Balancing the Electrical and Mechanical Requirements of Flexible Circuits

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Abstract

Circuits, by definition, have electrical requirements they must meet. Flexible or rigid-flex circuits, because they will be bent one or more times, have mechanical requirements as well. These two sets of requirements can conflict with one another, posing challenges for the designer. This paper examines the two sets of requirements, potential areas of conflict, and ways of overcoming those conflicts.

Electrical Requirements

Flex circuits have most of the same electrical requirements that rigid PCBs have, including:

1. **Point to point connectivity** - Like a wired circuit, a flex circuit must transport electrons from one point to another.

2. **Current requirements** - Also like a wired circuit, the flex circuit must transport those electrons in sufficient volume, with minimal voltage drops, and with minimal generated heat within the conductors.

3. **High-speed signal integrity** - As the edge rates of logic circuits get faster, the flex circuit must resist distortion of the transmitted electromagnetic wave. Common causes of distortion include reflections due to dissimilar impedance, cross talk from adjacent conductors, and noise from nearby circuits.

4. **High component density** - Electronic devices are getting smaller at the same time that they incorporate more components. This is particularly true of rigid-flex circuitry.

5. **Terminations** - The circuit termination must meet requirements for current flow and signal integrity, must be compatible with the mating terminations within the assembly, and must be robust enough to survive handing during installation.

Mechanical Requirements

Because these circuits are designed to flex, they must also meet mechanical requirements including:

1. **Physical size and shape** - The circuit must fit into the allotted space, both in footprint and thickness.

2. **Bending** - The circuit must bend and flex as necessary both without cracking or wrinkling conductors and without tearing or delaminating insulating materials.

3. **Thermal properties** - The circuit must withstand elevated temperatures, as necessary, without exhibiting plating cracks or delamination.

4. **Dimensional stability** - The circuit must be dimensionally stable enough to support required surface mount components.

5. **Dielectric properties** - Materials used for insulation must withstand very high voltages with minimal thickness. Typical dielectric strength of materials used in flex circuitry run from 1000-4000 volts/mil.

Of course, in addition to these requirements, a flex circuit must also achieve its intended purpose and do so at an acceptable cost.

Feature Interactions

Electrical Issues

As the current requirement in a circuit increases, the conductor cross-sectional area needed to carry the current with minimal heat generation or voltage drop increases as well. The cross sectional area can be increased by making the conductor either wider or thicker (or some combination of the two). Making the conductors wider uses more "real estate" and may drive the circuit to a higher layer count. Making conductors thicker requires more adhesive on covers and internal insulation layers to ensure complete encapsulation. More adhesive increases the thickness of the circuit, reducing flexibility. A thicker, stiffer circuit cannot be bent as tightly as a thinner circuit without risking fractured conductors or delamination.

In circuits carrying high-speed signals with very short rise times, signal integrity is critical, requiring impedance, noise, and cross talk control. To achieve good electrical coupling, high speed circuits often include one or more ground and/or power reference planes. These can drive up the layer count, reducing flexibility. Since these layers are usually solid copper, if they extend through areas that will be required to flex they will further impair the flexibility of the circuit.

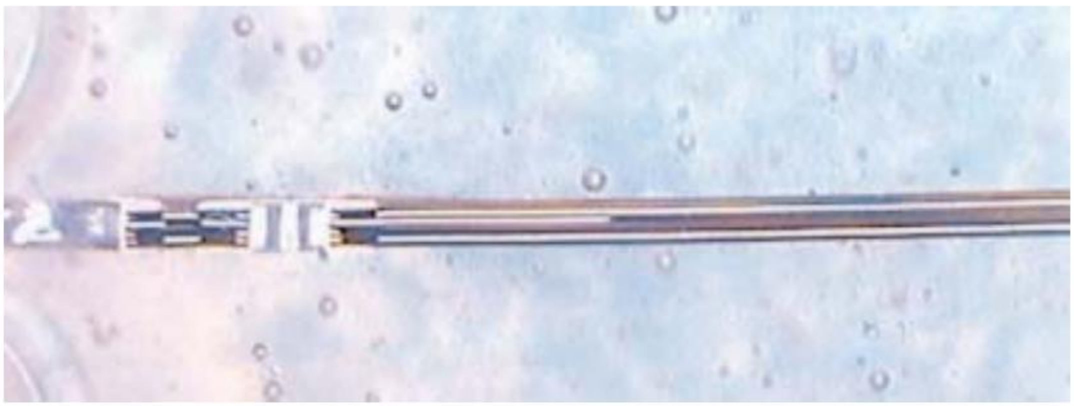
When impedance control is required, the nominal value is typically 50 ohms (100 ohms differential). Achieving these values in a flex or rigid-flex circuit usually requires thicker flex substrates than those required for a flex circuit with no impedance requirements. Also, the layers that require impedance control must be fully bonded to ensure that the signal-to-reference plane spacing remains constant. As a result, circuit thickness and stiffness both increase. To complicate matters further, high speed transmission lines are typically less than .007" wide, which makes them fragile. Thin conductors on a thick circuit pose a high risk of breakage when the circuit is flexed. These features tend to drive up the cost of the circuit since extra plane layers increase material costs and processing time, thicker substrates increase base material costs, and thinner conductors can cause lower etch yield.

Flexible circuits used in a high-speed environment, particularly rigid-flex circuits, often have very high component density. As the available real estate on the circuit decreases, the size of plated through-holes, pads, conductors, and spacing between conductors shrinks. This, in turn, can increase cost and decrease reliability. A smaller plated through-hole means a higher aspect ratio (board thickness to hole size), which can lead to plating defects such as voids or uneven plating. Shrinking through hole pads can cause registration problems when drilling the holes. And smaller etched features can impact etch yield, translating to higher costs for finished boards.

Mechanical Issues

The fundamental mechanical concern in a flex or rigid-flex design is whether the circuit will be able to bend or form reliably into its final configuration. It may also have to withstand flexing during servicing or vibration without cracking or breaking conductors. The most obvious way to ensure flexibility is to reduce the overall thickness in the flexible area. In order to accomplish this, the mechanical designer will attempt to specify the thinnest possible base laminates and dielectrics. An alternative is to selectively bond layers in the flexing area.

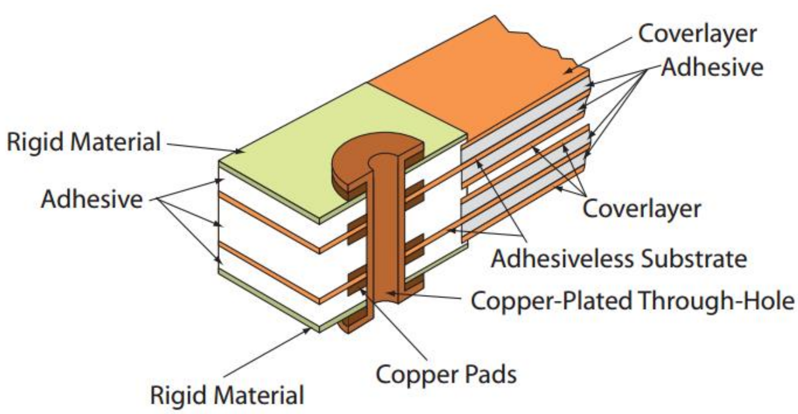
Selectively bonded layers can increase flexibility in critical areas



Fully bonded construction

Both of these design practices can directly conflict with electrical performance. Reducing the thickness of the base laminates and dielectrics lowers the circuit's impedance, while reducing the thickness of the base copper will lower current carrying capacity. Selective bonding makes it impossible to control the spacing of layers in the selectively bonded area, making it impossible to control impedance in these areas.

Thermal performance is another key concern. A circuit must be able to withstand temperature excursions without exhibiting PTH cracks or delamination. One method of making a circuit more thermally robust is to make areas containing plated through holes as thin as possible. Another method used in rigid flex construction is the use of cut-back or "bikini' covers to reduce or eliminate the amount of acrylic adhesive in critical areas.



A method used in rigid flex construction to reduce or eliminate the amount of acrylic adhesive in critcal areas is called a cut-back or "bikini" covers.

However, while enhancing mechanical performance, these features can impair electrical performance. Reducing thickness entails reducing the thickness of materials in the PTH area. This reduces layer-to-layer spacing and affects impedance in the area. Removing the flexible covers in the rigidized area of a rigid-flex can also cause impedance mismatches. Since the dielectric constant of acrylic adhesive is different from that of epoxy or polyimide pre-preg, the impedance will change as a conductor passes from a rigid area to a flex area.

Another mechanical concern is overall circuit size. As devices shrink, components must also shrink. Reducing circuit size requires that etched features become smaller and closer together. Since conductors act as antennae, picking up noise from other conductors, closer spacing can disrupt the signals traveling on them.

Balancing Demands

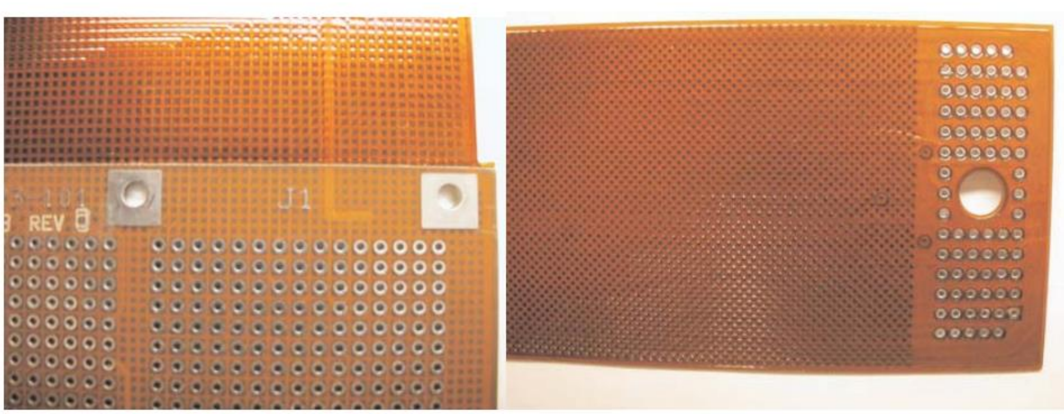
The challenge is to design a flex circuit that will meet both mechanical and electrical requirements. Start by defining optimum, nominal, and minimal performance for each electrical and mechanical requirement. The final design may fall short of optimum in some areas but still function well at the nominal level. For instance, if optimal impedance is 50 ohms and 40 ohms is acceptable, and optimal thickness of the circuit is .020" with .028" being acceptable, it may be possible to design the circuit with acceptable performance for both properties. In contrast, if one feature has to be optimal, the other may fall short of acceptable performance.

There are many enhancements that can be incorporated into flex or rigid-flex circuits designs to improve either electrical or mechanical performance without impairing the other. Some of these will have cost impact; others will not. Their benefits must be evaluated along with cost to determine whether they are warranted. The following are some potential enhancements:

1. **Micro-strip construction**
   Consider micro-strip rather than stripline construction for high-speed applications. Micro-strip construction requires one reference plane rather than two. Eliminating one layer reduces overall thickness, increasing circuit flexibility. Also, micro-strip construction allows smaller signal-to-plane spacing than does stripline, further reducing both circuit thickness and total cost. In this type of construction, try to place the signal layer on the inside and the reference plane layer on the outside of the bend. The small conductors in a signal layer will be more likely to tolerate compressing than stretching without fracturing when the circuit is bent or formed.

2. **Placement for maximum heat dissipation**
   Place conductors with the highest current requirement on the outer layers. They will be better able to dissipate heat there than in the middle of the circuit. Also, outer conductors generally have additional copper plating over the base copper foil, providing greater cross sectional copper area to carry the higher current.

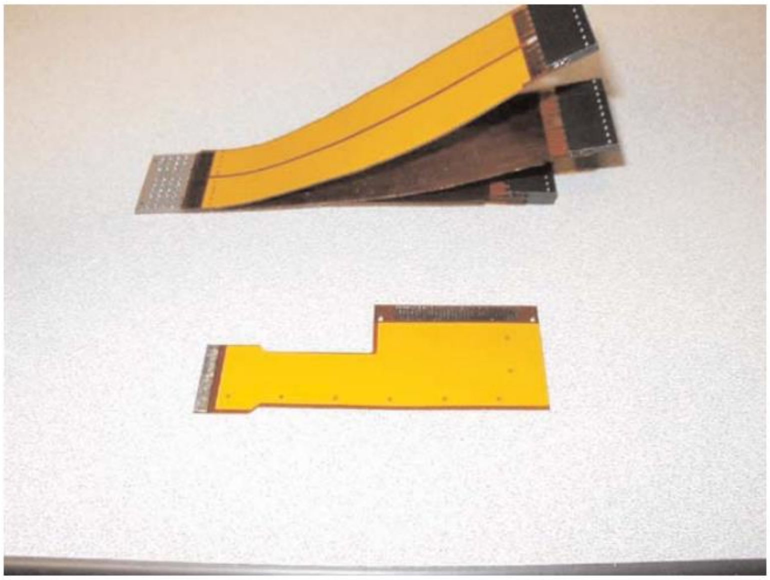
3. **Cross-hatching plane layers to increase flexibility**
   Use a cross-hatch or dot pattern to reduce the copper area on plane layers.



The use of cross hatch plane layers to control EMI can, in some cases, increase flexibility without impairing electrical performance.

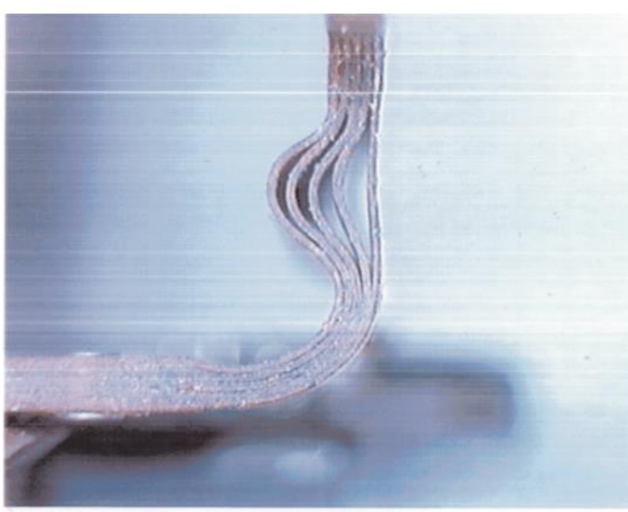
The amount of flexibility gained will be directly proportional to the percentage of copper removed from the plane. A cross hatched plane pattern can also increase bond strength between that layer and the adjacent layer since adhesives bond better to polyimide than to copper. This method should be used in cases where the plane functions primarily to control EMI. The percentage of copper that can be removed will depend on the frequency of the noise that the plane is functioning to keep out of the circuit. It should be noted that reducing the copper plane coverage will significantly impact the impedance of any signals using that plane as a return path. For this reason, it is advisable to look for alternate methods (such as silver epoxy planes) to increase circuit flexibility when impedance is a concern.

4. **Replace copper planes with flexible conductive coating**
   Replace a copper plane with a conductive coating. Coatings such as silver epoxy are highly conductive and considerably more flexible than a copper plane.



Silver epoxy coatings are more flexible than a copper plane.

5. **Unbonding layers in critical areas**
   Use unbonded construction with critical signal and plane layers paired in a microstrip configuration on a single substrate. This keeps signal-to-plane spacing constant while allowing individual substrates to flex independently. This will not work for every application and requires evaluation of sensitive conductors to ensure that puckering caused by flexing will not expose the conductors to excessive noise or mechanical forces.



Unbonded construction allows individual substrates to flex independently.

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6. **Selective removal of cover material**
   Cover material can be removed on outer layers where there is a tight bend and no circuitry. This will have little cost impact, requiring only a quick punching operation prior to cover lamination, and allows circuit thickness to be reduced in those areas by .004" to .006".

7. **Add a "pads-only" layer**
   If current requirements are low, consider adding a "pads-only" layer to the top and bottom of the circuit. This may increase the overall thickness of the circuit, but any increase would be slight. Any increase in thickness will be offset by the fact that there will not be any copper plating on any of the conductors of the internal layers. The advantage here is that the annealed copper on the base laminates is much less brittle than plated copper. If a plated copper conductor develops a fracture, it can propagate through both the copper plating and base copper resulting in an open.

8. **Heat-form the circuit**
   Consider heat forming the finished circuit prior to installation. Flex materials soften considerably at temperatures of 250 to 300 F, and forming the circuit when materials are soft puts less strain on conductors and insulation materials. However, since circuits become more fragile as materials soften, heat forming generally requires specialized tooling to form the circuit and hold it in its finished configuration while it cools. Depending upon the complexity of the finished circuit shape, this tooling can be costly.

9. **Employ custom tooling for cold forming**
   Consider custom cold forming tooling. A flex formed at room temperature will be more resistant to taking and holding a new shape, so properly designed tooling will slightly over-form the circuit so it relaxes to the desired configuration. It is very important to design tooling that supports the circuit across the entire bend area with pressure on both sides of the circuit. This will reduce the chance of delamination during the forming process. Problems can occur when flex circuits are cold formed without proper forming fixtures (e.g., fingers and the edge of a desk). Cold forming is faster than heat forming, but the tooling can be costly and the circuit will not hold the form as long as a heat formed circuit.

10. **Know your termination schemes before designing the circuit**
    Pick termination schemes at the beginning of the design process. Many types of PCB termination hardware are made only for rigid PCBs, so be certain that appropriate hardware is available for flex applications. The designer who waits until the end of the design process to pick termination hardware may find that what is needed does not exist or only exists for rigid board applications. Also, make sure that the connectors, sockets, pins, or other terminations will fit the allotted space and satisfy your electrical requirements. Since the choice of termination hardware will also drive the part outline at each termination point, this can be a good starting point for a design.

Probably the most important tool to use during the design process is the knowledge and experience of a reputable flex circuit manufacturer. In fabricating hundreds or thousands of designs for a variety of applications, manufacturers gain insight as to what works and, more importantly, what does not. They can assist the designer by flagging features that may cause problems during fabrication, assembly, or use. The manufacturer can also suggest termination options based on cost, ease of assembly, and robustness. When the PCB designer works closely with the manufacturer during the design process, costly oversights can be fixed before the circuit goes to production. Mistakes are easier to fix in the design phase than when they turn up in prototypes.

Summary

Many apparent conflicts between the electrical and mechanical requirements of flex or rigid-flex circuits can be reconciled. This is best achieved through clear understanding your requirements, thoughtful planning, careful choice of materials, and application of best-practices in circuit design. The knowledge and experience of a reputable flex circuit manufacturer can be helpful in maximizing both electrical and mechanical performance.

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