

# Bending, Forming and Flexing Printed Circuits

John Coonrod  
Rogers Corporation

## **Introduction:**

In the printed circuit board industry there are generally two main types of circuit boards; there are rigid printed circuit boards and flexible printed circuit boards. There is a tremendous variety of these general types; however the industries that specialize in one type may have some weakness in understanding some issues related to the other type. Specifically, the flexible circuit industry has come to understand bending, forming and dynamic flexing motion of circuits. The rigid circuit board industry typically will not understand these issues as well. Those who work in the rigid board circuit industry are typically those who fabricate the High Frequency circuit boards. Due to this, there have been several issues with bending, forming and flexing high frequency circuit boards.

All types of circuit boards have the same basic theory for bending, forming and flexing. However the circuit board construction and the materials used, will limit which type of board can feasibly be bent, formed or flexed. Normally woven glass reinforced circuit boards cannot be bent, formed or flexed reliably. There are many different types of materials used for fabricating high frequency circuit boards and there are several that are non-glass woven reinforced. This paper will address bending, forming and flexing circuits built with non-glass woven circuit materials.

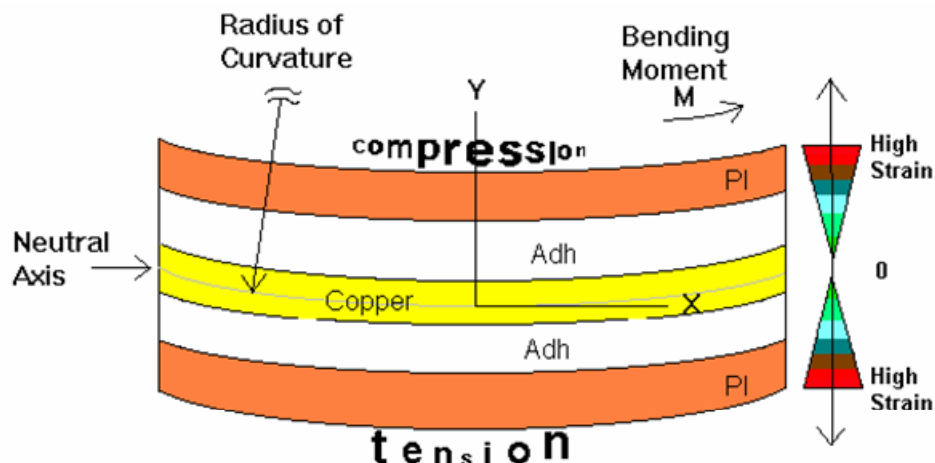
## **Basic Theory:**

The basic theory will be given in several sections. The first is the circuit construction and the basic mechanical properties associated with this aspect. The next issue will be related to materials. A discussion on copper properties will follow and finally a section on mechanical theory for bending.

## **Basic Theory: Circuit Construction and Basic Mechanical Properties:**

To begin with, the theory that will be discussed will be in regards to simple adhesive based flexible circuits. It will be made obvious that these same principles apply directly to non-glass woven high frequency circuits. The term “flex circuit” will apply to both of these types.

A flexible circuit is made up of a composite of different materials. There are conductive layers (copper), bonding layers (adhesive) and insulating or dielectric layers. For a traditional adhesive based, single sided (one copper layer) flex circuit; there are 5 layers of materials. Two outer layers are polyimide films (PI), the center layer is the copper layer and there is a layer of adhesive top and bottom of the copper layer to bond the circuit together. This is shown in figure 1 below.



**Figure 1, Cross-sectional view of single sided adhesive based flex circuit**

In mechanical terms, the flex circuit is considered a composite beam. When a bend is applied to any beam there are several things worth noting. The material that is near the surface of the inside of the bend radius will be compressed. The material near the surface on the outside of the bend radius will be stretch or will experience tension. There is an infinitely thin plane where the transition of compression becoming tension occurs. This plane is the neutral axis and will have zero strain. The

amount of strain at any plane within the thickness of the circuit with an applied bend is based on how far that plane of interest is from the neutral axis. There are several other considerations; however the neutral axis location in regards to other layers of interest is critical.

#### **Basic Theory; Material Properties:**

Understanding some mechanical properties of the circuit materials used are also important. One of the key properties to consider is the modulus or stiffness of the circuit material. Since the flex circuit is a composite beam, the different materials will also have different properties. A list of a few materials used in the printed circuit industry, which are considered flexible, is shown in table 1. It should be noted that the modulus of the copper is orders of magnitude larger as compared to any other material type. Therefore the amount of copper in the circuit is very important to understand.

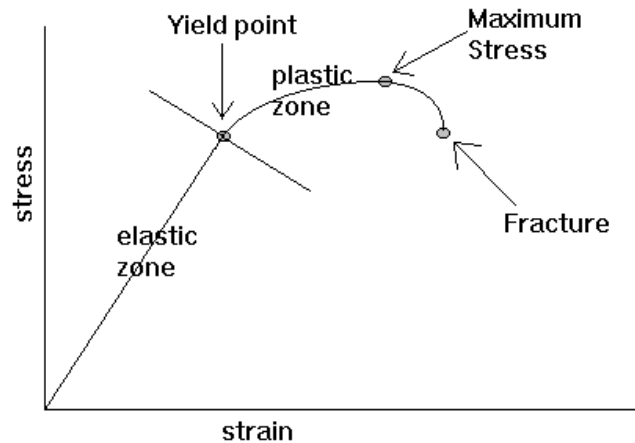
**Table 1, Modulus of different materials**

|                                          | Modulus |        |
|------------------------------------------|---------|--------|
|                                          | Gpa     | Kpsi   |
| Rolled Annealed copper                   | 117.3   | 17,000 |
| Dynamic ED Copper                        | 82.8    | 12,000 |
| Traditional Flex Materials               |         |        |
| Kapton HN Polyimide film                 | 2.553   | 370    |
| Apical AV Polyimide film                 | 3.174   | 460    |
| Apical NP Polyimide film                 | 4.278   | 620    |
| Kapton E Polyimide film                  | 5.52    | 800    |
| Upilex S Polyimide film                  | 8.832   | 1,280  |
| Typical Flex adhesive epoxy based        | 0.828   | 120    |
| Typical Flex adhesive acrylic based      | 0.621   | 90     |
| Rogers flex adhesive, epoxy based        | 1.311   | 190    |
| Rogers flex adhesive, acrylic based      | 1.035   | 150    |
| High Frequency Circuit Board Materials   |         |        |
| Micro-fiber glass PTFE, Nearly pure PTFE | 0.897   | 130    |
| Ceramic PTFE                             | 2.07    | 300    |
| Rogers LCP laminate                      | 2.2563  | 327    |
| PCTFE bonding film                       | 1.0005  | 145    |
| FEP bonding film                         | 0.552   | 80     |

Another issue that sometimes gets more attention than it should is the bond strength between the various layers of the circuit. The bond strength will generally not be an issue for bending, forming or flexing a circuit. This is mainly due to the fact that the mechanical issues have very little to do with shear force between the circuit layers.

#### **Basic Theory; Copper considerations:**

When the copper is fractured due to excessive strain and / or flexural repetition, then the circuit will be defective. Therefore the effects of strain within the copper and the relationship of strain at the copper interfaces within the circuit are important. A general stress / strain curve for a standard rolled anneal copper is shown in figure 2.



**Figure 2, Stress / Strain curve for a standard rolled annealed copper**

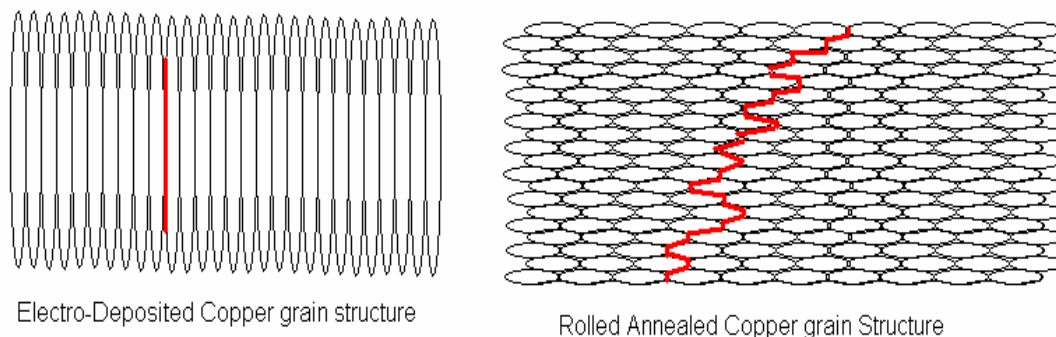
The elastic zone shown in figure 2 is the zone where the copper is not being deformed to the degree of causing any grain fracturing. Beyond the yield point and in the plastic zone, the copper is being deformed to the point where permanent damage is being done to the copper grain structure.

If the circuit is used in a dynamic flexing application, then minimizing the strain at the critical copper interface is important. In theory, if the strain on the critical copper layer of a dynamic flex circuit were less than the yield point of the copper then the circuit would have infinite flexural endurance. In reality there are several other factors, however strain numbers around the yield point is very important to consider for some dynamic applications.

For applications that are non-dynamic and are bending / forming applications, the strain at the critical copper interface is still important however can well exceed the yield point. Copper strain numbers for different applications, will be discussed in more detail later in this paper.

Elongation properties of copper have been a large focus of attention in the rigid board industry and very little interest in the flex circuit industry. There are several reasons for this, however assuming that the elongation properties are moderately good then the real interest is the grain structure and surface roughness of the copper.

Very generally speaking, there are two types of copper used in the printed circuit board industry; there are electro-deposited (ED) copper and rolled annealed (RA) copper. There are a couple of meaningful considerations for copper grain structure and these two types of copper have significantly different grain structure.

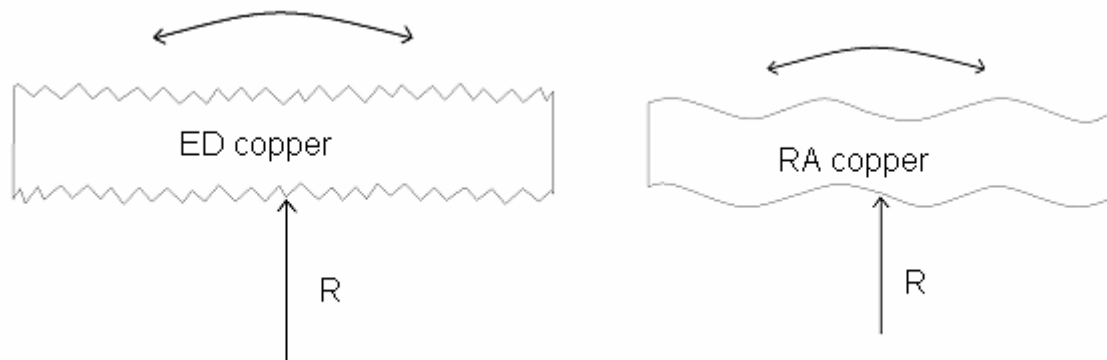


**Figure 3, simple cross-sectional drawing of ED and RA copper grain structures and possible fracturing**

Figure 3 shows simple drawings of ED and RA copper grain structures. Things to note would be the vertical grain structure of the ED copper and horizontal for the RA copper. When a bend radius is applied to the copper structure and with enough force to fracture the copper, there are two fracturing properties to consider. The properties are the crack initiation and crack propagation. The copper grain structure of ED illustrates that it will be worse for both properties. When a bend is applied, the initiation of the crack will occur relatively easily because there are sharp mountain-valley relationships at the surface, which cause stress concentrators in the valleys. Once the crack is initiated, then the vertical grain structure will fracture

through the boundary nearly immediately. In regards to the RA copper, the surface is smoother, so there is less of a stress concentrator to initiate a crack at the surface. However once a crack is initiated, then the crack will have to work through many grain boundaries in order to fracture through the entire copper structure.

To further illustrate the copper initiation consideration due to the copper surface, figure 4 is shown. The surfaces of the ED and RA copper are exaggerated, however one can see when a bend radius is applied which surface would initiate a crack easier.



**Figure 4, simple drawing of exaggerated surfaces of ED and RA copper with applied bend radius**

In applications where bending, forming and flexing are done, RA copper is more robust and recommended. There are situations where ED copper could be used or specific types of ED copper could be used as well.

The last comment about copper would in regards to circuit fabrication. In the case of the choice of a specific copper for good bending / flexing performance, the circuit fabrication process can completely negate the benefits. For example...considering an application where a critical bend is applied and RA copper is used. If the circuit fabrication process is not a specific type of process then a layer of ED copper would be plated on top of the RA copper and the bending benefits of RA will be negated. In this case a selective plating process should be used to plate copper in the holes only and protect the RA copper. Another issue in circuit fabrication that can have detrimental effects on bending is the type of finish that is applied to the copper in the bending area. With a traditional flex circuit, this is not a concern because the bend or dynamic areas are typically covered with a coverfilm material and there is no exposed copper with an applied finish. However in the rigid printed circuit board industry they very often will apply a bend in an area with exposed copper and it will usually have some type of finish. The finishes with nickel are more problematic, due to the fact that nickel is so brittle. When a gold finish is applied to copper, nickel is typically used as a migration barrier. In some cases the nickel is removed in the bending area and a calculation is done to establish how much gold will be needed. There are diffusion equations that are used to determine how much time that a certain amount of gold will remain in a good condition, assuming certain environmental conditions.

#### **Basic Theory; Mechanical theory of bending**

When a circuit construction has a bend radius applied, there is strain in the various layers of the circuit. The amount of strain on certain layers within the circuit construction, such as the copper layers is of interest. The non-glass woven flexible materials usually have mechanical properties that will allow them to elongate more than the copper without fracturing. So the copper is typically the worse case layer for material fracturing with a given strain. And since copper is the conductive layer and keeping the circuit electrically sound, then it makes sense that the copper is evaluated for strain with a given bend radius. More specifically the weak link of the copper – material interface is what should be evaluated. The copper surface that is adhered to the bonding material (adhesive or prepreg) is generally the weak link and that is the interface that should be considered for strain. And the interface should be the interface that is furthest from the neutral axis.

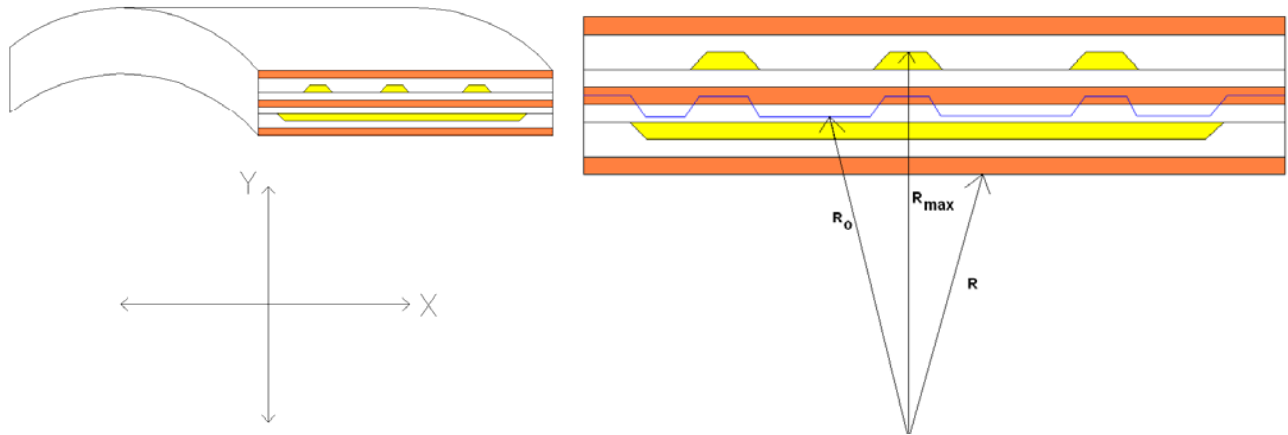
Strain in this case, is a percent elongation. When the cross-section of the circuit that will be bent is considered, it will be modeled flat and with no elongation. After a bend radius is applied then the amount of strain will be modeled at the critical interfaces. Once the amount of strain is understood for the critical layers, then the use of empirical data will guide to whether the critical layer of the circuit should be able to withstand the given bend radius. The strain ( $\epsilon$ ) calculation is relatively straightforward and shown below in figure 5.

$$\varepsilon := \frac{\left[ (2 \cdot \pi \cdot R_{\max}) - (2 \cdot \pi \cdot R_o) \right]}{(2 \cdot \pi \cdot R_o)} * 100$$

$$R_o := R + \frac{\sum_{i=1}^n E_i \cdot Y_i \cdot A_i}{\sum_{i=1}^n E_i \cdot Y_i}$$

**Figure 5, Formulas for Strain and Neutral Axis location**

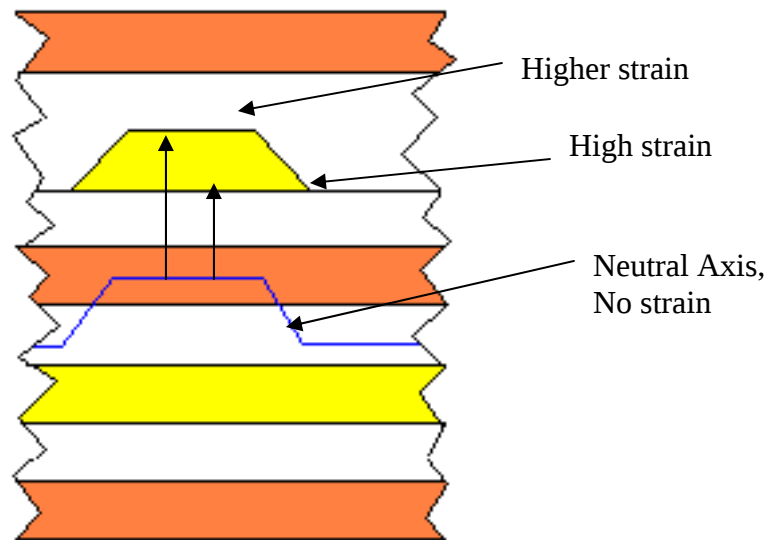
The neutral axis location ( $R_o$ ) is needed to calculate the percent strain. The formula for the neutral axis is also given in figure 5.  $R_{\max}$  is the interface to be modeled. The “i” index in the summation is related to the number of different materials in the circuit cross-sectional construction. The variable Y is the mean distance from the base of the circuit for a layer and E is the modulus of that particular layer.



**Figure 6, bending a double-sided flex circuit**

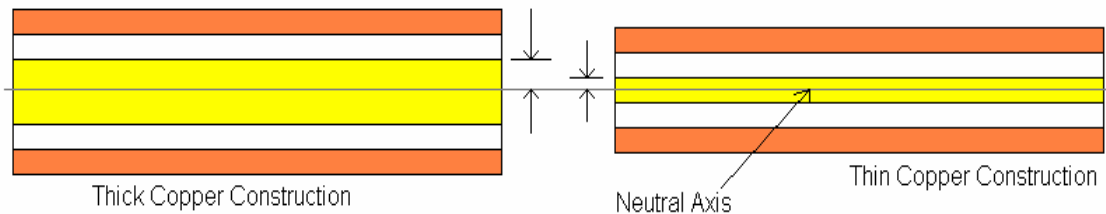
The neutral axis is drawn correctly in figure 6 and it can be seen to vary in location across the cross-section of the circuit. In areas where the circuit is completely balanced, then the neutral axis will be at the geometric center of the circuit. In the isolated areas where there is no copper on the top layer, then the neutral axis will shift down to be closer to the bottom layer copper.

Understanding the location of the neutral axis is very important and understanding the distance from the neutral axis to the feature of interest is critical. The further any feature is away from the neutral axis, the greater the strain will be and figure 7 shows this.



**Figure 7, distances from the neutral axis**

In the flex circuit industry there has been a trend over many years to use thinner materials. There are actually a few different reasons, depending on the application; however minimizing the distance from the neutral axis is definitely one of them. It has been proven many times that a balanced single sided flex circuit with thinner copper will out mechanically perform the same circuit with thicker copper. If the circuit is balanced then the neutral axis will go through the center of the copper layer and the distance to the edge of the copper will be shorter with the thinner copper. This is shown in figure 8.



**Figure 8, thick vs. thin copper and minimizing the distance from the neutral axis**

One other reason why thinner materials have been used in the flex industry and more specifically the hard disk drive industry is to minimize deflection force (bias force). The deflection force is the spring force that the flex circuit will have in regards to moving it. For micro hard disk drives the mechanisms used to position the heads are very small and sensitive to any mechanical resistance of motion. If there is much resistance to motion, then the positioning mechanism can fail early in the product life. To minimize deflection force, thinner materials are used as well as low modulus materials. The physical property of the circuit, which accounts for the deflection force, is flexural stiffness and the formula for that is shown in Figure 9.

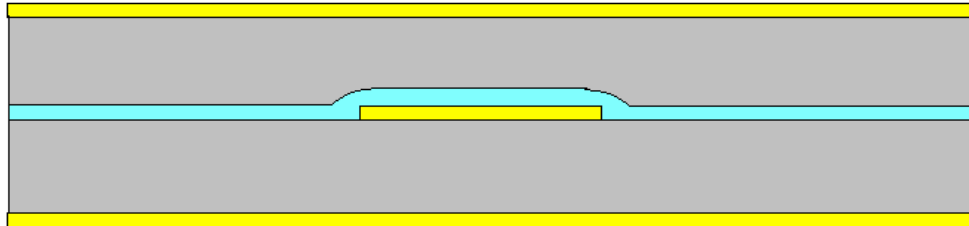
$$EI := \sum_{i=1}^n \frac{E_i \cdot w_i}{3} \cdot \left[ (Y_{Ti} - R_o)^3 - (Y_{Bi} - R_o)^3 \right]$$

**Figure 9, flexural stiffness formula**

The variables that were previously mentioned still apply and the  $w_i$  variable is the width of the circuit feature at the indexed layer. The  $Y$  variables are the distance of the top and bottom edges, from the bottom of the circuit, for that particular index in the summation.

### **Applications: modeling and real life results**

The first application that will be discussed is a three-layer stripline high frequency circuit board. The circuit was intended to be bent one time during an installation process. The outer copper layers are ground planes and the signal layer was near the geometric center of the circuit. In this case the neutral axis was located very near the center of the signal plane, so there was very little strain on the edges of the copper at that plane. However the copper on the outside layers had significant strain. Also the copper on the outer layers had a nickel / gold finish. The material that was used was Rogers 5mil thick RT/Duroid® 5880 with 1oz ED copper. The bonding material was DuPont Teflon® FEP. As work progressed on getting this circuit to bend well, the substrate remained the same, however different coppers were used. The circuit construction is shown in figure 10.



**Figure 10, stripline 3 layer circuit cross-sectional construction**

The bend radius was approximately 5.08mm (0.200”) and the amount of strain on the various copper layers is shown in figure 11.

|                       | Strain (%) on the copper layers |                |               |
|-----------------------|---------------------------------|----------------|---------------|
|                       | Top, Gound                      | Center, Signal | Bottom, Gound |
| 1oz-5mil material     | 3.631                           | 0.508          | 3.543         |
| 1/2oz - 5mil material | 3.140                           | 0.342          | 3.054         |
| 1/4oz - 5mil material | 2.926                           | 0.272          | 2.844         |

**Figure 11, strain numbers for the same circuit using different copper thickness**

For a one-time bend, experience has shown that a strain of approximately 2% or greater can be problematic. Obviously the elongation of the copper that is used in printed circuit industry has better elongation than 2%, however there are other variables that effect the bending of the copper. Some of the variables are the copper grain structure, copper surface profile and peel strength differences between the different surfaces of the copper.

After the models were done and the proper copper thickness determined, then there were several other issues that needed to be addressed. With the lower strain numbers for the 1/4 oz copper, one may assume that the bend could now be successfully done however that is not the case. The copper had to be changed to RA copper and the finish on the copper had to remove the nickel barrier. There was also an option to replace the nickel / gold finish with silver. There was one other fix that had to take place to get the circuit to bend well. This circuit had plated through holes and there was ED copper plated on top of the base copper. The fabrication of the circuit was changed so the base RA copper is protected from the ED copper plating. After these changes were implemented, then the circuit was bent without issue and done with a large number of circuits. The amount of strain is still a little higher than what is desired, however in the case it performed well.

The next application to be discussed is a dynamic double-sided microstrip high frequency circuit board. The circuit used Rogers RT/Duroid® 5880 that was 5mils thick and 1/2oz RA copper. The circuit needed plated through holes and had a nickel / gold finish on the copper. The dynamic flex life that was desired was 100,000 cycles and the bend radius was 12.5mm (0.5”). A drawing of the circuit cross-section is shown in figure 12.



**Figure 12, cross-sectional view of a high frequency double-sided circuit board**

All of the issues that were discussed for the one-time bend application still apply for a dynamic application; however there are a couple of other issues to consider for the dynamic application. In the case of a static bend and when many trade-offs are considered, it is sometimes acceptable to allow the ground plane/s to have a high enough strain to get some micro-fractures while keeping the critical signal copper layer with low strain. This should never be done in the case of a dynamic application. If fracturing occurs on the ground plane/s early in flex cycling, then those copper layers will have major isolated modulus differences. This translates to huge shifts in the neutral axis in very small areas and will negate the assumed flex life as a model would predict.

From empirical data the amount of strain on circuit using rolled annealed copper translates to the approximate flex life shown below in table 2.

**Table 2, Strain and approximate Flex cycle life**

| Strain | Approximate Flex Life |
|--------|-----------------------|
| < 0.2  | >10,000,000           |
| 0.4    | 1,000,000             |
| 0.6    | 100,000               |
| 0.8    | 50,000                |

It should be cautioned, that table 2 is only a guideline and there are several exceptions that can negate these relationships.

Some models were done and the option to use thinner copper was not acceptable for this particular application, due to electrical concerns. So another option was taking that would move the neutral axis. This shift would increase the strain on the signal layer; however decrease the strain on the ground plane. Making the ground plane a crosshatched pattern, instead of a solid copper pattern, achieved this shift.

In many RF / high frequency applications a crosshatched ground plane cannot be tolerated; due to many electrical concerns, however it was acceptable in this case. The strain numbers were in the range to be acceptable for the desired flex life and are shown in table 3 below.

**Table 3, Strain numbers for a solid copper pattern vs. a crosshatched pattern.**

|                        | Strain (%) on Copper layers |                |
|------------------------|-----------------------------|----------------|
|                        | Top, Signal                 | Bottom, Ground |
| Solid Ground pattern   | 0.792                       | 0.439          |
| 50% Crosshatched Gound | 0.616                       | 0.616          |

The reason that the strain numbers are exactly the same for the crosshatched option is because the shift put the neutral axis at the geometric center of the circuit construction. After the modeling was understood, then there were several other issues that needed to be addressed. The option to remove the electroless nickel / immersion gold was not acceptable. However they were able to use a different plating option and plate the nickel in isolated areas (non-dynamic areas) and plate gold everywhere. The amount of gold had to be much thicker than normal to account for the nickel barrier missing. There are diffusion equations, which can calculate the needed thickness of gold for the amount of service time and given certain conditions. Next was the fabrication method and it had to be changed so the plated through holes were still plated and the RA copper in the dynamic area would not be plated. With these fixes in place the circuits were found to have acceptable flex life.

## Bibliography

Circuit Stiffness Modeling from Composite Beam Theory  
Internal Rogers Corporation Technical Report # 4340  
By John Arimond

Parameters in Bending a Beam  
Internal Rogers Corporation Presentation  
By Sam Guzit

Analysis of Flex Circuit Physical Characteristics  
Rogers Corporation  
By Andrew P. Magee

# **Bending, Forming and Flexing Printed Circuits**

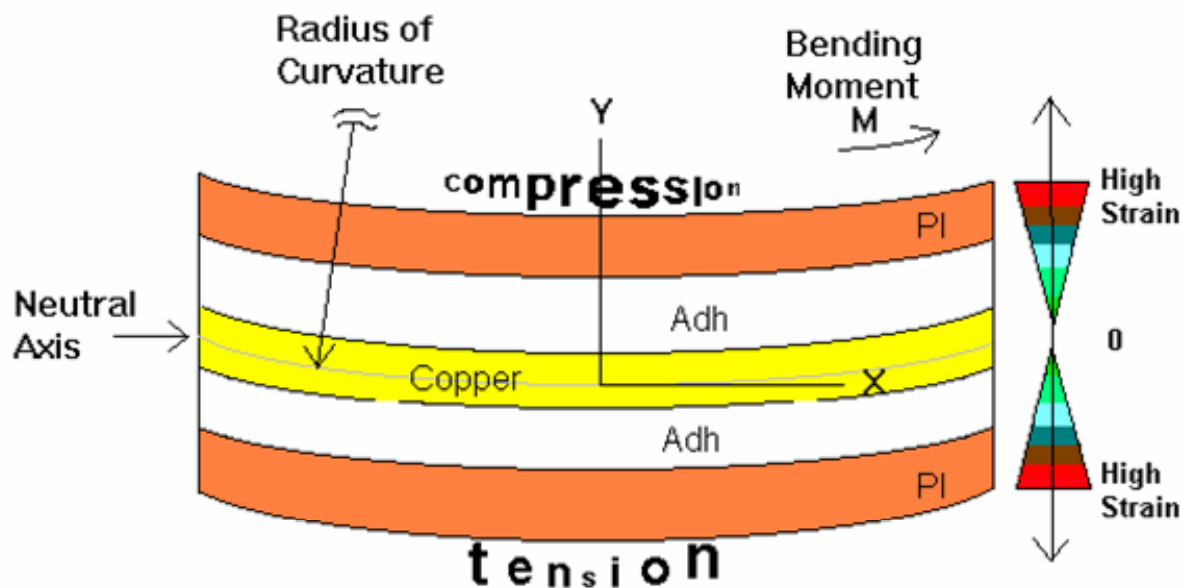
John Coonrod  
Rogers Corporation

# **Bending, Forming and Flexing Printed Circuits**

- Brief case history and terminology
- Composite Beam theory
- One time bend application
- Dynamic flexing application

## Bending, Forming and Flexing Printed Circuits

- Composite Beam theory
  - Material nearest bend radius is under compression
  - Material furthest from bend radius is under tension
  - The transition from compression to tension is the neutral axis
  - A further distance from the neutral axis yields higher strain
  - There is zero strain at the neutral axis



## Bending, Forming and Flexing Printed Circuits

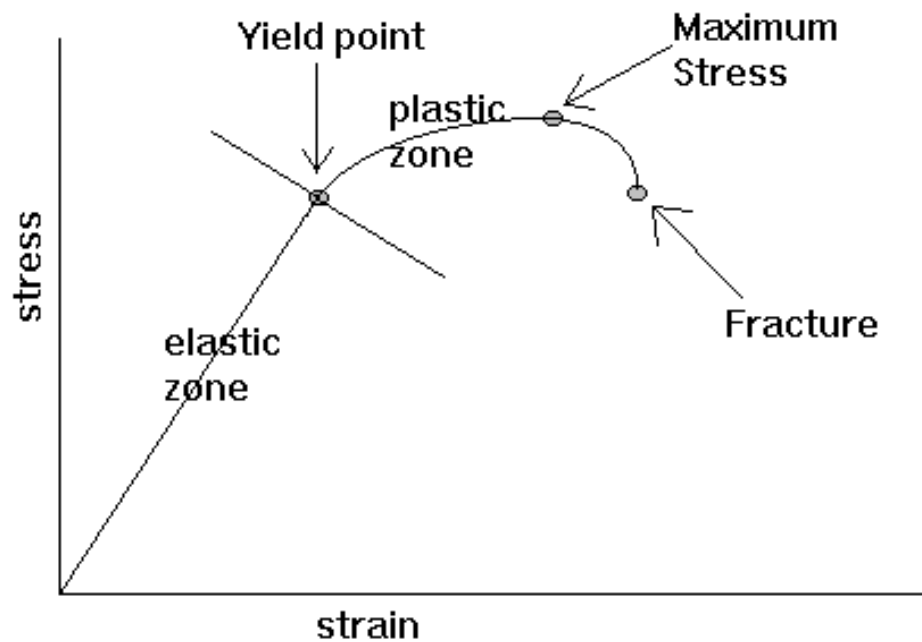
- Composite Beam theory
  - The 3 major topics associated with bending and flexing
    - Neutral axis location
    - Bend radius
    - Modulus of the materials that are used in the printed circuit

|                                          | Modulus |        |
|------------------------------------------|---------|--------|
|                                          | Gpa     | Kpsi   |
| Rolled Annealed copper                   | 117.3   | 17,000 |
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| PCTFE bonding film                       | 1.0005  | 145    |
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Materials with glass reinforcement are not considered here.

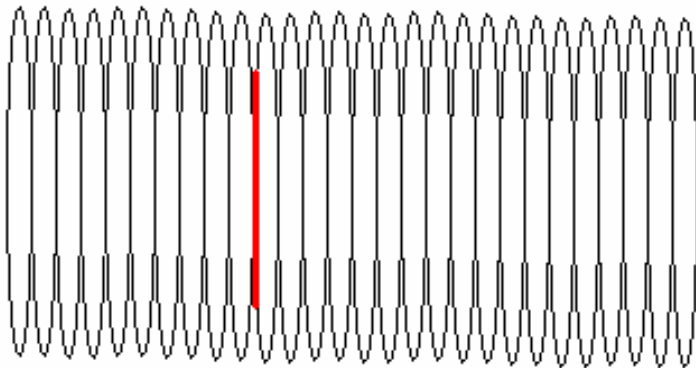
## Bending, Forming and Flexing Printed Circuits

- Composite Beam theory
  - Modulus, slope of the stress-strain curve in the elastic zone
  - Stress – Strain curve

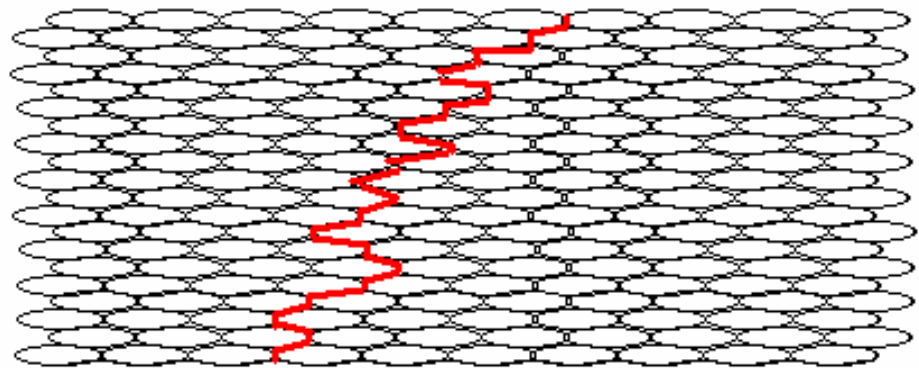


## Bending, Forming and Flexing Printed Circuits

- Other factors that can be major topics for bending and flexing
  - Copper grain structure and size
  - Copper surface roughness
  - Modulus differences in adjacent layers
  - Neutral axis location variation
  - Bond strength differences at substrate-copper interfaces



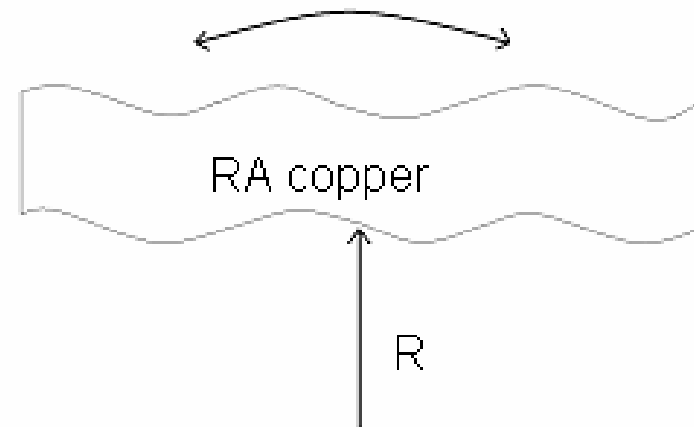
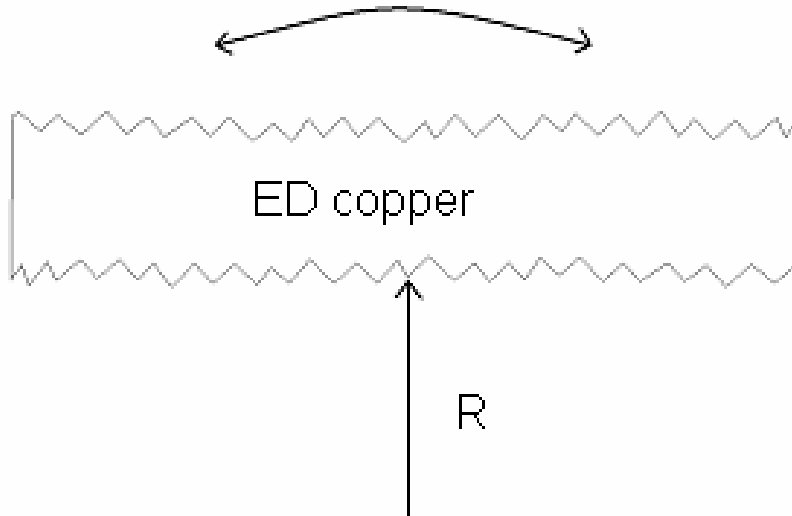
Electro-Deposited Copper grain structure



Rolled Annealed Copper grain Structure

## Bending, Forming and Flexing Printed Circuits

- Other factors that can be major topics for bending and flexing
  - Copper surface roughness
    - Peaks and valleys of rough copper
      - The valleys will be a major stress concentrator during bending
      - Stress concentrator will enable easy crack initiation



# Bending, Forming and Flexing Printed Circuits

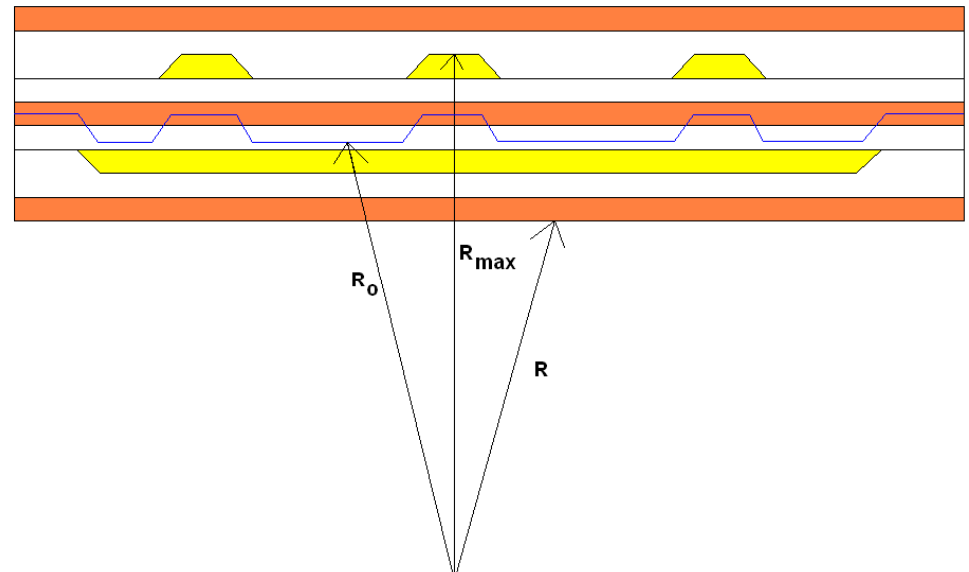
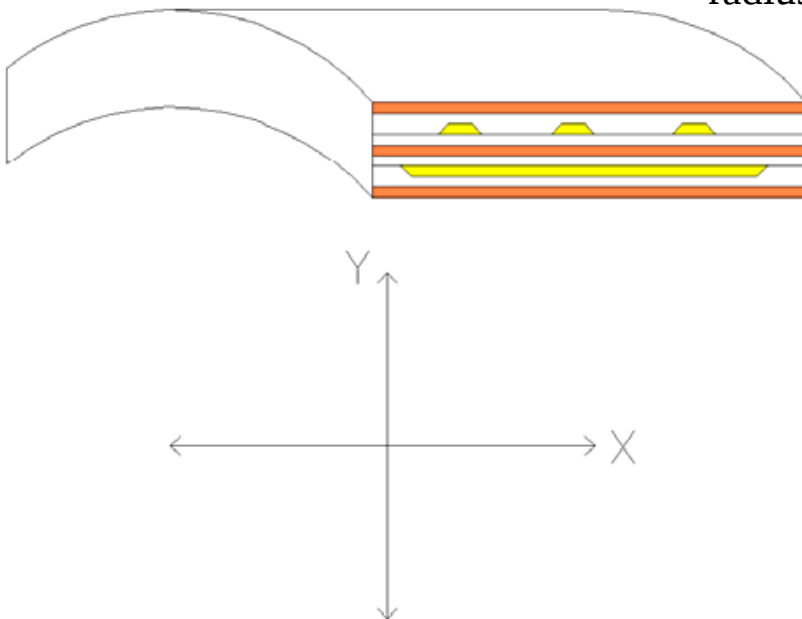
## • Basic Theory

- Calculation of neutral axis location
- Calculation of strain as a percent elongation
- Neutral axis location variation due to design
  - Neutral axis variation due to fabrication

$$\varepsilon := \frac{\left[ (2 \cdot \pi \cdot R_{\max}) - (2 \cdot \pi \cdot R_o) \right]}{(2 \cdot \pi \cdot R_o)} * 100$$

$$R_o := R + \frac{\sum_{i=1}^n E_i \cdot Y_i \cdot A_i}{\sum_{i=1}^n E_i \cdot Y_i}$$

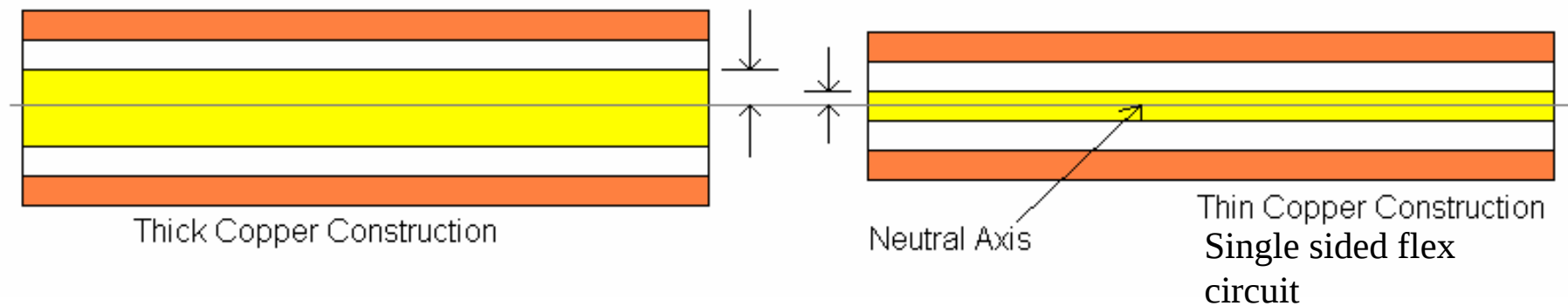
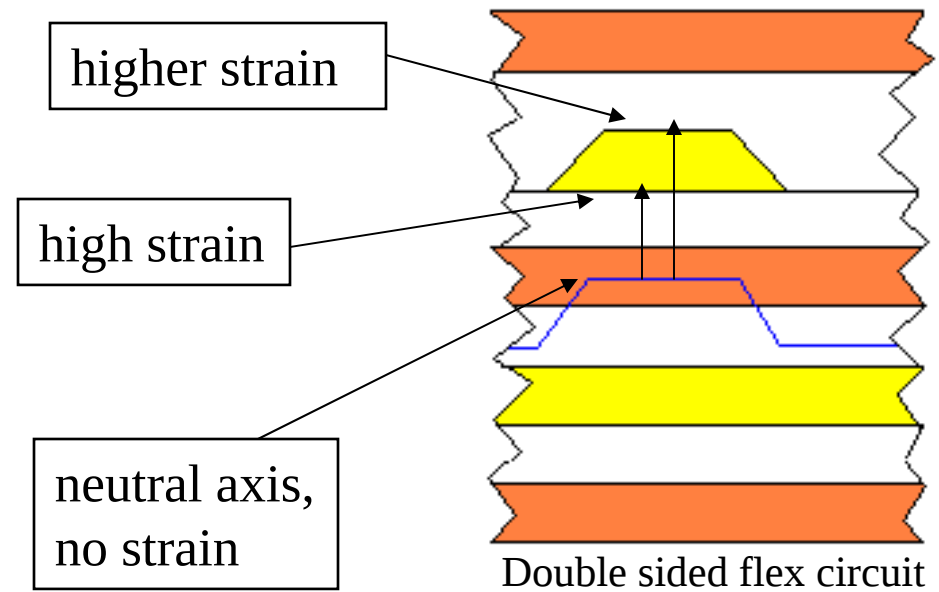
E is modulus, Y is mean distance from origin, A is area, R is bend radius,  $R_o$  is neutral axis and  $R_{\max}$  is the interface in question.



# Bending, Forming and Flexing Printed Circuits

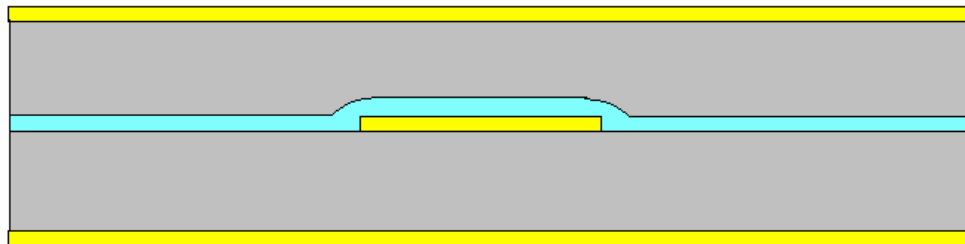
- Basic Theory

- Distance from neutral axis
- Thinner is better
- Flexural Stiffness



## Bending, Forming and Flexing Printed Circuits

- A model of a practical application
  - Forming a high frequency circuit board
  - 3 copper layer, stripline, using:
    - Rogers RT/Duroid® 5880, 5mil core, 1oz / 1oz
    - DuPont Teflon® FEP Type C-20 as bonding material
    - Pattern plated process
    - Electroless nickel / immersion gold finish over copper
    - Bend radius = 5.08 mm (0.200")
    - Bent one time only, non dynamic



Cross-sectional view of circuit

## Bending, Forming and Flexing Printed Circuits

- A model of a practical application
  - 3 copper layer, stripline, several issues to overcome
    - Model the strain on various layers
      - For a one-time bend the strain should be  $\sim 2\%$  or less
  - Change copper thickness according to model
  - Change copper type for improved grain structure
  - Change pattern plated process to selective plating
  - Change electroless nickel / immersion gold with silver

|                       | Strain (%) on the copper layers |                |               |
|-----------------------|---------------------------------|----------------|---------------|
|                       | Top, Gound                      | Center, Signal | Bottom, Gound |
| 1oz-5mil material     | 3.631                           | 0.508          | 3.543         |
| 1/2oz - 5mil material | 3.140                           | 0.342          | 3.054         |
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## Bending, Forming and Flexing Printed Circuits

- A model of a practical application
  - 2 copper layer, microstrip, using:
    - Rogers RT/Duroid® 5880, 5mil core, ½ oz – ½ oz
    - Pattern plated process
    - Electroless nickel / immersion gold
    - Bend radius = 12.5mm (0.500")
    - Dynamic rolling radius motion with 100,000 cycles needed



Cross-sectional view of circuit

## Bending, Forming and Flexing Printed Circuits

- A model of a practical application
  - 2 copper layer, microstrip, the issues were:
    - The ground plane copper strain was too high
    - Change the location of the neutral axis
    - Changed the fabrication process from pattern plated to selective plated
    - Removed nickel from the dynamic area and increased the gold thickness

|                        | Strain (%) on Copper layers |                |
|------------------------|-----------------------------|----------------|
|                        | Top, Signal                 | Bottom, Ground |
| Solid Ground pattern   | 0.792                       | 0.439          |
| 50% Crosshatched Gound | 0.616                       | 0.616          |

| Strain | Approximate Flex Life |
|--------|-----------------------|
| < 0.2  | >10,000,000           |
| 0.4    | 1,000,000             |
| 0.6    | 100,000               |
| 0.8    | 50,000                |