Designing a Flex Circuit for Flexibility

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Introduction

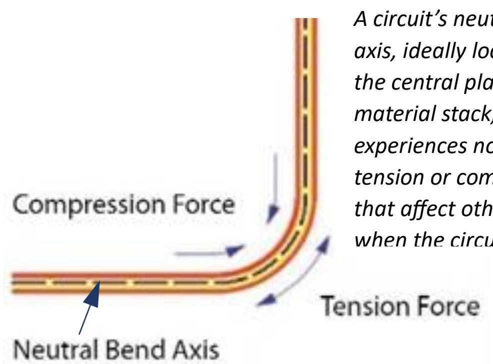
Flex circuits are a great alternative to traditional wiring in modern electronics. A flex circuit is lightweight, compact, resilient, and robust - attributes that make them ideal for smaller and more portable electronics in new designs, and as replacements for traditional wire harnesses and circuit boards in existing devices. Since they are flexible, there are specific requirements that must be considered for a flex circuit that differs from a traditional rigid circuit. Materials, feature placement (pins, connectors, components, etc.), circuit layout, and the number of layers in the circuit must all be considered in the design process. The degree to which the circuit will be bent, how tight the bend will be, how the bend will be made, and how frequently the circuit will be flexed are key attributes to define. By carefully defining the application and design priorities, recognizing the unique demands made upon flex circuits, and understanding the materials they are made of, the designer can work within these requirements to design and produce a successful flex circuit.

Basic Flex Circuit Theory

It is important to recognize that, while the materials that comprise a flex circuit may be individually flexible, their performance in a completed circuit is greatly impacted by the overall circuit's construction.

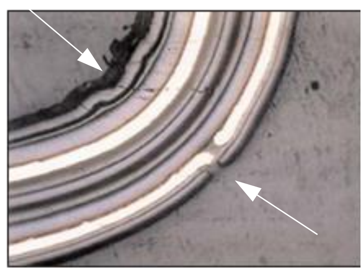
Every flex circuit has a neutral bend axis. This plane, which is ideally located on the central plane of the material stack, theoretically experiences no compression or tension forces when the circuit is flexed. Toward the outside of the bend, however, outer layers experience increasing tension, which can tear or crack the materials. This can lead to immediate circuit failure or, potentially worse, partial or hairline breaks that will fail after the circuit has been put into service. Toward the inside of the bend, layers are subject to increasing compression. This can cause layers to wrinkle or delaminate, again a potential cause of immediate or eventual failure. Careful design can help prevent these problems.

Figure 1 – Single Layer Flex Circuit Bent 90 Degrees



A circuit's neutral bend axis, ideally located on the central plane of the material stack, experiences none of the tension or compression that affect other layers when the circuit is bent.

Figure 2 – Multi-Layer Flex Circuit Bent 90 Degrees



Improper circuit design and/or handling can cause outer layer cracks/tears, and inner layer wrinkling or delamination.

Overall Circuit Design Considerations

There are many factors that can impact a circuit's performance when flexed. These include:

- Neutral bend axis: When the neutral bend axis falls close to the center of the circuit's material stack, the forces are more evenly distributed among the other layers of the circuit when it is flexed.
- Bend angle: The smaller the angle a circuit is flexed, the lower the risk of damage.
- Bend radius: A larger bend radius helps reduce the risk of damage.
- Thickness of the circuit: Thinner circuits present less risk of damage when flexed.
- Frequency of flexing: A circuit designed and constructed for a static application (where the circuit is designed to bend only once for installation) may not be acceptable for a dynamic application (where the circuit will be flexed regularly).
- Material selection: Select the proper materials that possess sufficient strength to withstand the stresses associated with bending or flexing. This includes both tensile strength (resistance to pulling forces) and compressive strength (resistance to crushing forces). The way materials in a stack transmit these forces to other layers in the bend area without causing tensile or compressive failure will improve overall circuit performance.
- Construction: Careful placement of features away from the bend area is crucial to ensure the reliability of the flex circuit. Features that are vulnerable to forces generated in the bend area, or features that can weaken surrounding circuit structure when flexed, should not be placed in or near the bend area during the design process.

Designing for Reliability

Designing a flex circuit that is reliable, meets size and weight specifications, has excellent longevity, and is cost effective is a balancing act that requires the designer to understand the factors that affect overall flex circuit performance.

Neutral Bend Axis

Identifying and understanding the neutral bend axis is essential for designing reliable and durable flex circuits, particularly in applications where repeated flexing is expected. It helps ensure that the flex circuit can withstand the intended bending or flexing without compromising electrical performance or mechanical reliability.

The neutral bend axis refers to the location within the flex material stack-up where there is minimal stress or strain during bending or flexing. The amount of tension or compression forces on the outer layers of the circuit increases the further away from the neutral bend axis they are placed. To equalize these forces, the neutral bend axis should be placed as close as possible to the middle of the material stack-up.

Utilizing balanced construction helps center the neutral bend axis in a material stack-up. Heavy copper conductors, copper planes, or a thick layer of polyimide dielectric (greater than .003”) will shift the neutral bend axis towards that face of the circuit. Placing these layers above and below the center plane of the stack-up in a balanced fashion can equalize the distance from the neutral bend axis, minimizing tension and compression forces acting on these layers in the bend area of the circuit.

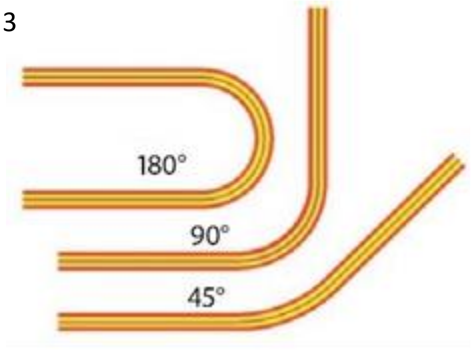
Bend Angle

When a circuit is flexed, tension and compression forces created within the circuit increase as the angle of the bend increases. Generally, 90° is the maximum angle any circuit should be bent more than once, although a properly designed circuit may be bent more than 90° once for installation purposes. If the circuit is intended for a dynamic application (to be flexed repeatedly), the bend angle should not be greater than 90°.

If a circuit must be bent for installation, utilizing a forming tool is recommended to control the precise location and angle of the bends required, to prevent uneven bending that can cause circuit failure.

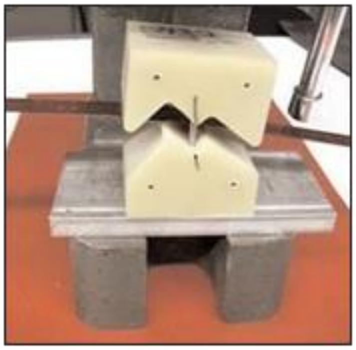
Over-forming a circuit can cause damage (bending beyond the intended bend angle to compensate for spring-back after forming) and should be avoided if the bend angle is close to the circuits design limits. Instead, securing the circuit in its intended bend angle with a guide or constraint device is recommended to prevent the circuit from relaxing before installation.

Figure 3



As the angle of the bend increases, tension forces on the outside and compression forces on the inside of the bend area are increased.

Figure 4

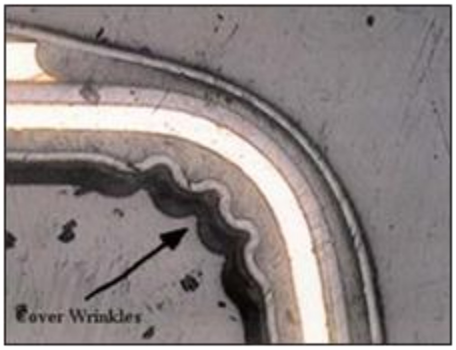


Use of a forming tool controls the precise location and angle of each bend – eliminating risk of uneven bending done by hand.

Bend Radius

Bend radius is measured from the inside surface of the circuit at the bend. Utilizing a larger bend radius reduces the risk of damage to the circuit caused by a smaller bend radius. This is especially important as the bend angle increases.

Figure 5



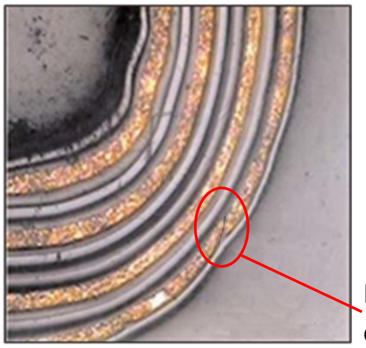
Damage to a circuit caused by too-small of a bend radius.

Thickness

Designing circuit thickness for proper flexibility is a balance between mechanical and electrical performance. A thicker circuit can flex less than a thinner circuit, but a circuit designed thin for flexibility may experience failures in electrical performance. It is possible to decrease circuit thickness to achieve both mechanical and electrical performance parameters, but doing so may increase the cost of production.

The number of copper layers needed to create a circuit, the thickness of individual materials, as well as the way they are put together all affect the overall thickness of the finished flex circuit. Reducing the "weight" or thickness of the base copper, reducing the adhesive thickness, and reducing the dielectric thickness can all be utilized to reduce overall circuit thickness in the bend area. Using adhesiveless copper-clad base materials can also reduce thickness without sacrificing electrical performance.

Figure 6



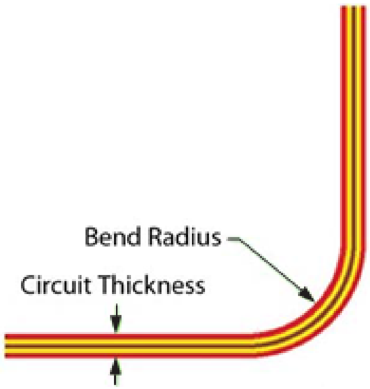
Hairline crack in conductor

Damage to circuit due to excessive thickness in bend area.

Bend Ratio

The term *Bend ratio* refers to the ratio of bend radius to circuit thickness. For single-layer circuits, the minimum bend ratio should be 10:1 – where the bend radius is 10 times greater than the thickness of the circuit. For double-sided circuits, the minimum bend ratio should be 10:1, and for multi-layer circuits, the minimum bend ratio should be 20:1. **These are *minimum* values for static applications where the circuit is intended to be bent once for installation**. Circuits designed close to the minimum bend ratio should be constrained after forming to avoid damage caused by additional flexing.

Figure 7



Bend Ratio = ratio of bend radius to circuit thickness.

IPC-2223 contains detailed information on safe bend radii for various circuit types and thicknesses. The values in this standard are conservative to consider the many factors that can affect circuit resilience. It is possible to safely achieve lower-than-standard bend ratios, but designers should always consult experienced flex circuit manufacturers in developing designs that fall below the published standards.

Static vs. Dynamic Applications

Knowing how many times a circuit is intended to be flexed in its application is important in the design process of the circuit.

Static applications are those where the circuit is bent once for installation and never moved again.

Semi-static applications are those where the circuit does not flex during normal use but may be flexed up to 20 times during the life expectancy of the circuit (e.g., a circuit that is handled for maintenance or repair).

Dynamic applications are those where the circuit is flexed regularly, perhaps thousands or even millions of times.

Again, the recommended minimum bend ratios for circuits are for *static* applications. After the initial bend, materials in the circuit stack-up are subject to different forces during subsequent flexing. The first time a circuit is flexed, copper layers on the outside of the neutral bend axis are stretched since copper is ductile – which is not a problem if minimum bend ratios are adhered to. But in the case of dynamic (and some semi-static) applications, when the circuit is then flattened, the stretched copper cannot resume its original shape, so it will ripple. In subsequent bends, these ripples in the copper are flexed, will work-harden and eventually crack the copper. Similarly, materials on the inside of the neutral bend axis are rippled when flexed and then flattened when the bend is opened. This can also work-harden the copper, increasing the likelihood of broken conductors.

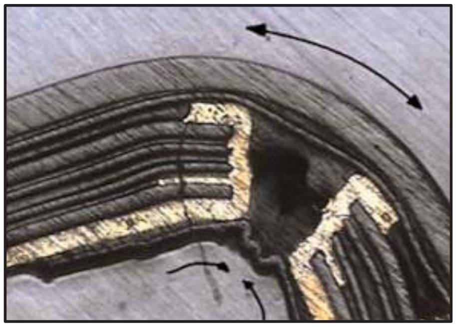
Circuits designed for dynamic applications should have only single-layer circuitry in the bend area. The bend ratio must also be significantly larger (e.g., 30:1) than the standard ratio recommended for static applications. And the designs should be perfectly balanced, with the conductor (the neutral bend axis) centered between identical top and bottom layers.

Materials and Construction

There are numerous considerations in designing any flex circuit.

- Very small conductors (less than .010" wide) can tolerate compression better than stretching and should be placed to the inside of the neutral bend axis in the material stack-up.
- A copper plane layer in a circuit should be placed near the center of the material stack to help keep the neutral bend axis centered.
- Avoid placing any plated through holes in the bend area, as the holes can be stretched on one side and compressed on the other. If positioned near the end of the bend, the hole can shear. Copper in the holes can crack, and unsupported polyimide insulation over a hole can stretch and crack.

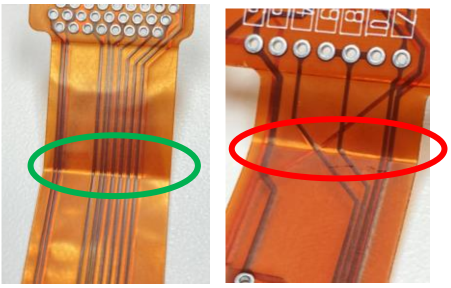
Figure 8



Plated through-hole located near center of a bend being compressed on the inside of the bend and stretched on the outside of the bend.

- Conductors running through a bend area should always run perpendicular to the bend. Twisting forces on a conductor running at a non-right angle to the bend can damage the conductor.

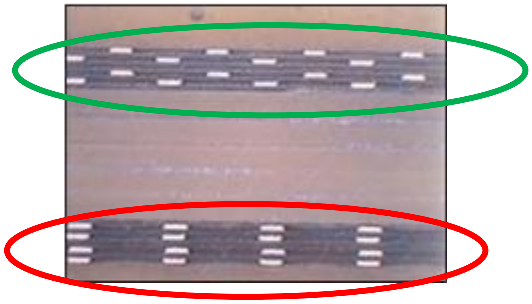
Figure 9



Run conductors in a bend area perpendicular to the bend radius as shown on the left, not at an angle as shown on the right.

- When using rolled-annealed copper, run the grain direction of the material parallel to the conductors in the bend area to increase flex endurance.
- In multi-layer circuits, avoid stacking conductors on top of one another ("I-beam") since this increases the effective thickness of the circuit. Stagger the conductors to lower circuit thickness and the resulting bend ratio whenever possible.
- Where signal and return lines are "stacked" in pairs to reduce emitted noise, try to stagger the pairs of conductors.

Figure 10



Stagger conductors to reduce effective thickness of the circuit in bend areas.

Do not stack conductors which creates an I-beam effect.

- Do not place Surface mount components (SMT) on bend areas. Circuits with SMTs typically utilize photo-imageable coverlay to allow complete exposure of the components, and adhesiveless base material to prevent pad lifting during the reflow process. They are also stiffened on the opposite side of the mounted SMT components - and usually only on one side of the circuit. Rigid-flex circuits are an exception where SMT components are often on both sides of the circuit. Rigid-flex circuits typically have unstiffened bend areas to act as hinges or flexible arms between the stiffened SMT areas.
- Avoid items that cause weak or stiff points in or near the bend area. Weak areas can be damaged when the circuit is formed. Stiff areas can transfer bend forces to adjacent areas, creating damage in those other areas. Examples of items to be avoided in the bend area include: changes in conductor width, plated finishes on conductors, openings in cover insulation, slits or cut-out areas.
- Avoid stitched vias. Since flex circuit dielectrics are so thin, stitched vias are of questionable value in protecting against EMI. If they are incorporated in a circuit design, they should be kept away from the bend area, as they are items that can lead to cracks in insulation.

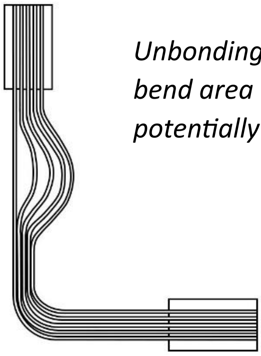
Additional Design Considerations

While flex circuit design carries basic rules that have been tested and proven in countless designs, there are ways to work around standard design limitations:

- Unbonding the layers in the bend area can reduce the forces acting in the area if the circuit's bend ratio is too small. Instead of being the total circuit thickness in the bend area, the functional thickness becomes the thickness of only the individual layers. This typically allows the unbonded layers to bow inward with bend radii smaller than the overall bend, but each individual circuit's reduced thickness lowers the overall acceptable minimum bend ratio.

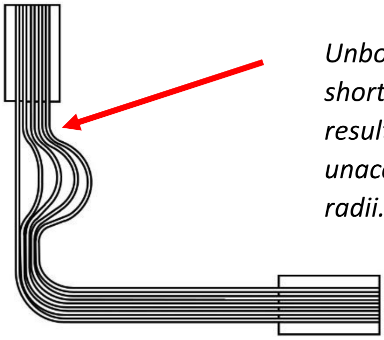
Caution must be taken during design to ensure the unbonded area is at least 0.75″ long, to eliminate unacceptably tight bend radii where layers are buckled.

Figure 11



Unbonding the layers in the bend area can reduce potentially damaging forces.

Figure 12



Unbonded area that is too short (less than 0.75″) resulting in buckling and unacceptably tight bend radii.

- Eliminating copper plating on conductors in the bend area reduces overall circuit thickness in the bend area due to lack of plating thickness and reducing the required thickness of the cover adhesive. Copper plated conductors are more susceptible to cracking when flexed compared to unplated copper, which is much more ductile than plated copper. Selectively plating on only the circuit pad areas eliminates plating on flexible conductors in the bend area.
- Adhesiveless substrates can reduce thickness by .001-.002″per layer. These materials cost somewhat more than adhesive-based materials but may be worth the cost by eliminating problems in a circuit that is too thick.
- Selecting a dielectric material with the proper ratio of stiffness to thickness will result in a flex circuit that will perform reliably.
- Add fillets on transitions from conductors to termination pads to reduce the stress concentration at these points in a flex circuit. Best practice is to fillet all termination pads, but this is particularly important within 0.1″ of bend areas, especially if the cover opening does not entirely capture the pad.
- If shields or ground planes are required, use a crosshatched pattern instead of solid copper to maximize circuit flexibility. Openings in the crosshatched shield should be sized to attenuate the EMI frequencies. On controlled impedance circuits, a reduced plane area will significantly increase impedance over that of a solid plane. Conductor width and dielectric thickness can be adjusted to achieve desired impedance.

Summary

Careful design planning with all of these factors considered can produce a flex circuit that meets all of the reliability and longevity goals required, at the lowest overall cost.

For help on how to achieve the goals for your flex circuit application, you should always contact an experienced flex circuit manufacturer who can evaluate and balance requirements, answer questions, and provide successful solutions to your flex circuit needs.