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## BATTLEFIELD TECHNOLOGY

and the Army's carbine competition

page 22

**INNOVATIVE IMPLANTS KEEP BLOOD FLOWING, page46**

**HOW TO SIZE UP HYDRAULIC HOSE, page 52**

**SOCIAL NETWORKS PLAY A ROLE IN PROTOTYPING, page 58**

**DESIGNING FLEX CIRCUITS, page 63**

# Basics of flex-circuit design

For reliability, designers must create flex circuits that are neither too thick nor bend too much.

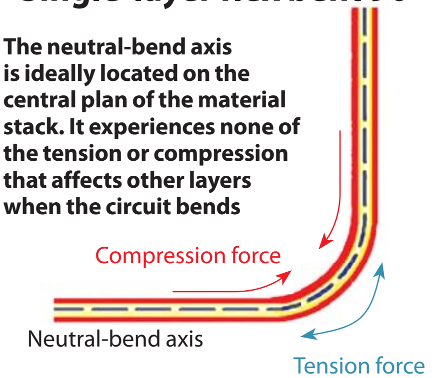
**Improper design and handling can create tears and cracks in the outer layers and wrinkling or delamination of the inner layers.**

Flex circuitry can be light, compact, and robust. Because it bends, however, a flex circuit has specific needs different from those of traditional rigid circuits. Designers must consider materials, circuit architecture, placement of features, and the number of layers in the circuit during the design process. Other items of concern include the degree to which the circuit will bend, how tight the bend will be, how the bend will be formed, and how frequently the circuit flexes.

## Neutral-bend axis

The neutral-bend axis is a key concept in flexible-circuit design. It is a plane within the circuit where there is neither compression nor tension when the circuit flexes. It usually sits on the central plane of the material stack: the layers of printed circuits, insulation, and adhesive that make up the flexible circuit. The layers near the outside of the bend experience tension that can tear or crack the material. This can lead to immediate circuit failure or, potentially worse, hairline breaks that fail after the circuit goes into service. Toward the inside of the bend, layers see compression that causes wrinkles or delamination. Again, this can create conditions leading to eventual or immediate failure. The amount of tension or compression on the outer layers of the circuit depend on their distance from this neutral-bend axis and the radius of the bend. It's critical to keep the neutral-bend axis as close as possible to the middle of the stack to minimize the potential damage from these tension and compression forces.

### Single-layer flex bent 90°

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## Key points:

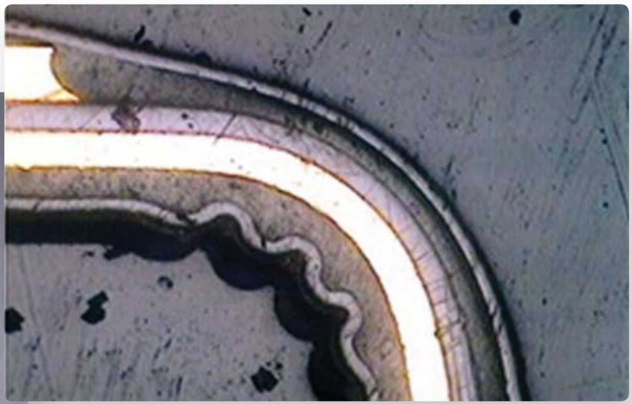
- Every flex circuit has a neutral-bend axis.
- Smaller circuit thickness reduces the risk of damage when flexed.
- Detailed information on safe bend radii is found in IPC-2223.

## Resources:

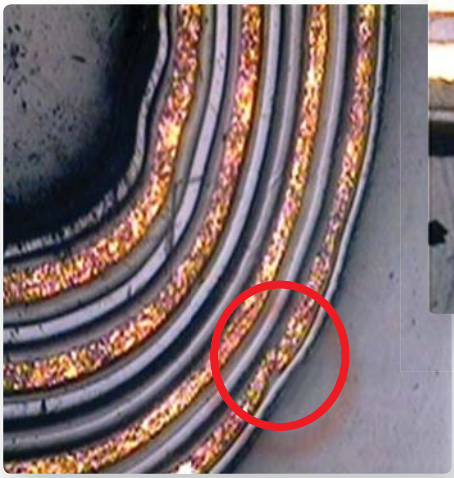
**Minco,** *www.minco.com*

**Flex Design white paper,** *http://www.minco.com/download-media.aspx?id=2304*

**Staying Flexible,** *http://machinedesign.com/article/staying-flexible-0712*



Sharp or small radius bends heighten the risk of damage when a circuit bends. Here the inner layer has wrinkled while the outer layer shows signs of delamination.



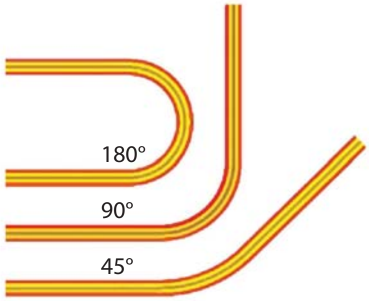
The thicker a circuit is, the less it can flex without damage. Here a hairline crack has formed in an outer trace from a bend radius that was too tight.

It may help to envision the neutral-bend axis as an imaginary plane within the circuit. A heavy copper plane, a layer of heavy copper conductors, or a thick layer of polyimide dielectric (typically greater than 0.003 in.) will shift the neutral-bend axis toward that face of the circuit. A designer can equalize the distance from the neutral-bend axis of the circuit's outer layers and minimize the stretching and compressing forces along these surfaces by balancing the placement of such layers above and below the center plane of the material stack.

## Bend angle

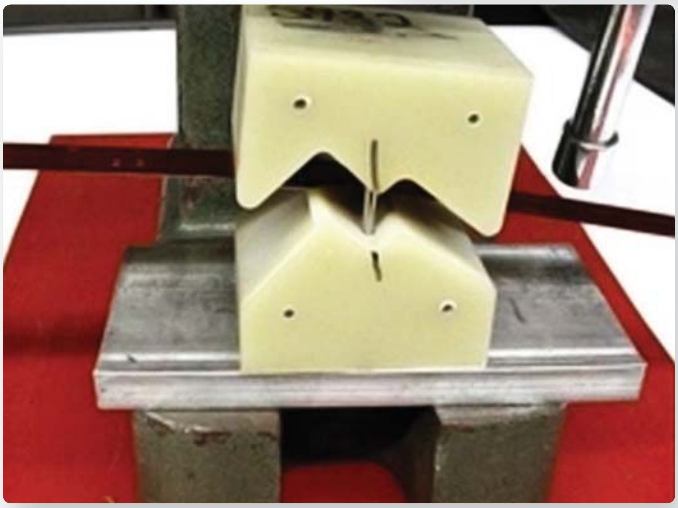
All other factors being equal, the tension and compression forces created when a circuit flexes rise as the bend angle grows. For this reason, a circuit should flex no more than necessary to handle the goals of the design. In general, 90° is considered the maximum angle any circuit should bend. In certain cases, a properly designed circuit may be bent more than 90° once, for installation. But the bend should never exceed 90° if the circuit is flexed, flattened, and reflexed multiple times.

The forces created when a circuit is flexed grow with greater bend angles.




The way a circuit is bent for installation can be critical. Circuits formed by hand may contain areas that exceed acceptable bend angles. It is preferable to use a forming tool that controls every point of the bend when it is made.

Sometimes circuits are "overformed," or bent beyond their intended bend angle to compensate for material memory that makes them spring back after forming. Overforming should be avoided to prevent damage if the bend is close to the limits. Typically, the circuit is flexed to its intended angle and then held in position by some means such as a clip. The clip keeps the material from springing back.



Circuits formed by hand can bend unevenly. A forming tool that controls the formation and amount of the bend is the preferred method.

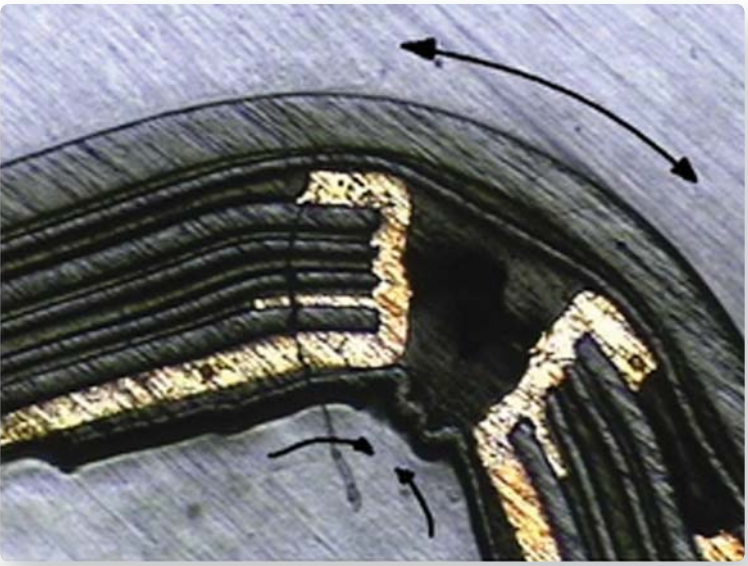
## Thickness

Simply stated, avoid unnecessary thickness. The thicker the circuit, the less it can flex without damage. However, there is a trade-off between mechanical performance and electrical performance. Keeping a circuit thin can impact electrical performance.

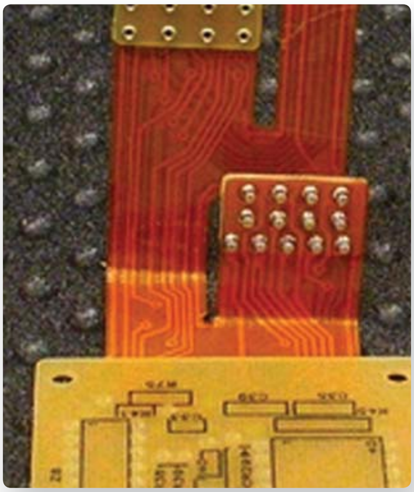
A number of factors affect the thickness of a circuit including the thickness of individual materials, the way they are put together, and the number of copper layers needed to create the circuit. Designers can reduce circuit thickness in the bend area by reducing the base copper weight, the adhesive thickness, and the dielectric thickness. For example, the use of adhesiveless base materials takes adhesive thickness out of play.

## Bend radius versus bend ratio

Tighter bends boost the risk of circuit damage. It's often possible to use a more-gradual (large-radius) angle rather than a right-angle bend with a sharp (small-radius)



**Plated-through holes or vias located near the center of a bend can stretch on one side and compress on the other leading to circuit failure.**



**Conductors passing through a bend area should always run perpendicular to the bend as seen on the left, not at an angle as seen on the right.**

angle. Obviously, the more-gradual bend is safer for the flex circuit. When measuring bend radius, the distance is measured from the inside surface of the bend to the radius center.

The bend ratio is the ratio of the bend radius to circuit thickness. Ideally, multilayer circuits 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 also be at least 10:1.

These limits assume static applications, ones where the circuit will not be flexed after installation. Circuits close to the minimum bend ratio should be constrained once formed to avoid damage from additional flexing. IPC-2223 lists detailed information on safe bend radii for various circuit types and thicknesses.

The IPC standards are conservatively written to take into account many factors that can affect circuit resilience. So it is possible to safely use lower-than-standard bend ratios. However, there are a number of factors that can affect performance at smaller-than-recommended bend ratios. Designers should work with experienced flex-circuit manufacturers to develop such designs.

## Static versus dynamic applications

It is critical to know how many times a circuit can flex. After the initial bend, materials in a circuit see different forces than during the first bend. The first time a circuit bends, copper layers on the outside of the neutral-bend axis stretch. This is typically not a problem if the circuit adheres to minimum bend ratios. Copper is ductile and able to stretch. But if the circuit is then flattened, the stretched copper cannot resume its original shape. Instead, it ripples to try to make room for the stretched material. Subsequent bends repeatedly stretch and ripple the copper causing it to work harden. The hardened copper eventually cracks and the circuit becomes inoperative.

Similarly, materials on the inside of the neutral-bend axis ripple when flexed and then flatten if the bend is opened. This, too, leads to work-hardened copper and broken conductors.

The recommended minimum bend ratios mentioned earlier apply to static applications where the circuit is installed once and never again moves. Semistatic applications cover those situations where the circuit does not flex in normal use, but may flex as many as 20 times over the life of the circuit for activities such as maintenance or repair. Dynamic applications identify those circuits that potentially flex thousands or even millions of times during its lifetime. Circuits designed for dynamic applications should not be more than one layer thick and their bend ratio must be many times larger than the standard ratio recommended for static applications. The perfectly balanced design should place the conductors in the neutral bend axis sandwiched between identical top and bottom layers.

## Materials and construction

Small conductors of less than 10 mils can tolerate compression better than stretching. For this reason, they should go on the inside of the neutral-bend axis. If the circuit incorporates a copper plane layer, it should sit 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 stretch on one side and compress on the other. Near an end of the bend, the hole can shear. Copper in the holes can crack while the unsupported polyimide insulation over a hole can stretch and tear.

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

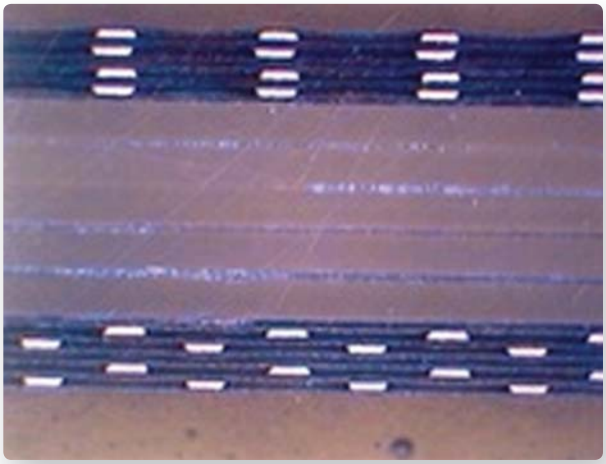
In multilayer circuits, conductors stacked on top of one another increase the effective thickness of the circuit and should be avoided. If possible, stagger the conductors to lower the circuit thickness and the resulting bend ratio. Where signal and return lines are "stacked" in pairs to reduce emitted noise, try to stagger the pairs of conductors.

If you use surface-mount (SMT) components, be aware of their special requirements. These usually entail the use of photo-imageable coverlay to fully expose the components and adhesiveless base material to prevent pad lifting during the reflow process. Circuits must be "rigidized" by laminating a stiffener on 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.

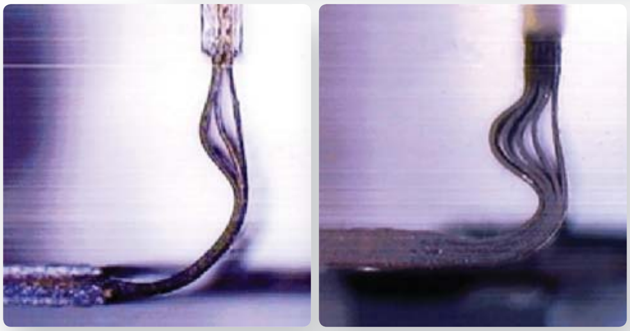
The exception is rigid flex circuitry, which often has SMT components mounted on both sides. Rigid flex circuits are stiffened along most of their surface, with relatively small areas left unstiffened to act as hinges or flexible arms.

Avoid "discontinuities" in the bend area. These are weak or stiff points in or within 0.1 in. of the bend area. Weak areas can suffer damage when the circuit is formed. Stiff areas can transfer forces creating damage nearby. 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.

Because flex-circuit dielectrics are so thin, stitched vias are of questionable value in protecting against EMI and thus should be avoided. If they are incorporated in a circuit design, they should be kept away from the bend area. They are discontinuities that can lead to cracks in the insulation.



**Because stacked conductors increase the effective thickness of the circuit, it is preferable to stagger conductors between layers as shown in this cross-sectional view.**



**Potentially damaging forces can sometimes be reduced by unbonding layers in the bend area, as shown on the left. However, if the unbonded area is too short, buckling can lead to unacceptably tight bend radii as shown on the right.**

## 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.

Unbonding the layers in an area where the bend ratio is too small can sometimes reduce the forces acting on the bend axis. This reduces the functional thickness in the bend area; instead of being the total thickness of the circuit, the functional thickness now becomes the thicknesses of the individual layers. The unbonded layers tend to buckle inward. While their bend radii may be smaller than that of the overall bend, their reduced thickness significantly lowers the overall acceptable minimum bend ratio. However, be careful not to unbond too short an area (typically less than 0.75 in.), as the buckling can lead to unacceptably tight bend radii in the unbonded layers.

Another way to 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, such as plating pads only, eliminates both the thickness of the plating and the needed thickness of the cover adhesive in the bend area. It can boost cost, but may be worth the price if it prevents circuit failure.

Adhesiveless substrates can reduce thickness by 0.001 to 0.002 in./layer. These materials cost somewhat more than adhesive-based products but again may be worth the expense if they eliminate problems in a too-thick circuit.

Dielectrics differ in their ratio of stiffness to thickness. Choose a dielectric material that fits the application and gives the finished circuit the qualities it needs.

Unless they are filleted, termination pads can act as a concentration point for stress in a flex circuit. While it is good practice to fillet all termination pads, it is particularly important in or within 0.1 in. of bend areas, especially if the cover opening does not entirely capture the pad.

If shields or ground planes are needed, use a crosshatched pattern instead of solid copper to maximize circuit flexibility. Openings in the crosshatched shield should be sized to the EMI frequency of interest. Note that if controlled impedance is required, a reduced plane area will significantly exhibit more impedance than that of a solid plane. Conductor width and dielectric thickness can be adjusted to meet the desired impedance.

Another flexible alternative to solid copper for shields is a screen-printed conductive coating such as silver epoxy. Screen printing provides similar electrical performance to a copper shield but is much more flexible.

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. A manufacturer experienced in flex-circuit applications can help evaluate and balance requirements, answer questions, and provide options on how to best achieve specific goals. **MD**