

Basics of Flex Circuit Design

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Abstract

Flex circuitry is ideal for many of today's electronics needs. It is light, compact, and, if properly designed, extremely robust. Because it bends, however, a flex circuit has some very specific requirements that are different from those of traditional rigid circuits. Materials, circuit architecture, placement of features, and the number of layers in the circuit must all be considered in the design process. So must the degree to which the circuit will be bent, how tight the bend will be, how the bend will be formed, and how frequently the circuit will be flexed. By carefully defining the application and design priorities and recognizing the unique demands made upon flex circuits, the designer can work within these requirements to realize the technology's full potential.

There are plenty of good reasons to use flex circuits. They are light, compact, robust, and resilient, and ideal for today's smaller and more portable electronics. They are ideal for new product designs, but can be used to replace traditional wire harnesses and circuit boards as well. But to realize their full potential, designers must consider the unique requirements of these circuits and the materials they are made of. 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 a circuit's construction.

Single Layer Flex Bent 90 Degrees

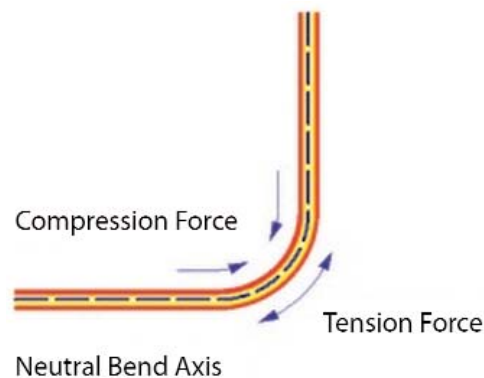


Figure 1: A circuit's neutral bend axis, ideally located on the central plane of the material stack, experiences none of the tension or compression that affect other layers when the circuit is bent

Every flex circuit has a neutral bend axis. This plane, which is ideally located on the central plane of the material stack, experiences, at least in theory, 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, 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 2: If a circuit is not properly designed and handled, outer layers can tear or crack and inner layers can wrinkle or delaminate

Critical Factors

A variety of factors can impact a circuit's performance when flexed. These include:

- The closer the neutral bend axis falls to the center of the circuit's material stack, the more evenly forces will be distributed among the other layers of the circuit when it is flexed
- Bend angle – the less a circuit is flexed, the smaller the risk of damage
- Thickness of the circuit – less thickness reduces the risk of damage when flexed
- Bend radius – a larger radius helps reduce the risk of damage
- Frequency of flexing – construction that might not be acceptable for a dynamic application, one in which the circuit will be flexed regularly, may be acceptable in a circuit designed to bend only once for installation
- Materials – proper selection of materials for their ability to accommodate flex and the way they transmit those forces to other layers in the bend area will improve performance
- Construction – designers should avoid placement in or near the bend area of features that are particularly vulnerable to forces generated in the bend area, or that can weaken surrounding circuit structure when flexed

Creating a Reliable Design

Flex circuitry is a powerful technology, but like any technology, it involves tradeoffs. The designer's goal is to produce a robust and effective circuit that meets performance goals and fits space and weight requirements at the lowest price. Balancing these various expectations depends on a clear understanding of the factors that affect flex circuit performance.

Neutral Bend Axis

This is a key concept in flexible circuit design. The neutral bend axis is the plane within the circuit where there is neither compression nor tension when the circuit is flexed. The amount of tension or compression on the outer layers of the circuit depends on their distance from this neutral bend axis. The only way to keep both these distances, and the potentially damaging forces that result, as small as possible is to get the neutral bend axis as close as possible to the middle of the stack.

The best way to center the neutral bend axis is through balanced construction. It may help to envision the neutral bend axis as an imaginary plane that may or may not coincide with an actual structure within the circuit. A heavy copper plane, a layer of heavy copper conductors, or a thick layer of polyimide dielectric (>.003") will shift the neutral bend axis toward that face of the circuit. By balancing the placement of such layers above and below the center plane of the material stack, a designer can equalize the distance from the neutral bend axis of the circuit's outer layers and minimize stretching and compressing forces at these surfaces in the circuit's bend area.

Bend Angle

All other factors being equal, the forces created when a circuit is flexed—tension on the outside and compression on the inside of a bend—increase with the angle of the bend. For this reason, a circuit should be flexed no more than necessary to achieve the goals of the design. In general, 90° is considered the maximum angle through which any circuit should be bent more than once. In certain cases, a properly designed circuit may be bent more than 90° once, for installation. But if the application is dynamic—if the circuit will be flexed, flattened, and re-flexed multiple times—the bend should not exceed 90°.

The way a circuit is formed (bent for installation) can be critical. If circuits are formed by hand rather than with a forming tool, they can easily be bent unevenly, so that some areas of the bend exceed acceptable bend angles. It is preferable to use a forming tool that controls every point of the bend when it is formed.

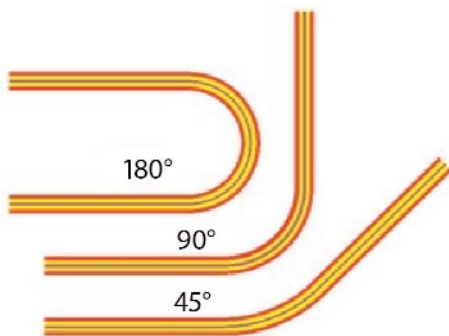


Figure 3: The forces created when a circuit is flexed—tension on the outside and compression on the inside of a bend—increase with the angle of the bend

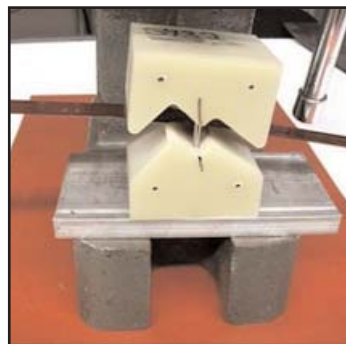


Figure 4: Because circuits that are formed by hand can be bent unevenly, it is preferable to use a forming tool that controls the bend when it is formed

Also, circuits are sometimes “overformed,” bent beyond their intended bend angle to compensate for material memory that will cause them to spring back after forming. If the intended bend is close to the circuit’s limits, overforming should be avoided to prevent damage. This can be done by flexing the circuit to its intended angle and then using some means of holding it at that angle to keep it from springing back.

Thickness

Simply put, the thicker the circuit, the less it can flex without damage, so unnecessary thickness should be avoided. At the same time, however, designers should be aware that there is a tradeoff between mechanical performance and electrical performance. Keeping a circuit thin, if not done properly, can impact electrical performance. In some cases, circuit thickness can be reduced without impacting performance, but at some increase in cost of production.

A number of factors affect the thickness of a circuit including the thickness of individual materials, the way they are put together, and the number of copper layers needed to create the circuit. Ways of reducing circuit thickness in the bend area include reducing the base copper weight and adhesive thickness and reducing dielectric thickness. Designers can also reduce thickness by using adhesiveless base materials.

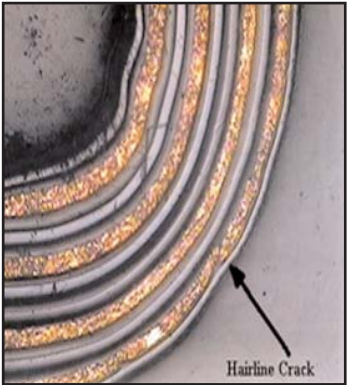


Figure 5: The thicker a circuit is, the less it can be flexed without damage

Bend Radius

Tighter bends increase the risk of damage to the circuit. In the case of a 90° bend, for example, the same right-angle can often be achieved with a sharp (small radius) angle or a more gradual (large radius) angle. Obviously, the latter is safer for the flex circuit. (Note that bend radius is measured from the inside surface of the bend.)

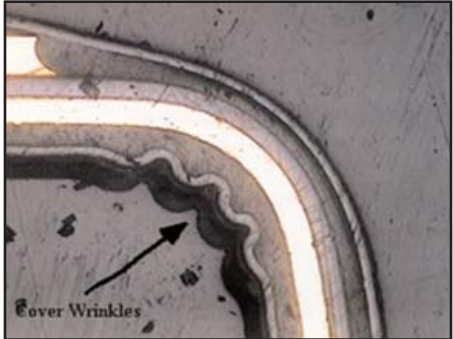


Figure 6: Sharper, i.e., small radius, bends increase the risk of damage when a circuit is bent

Bend Ratio

The reliability of a well-designed flex circuit depends on the ratio of bend radius to circuit thickness. This is the "bend ratio." Ideally, a multi-layer circuit should have a bend ratio of at least 20:1. For double-sided circuits, the minimum ratio should be at least 10:1. And for single-layer circuits, the minimum ratio should be at least 10:1. *These limits assume static applications, in which the circuit will not be flexed after installation.* Circuits that are close to the minimum bend ratio should be constrained once they have been formed to avoid damage due to additional flexing. Detailed information on safe bend radii for various circuit types and thicknesses can be found in IPC-2223.

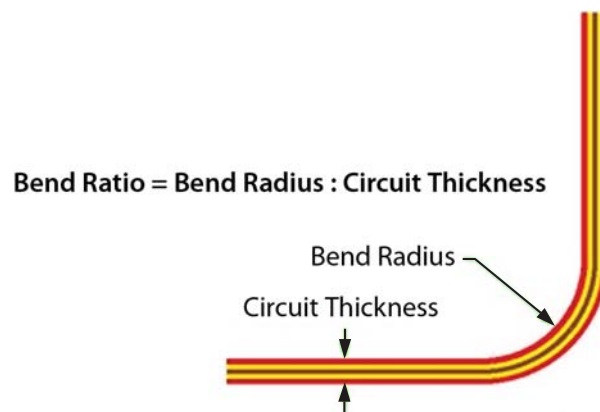


Figure 7: Bend ratio is the ratio of bend radius to circuit thickness

Because the IPC standards are conservatively written to take into account many factors that can affect circuit resilience, it is possible to safely achieve lower-than-standard bend ratios. However, due to the number of factors that can affect performance at smaller-than-recommended bend ratios, it is highly advisable that designers work with an experienced flex circuit manufacturer in developing such designs.

Static vs. Dynamic Applications

The number of times that a circuit will be flexed is a critical question. The reason is that, after the initial bend, materials in a circuit are subject to different forces than during the first bend. The first time a circuit is flexed, copper layers on the outside of the neutral bend axis are stretched. If minimum bend ratios are adhered to, this is typically not a problem, since copper is ductile and able to stretch. But if 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 and 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 if the bend is opened. This too can work-harden copper, increasing the likelihood of broken conductors.

As mentioned previously, the recommended minimum bend ratios for circuits are for static applications, in which the circuit is installed once and never moved again. *Semi-static* applications are those in which the circuit does not flex in normal use, but may be flexed as many as 20 times over the life of the circuit when, for example, it is handled for maintenance or repair. *Dynamic* applications are those in which the circuit is regularly flexed, potentially thousands or even millions of times.

Circuits designed for dynamic applications should not be more than one layer thick. Their bend ratio must be significantly larger 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

A number of issues should be considered in designing any flex circuit.

- When routing conductors, note that very small conductors (less than 10 mils) can tolerate compression better than stretching. For this reason, they should be placed to the inside of the neutral bend axis.
- If the circuit incorporates a copper plane layer, this should be placed near the center of the material stack to help keep the neutral bend axis centered.
- Avoid plated through holes in the bend area. Near the center of the bend, such holes can be stretched on one side and compressed on the other. Near an 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.
- 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.
- In multi-layer circuits, conductors stacked on top of one another increase the effective thickness of the circuit and should be avoided. If possible, stagger the conductors to lower circuit thickness and the resulting bend ratio. Where signal and return lines are “stacked” in pairs to reduce emitted noise, try to stagger the pairs of conductors.
- If you use surface mount (SMT) components, be aware of their unique requirements. These usually entail the use of photo-imageable coverlay to allow full exposure of the components and adhesiveless base material to prevent pad lifting during the reflow process. Circuits also typically must be “rigidized” by laminating a stiffener of the side of the circuit opposite the SMT. Because of the need for stiffening, flex circuits usually have SMT components on only one side of the circuit. The exception is rigid flex circuitry, which often has SMT components of both sides. Rigid flex circuits are stiffened along most of their surface, with relatively small areas left unstiffened to act as hinges or flexible arms.

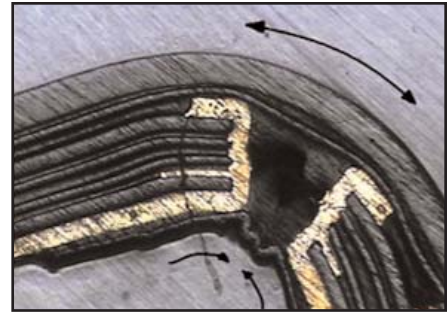


Figure 8: Plated through holes located near the center of a bend can be stretched on one side and compressed on the other leading to circuit failure

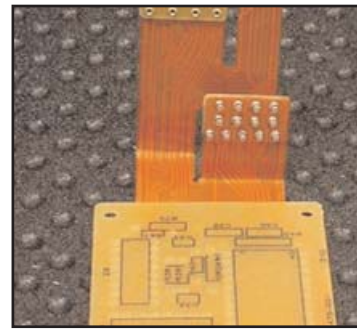


Figure 9: Conductors running through a bend area should always run perpendicular to the bend as shown on the left, not at an angle as seen on the right

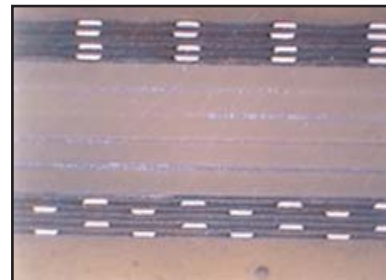


Figure 10: Because conductors stacked on top of one another increase the effective thickness of the circuit, it is preferable to stagger the conductors

- Avoid “discontinuities” in the bend area. These are weak or stiff points in or near (within .1” of) the bend area. Weak areas can be damaged when the circuit is formed. Stiff areas can transfer forces to adjacent areas, creating damage in those other areas. Examples of discontinuities to be avoided in the bend area include: plated finishes on conductors, openings in an insulation cover, slits or cut-out areas, or changes in conductor width.
- 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 discontinuities that can lead to cracks in insulation.



Figure 11: Stitched vias, like through holes, should be kept out of bend area

Tips and Tricks

The basic rules of flex circuit design have been tested and proven, but there are a number of ways to work around standard design limitations:

- If a circuit's bend ratio is too small, forces acting in the area can sometimes be reduced by unbonding the layers in the bend area. This reduces the functional thickness in the bend area; instead of being the total thickness of the circuit, the functional thickness becomes the thicknesses of the individual layers. When this is done, the unbonded layers will tend to buckle inward. Their bend radii may be smaller than that of the overall bend, but their reduced thickness will significantly lower the overall acceptable minimum bend ratio. Be careful not to unbond too short an area (less than .75"), as the resulting buckling can lead to unacceptably tight bend radii in the unbonded layers.

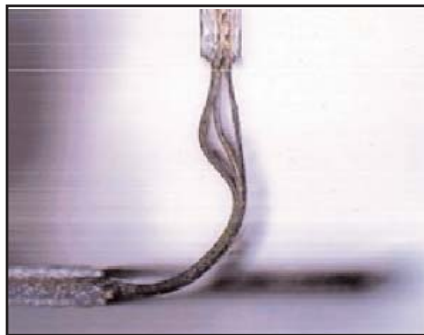


Figure 12: Potentially damaging forces can sometimes be reduced by unbonding layers in the bend area

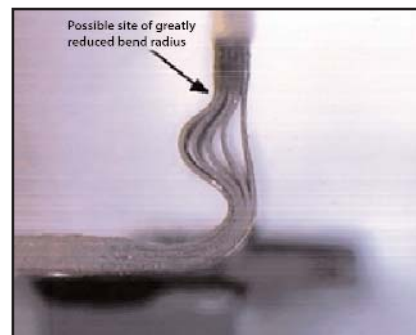


Figure 13: If the unbonded area is too short (less than .75") the resulting buckling can lead to unacceptably tight bend radii

- Another way to help address low bend ratios is to eliminate copper plating on conductors in the bend area. Copper plating is less ductile than rolled, annealed copper, making it more susceptible to cracking when flexed. Selective plating, on pads only, can eliminate plating on flexing conductors. Eliminating plating in the bend area reduces thickness by eliminating both the thickness of the plating and the required thickness of the cover adhesive. Selective plating can increase cost, but it may be worth the price if it prevents circuit failure.
- 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 too-thick circuit.
- Dielectrics differ in their ratio of stiffness to thickness. Choose a dielectric material that fits your application and gives your finished circuit the characteristics you want.
- Unless they are filleted, termination pads can act as a concentration point for stress in a flex circuit. It is generally good practice to fillet all termination pads, but this is particularly important in, or within .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 in to EMI frequency. Note that if controlled impedance is required, a reduced plane area will significantly increase impedance over that of a solid plane. Other factors, such as conductor width and dielectric thickness can be adjusted to achieve desired impedance.
- Another flexible alternative to solid copper for shields is a screen-printed conductive coating such as silver epoxy, which provides similar electrical performance to a copper shield but is much more flexible.

Summary

The reliability of flex circuits depends on careful design. Factors that can affect that reliability include:

- symmetry of design
- bend angle
- circuit thickness
- static vs. dynamic application
- choice of materials
- placement of features
- forming technique
- conductor routing
- discontinuities in the bend area

Careful planning and attention to these factors should produce a circuit that suits its application and delivers all the benefits of flex circuitry at the lowest cost. When in doubt about how to best achieve specific goals in a flex circuit application, an experienced manufacturer can be invaluable in evaluating and balancing requirements, answering questions, and providing solutions.

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