

Optimizing the Insulated Metal Substrate Application with Proper Material Selection and Circuit Fabrication

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Abstract

The ever expanding growth in the use of insulated metal substrates (IMS) in power electronics requires a focus on material and mechanical configuration for each application. By optimizing the material makeup and printed board format, performance and reliability expectations can be further achieved. The thermal performance and electrical isolation needs are driven by the power requirements, but considerations of temperature range, mechanical durability and format, along with the physical package surrounding the substrate must also be managed. With a variety of material configurations and circuit format capabilities, the choices become a balancing of options to maximize performance and minimizing cost through Design For Manufacturability (DFM) in the circuit board fabrication. These challenges present the IMS printed board fabricator with material selections and fabrication processes unlike those for other printed board or ceramic applications.

Introduction

With the enormous growth of (IMS) used in LED lighting, automotive applications, power conversion, motor drives and semiconductor modules the complexity of the designs will require proper material selection and optimized circuit fabrication processes. Designs have gone beyond the basic platform to mount specific devices that need thermally efficiency. Critical control of maximum junction temperatures and power densities require optimum thermal performance. Electrical isolation requirements will continue to vary, but most applications will continue to require safety agency testing at higher than operating voltages. Thus the importance of proper material selection, including type of base substrate, dielectric thermal performance and thickness, along with circuit foil weight cannot be lightly considered. Lastly the extreme cost sensitivity of all the components in the application requires realistic expectations from the printed board fabrication and the (DFM) process be utilized throughout the design, from printed board fabrication through printed board assembly. There is also the importance of proper safety agency recognitions, RoHS and REACH compliance, along with the need for Pb-free assembly processes.

Material Selections

Making the major decision as to what use for IMS substrate printed board is much more than finding a thermal solution. The selection of materials from base substrate material to dielectric type to foil weight will have significant outcome on the design and its ability to meet performance requirements and fulfill the challenges of reliability in the applications operating environment. The construction of these composite materials forces considerations of thermal-mechanical effects not only on substrate material, but also on the components mounted to the circuit board. The most common base material in use today is aluminum, but underwater lightning applications require a copper base metal. As the power requirements continue to increase, the circuit copper increase in thickness to support the amperage needs. The copper/dielectric/aluminum composite are more heavily affected by differences in Coefficient of Thermal Expansion (CTE). A general "Rule-of-Thumb" has been as the copper foil thickness becomes greater than 10% of the base aluminum thick, not only is CTE effects during temperature cycling an issue, but printed board overall flatness becomes a real challenge. That is to maximize the thermal transfer to a heatsink full contact must be made, air gaps are not acceptable.

Cte Effects

Differences in CTE in composite materials can dramatically affect reliability in applications that have a large operating temperature range. This CTE mismatch can mechanically stress the design causing solder joint fatigue and component fracture. As a result, the choice of base metals needs to be carefully considered. Choosing copper base material instead of aluminum has emerged as a popular solution to the requirements of heavy weight copper foil as devices need to carry more and more power. With a copper base, the foil and base metals are the same resulting in considerably reduced stress in the composite, although at a cost. Copper is more expensive than aluminum and often requires additional processing to meet all of the product requirements. The difficulty in bonding dielectric to wrought copper has limited suppliers, and the copper base substrate usually requires a robust protective finish to prevent corrosion, such as nickel plating. Emerging materials such as Aluminum-silicon carbide (AlSiC) metal matrix composites can address the CTE mismatch issues and the costly process of surface protection of the bare copper.

Dielectric Considerations

The choice of dielectric materials should focus on Thermal Impedance, Dielectric Strength and Glass Transition Temperature (T_g). There seems to be a common misunderstanding of these characteristics by most initial users of IMS. Yes, thermal conductivity, as expressed as W/mK is important. But thinner dielectrics, with the same bulk conductivity, will have improved thermal impedance. Conversely, thicker materials will have increased thermal impedance. IMS Thermal Impedance is really what is important: which also includes the interfacial resistance in the layers of the composite. This combined with the solder joint and the device should be a very important consideration to the designer. The overall thermal impedance combined with that of the operating device will determine the junction temperature at a power level in the ambient temperature operated. Solely focusing on thermal conductivity can be deceptive when trying to determine the true performance of the substrate. The understanding of thermal impedance is needed when comparing to pure ceramic substrates, such as direct bond copper (DBC) or Thick-Film. Although these materials have a much higher thermal conductivity than IMS, their overall substrate thickness yields thermal resistance values very similar to high performance IMS substrates.

Glass Transition Temperature (T_g)

A common misconception is the concern of operating IMS above the T_g of the dielectric. Above the T_g of the material, mechanical and electrical properties begin to change. Mechanical changes of note are reduction of peel strength of the copper foil, an increase in the CTE, and decreasing storage modulus. Due to the ceramic-polymer blend dielectrics in IMS, the absence of glass, and the thinness of the dielectric layer, strain from Z-axis expansion is significantly reduced. With these very thin dielectrics, the base metal material is totally dominant in the composite. There is a real potential benefit of relieving residual stress on the dielectric interfaces, in solder joints, and other interconnects due to CTE mismatches by choosing a dielectric with T_g below the operating temperature. This is because the dielectric material above T_g is in its elastomeric state (much lower storage modulus) allowing some of the stresses to relax. Changes in electrical properties must also be considered in operation above T_g, although they commonly are only important at frequencies above 1 MHz. Effects to consider are changes in the permittivity, dielectric loss and breakdown strength of the material.

Another key note here is that most available IMS substrates have a T_g in the 105°C range, but some have UL maximum operating temperatures of 130°C or greater. This is really not an issue in LED lighting applications where 95°C is the maximum junction operation temperature. Operating above the UL MOT limit will cause a reduction in the electrical and mechanical performance characteristics over the 100,000-hour life prediction.

Current Capacity

Copper foil weight is a very important consideration in the design. The copper foil thickness needed to meet current requirements and the effective heat spreading needed for the devices must be considered. Additional current that can be accommodated by IMS is due to its ability to spread and dissipate the heat generated by I²R losses this is shown in figure 1.

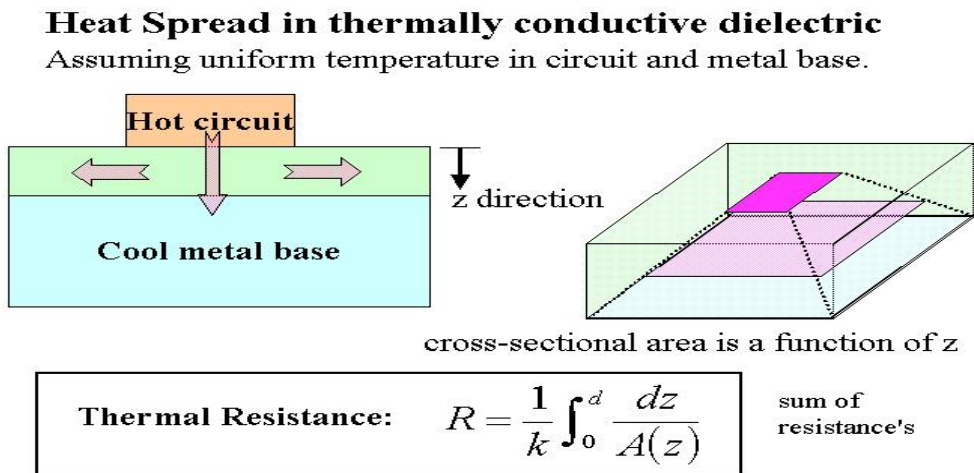


Figure 1 – Heat Spreading

The dielectric thickness and foil thickness both influence the heat spreading capability of IMS and it is one of the most powerful advantages derived from IMS. By increasing copper conductor thickness, heat spreading increases and brings

device temperature down, along with I^2R losses in the copper traces. This allows for much higher current carrying ability with IMS over FR4, because of the ability to dissipate heat due to the I^2R loss in the copper circuitry.

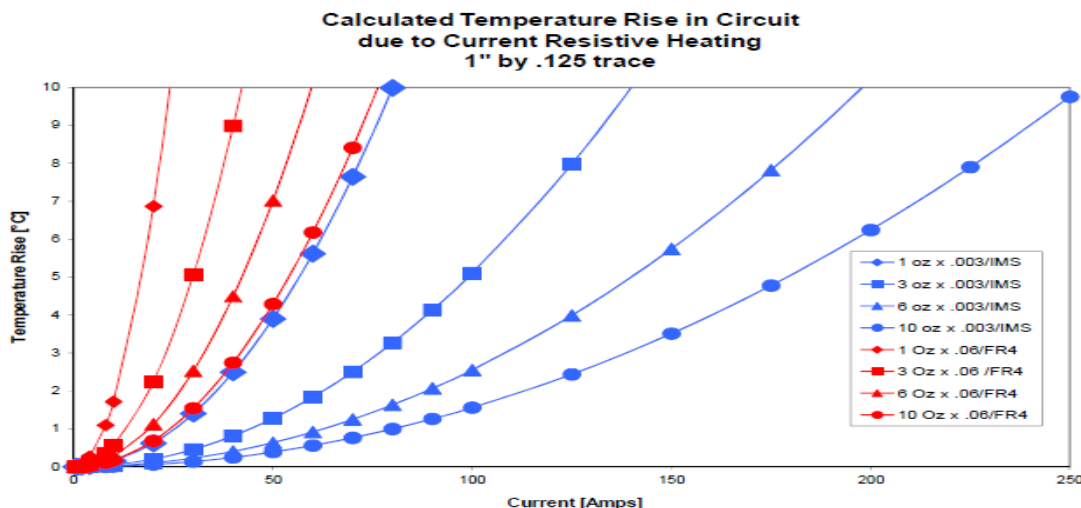


Figure 2 – Current Capability

Heat Spreading

The heat spreading capability of the IMS is also very important. Both the copper thickness and dielectric thickness influence the heat spreading. The ability to increase the heat spreading brings junction temperatures down to enable higher power and increase reliability. As shown in figure 5, increasing copper thickness decreases the representative power device case temperature. The importance of this cannot be overstated with respect to available power and long-term reliability. As a rule of thumb, a two-fold increase in mean time between failures (MTBF) can be realized with a 10°C reduction in junction temperature. This has been most evident in the rapid adoption of IMS in almost all LED lighting applications.

Metal Base

The selection of IMS base layer metal and thickness is application specific. Aluminum is the most commonly used material, and the alloy is primarily driven by fabrication method. Alloy 6061 T6 is the most machinable, but if forming is required, a softer alloy like 5052 H34 is recommended. The thickness of the base metal is driven by mechanical rigidity requirements, mechanical fasteners (Press-Fit), other machining, such as threaded-holes, need for thermal mass and in many cases price. The high-volume DC-DC market has chosen the thinner base materials, due to price. The motor drive markets typically choose thicker materials for thermal mass and mechanical rigidity. The LED applications chose the thinner aluminum materials primarily to reduce cost, except in very high performance applications where copper is the choice. In these applications, where die are directly attached the use of thicker aluminum bases or a copper base is common, with base materials up to .125 inches thick. A capability seeing more and more use is the ability to directly solder to or make plated-through connects on a copper base substrate or ablated openings to allow direct attachment to the copper metal base. There is a process that allows coplanar metal base attachment, such as pedestals. This is obviously not possible on thin aluminum. Although press-in hardware has been successfully used to make base connections, designs where the dielectric is ablated away and a connection is ultrasonically welded to the base aluminum has been used successfully.

Other specialty materials are available as base material as well, depending on the need for magnetic properties, specific CTE ranges, or other properties. This broad offering of base material metals and thickness allows the designer to tailor the design to the application requirements. This flexibility in the IMS allows its use to go beyond just a component mounting and interconnect platform. The IMS material selections give the designer the ability to minimize thermal resistance, maximize electrical isolation needs, and optimize the copper circuit thickness for current requirements and/or heat spreading and the optimum baseplate to package the application.

Safety Agency Testing Considerations

Often the designer will choose the thinnest material possible to optimize thermal performance at the expense of those required distances. Published dielectric breakdown values are generally material properties tested in lab conditions and not directly applicable to specific designs. Furthermore the breakdown voltage is the voltage at which the dielectric breaks down, and not appropriate as a test voltage. So, the designer needs to consider the isolation needed to pass testing without degradation to the dielectric or test faults. The small increases in dielectric thickness needed to provide electrical safety test margin do not necessarily cause detrimental affects to thermal performance. It is critical that voltage isolation distances required in safety agency standards are considered when using IMS materials. The printed board fabricator really cannot determine the proper "Creepage Clearance" requirements; only the designer can determine the clearance required for reliable testing and operation. It is the fabricators responsibility to use proper recognized materials and printed board recognitions to meet the customer requirements of their safety agency requirements.

Circuit Fabrication

Although similar to the circuit processing done to produce FR-4 PWB's, IMS fabrication really differs at the final singulation or depanelization stage; separating the individual boards from the panel. The initial steps of imaging, etching, soldermask and surface finishing uses the similar type of equipment and processing as FR-4. Where as most FR-4 boards are double-sided or multi-layer constructions, IMS is single-sided and process methods to protect the base-side must be utilized. The primary design consideration for manufacturability is that IMS boards are built using heavier copper weights for high power applications. The average copper weight is typically 4 oz, with many designs on 6oz to 10oz. Due to these copper weights the board layout must allow for the etching characteristics of the heavy copper. The typical LED application is primarily 2 oz, but finer line and spaces are typical, with a significant amount of fill copper to enhance heat spreading. The process capability of the fabricator varies slightly, but the design rule check (DRC) requirements take into account the minimum trace spacing and width. Thus the board layout must take into consideration the larger spacing between features; such as 0.014" for 4oz to 0.030" for 10oz and minimum widths of 0.008" for 4oz and 0.015" for 10oz. Thus the ability to place finer pitch components and the needed SMD power devices on the same circuit board may not be possible. This is seen in the typical approach used for DC-DC converters; the power devices are mounted to the IMS board and the finer pitch devices are on a multi-layer FR-4 board attached above using SMD interconnect pins.

Heavy Copper Foil

With the need for the heavy copper to support current and heat spreading requirements, other process considerations must be addressed. The application of soldermask requires process optimization to allow adequate coverage both between the circuits and on the edge of the traces. This is due to the height of the thick copper and the ability to screen the soldermask down into the valleys, but yet have the proper thixotropic properties to remain on the edge or knee of the trace. Also another consideration in soldermask coverage is the recommendation to aperture the solder pads. The need to maintain Ionic cleanliness is critical for long-term reliability.

To ensure the cleanliness after reflow having soldermask coverage on the edge of pads eliminates flux residuals from being trapped in the corners and causing future contamination that could lead to a latent field failure. With this recommendation in mind, DRC will check to verify enough overlap had been designed into the aperture to maintain good soldermask adhesion through subsequent processes. With IMS used in many direct die attachment applications, soldermask is often used as a solder dam. The design consideration here is minimum line width to again maintain soldermask adhesion through plating and reflow soldering processes. Board designers should also consider soldermask compatibility in their application, as many IMS boards end up in modules that require potting compounds or conformal coating. As in plating requirements, soldermasks are different by supplier and should be verified for compatibility to processes.

Another design consideration with the heavy copper features involves boards requiring Legend or silk-screen. As this is also a screening process, the height of the copper and placement of characters or features must be considered in the layout. This includes the bridging of characters or features across copper circuits and the relationship to the edge of the finished part. This problem can be elevated with the use of digital printing of the Legend in most cases, but it is mostly limited to white only, currently.

Surface Finish

The surface finish requirements for IMS boards are also similar to those of FR-4 boards, but circuit features are usually much larger, due to the power devices. This does affect final thickness variations on HASL finishes, due to the feature sizes. Maintaining adequate thickness on large pads will cause greater thickness on small pads. Process optimization is required by the fabricator to balance the thickness across feature sizes. In plating requirements, such as ENIG and ENEPIG used in aluminum and gold wire-bond applications, the fabricator has to isolate the base metal from the plating process.

The applications requiring such plating need to consider the pricing of the surface finish square inch, so plated area should be kept to a minimum using soldermask. The other surface finishes commonly used to provide good solderable surfaces are

organic solderability protect ant's (OSP), but these due have shorter shelf lives and require more careful handling during assembly. The use of immersion tin and silver has seen volume production. It has been extensively used on boards with a copper base metal, to surface finish the circuits for solderability and the base to prevent copper oxidation. These types of surface finish also require similar careful handling and packaging to prevent corrosion.

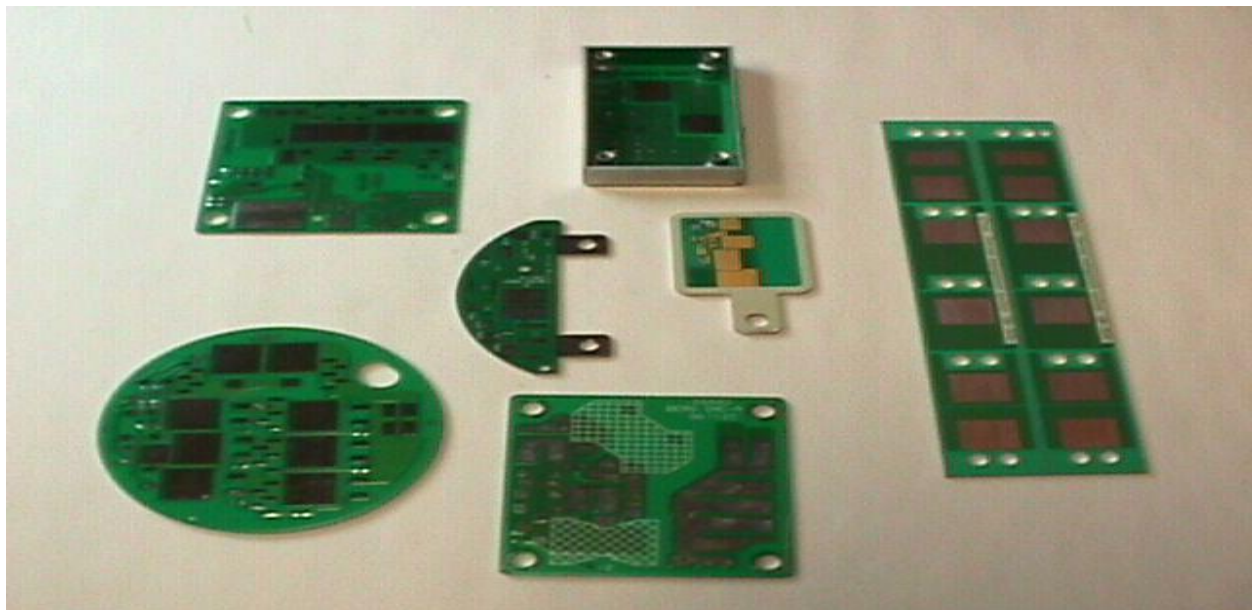
Surface finishes can also include those for the metal base side of the IMS substrate; these include anodization and conversion coating for aluminum and plating for the copper. Depending on the part requirement this can be done in panel form or at the individual part level. If the part requires coverage on the edges this finishing process must be done on the singulated part. It should be realized the price for individually surface finished parts is substantial higher in price than one done in panel form due to handling labor.

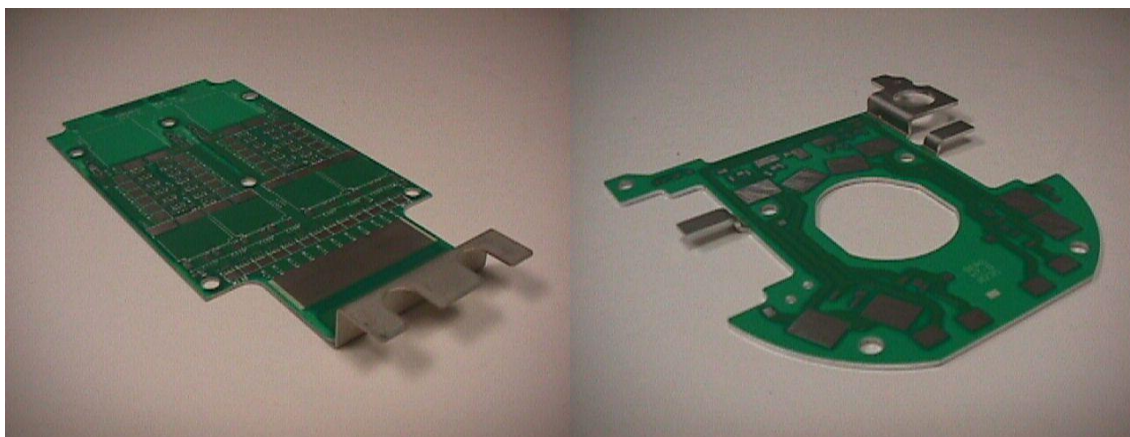
Addition Of Holes/Slots

Drilling, which is considered routine for FR-4 material is much different for IMS substrates. Drilling ceramic filled polymer with usually a thick metal base, definitely affects holes size capability and drill bit life. Typically, hole sizes vary from 0.010" diameter for plated through vias to 0.250" diameter for non-plated mounting holes. In the case of larger holes, a pilot hole is required. Also a deburring step is usually required, due to the exit burr at the metal base. The optimum method for large holes is to punch them. In a process comparison using a high-volume CNC punch press, the completed hole rate is 4 to 1 or more, over drilling. On higher volume applications this can be a significant price driver. A key factor to be remembered in IMS fabrication, final processes relate more to metal fabrication than they do to circuit board methods, but due to the dielectric materials; tooling and its maintenance is critical to overall fabrication quality. Therefore the use of technologies like carbide and diamond are essential.

Secondary Processes

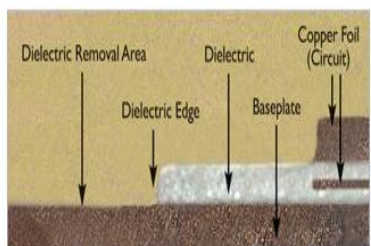
IMS substrates with its metal base can also have a number of other mechanical processes done, such as counter-sinks, counter-bores, threads, formed flanges and ablation of the dielectric material to expose the base metal for electrical connections. The designers need to consider the process capabilities of the fabricator. Tolerance and positional accuracy required affects type of process and final finished board yields, which directly influence price. These features, not available for ceramic and even FR-4 boards, can be provided by a proficient IMS fabricator at an acceptable price, in most cases. The use of mechanical fasteners is very common in IMS and not available for ceramics. Special processes that can be applied to meet specific application requirements include: selective dielectric removal, a pedestal, blind Via to metal base, via's both filled and unfilled and via in pad, as shown in figure 3.





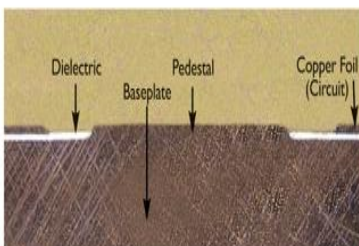
Advanced Circuit Processing

Custom Baseplate Applications



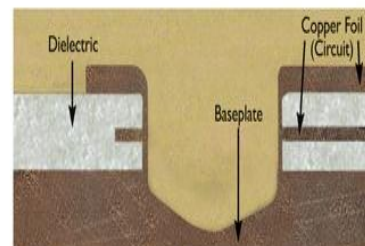
Selective Dielectric Removal

A process for selectively removing dielectric to expose the baseplate. This surface can be surface finished like the other circuit pads. We are not limited to geometry or size of the dielectric removal area. Selective removal features can be placed very accurately with respect to the circuits.



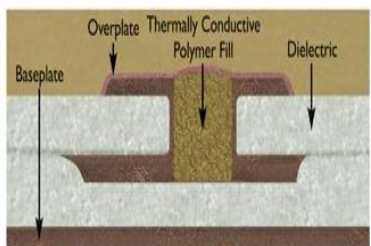
Pedestal

Using a copper base and by selectively removing the dielectric a pedestal can be formed moving the baseplate metal up to be co-planar with adjacent circuits.



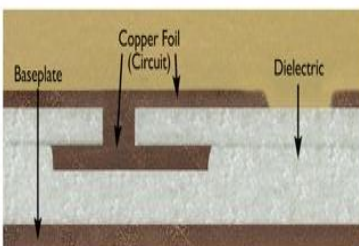
Blind Plated Via to Baseplate

Allows for a copper base metal connection to the surface copper circuit and the inner-layer copper circuit can also be included if required. Provides a direct thermal path to baseplate.



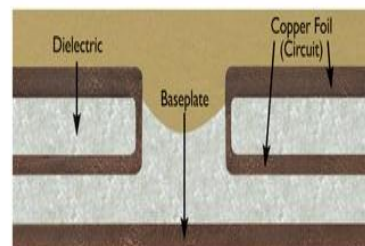
Filled Via

This has been filled with an electrical and thermally conductive polymer material. It is also overplated to provide a plateable, solderable and nearly coplanar surface that is void free.



Via in Pad

Allows for minimum via size, full copper plating for good electrical and thermal conductivity. Provides for a truly coplanar surface.



Electrical/Thermal Via

Typical "Thru Via" connecting inner to outer layer. Reduces thermal impedance by shortening the thermal path while maintaining electrical isolation.

Figure 3 – Special Processes

Singulation

Final fabrication process methods significantly differentiate IMS from FR-4 or ceramic materials. This is the primary reason that only fabricators that have dedicated the process development time, and provided the necessary equipment to support the singulation process, have successfully processed IMS boards. The metal fabrication techniques and equipment required are critical for successful IMS fabrication. The V-scoring process similar to that used in the FR-4 world is used, but machine process speeds are very different and special metal cutting blades are necessary, along with the use of coolant to ensure sufficient tool life. The CNC capabilities of the machine allow for a variety of board geometries, but limit the board to a square or rectangle in most cases. It is also difficult in some cases to deal with the physical properties of the material, as it

relates to part flatness with this process. The v-scoring process does not influence the part; the part retains the character of the panel as it enters this cutting step. So, if the panel has a bow due to CTE mismatch of the copper and aluminum, the proportional bow will remain with the part.

Although routing and milling are usually reserved for small volume or primarily prototypes, they remain singulation alternatives. The costs of these processes are extended machine times, tool wear, and typically require secondary deburring and cleaning operations. The advantage of these processes over v-scoring is the variety of PWB profile geometries that can be produced. IMS boards are possible in circular formats, to validate prototype designs. The milling process is also useful design verification for specialized array format designs. The combination of v-scoring and milling is useful in complex array formats as shown in figure 4.

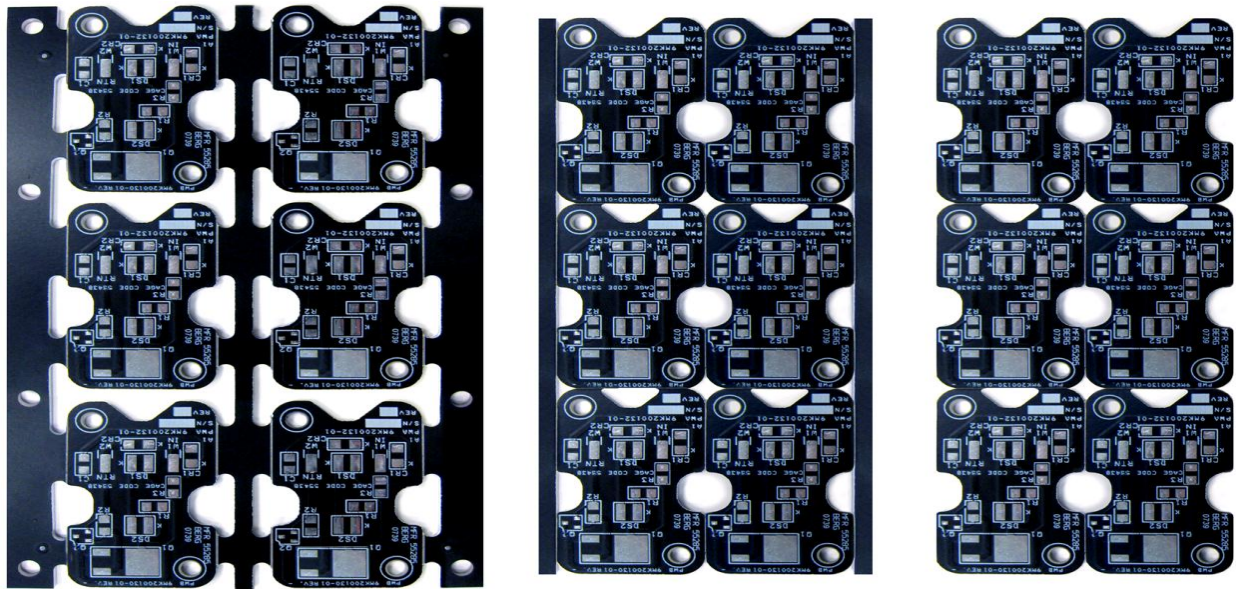


Figure 4 – Fabrication combinations

The preferred and most price competitive method to singulate IMS boards is punching. This method can generate board geometries in a vast variety of shapes and sizes. It is available for any of the material selections IMS has to offer. The only limiting factor is part size as it is related to tooling cost, but typical IMS boards are small in size. Using the same type of single-action and high-speed punch presses found in metal fabrication. The tool; punch/die sets are also very similar. The primary difference is in punch design to accommodate the exposed circuits on the IMS board. Punch relief is necessary to avoid punch contact with the circuitry, so there is no deformation of the copper into the dielectric. Any displacement of the copper and the dielectric can lead to a voltage breakdown fault, which renders the board defective. Due to this requirement, DRC rules require a minimum circuit-to-edge for the punch design. The minimum for aluminum is one material thickness. For copper-base boards this minimum has to be increased due to tensile strength of the material, to avoid fractures at the edge of the board. Tooling designs commonly employ multiple operations, such as piercing holes and profiling the perimeter. Progressive tools do have more front-end cost, but reduce the actual fabricated part price by reducing machine time and labor. The other option is CNC punch processes where a multiple number of tools can be loaded in the press to create the holes or slots required and the final perimeter punch of the PWB. It is also very cost effective in fabrication of complex arrays where a variety of shapes are required. This type of punch press can also create pedestal with special tooling.

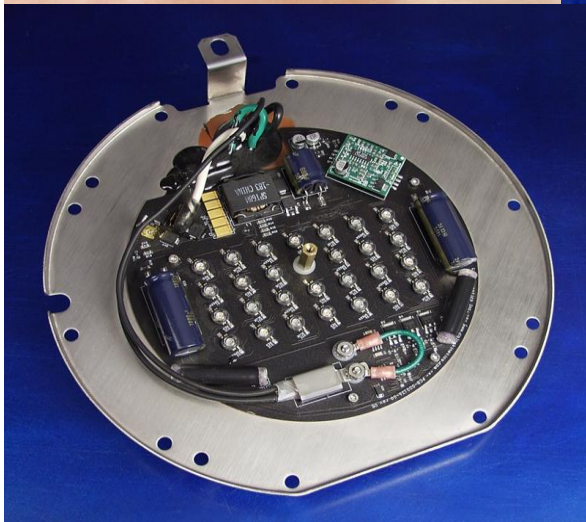
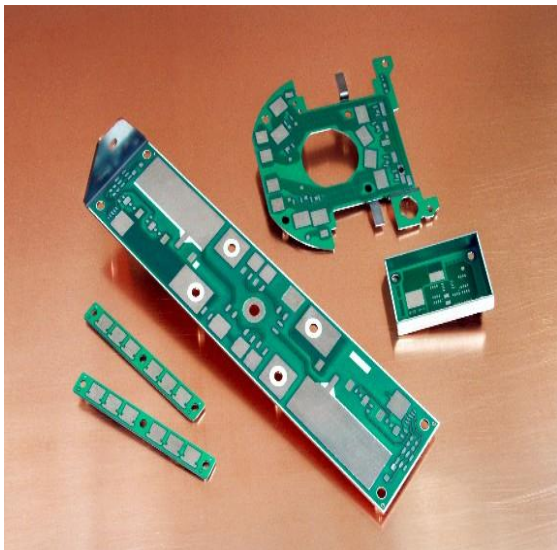
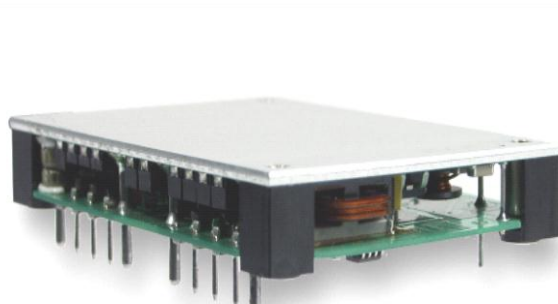
Another emerging process used on IMS boards is the forming of the metal. Utilizing the metal base as the fundamental platform IMS can be shaped into various requirements, including partial boxes, mounting flanges and other creative designs.

Conclusions

IMS substrates provide many advantages in power electronics and LED designs with the variety of material selections and circuit fabrication possibilities, examples shown in figure 5. The design does need to narrow down the choices of material configurations to meet performance and price requirements. Matching thermal performance, safety agency testing needs and best fabrication method can be greatly enhanced with a strong technical relationship with the material/fabricator vendor.

As originally published in the IPC proceedings.

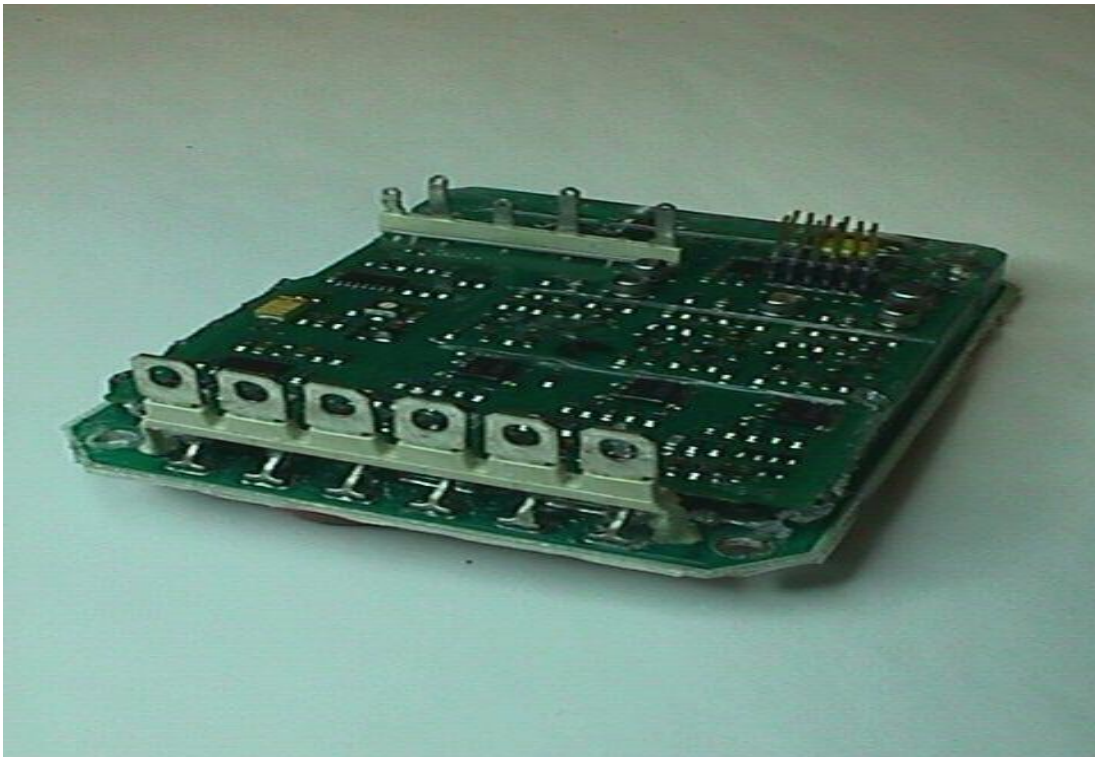
With the continued increases in power density and the exploding LED lighting market, more and more designers will have to look to IMS substrates for their applications needs. However the amount of differentiation from traditional FR-4 fabrication forces the need apply design practices not previously considered.



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Specialized LED lighting applications



As originally published in the IPC proceedings.

