oz	0.0056”	0.120 mohm/sq.	0.171 mohm/sq.
6.0 oz	0.0084	0.080 mohm/sq.	0.114 mohm/sq

In addition to the standard ED copper foil, other copper foil thicknesses are available, and compatible with the T-lam system. The initial foil thickness may be increase during via plating, or reduced during surface conditioning. Aluminum foil is also available, and can provide a lower cost and lower weight alternative for thermal planes, but does have some process compatibility issues with vias and electrical connections. In some applications, it may be possible to use the aluminum foil for wire bonding.

4.2 Line Width and Edge-to-Edge Space Considerations for Manufacturability

In principle, the T-lam etching and plating processes are identical to those used with standard PWB. T-lam can typically achieve the same lines and spaces as PWBs, with the same manufacturing trade-offs. The etched copper foil tolerance is typically +/-20% of the foil thickness. There are two differences that may apply to T-lam:

4.2.1 The T-preg dielectric is softer and line position stability may be less with very fine lines.

4.2.2 T-lam is usually used for improved performance at higher power levels, and foil thicknesses are typically greater than standard PWB.

The following are minimum line widths and edge-to-edge spaces and preferred minimum line widths and spaces for manufacturability with standard processes. The preferred limits can increase yield or process ease, but they are not required. Smaller lines and spaces may be achievable, but may require special processing and increase cost.

Copper Weight	0.5 oz	1.0 oz	2.0 oz	3.0 oz	4.0 oz	6.0 oz
Minimum Line Width	0.005”	0.008”	0.012”	0.015”	0.020”	0.025”
Minimum Line Spacing	0.005”	0.010”	0.015”	0.020”	0.025”	0.030”
Preferred Min. Line Width	0.010”	0.015”	0.020”	0.020”	0.025”	0.030”
Preferred Min. Line Spacing	0.010”	0.015”	0.020”	0.025”	0.030”	0.035”

4.3 Line and Space Considerations for Performance and Safety

Electrical or safety considerations may require greater line widths and/or spaces, than are defined by the minimum or preferred limits for manufacturability.

4.3.1 High currents may require increased line width. The T-lam width for high currents are significantly less than for standard FR4 PWBs, because the T-lam is much more effective at removing the heat from the traces. The Thermagon T-guide for Performance provides the maximum current for various line width and foil thickness. Note, if the line width is very fine or the foil very thick, it may be necessary to compensate for edge etching contours, but such factors will vary with fabricators and their processes.

4.3.2 The T-lam line spacing for performance and safety are a function of working and rated voltages, and are often defined by the safety regulatory agency, which govern the end product. These agencies may include UL, VDE, EC and CSA. The spacing may be limited by operating voltages, peak transient voltages, peak recurring voltages and comparative tracking index (CTI). Other influencing factors may include power levels, function and environment exposure. UL and EC have spacing requirements based on levels of moisture and cleanliness, as defined for different pollution levels. These regulations are complex and product specific, and beyond the scope of this design guidelines. It should be noted that there are major differences in spacing for applications, environment, and interpretation of the application. For example UL508C and UL840C cover industrial controller products, but UL840 can allow much smaller spacing, if the pollution level or transient levels are controlled or known. This is important for manufacturing, because it can allow the product to be designed much smaller, and may make significant reductions in material and labor costs. Size can also be a major competitive feature of the end product.

If the minimum spacing is not controlled by regulatory agencies, there may still be special spacing requirements imposed by the end product working or rated voltage, or by the spacing required for hipot testing. The use of the safety agency rules for minimum spacing is recommended for products with high working and rated isolation voltages, even if those agencies do not govern the products.

4.3.3 Hipot testing is often required at levels above the rated operation and isolation voltages, as a screen for potential defects or to reduce hipot testing time. Therefore, the spacing between lines and the edge of the substrate, mounting holes and ground pads, must be increased to insure that there is no arcing during such hipot testing. The following minimum spacings are recommended to prevent surface arcing at 20 C and 60% relative humidity.

Hipot Test Voltages	Minimum Spacing
1000 VAC or 1500 VDC	0.040”
1500 VAC or 2000 VDC	0.060”
2000 VAC or 3000 VDC	0.100”
2500 VAC or 3500 VDC	0.150”
3000 VAC or 4200 VDC	0.200”
3500 VAC or 5000 VDC	0.250”

4.4 Surface Preparations, Plating, Solder Coating and Other Special Treatments

The exposed copper foil can be a good material for the most common electrical and mechanical connections, including soldering, epoxy chip attaching, wire bonding and mechanical contacts. Although the copper is metallurgically compatible with many solders, epoxies and wire bond materials, copper is easily oxidized in storage and high temperature processes. Therefore, the surfaces are often cleaned, coated or treated, to improve the ease, quality and reliability of the solder, epoxy and wire bond joints and interfaces.

4.4.1 Exposed Copper Surfaces

Exposed copper surfaces should be ED copper plated, and shipped in sealed packing materials, and stored in nitrogen after opening. Exposed copper will have a limited shelf life, which is dependent on initial condition, packing, storage and final application.

Exposed copper that will be used to solder surface mount components and leads are often coated with an anti-oxidant, which is removed by the heat during the soldering operation. Such materials maintain a clean and un-oxidized solder surface, and extend the shelf life of the T-lam substrate or PWB.

Exposed copper that will be used for aluminum ultrasonic wire bonding, must be smooth and continuous, and must be kept exceptionally clean. Slightly oxidized copper surfaces may require a chemical, abrasive or plasma cleaning to assure a good wire bondable surface.

4.4.2 Solder Resist

Solder resists are often required to limit and control solder coverage, and to protect lines from mechanical or environmental damage and contamination. Standard PWB solder resist processes and materials are used with T-lam. Since the T-lam is typically used at higher powers and currents, the foils are generally thicker and more difficult to completely cover at the edges of tracks. Therefore, it is often necessary to apply thicker or multiple coats of solder resist, where complete edge coverage is required. If the design requires guaranteed edge coverage for safety or regulatory rules, the solder resist is generally not sufficient, and an appropriate conformal coating or potting compound can be applied after assembly to guarantee coverage.

4.4.2 Solder Coating

The T-lam substrates can be provided with the standard solder coatings on copper pads and traces. Although solder dipping, solder plating and solder paste screening are all available processes, the standard Hot-Air Leveling solder coating is the most common technique, and it is often the most economical coating. It is also easier to apply to products with metal base plates. Hot-Air Leveling eliminates copper oxidation, guarantees good wetting, and provides a thin and uniform solder coating. A tin-lead eutectic solder is usually used, but other low temperature soft solders are also possible.

4.4.3 Plating

Plating can reduce oxidation, provide mechanical protection, and improve the surface for special soldering and wire bonding operations. T-lam materials can be used with all the standard plating materials that are used with PWB and ceramic substrates. These can include Nickel, Solder, Silver, Gold, Tin, etc. The most common include:

1) Nickel (Ni) plating can be used for both soldering and wire bonding, and the typical thickness is 100 to 300 micro-inches. Ni does slow the oxidation rate, but Ni oxide is more difficult to see and remove, relative to copper oxide. Ni can improve the wire bond surface, and is often plated with a 7 to 12% phosphorous content, to improve the surface finish for aluminum ultrasonic wire bonding. Nickel plating can be electroless or electrolytic, but electroless is normally preferred for PWB and T-lam.

2) Nickel plus a flash of gold (Au) is often used to prevent the Ni from oxidizing. The Au thickness should not exceed 15 micro-inches on a surface that will be soldered. The Au is lost in the soldering and ultrasonic wire bonding operation, and both joints are made to the underlying Ni plating. The gold plating can be electrolytic Au or immersion Au. Electrolytic Au should be 3-5 micro-inches, but immersion Au should be 8-10 micro-inches to eliminate porosity that could allow the underlying Ni to oxidize. Immersion Au is typically used with electroless Ni, and preferred for board manufacturability. If the surface is used for gold wire bonding, thicker Au may be required and 15 to 50 micro-inches are recommended.

3) Solder plating is possible, but today Hot-Air solder coatings are quite well controlled, more common, and they cost less. If solder plating is required, the recommended nominal thickness for unfused Sn/Pb is 300 micro-inches.

5.0 Electrical & Thermal Vias

Vias are used to make electrical connections between foil layers of the T-lam multilayer boards as they are used in standard PWBs. They can also be used to enhance the thermal conductivity between non-isolated copper foil layers. In general, the process and capability is identical to those for PWBs, with the exception that the isolated vias cannot go through the metal base plate or heavy metal core foil of the T-lam.

5.1 Via Size, Pitch and Plating

Vias and some mounting holes are drilled in panel form. Vias are typically drilled in the DSL prior to the complete T-lam lamination, and often, additional vias or holes are added to the fully laminated panel. Vias that go completely through the DSL are less expensive, because they allow panels to be stacked and drilled together. As with standard PWBs, blind vias are only used, where they can improve board density or performance, or where they limit unwanted T-preg flow, and bind vias do increase cost.

Via size and pitch can be the same as with standard PWBs, but there are potential limitations with very fine lines for thicker T-preg or too many T-preg layers. The minimum via drill diameter is 0.008-0.010", although smaller vias may be possible in special circumstances. In general, T-lam is used at higher currents and power levels, and larger vias and/or multiple vias are more common. Larger but fewer vias are often preferable for manufacturing yield and minimum cost.

Pitch and pad size rules are generally identical to PWBs, except where pitch is defined by thermal or electrical performance requirements. See the T-guide for Performance for specific recommendations on via size and pitch for performance.

Via wall plating thickness can be very important where vias are designed to carry high currents or to transfer significant heat. Therefore, wall-plating thickness must be well controlled and uniform. If small vias must be used for high current, it is best to plate via walls above the necessary nominal thickness to compensate for any potential thin areas.

5.2 Electrical Connections

Although small vias or PTHs are often use for lower currents, T-lam is often used on high current products where small vias must handle significant currents. The maximum current ratings for vias are a function of size, wall thickness, foil thickness, dielectric thickness, type of dielectric, and maximum base plate temperature. The maximum current of vias is limited by the maximum via temperature, and because the T-lam is thermally superior to the standard PWB, T-lam vias can handle significantly higher currents. See the Thermagon T-guide for Performance for maximum current rating of T-lam vias.

5.3 Thermal Enhancement

As with standard FR4 PWBs, the vias can be used to transfer heat from one foil layer to another. However with T-lam, the heat transfer can be further improved by removing the heat through the T-preg and the aluminum base plate. It is the combination of the thermal vias and T-preg dielectric that makes the T-lam multilayer system so thermally effective. The thermal resistances between the Topside pads and the base plate, using multiple thermal vias, are shown in the Thermagon T-guide for Performance, and are a function of via size, via pitch, via wall thickness, foil thickness, dielectric thickness, and maximum base plate temperature. See Figures 5 and 6 for examples of thermal vias in T-preg and hybrid multilayer IMpcb.

Many layered multi-layered T-lam boards are often T-preg and FR4 hybrids. These boards use the T-preg in critical thermal layers that require excellent electrical isolation, and use FR4 with Thermal vias to enhance thermal conductivity through the less critical and lower cost FR4 layers. The combination reduces the total board cost and increases trace stability in complex fine line computer board applications. The location of the thermally critical T-preg depends on the heat source, the method of heat removal, the internal via configuration, and the metal pattern and plane layers. In principle, the highest thermal resistance in the path from source to ambient must be identified, and reduced with copper planes, PTVs, T-preg dielectrics, and/or heat removal system.

6.0 Component & Mechanical Hardware

6.1 Component Considerations

T-lam system is designed for SMD and Chip & Wire components and connectors. The Standard PWB and Ceramic substrate assembly rules are generally applicable. Thru-hole components are not generally suited for metal-based substrates like T-lam, but provisions can be made for select thru-hole components. Such Thru-Hole provision will carry a cost penalty, and should be very limited.

6.2 Mechanical Hardware and Mounting Issues

As with PWB, the T-lam foil and surface mount pads are not recommended as supports for mechanical hardware and substrate mounting. The flexibility of the T-preg, which provides the superior resistance to thermal-expansion damage, does reduce the absolute peel strength of the T-lam. This is generally not a problem with components, but can be an issue with mechanical hardware and support, which can generate both higher forces and higher torques. Torque is important because it can create a peeling action on the pads. Components generally do not exert torque, and their strength is a function of pull strength.

Mounting holes with screws, rivets and clamps are generally recommended to support the substrates, subsystems and larger hardware. If it is necessary to solder large components or hardware to the T-lam without mounting screws, the components or hardware should be designed to only apply pull forces and not peel forces, because T-lam pull strength is very much higher than the peel strength. The T-lam peel strength is 6 pound per linear inch (pli), whereas the pull strength is approximately 1000 psi. This relationship between peel and pull strength is also true for standard PWBs, and it is generally not recommended to attach heavy components or mounting hardware by solder on standard PWBs.

6.3 T-lam Board and Substrate Mounting Issues

6.3.1 Card or Slot Mounting

T-lam substrates or boards that replace a PWB may be mounted as a card or in slots. If the base plate is thicker and heavier than a standard PWB, wider slots or additional mechanical support may be required. Also, double-sided connector contacts are not applicable with base plates. Often it is necessary to select thinner base plates and layers to fit standard slots, and a thinner copper base plate can provide the same function as aluminum at a slightly higher cost.

The T-preg improves thermal conductivity to ground planes or the base plate, but it is important to be sure that the extra heat is removed. The mounting technique may remove some heat and be important to overall thermal performance of the system. Important factors include;

1) The ground plane or base plate provides excellent heat distribution, and may be sufficient to provide transfer of the heat to ambient air in the conventional card rack.

2) If the power levels are sufficiently high, it may be necessary to remove heat with metal slot clamps, increased board spacing, or forced convection. It should be noted that slot or clamp temperatures may be different than the ambient air temperature. See the T-guide for Performance for more specific thermal data and recommendations.

6.3.2 Heat sink Mounting

At high power levels, it is often necessary to mount the T-lam substrate directly to a heat sink, or the heat sink directly to the T-lam. The heat sink must be flat and have a satisfactory surface finish. Mounting holes and base plate thickness must be sufficient to guarantee good thermal contact and pressure through the life of the product, and through the heating and cooling cycles of the specific application. Good thermal contact can be improved with a convex surface on the bottom of the T-lam base plate, and with the addition of thermal interface materials, like greases, pads or coatings. Thermagon provides a broad range of high performance interface materials. The mounting and thermal interface issues are more like those encountered with power component and modules, than with PCB component mounting. Good thermal contact may depend on many factors including base plate material, size, shape and thickness, mounting screw size, number, location and torque, and support/rigidity from components, potting and mechanical braces. The Thermagon T-guide for Performance provides additional information to help with your system thermal management.

7.0 Inspection & Test

7.1 Electrical Testing

7.1.1 Short and Open Testing
Most boards of any complexity, or with fine lines and spaces should be 100% Short & Open tested. This capability is available at most fabricators. If the lines and space can be sufficiently over designed or simplified, it may be possible to eliminate short and open testing, and associated costs. High current testing may be required in some power products, but this capability is not as readily available at all fabricators, and should be avoided if possible with adequate design margins.

7.1.2 Hipot Testing
Substrates or boards that have a high isolation voltage requirement, or rated isolation voltage should be 100% hipot tested by the fabricator before shipment, and should be sample checked at incoming inspection or before assembly. High isolation voltage may be required between circuitry and base plate, or between input and output circuitry. DC hipot testing is preferred for T-lam and other metal-based substrates, because of the higher capacitance, but AC is usually possible. If the end product requires 100% hipot testing by regulatory agencies, it is generally preferable to test at 120% of the rated voltage, to allow reduction of the test time from 1 minute to 1 second. If the material, layout and edge spacing is not sufficient for such elevated voltage testing, the necessary testing may be very time consuming and expensive.

7.1.3 Special testing
If there are special critical electrical substrate requirements for the end product, it may be worth testing them at the substrate level. These may include capacitance, resistance, high current, etc. These tests are not typically performed by the fabricator, and need to be specified and agreed upon if required. Optionally, such tests can be performed by the user at incoming inspection, or simply guaranteed by over-design. The T-guide for Performance can help with requirements to guarantee by design and nominal values.

7.2 Mechanical and Dimensional Inspection

In general, mechanical dimensions and tolerances are determined by artwork and tooling, but select critical dimensions should be checked to assure that the process is in control. Critical dimensions should be sampled at the fabricators outgoing inspection and the users incoming inspection. Important parameters may include substrate size, hole locations & size, pattern to substrate location, line width and spacing, and base plate & metallization flatness & finish.

7.3 Visual Inspection

Visual inspection should include workmanship, cleanliness and condition, visual color, oxidation & finish, special marking requirements like part number, date code, serial number, etc., and special packaging requirements.

Visual inspection should not be used to guarantee critical performance or as a screen for critical defects.

8.0 T-lam Procurement and Ordering

Thermagon primarily provides T-preg, T-lam DSL and IMpcb materials, and the T-lam substrates and boards are usually ordered through qualified PWB fabricators. Thermagon can provide a list of qualified fabricators. Initial samples or samples with special engineering issues are often procured directly through Thermagon. Specification of T-lam materials in procurement drawings, either to Thermagon or to fabricators, should use the Thermagon part numbers.

8.1 Part Number System

The T-lam materials or building blocks are defined as T-preg Dielectric, Single Sided Board (SSB) and Double Sided Layer (DSL). Multilayer Boards are constructed from the building bocks listed above, and are sometimes used in conjunction with standard prepregs, foils, base metals, resist, and other materials. The Thermagon part numbers for the three primary building blocks are:

8.1.1 The T-preg part Numbers System: **T-preg-1KA-08-F1** is an example where,

1KA is Standard T-preg Material
-08 is the 0.008" T-preg Thickness(Thicknesses of 06, 08, 10, 12 & 20 are standard.)
-FG1 is a Single Layer of Fiberglass

8.1.2 Single Sided Board Part Number System: **IMPCB-1KA-06-AL6-125-06** is an example where,

1KA is the Standard T-preg Material with one layer of fiberglass.
-06 is the 0.006" T-preg Thickness (Thicknesses of 06, 08, 10, 12 & 20 are standard.)
-AL6 is a 6061-T6 Aluminum Base Plate (AL5-5052-H34/H38 aluminum and CU-C11000HH Copper are also standard base plate materials.)
-125 is the 0.125" Aluminum Base Plate Thickness (see section 2.1 for standard base plate thicknesses.)
-06 is the 6 oz Copper Foil weight (See section 4.1 for standard foil weights and thicknesses.)

8.1.3 Double Sided Layer Part Number System: **DSL-1KA-12-02/02** is an example where,

1KA is the Standard T-preg Material with one layer of fiberglass.
-12 is the 0.012" T-preg Thickness (Thicknesses of 06, 08, 10, 12 & 20 are standard.)
-02/02 is 2 oz Copper Foil on both sides (See section 4.1 for standard foil weights and thicknesses.)

8.2 Typical Procurement Specification

The procurement specifications and drawings will vary with products and product applications, but the following is a checklist of items that may be important to in a typical T-lam substrate and board procurement specifications:

8.2.1 Substrate or Board Outline Drawing with dimensions on length, width and thickness, hole locations and sizes, dimensions on radii and special features, base or board flatness, shape and surface finish requirements, and tolerances on all of the proceeding parameters where applicable.

8.2.2 Gerber files or equivalent files for all foil layer layouts, interconnect via locations, special panel drilled hole locations, marking, solder resist layout, labeling and logo artwork, and location reference points.

8.2.3 Specification for individual layers with base plate and core material and thickness, foil type and weight, dielectric type and thickness, DSL type, thicknesses/foil weight, solder resist type, thickness and layers, marking ink type and color, and special plating, coatings, and solder requirements. The plating and solder requirements may need details on application technique, composition and additives, thickness and surface finish. The details and tolerances may be left to the fabricators discretion in standard or non-critical products, or they may need to be defined precisely in products with high performance requirements, or with special assembly processes and materials. Chip & Wire products generally require more detailed specifications to insure compatibility with special materials, processes, and equipment. Fine line SMD may require more precise position and tolerance details. Special fiducial or reference points may be required for automatic assembly.

8.2.4 Special electrical requirements may be specified, or they can be controlled by the selection of materials and design. It is important to be specific if requirements are critical, non-standard, and if special testing or screening is required. See section 7.1 for typical electrical requirements and tests. If testing is specified, define as 100% or the required sampling plan. Special testing may increase the fabricators cost and prices, and should only be used when the parameters cannot be controlled with materials, process or design.

8.2.5 Mechanical requirements are generally controlled by the drawings and specifications, and the selection of materials. If such requirements are critical, lot sampling or screening tests can be defined to monitor and confirm compliance. See section 7.2 for examples of special mechanical requirements. As with special electrical testing, special mechanical testing will also increase cost, and should be avoided where possible.

8.2.6 Other requirements may include C of C, special packing, storage, cleanliness, labeling, etc. The fabricator will use their internal standards, if such special requirements are not clearly specified and agreed upon in advance.

9.0 Assembly Guidelines

T-lam is essentially a printed wiring board with special mechanical, thermal and electrical performance properties. The top foil, coatings and solder resists are the same materials and use the same fabrication processes as standard printed circuit boards, and therefore are generally compatible with the same assembly processes. The primary differences for T-lam that may affect assembly are 1) higher physical and thermal mass with metal base plate, 2) typically thicker copper foil for higher current and power levels, 3) softer and less rigid dielectric layers, 4) not suited for thru-hole components, and 5) often mounted on heat sinks to dissipate more heat.

9.1 SMD Assemblies

The top metal foil pattern and solder resist should be designed for SMD components using the same pad size, space and tolerance guidelines used with standard PWB. Very fine lines may be a little less stable, because of the softer dielectric, but this is typically not a problem in most products. In general, the more flexible T-preg eliminates or reduces thermal mismatch problems, which may occur with standard FR-4 PWBs, and generally this makes T-lam more accommodating with the fragile and larger components that are most effected by TCE mismatch.

The solder reflow process must transfer more heat to the T-lam substrate because of the higher thermal mass or heat capacity of the base plate and the thicker copper foil. This may require higher temperature settings and/or slower belt speeds for the reflow equipment. Equipment with conduction heating is ideal for maximum heat transfer with products that have metal base plates, but convection and IR heating are often used because that equipment is more readily available on standard PWB assembly lines. Many convection and IR systems allow a larger degree of heating from the bottom or base plate side, which provides faster heat transfer without over heating topside components. T-lam with no base plate, or with components on both sides is most easily reflowed in convection or IR systems, but it is still important to guard against overheating low mass components.

Tin/Lead (Sn/Pb) eutectic solders are most commonly used, but some non-eutectic Tin/Pb and Tin/Silver (Sn/Ag) eutectic solders can be used. The Sn/Ag solders are stronger with a slightly higher reflow temperature, and are often used for power die or when a two solder system is required. The maximum recommended reflow temperature is 260 C, and the time at temperature should be minimized to reduce flux hardening. A nitrogen or forming gas atmosphere will also reduce flux burning and hardening, and usually is required if reflowed at the higher temperature extremes or with a higher temperature solder like the Sn/Ag solder. The T-preg resin is similar to the FR4 resin, and the same fluxes, cleaning materials and cleaning systems are typically used.

Solder rework is possible, but will require supplementary heating, because of the large thermal mass of the base plate. In general the T-lam substrate should be pre-heated from 85 to 115 C, and then the components can be removed by applying local heat to the individual components using a soldering iron or a hot air jet. As with PWB, rework should be avoided whenever possible.

9.2 Chip & Wire Assemblies

Chip & Wire assembly is basically like Chip-On-Board assembly, except for higher power products. The power dissipation is often similar to ceramic power modules, but costs are much lower and more like a printed circuit board. In fact, with the heat spreading of the thicker copper foils or soldered copper heat spreaders, the T-lam can often provide thermal resistances as low as the Direct Bond Copper (DBC) alumina and aluminum nitride, without the inherent high prices and the TCE mismatch cracking weaknesses of the DBC alumina and aluminum nitride.

9.2.1 Die Attach

Die attach can be performed with epoxy or soft solder, although some higher temperature soft solders or long curing epoxies may not be compatible with the 1KA T-preg.

Most common silver, gold and insulating die attach epoxies are suitable, with curing temperatures of 150-175 C for periods of 1 to 1 ½ hours. Epoxy die attach is typically done directly to exposed copper pads. Many conductive epoxies are not compatible with Ni plating or aluminum metallization, although most common plating materials are available for T-lam. Epoxies are typically dispensed or screened. Screening provides the best control and uniformity, but does require a flat surface with no pre-assembled components. Die attach epoxy curing should be done in ovens with a nitrogen atmosphere, to prevent oxidation of wire bond pads. A programmable heating/cooling cycle is preferred, although manual curing with adequate cooling in a closed nitrogen oven is acceptable. Although these generalizations apply to typical die attach epoxies, each die attach epoxy is different and compatibility should be compatibility should be reviewed with manufacturer and testing.

Typical T-lam die attach solders are Sn/Pb eutectic or Sn/Ag eutectic. Typically, solder die attach metallization is copper, Ni plated copper, Ni plated copper with Au flash, or Hot solder leveled copper. Solder application can include preforms or pre-coated solder pads, screened solder pastes and dispensed solder pastes. Solder reflow temperatures should not exceed 260 C, and lower times and temperatures are preferable to reduce flux hardening and burning. Reflowing in nitrogen or forming gas may be required to reduce flux burning and hardening, and to make cleaning easier. The T-preg resins are similar to FR4 resins, and the same flux and cleaning systems are typically compatible.

9.2.2 Wire Bonds

Wire bonding to T-lam is equivalent to wire bonding to standard Chip-On-Board, and standard Chip-On-board techniques and controls are generally applicable. Gold Thermo-Sonic and Aluminum Ultrasonic wire bonding are both commonly used. Gold wires of 0.7 to 2.0 mils are common, but 3.0 is available with special equipment. Aluminum wires of 1.0 to 2.0 are common, but wire of up to 25.0 mils is available with special equipment. Aluminum wire of 5, 8, 10, 12 and 15 mils are common in power products.

Gold wire bonding is typically bonded on copper foil with a Ni plated barrier and a gold plated finish. See section 4.4.3 for additional plating information and recommendations.

Aluminum wires can be bonded to clean copper foil or Ni plated copper foil. A gold flash is often added to the Ni plating to minimize oxidation. See section 4.4.3 for additional plating information, including thicknesses and finish.

Large Aluminum Wire Bonding may be required or preferred for the high current T-lam products. Such bonding requires high ultrasonic energy, which is sensitive to proper bonding equipment, tools and clamping. These details are outside of the scope of this paper, but specific application support is available from Thermagon or through the large aluminum wire bond equipment manufacturers.

9.3 Mechanical Assemblies

The T-lam with integral base plate provides its own mechanical structure. In power module applications, T-lam replaces both the ceramic substrate and their more expensive copper base plate, and it eliminates the solder or epoxy substrate attachment process and alignment, and it eliminates the inherent ceramic/base plate reliability problems in temperature and power cycling of ceramic modules. In PWB applications, the base plate can provide the mechanical structure for the system and larger components, and often eliminates multiple supplementary hardware.

The inherent thermal properties of the T-lam often eliminate the need for mounting, and for individual component heat sinks, insulators, screws, clips, and brackets. This often reduces the total system cost in power products, despite the higher cost of the high performance materials. These simplifications often make possible easy assembly automation with simple pick & place equipment.

As with standard PWBs, mechanical connections for board mounting or very heavy components should generally not be made with solder joints to the copper foil. This can be more important where the metal bases are heavier, and the T-preg layers are softer than FR4. Mechanical connections may include screws, rivets, clamps, slots, etc. When the proper mechanical support is used, the softer T-preg can provide superior mechanical reliability with better resistance to thermo-mechanical mismatch and mechanical vibration.

The mechanical support can also be an integral part of the thermal management system, and sometimes the primary means of removing heat from the system. Normally, the mounting is a supplement to the natural or force convection cooling of the board or the primary heat sink. See section 6.0 for details on mounting, and related thermal issues. See the T-guide for Performance for related thermal performance data.

9.4 Coating, Encapsulations and Potting

T-lam substrates can be stand-alone end products, or they can be integrated into a system. They can be packaged as an integral part of a power module, or they can be mounted, inserted, or stacked like a standard PWB. As with the standard ceramic substrate or PWB that they replace, they often require a coating, encapsulation or potting as protection against the environment conditions. Those conditions can include moisture, dirt, chemicals and mechanical damage. The protective materials are often controlled by regulatory agencies in many of the high voltage and high power products.

As a general rule, the materials that are used on the equivalent ceramic substrate or PWB are applicable, but because of the broad range of available materials, compatibility should be confirmed with the protective material supplier and Thermagon. There are a number of special circumstances that may be applicable to T-lam and other similar type products:

9.4.1 T-lam with metal base plates replacing PWB with spray or dip coatings may require masking for cleaning, to keep thermal and mounting surfaces free of coating material.

9.4.2 Large area T-lam substrates replacing many smaller ceramic substrates may have thermal-expansion mismatch problems with rigid coatings or potting. This can cause warping problems, or shear-off components or wires in curing or subsequent operation and temperature cycling. In such applications, attention must be paid to TCE match, material flexibility and total expansion differential. Chip & Wire assemblies are especially sensitive. Large areas and flexible components may require locks or special surface conditions to guarantee adhesion.

9.4.3 Potting compounds are often used in modules, to provide additional support to the soft aluminum base plate, and to allow firm thermal clamping to a heat sink or other mounting surface. Such materials are generally semi-ridged to provide support, while still accommodating short-range expansion mismatch forces.

9.4.4 Any changes in Chip & Wire coating or potting materials to accommodate structural changes should be reviewed for compatibility with semiconductor die and wire bonds. They can be very sensitive to ionic contaminants, moisture penetration, surface stress, and other subtle conditions. If you must use a new material, it should be semiconductor grade and it should be tested through appropriate life and environmental testing

In general, any new designs and materials should also be tested to insure reliable performance in the intended application. In SMD assemblies, with no coating or with soft conformal coatings, the risk is low and reliability is usually higher than with standard FR4 PWB. As power, size, rigidity, expose C&W, and environmental stress increases, the risk and need for additional testing increases.

10.0 Special Applications

The Metal Core, Insulate Metal Substrate or Metal Base Substrate technology has been used in Japan for over 20 years, but it is now coming into its own in the United States with new and improved materials, like the Thermagon T-lam system and the T-preg thermal dielectric. It is being used in high voltage and high current application like motor controls, UPS and welders to replace high power DBC ceramic modules. It is being used in standard and state-of-the-art power supplies with thermal multilayer boards, and in many other high volume commercial, industrial, military and space products including appliance, automotive, TV deflection, audio power, single-board computers, telecommunication, satellite, and more.

The T-lam materials are being integrated with other board and assembly technologies, to get optimum performance with the lowest possible cost. The T-lam material offers the flexibility and fast turn-around of PWB technology, while delivering the thermal performance and reliability of the highly tooled and long lead-time semiconductor ceramic power module packages.

The manufacturing guidelines shown here have focused on existing applications, but the basic technology is much broader, and is expanding into many other high power, high current and high temperature applications. Therefore, Thermagon would like to work with you in applying this technology to your special application.

Figure 1: Four Basic Materials used in the T-lam System

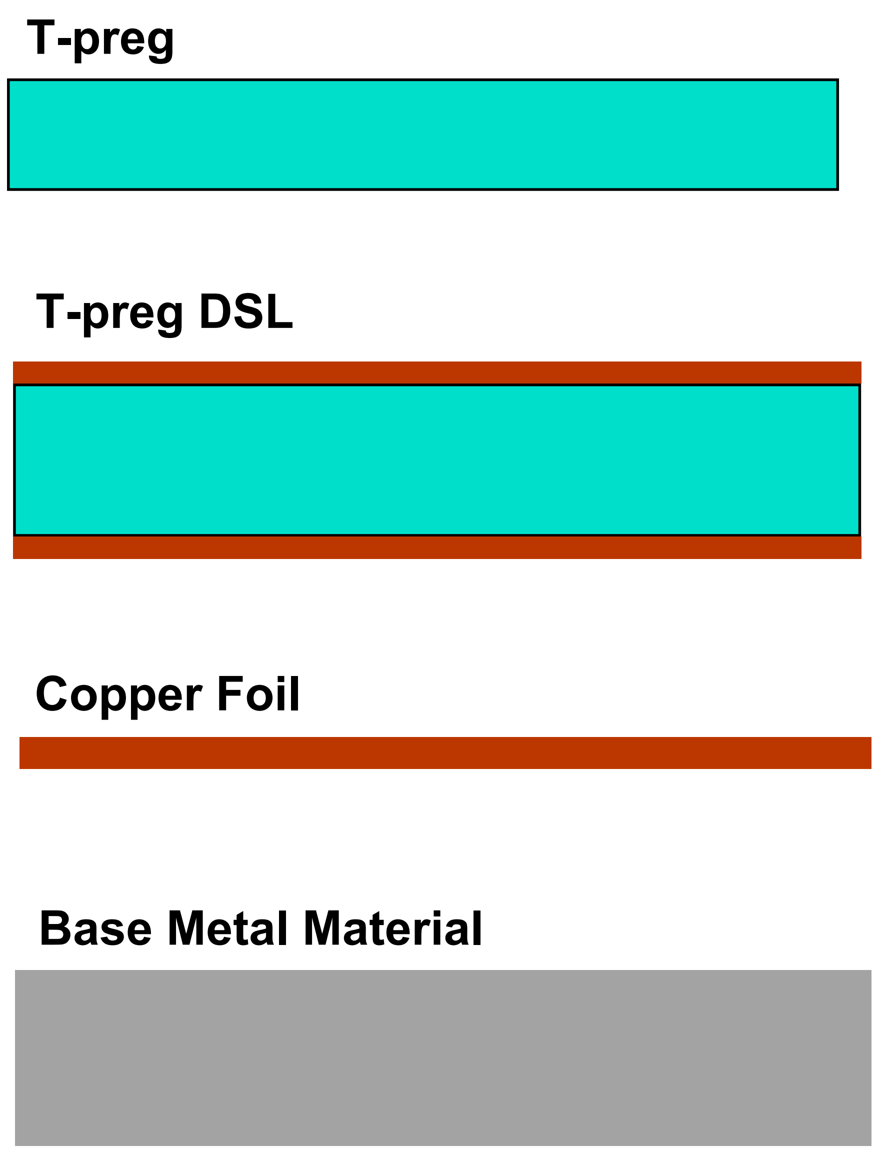
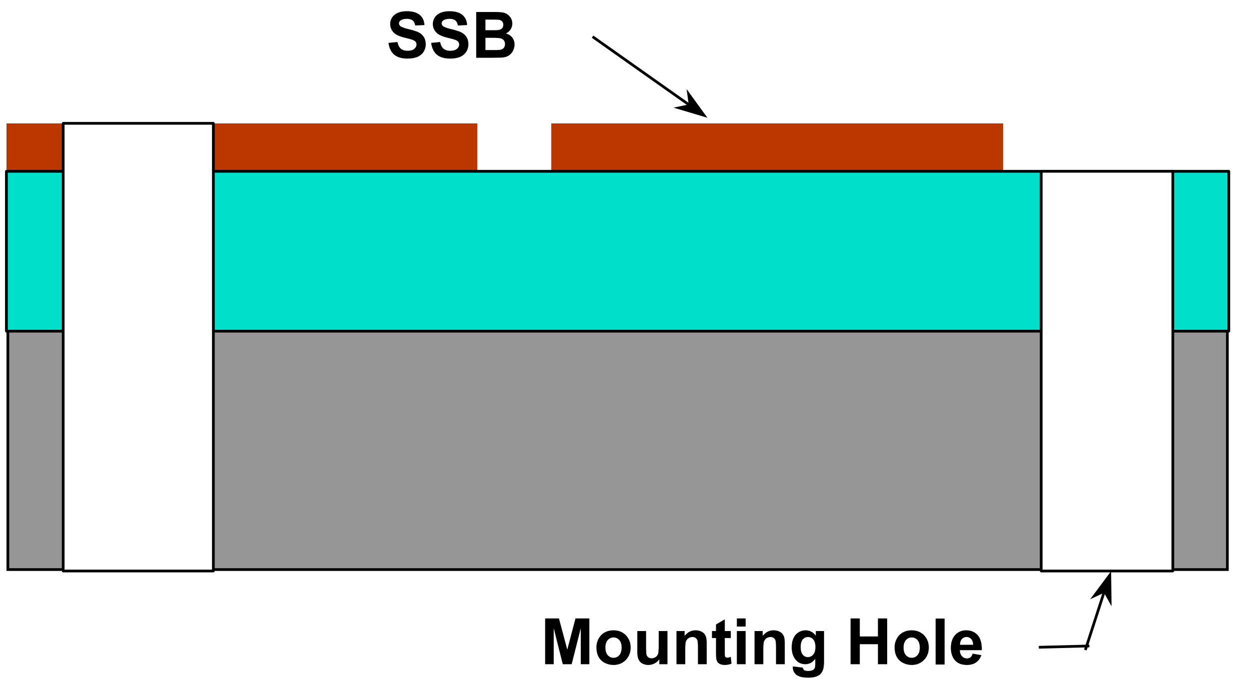
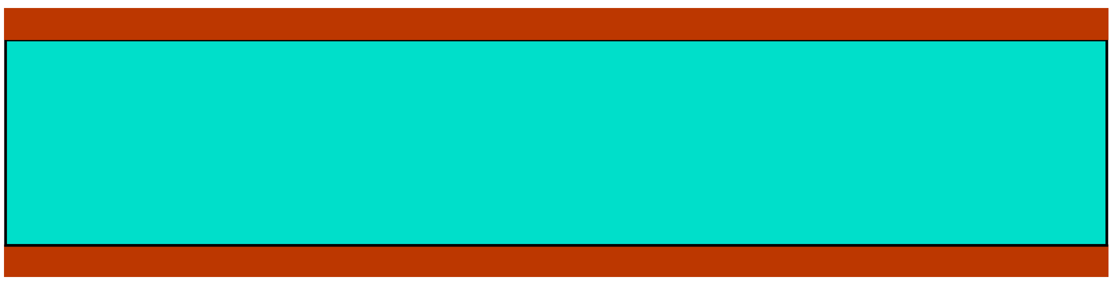


Figure 2: Single Sided Board or Substrate



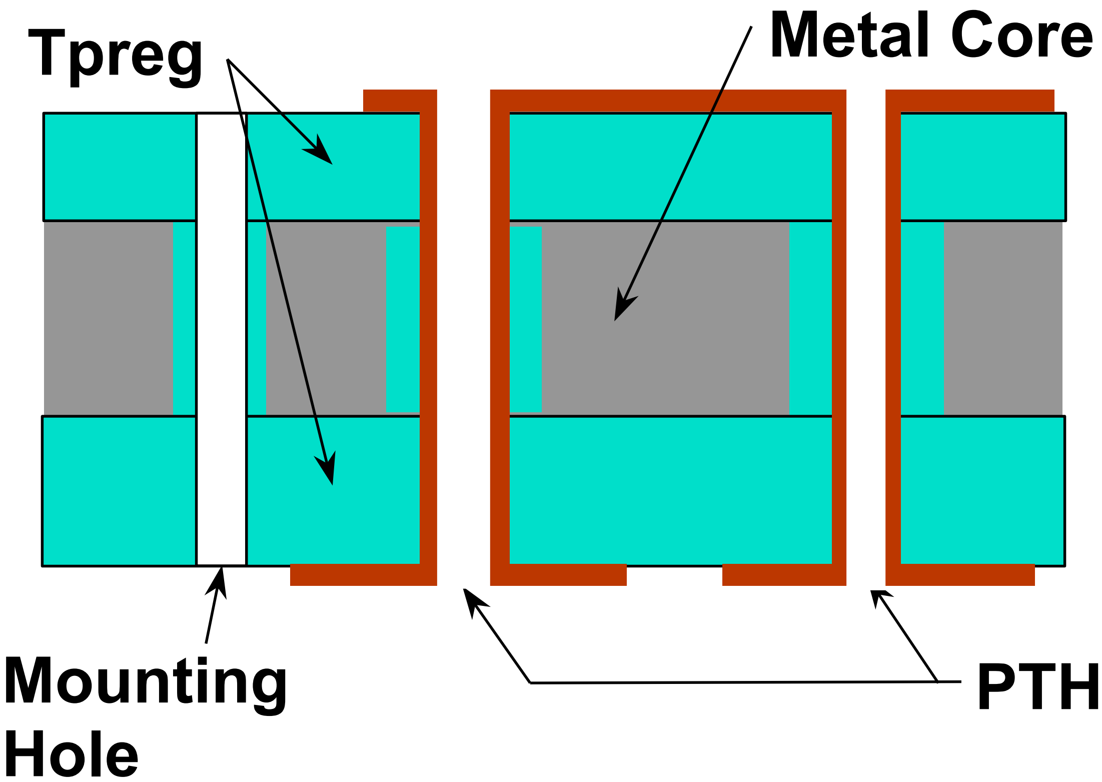
- Copper Foil
- T-Preg
- Metal Base

Figure 3: Double Sided Laminate (DSL)



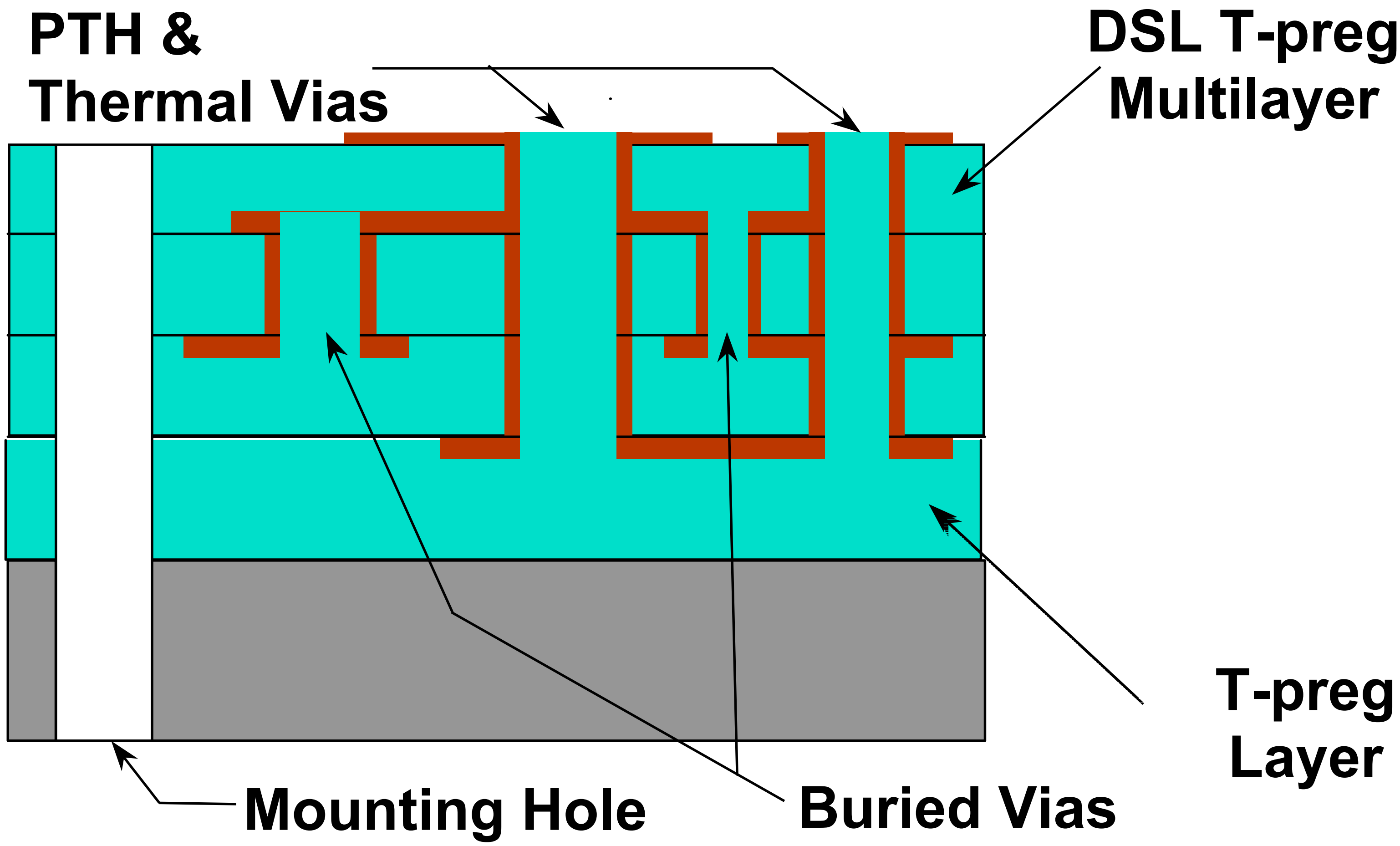
- **One or Multiple Layers of T-preg**
- **Laminated to Copper Foil on Both Sides**
- **Used as Core Material to Replace Double-Sided FR-4**

Figure 4: Double-Sided IMpcb with Metal Core IMpcb



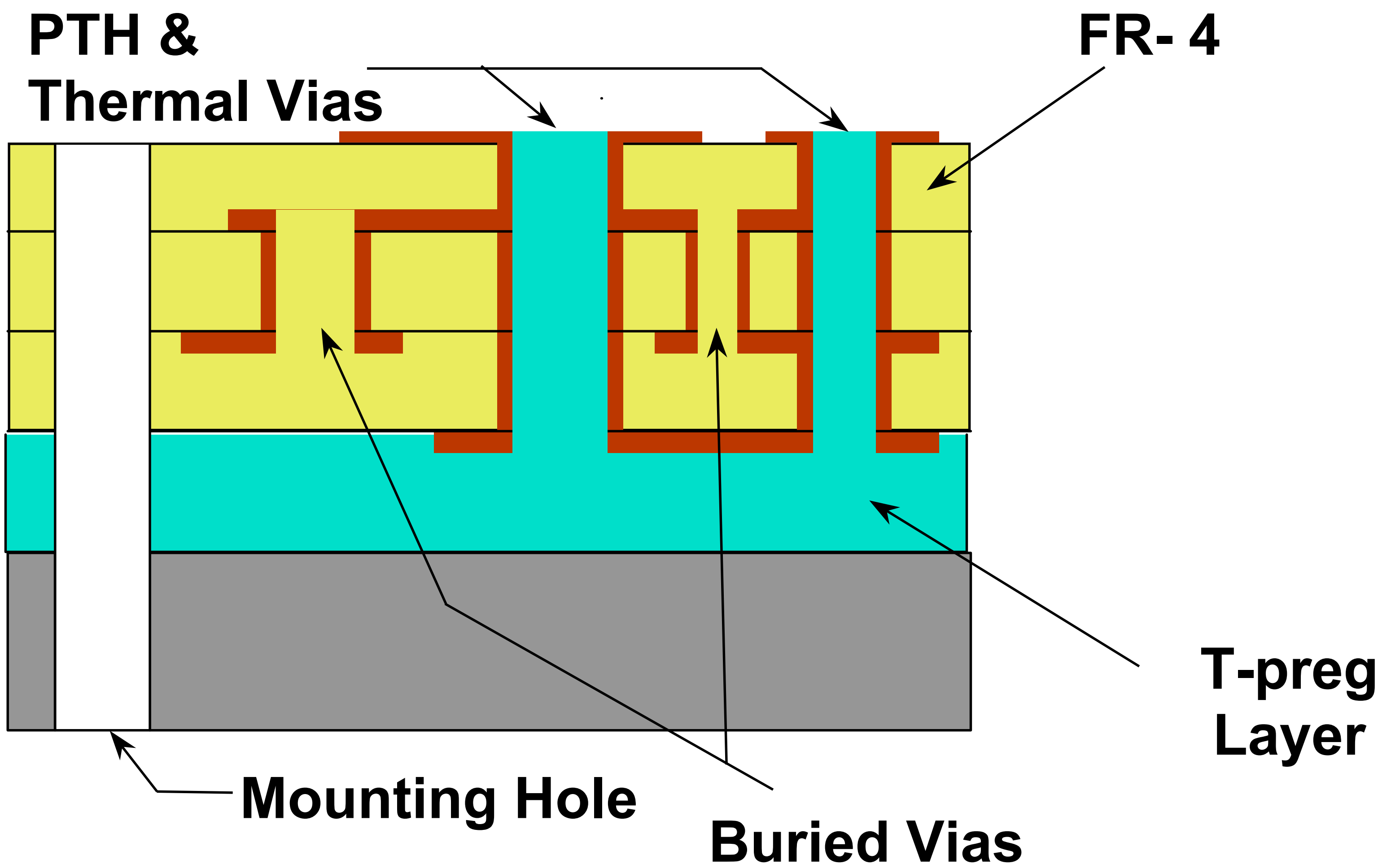
- 2 Cu Foil
- 2 T-preg
- Metal-Core

Figure 5: Multilayer IMpcb With Metal Base



- 2 DSL
- 2 T-Preg
- Metal Base

Figure 6: Hybrid T-preg & FR-4 Multilayer IMpcb with Metal Base



- FR- 4 Multilayer
- T-Preg
- Metal Base