ADVANCES IN PRINTED WIRING BOARD MANUFACTURING: ADD DURABILITY AND RELIABILITY TO YOUR POWER ELECTRONICS PROJECT

HEAVY COPPER CIRCUIT BOARDS DRAMATICALLY INCREASE POWER HANDLING AND PROVIDE A ROBUST PLATFORM FOR EXTREME CONDITIONS

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There are many new power electronics products being designed specifically for military and aerospace applications. More and more of these projects are taking advantage of a new trend in the printed wiring board (PWB) industry: Heavy copper circuits.

What defines a heavy copper circuit? Most commercially available PWBs are manufactured for low voltage/low power applications, with copper traces/planes made up of ½ oz/ft^2 – 3 oz/ft^2 copper weights. A heavy copper circuit is manufactured with a copper weight anywhere between 4 oz/ft^2 – 60 oz/ft^2. The increased copper weight combined with a suitable substrate transforms the once un-reliable, weak circuit board into a durable and reliable wiring platform.

Current Carrying Capacity and Temperature Rise

What amount of current will a copper circuit safely carry? This is a question that I hear often from designers that wish to incorporate heavy copper circuits into their project. I usually answer that question with a question of my own; how much heat rise can your project withstand? I always pose this question because heat rise and current flow go hand in hand. In the next couple of paragraphs, I will try to answer both of these questions together.

When current flows along a trace, there is an i^2R (power) loss that results in localized heating. The trace cools by conduction (into neighboring materials) and convection (into the environment). It therefore seems reasonable that in order to find the maximum current a trace can safely carry we need to find a way to estimate the heat rise associated with the applied current. An ideal situation would be to reach a stable operating temperature where the rate of heating equals the rate of cooling. There has been some work done on this subject and a model has been developed.

<u>Equation 1</u>: $I = 0.025 * \Delta T^{0.45} W^{0.79} Th^{0.53}$ (thanks to Douglas Brooks, UltraCAD Design, Inc.)

{I is current (Amps), ΔT is temperature rise (ºC), W is width of the trace (mil), and Th is thickness of the trace (mil)}

This model is based on extensive testing of external traces; internal traces should be derated by 50% (estimate) for the same degree of heating. Figure 1 shows the current carrying capacity of several traces of differing cross-sectional areas. What is an acceptable amount of heat rise will differ from project to project; most circuit board dielectric materials can withstand temperatures of 100 ºC above ambient; although this amount of temperature change would be unacceptable in most situations. Equation 1 can be rearranged to show that ΔT is directly proportional to power (I^2R), which acts to heat the trace, and inversely proportional to the square root of W (surface area), which helps to cool the trace. The results of this analysis lead to a fairly reasonable, intuitive understanding of the dynamics involved.

Figure 1 Current Carrying Capacity of Various Copper Traces Sizes

ΔT (ºC)	Trace Width (mil)	Trace Thickness (oz/ft^2)	Location (external/internal)	Max. Current (Amps)
20	50	1	External	2.629
20	50	10	External	9.137
20	500	1	External	14.663
20	500	10	External	50.958
20	2000	1	External	48.121
20	2000	10	External	167.237
50	50	1	External	3.996
50	50	10	External	13.888
50	500	1	External	22.288
50	500	10	External	77.459
50	2000	1	External	73.146
50	2000	10	External	254.209

We can take Equation 1 a step further to find the fusing current of a copper trace. Using the melting point of copper (1083ºC) and assuming ambient temperature to be 20ºC, the result is Equation 2. Another useful equation developed by M. Onderdonk relates current to the time it takes for a copper wire to melt (See Equation 3).

Equation 2: $I = 0.57528 * W^{0.79} Th^{0.53}$

{Same units as Equation 1}

Equation 3: $I = 0.188 * A/t^{0.5}$

{A is cross-sectional area (square mils), I is current (Amps) and t is time (seconds)}

Circuit Board Strength and Survivability

Circuit board manufacturers and designers can choose from a variety of dielectric materials, from standard FR4 (operating temp. 130ºC) to high temperature polyimide (operating temp. 250ºC). A high temperature or extreme environment situation may call for an exotic material, but if the circuit traces and plated vias are standard 1oz/ft^2 copper, will they survive the extreme conditions? The circuit board industry has developed a test method for determining the thermal integrity of a finished circuit product. Thermal strains come from various board fabrication, assembly and repair processes where the differences between the coefficient of thermal expansion (CTE) of Cu and the PWB laminate provide the driving force for crack nucleation and growth to failure of the current carrying capability of the board. TCT (thermal cycle testing) checks for an increase in resistance of a circuit as it undergoes air-to-air thermal cycling from 25ºC to 260ºC. An increase in resistance indicates a breakdown in electrical integrity via cracks in the copper circuit. A standard coupon design for this test incorporates a chain of 32 plated through holes, which has long been considered to be the weakest point in a circuit when subjected to thermal stress. TCT studies done on standard FR4 boards with 0.8-1.2 mil copper plating have shown that 32% of circuits fail after 8 cycles (a 20% increase in resistance is considered a failure). TCT studies done on exotic materials show significant improvements to this failure rate (3% after 8 cycles for Cyanate Ester) but are prohibitively expensive (5-10 times material cost) and difficult to process. An average surface mount technology assembly sees a minimum of four thermal cycles before shipment, and could see an additional two thermal cycles for each component repair, for a total of six. It is not unreasonable for a SMOBC board that has gone through a repair and replacement cycle to reach a total of 9 or 10 thermal cycles. The TCT results clearly show that the failure rate, no matter what the board material, can become unacceptable.

All printed circuit board manufacturers know that copper electroplating is not an exact science, changes in current densities across a board and through numerous hole/via sizes result in copper thickness variations of up to 25%. Most areas of "thin copper" are on plated hole walls, the TCT results clearly show this to be the case. Using heavy copper circuits would reduce or eliminate these failures altogether. An additional 1oz/ft^2 of plated copper to a hole wall reduces the failure rate to almost zero (TCT results show a 0.57% failure rate after 8 cycles for standard FR4 with a minimum of 2.5mil copper plating). In effect, the copper circuit becomes impervious to the mechanical stresses placed on it by the thermal cycling.

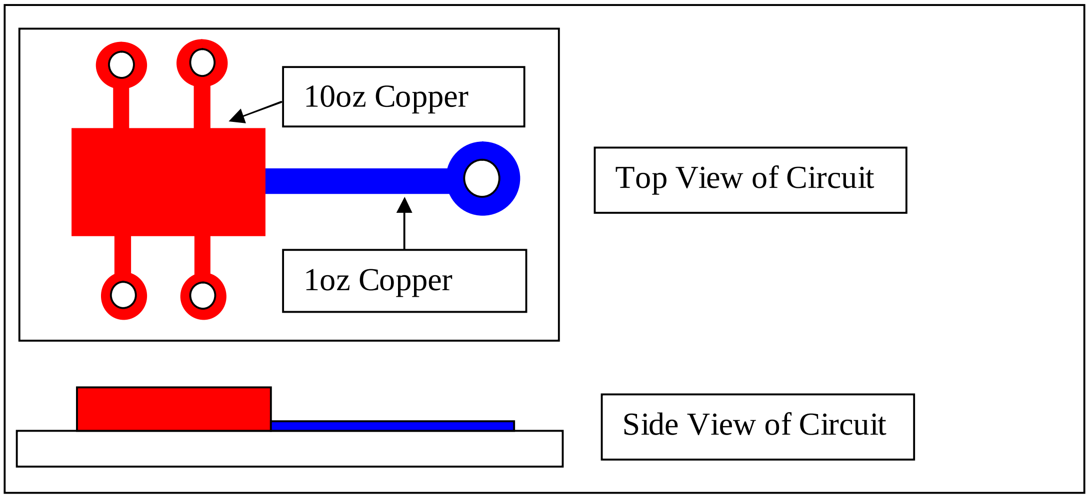
Heavy Copper Benefits

There are many benefits to using heavy copper circuitry, some of which of have touched on in this article.

1. Increased resistance to thermal strains
2. Increased current carrying capacity
3. Ability to use exotic materials to their full potential (i.e. high temperature) without circuit failure
4. Shrink product size by incorporating multiple copper weights on the same layer of circuitry (See Figure 2)

5. Increased mechanical strength at connector sites and in PTH holes
6. Ability to use heavy copper plated vias to transfer heat to an external heat-sink
7. Build heat-sinks directly onto the board surface using up to 60oz copper planes
8. Ability to produce high current planar transformers

Figure 2 Two Copper Weights on Same Circuit Layer



Closing

During the manufacture of heavy copper circuits, we are usually dealing with significant plating thicknesses and therefore allowances must be made in defining trace and pad separations and sizes. For this reason, designers are well advised to have the board fabricator on board early in the design process. UPE Inc. has developed a set of design guidelines for heavy copper circuits that will give designers a basic overview of what is required. UPE has been a pioneer in the development and manufacture of heavy copper circuits and continues to be an industry leader in providing technical expertise in this field to its customers. Power electronics products using heavy copper circuitry have been in use for many years in the aeronautical industry (Honeywell has been using this technology in many of their products for end user Boeing), and are gaining momentum as a technology of choice in military applications as well.

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