Effects of Adhesion Promotion Treatment On Electrical Signal Attenuation

Bruce Lee
MacDermid Incorporated, 245 Freight St
Waterbury, CT 06702 USA

Roger Krabbenhoft
IBM Systems and Technology Group, 3605 Hwy 52 N
Rochester, MN 55901 USA

Abstract
Oxide alternatives, as well as traditional and reduced oxide chemistries, are coatings or "adhesion promoters" used to enhance the bond between imaged and etched inner layer copper surfaces and the pre-preg resin used to bond the layers together in multi-layer printed circuit boards (PCBs). These chemistries impart varying degrees of roughness to the surface of the copper conductors and as a result electrical performance can be affected. The electrical performance characteristics of two oxide alternatives are examined in this study.

I. Introduction
As the electronics industry transitions to lead free assembly, PCBs will need to endure increased mechanical stresses due to the elevated reflow temperatures of Pb-free solders. This inherent change in process parameters has led some companies to examine the reliability relationship between laminate pre-preg and oxide alternative. It is important to note that historically it was assumed that "rougher is better" when it came to adhesive bond promotion. The thought being that the more surface roughness on the copper surfaces the better adhesion will be. In some cases this is true. In many other cases, however, rougher copper is not necessarily a prerequisite for good adhesion and may actually have a deleterious effect on electrical signals.

As PCB signal speeds increase, the signal's current path switches from the path of least impedance to the path of least inductance. This so-called path of least inductance is what is commonly known as the "skin effect" whereby an AC signal primarily flows nearer to the outside surfaces of a copper conductor rather than through the entire cross section of the conductor. As frequencies increase, the skin effect becomes more pronounced. Therefore, it is very important to understand not only the mechanical reliability aspects of a given PCB design but also the electrical performance criteria it must function under.

Some oxide alternative (OA) adhesion promotion chemistries, depending on their respective chemical make up and operating conditions, can achieve an acceptable combination of overall reliability with minimal impact on signal attenuation.

Due to more widespread and increasing use of OA across the PCB fabricator supply base, the authors chose to test the electrical influence of
two different OAs that were known to impart varying degrees of roughness on the inner layer copper surfaces.

It is well known that the roughness of the surface of copper conductors can negatively influence electrical signal propagation at high frequencies. The experiment and results described herein quantify the electrical effects an individual OA may have on signal attenuation as well as an examination of the measurement method itself.

PCBs were fabricated using a standardized test vehicle using two different oxide alternatives. The electrical characteristics were then measured using the Short Pulse Propagation (SPP) test method [1]. The conclusions are based on these characteristics.

II. Adhesion Promotion Using Oxide Alternative:
Lamination adhesion promoters, whether traditional oxide or OA, act as an intermediate layer between the copper surfaces of an inner layer and the b-stage pre-preg resin. Without this intermediate layer, the resin used to bond a multilayer PCB together would not reliably stick to the bare copper surfaces.

In the case of an OA, an organo-metallic layer is formed through a complex chemical reaction between the copper surface and the process chemistry. This chemical reaction results in a thin, micro-rough surface that greatly increases the surface area footprint of the copper features to which the resin will be bonded during the subsequent lamination process. During the chemical "etching" of the copper, an organic film is concurrently deposited on the surface of the copper.

Figure 1 is an SEM photomicrograph depicting typical surface topography that an OA will impart on the inner layer copper features. Note the rough texture. This texture is formed via selective and controlled etching of the copper surfaces through the use of a highly modified etch formulation. This rough texture enhances the mechanical bond between the adhesive resin and the various copper layers in a multi-layered PCB.

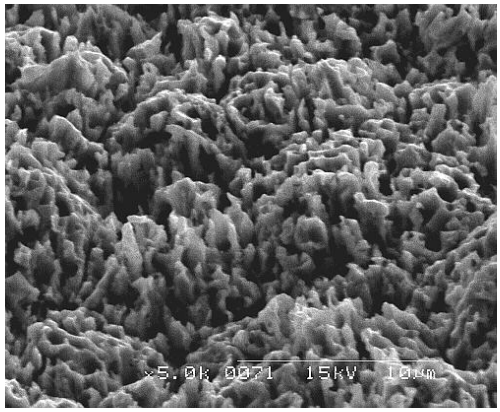


Figure 1. Typical OA Surface Topography

The second key functional attribute of an OA is the co-deposition of an organic within the micro-roughened surface formed on the surface of the copper. This organic component has two primary functions within the OA deposit. First, it acts as a "corrosion barrier" whereby it inhibits any corrosive effects various resin systems can have on the copper surfaces on the inner-layer. Secondly, it enhances the chemical bond between the OA and the resin. In addition to the organic that is co-deposited during the normal OA process, a secondary organic post dip is sometimes employed. This secondary step deposits a thicker layer of organic material in and on the surface of the copper and is used to increase the bond peel strength.

The topography that is created when copper is exposed to an OA is a very complex series of chemical reactions that results in a uniform, micro-roughened surface that is dark reddish –brown to black in color. This surface is the basic building block that ultimately holds the entire multi-layer PCB together so its importance should not be minimized. OAs are used successfully around the world in all types of electronic equipment from simple 4 layer PCBs using FR4 materials that may be in the GPS or radio in your car, to some of the most complex high layer count, "exotic" laminate PCBs used in space and defense applications.

As mentioned, OAs by their very nature create rough surface on the inner-layer copper. This rough surface can vary dramatically in both its micro and macro topography depending on the copper foil type and the components and concentrations of chemistry used in the formulation of the OA. One of the methods used to monitor OA process performance is through the use of etch rate coupons. These coupons are typically copper clad laminate of a known surface area. They are weighed, processed through the OA equipment, and then weighed again. The resultant etch rate is calculated based on the amount of weight loss, or copper etched. It is very important to understand that even though two different OA chemistries may operate at the same etch rate, they may impart very different surface topographies in the copper. The differences in surface topography, even at similar etch rates, is the result of the specific chemical components used in the OA formulation as well as the operating conditions of the chemical solution.

In past years the common thought pattern regarding OAs was "the rougher the better" in order to ensure good mechanical adhesion. Now with electrical signals commonly running at 5 GHz and faster some companies have had to rethink this old adage because of the negative effect the rough copper has on signal attenuation at higher frequencies. Simply put, the higher frequencies climb, the more inner layer copper roughness can negatively affect signals. This phenomenon is not new and many papers have been written on the topic but until recent years relatively few companies were affected by it. Now, more and more companies have to understand and address the issue.

III. Test Vehicle Description:

The test vehicle used in this experiment was a multi-layer PCB design that was developed by IBM with the expressed purpose of being used with the SPP apparatus and methods. The test vehicle is used to measure the relative impact a particular PCB material component, (i.e. laminate, Cu foil, or adhesion promoter) may have on the overall electrical performance of a PCB.

The test vehicle (TV) has specific design features that allow for the assessment of electrical performance. A signal – ground launch structure consisting of 0.006" plated through holes (PTHs) on a 0.020" pitch are utilized to minimize capacitive and inductive discontinuities. Two distinct stripline signal layers are included in the design, allowing two separate core/b-stage building blocks to be assessed.

The cross section of the specific test vehicle used in this analysis can be seen in **Figure 2.**

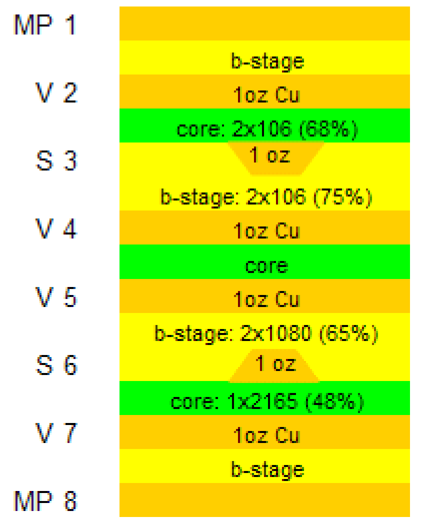


Figure 2. Test Vehicle Cross Section

Typically, an assessment of a resin poor and a resin rich building block are completed to provide the user with data spanning the range of the product. Depending on the target data, different Cu foil weights may also be employed in the two layers to provide an assessment of the inherently different properties of 1/2oz and 1oz Cu foil.

Various trace configurations are employed, ranging from 2.5 to 20 cm in length, at the desired width. These traces are laid out along x and y axis as well as along the diagonal. This allows the assessment of any effects imparted by the glass cloth weave configuration.

The test vehicle also contains multiple 1.27 cm (0.5") diameter disks on the signal layers used to assess the low frequency dielectric constant and loss tanδ characteristics.

IV. Test Vehicle Fabrication:

All of the TVs were fabricated from the same laminate manufacturing core and b-stage lot numbers in order to minimize any unwanted noise in the performance evaluation data. All of the inner-layers were cleaned, coated, printed, and develop/etch/stripped at the same time, again, in order to minimize any effect fabrication process variables may impart on the performance characteristics.

Once all of the layers had been fabricated and inspected through AOI, the layer lots were split into our test groups and the various OA treatments were applied.

A 4 cell matrix was developed, as outlined in **Table 1**. Two OAs, each yielding different surface roughness characteristics, were utilized, each with and without an additional organic post dip. As previously indicated, this organic post dip is a product developed to enhance the chemical bond between the OA and tough-to-bond-to resin systems. It was desired to determine if this post-dip had any effect on the electrical performance of the resultant structure.

Table 1 – Test Matrix

	OA 1	OA2
Post Dip	Panels: 6 Parts: 36	Panels: 6 Parts: 36
No Post Dip	Panels: 6 Parts: 36	Panels: 6 Parts: 36

Six (6) panels were run in each cell, each consisting of 6 TVs, for a total of 36 TVs in each cell. **Figure 3** and **Figure 4** depict the different surface topographies imparted by the two test OAs. Note the distinct difference in the macro and micro surface topography between the samples.

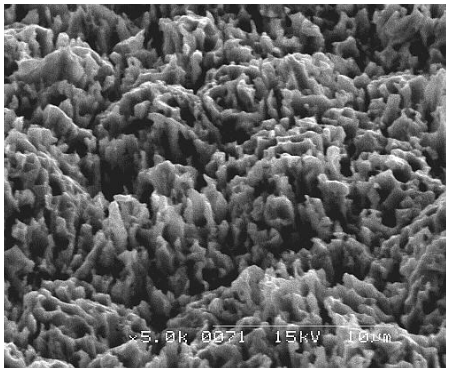


Figure 3 – SEM Example of Test OA 1

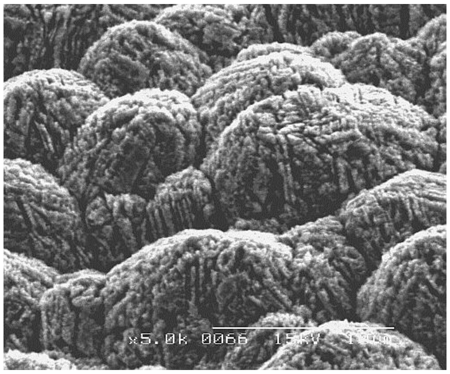


Figure 4 – SEM Example of Test OA 2

The TVs were sorted based on ability to meet impedance targets, and a minimum of 10 pieces from each cell were provided for the performance assessment.

V. Thermo mechanical Assessment:

Since a PCB not only has to have acceptable electrical characteristics, but also acceptable mechanical reliability characteristics, a subset of all test groups was submitted for T-240, T-260, and T-288 thermal stress testing utilizing a thermomechanical analyzer or TMA. This test method is described in IPC-TM-650, Method # 2.4.24.1. The results of the TMA testing are shown below in **Table 2**. All T-240 and T-260 samples exceeded the 30 minute threshold with no delamination. The T-288 results also performed beyond specification.

It shall be noted that the test vehicles used in this exercise are only approximately 40 mils thick, with no tight pitch PTHs arrays to exacerbate thermo mechanical issues.

Table 2. TMA Test Results

Sample	T-240	T-260	T-288
OA1D	> 30 min	> 30 min	6.57
OA1	> 30 min	> 30 min	6.56
OA2D	> 30 min	> 30 min	8.33
OA2	> 30 min	> 30 min	6.92

VI. Electrical Performance Assessment:

The theory behind the Short Pulse Propagation (SPP) technique is fully described in [1]. In summary, the technique allows for the extraction of frequency dependant dielectric constant, $\varepsilon_r(f)$, and effective dielectric loss tan $\delta(f)$ through the creation of broadband, fully causal transmission line models based on the measurement results.

The technique relies on the use of building block structures (core, b-stage, and trace cross section) which are as nearly identical to each other as the manufacturing process allows. To this end, the aforementioned TVs are sorted to identify those parts which are most likely to provide such structures. This sorting technique consists of impedance waveform matching and low frequency R & C analysis.

Standard TDR equipment can be used in conjunction with high performance cables and tight pitch probes to launch a fast rise time pulse through an Impulse Forming Network (IFN). The resultant waveform is then applied to two traces as nearly identical in nature as possible, but of sufficiently different lengths.
These measurement results, along with the low frequency characteristics, are then processed using IBM developed software (http://www.alphaworks.ibm.com/tech/gammazandcz2d), resulting in a frequency dependant attenuation which accurately describes the performance of the structure.

The parts are then cross sectioned and average physical attributes of the structure are documented. Through a subsequent iterative fitting process, models are created which accurately represent the effective performance of the tested structure. See sample data shown in **Figure 5**.

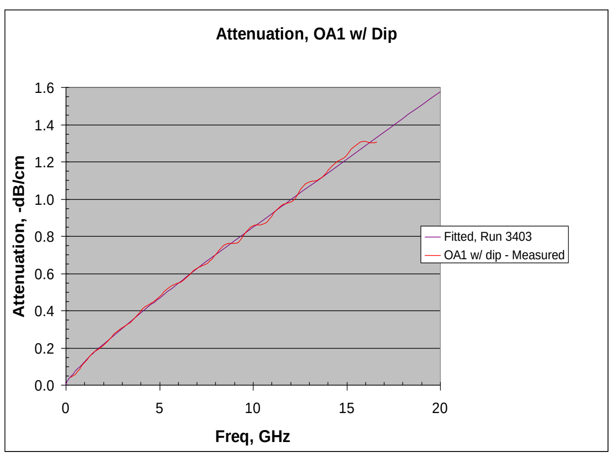


Figure 5. Sample Attenuation Results

It shall be noted that the laminate material losses determined through this test methodology are 'effective losses', lumping both laminate losses and losses due to skin effects. Therefore, when the Cu roughness is significant, the extracted tan $\delta(f)$ will contain both elements. This exercise focuses on the relative impact to overall performance, with all else constant except Cu roughness as a result of the OA process.

Finally, nominal design models are created using the previously extracted $\varepsilon_r(f)$ and loss tan $\delta(f)$ parameters. These models then result in attenuation characteristics in which the delta is solely driven by the skin effects resulting from the differing Cu roughness imparted by the two OA process chemistries. See **Figures 6 and 7** for a comparison of these nominal conditions.

Depending on the structure, one observes an increase in attenuation of between 15% ~ 25%   1 – 10GHz range due to use of OA1. This can be considered significant depending on the amount of margin within any given design.

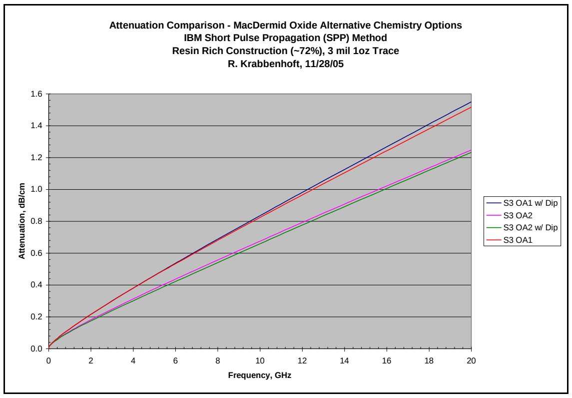


Figure 6. Nominal Attenuation Comparison, Resin Rich Layer, S3

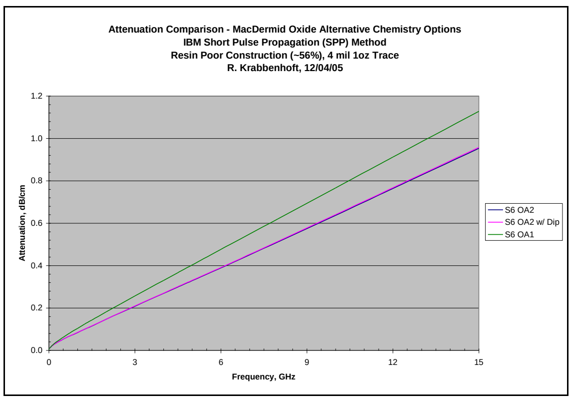


Figure 7. Nominal Attenuation Comparison, Resin Poor Layer, S6

VII. Surface Roughness Analysis:

Table 3 provides mean data for several industry standard parameters as measured using a Zygo white light interferometer. The Zygo interferometer was employed as a means to quantify the delta in roughness between the sample test groups. A follow up study will examine this and other roughness measurement apparatus in an effort to determine applicable metrology for process control.

Table 3. Roughness Comparison

Treatment	Rmax, um	Surface Area, um^2	Rms, um	Ra, um
OA1	12.63	40350	1.225	0.976
OA2	10.45	29372	1.205	0.965

Note that there is ~ 21% delta in Rmax, while the surface area shows a 37% delta. Thus, for the specification of Cu attributes which contribute to performance, it is then determined that these two characteristics are primary contributors to the impact on performance.

How these roughness attributes manifest themselves as physical characteristics can be observed in cross section as seen in **Figures 8 and 9** below.

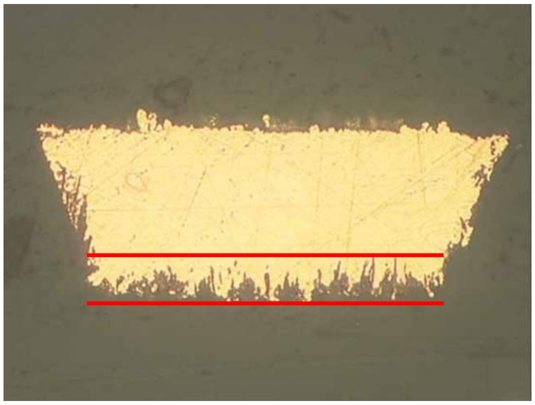


Figure 8. OA1 Cross Section

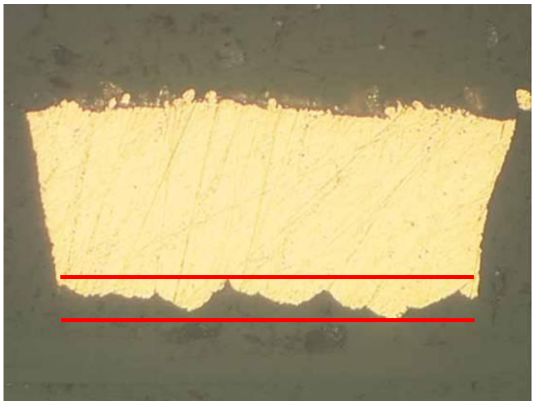


Figure 9. OA2 Cross Section

One observes that use of OA1 can result in a roughness on a finer scale, dubbed 'micro' roughness. This is an indication of an increased interaction of the OA chemistry with the Cu grain boundaries. Conversely, use of OA2 can result in less interaction with the Cu grain structure, effectively imparting a more 'macro' roughness surface texture.

Copper surface roughness can be quantified using a number of varied techniques and metrology. The method available to most PCB shops is through the use of potted cross-section samples of a layer or PCB. The sample is potted, polished, and read using a metallurgical microscope and the total or average roughness can be measured using the microscopes reticle system. The samples depicted in **Figures 8 and 9** were prepared using this method.

Two other quantitative methods that can be used to measure surface microstructure include atomic force microscopy (AFM) and vertical scanning interferometry.

AFM has a long history in the electronics field, has very high resolution capabilities, and is relatively inexpensive. Unfortunately, AFM is also somewhat limited in its ability to generate sample data in a manufacturing environment. This metrology is certainly capable of quantifying the roughness of copper surfaces but can be somewhat slow in data generation. AFM is generally a "contact" method of measuring surface roughness in that a tiny stylus mounted to the bottom of a cantilever is scanned across the sample surface. This "optical lever" has a laser focused on its upper surface which then reflects up to a position sensitive detector. Vertical movement of the optical lever is recorded and compiled into a data file and software within the measurement unit can generate surface maps depicting the peaks and valleys of the surface measured.

Interferometry apparatus utilize many different technologies and formats across many industries. The type used in semiconductors, MEMS, and PCB step and surface roughness measurements is usually the vertical scanning, white light variety. This metrology solution is a non contact method of measuring surface microstructure through the use of split light beams and the relative phase differences in the two optical paths. Interferometers are fairly easy to operate and can produce quantitative results fairly rapidly but do require a controlled environment for accurate results. **Figure 10** depicts output data of an interferometer that was used to measure the samples in this study. Note the output data includes Rmax / Rms / Ra, a digital oblique plot, a profile plot, and a filled plot.

Considering the authors opinions that copper roughness is a key PCB attribute in high frequency applications, it will be important for companies to investigate and understand metrology options and how it will be used to monitor process outputs.

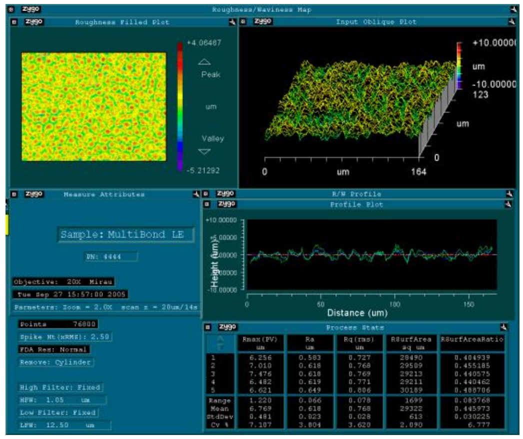


Figure 10. Interferometer Data Example

VIII. Skin Effects:

As previously indicated, skin effects are a well known phenomena. To briefly characterize their expected impact, one can use the following formula:

Skin Depth (δ) = Sqrt [$\rho/(f\pi\mu_o)$], $\mu_o = 4\pi10^{-7}$ (permeability in a vacuum), f in MHz [2].

Through our work cross sectioning and characterizing the Cu foils used in PCB manufacturing, an average resistivity has been determined: ρ, = 2.076 x 10^{-8} Ω-m (vs. textbook value of 1.76 x 10^{-8} Ω-m) at approximately 25^o C. Therefore, the skin depth (δ) at 1GHz = 2.35 um (0.09 mils). Since approximately 5δ are required to account for ~ 99% of the current flow [2], the bulk of the current flows in the outer 11.75 um (0.45 mils). From the data in **Table 3,** it is seen that the bulk of the current flow does penetrate the area of the increased roughness.

IX. Conclusion:

The results contained herein quantify the signal attenuation imparted by not only the incoming laminate / Cu foil characteristics, but also by two Cu foil adhesion promotion processes. The two different oxide alternative chemistries used in this assessment resulted in different ‘macro’ and ‘micro’ roughness characteristics. Based on the data presented here, these different roughness characteristics appear to result in distinctive performance levels in otherwise similar PCB designs.

The macro roughness characteristics alone, as dominated by R_{max} (peak to valley), appear to impart less performance degradation than when combined with added micro roughness characteristics. The latter is perhaps better characterized by the overall surface area. The metrology used to assess the roughness characteristics should be considered so as to ensure adequate, accurate representation is provided.

Generally speaking, performance will be degraded, and noticed at lower frequencies, as depth of the macro roughness and the addition of micro roughness increases. This is likely the result of the effectively larger distance that the signal must travel as the surface area increases.

The PCB fabricator has an opportunity to balance the electrical performance characteristics with the mechanical reliability of the particular design through optimization of the adhesion promotion process.

Furthermore, the OEM should be sensitive to the signal attenuation driven not only by the laminate material properties and the incoming Cu foil characteristics, but also by the output Cu foil roughness, as dictated by the adhesion promotion process.

X. Acknowledgments:

The authors would like to thank:

Time-To-Market (TTM) Interconnect Solutions and Cookson Electronics/Polyclad Laminates (now Isola Group) for their relative contribution of PCB fabrication and laminate materials used in this analysis.

David Braun, IBM, Integrated Supply Chain, is acknowledged for his contribution of taking the Short Pulse Propagation data used in this analysis.

Paul Dell'Anno and his team at MacDermid for their work providing the SEM, interferometer, TMA, and cross section results.

XI. References:

[1] A. Deutsch, T-M Winkel, G.V. Kopcsay, C.W. Surovic, B. J. Rubin, G. Katopis, B. Chamberlin, R. Krabbenhoft, "Extraction of $\varepsilon_r(f)$ and tan δ (f) for Printed Circuit Board Insulators Up to 30 GHz Using the Short-Pulse Propagation, IEEE Transactions on Advanced Packaging, Vol. 28, No 1., February 2005, pp. 4 – 11.

[2] Stephen C Thierauf, "High Speed Circuit Board Signal Integrity", Artech House, 2004.

Bending, Forming and Flexing Printed Circuits

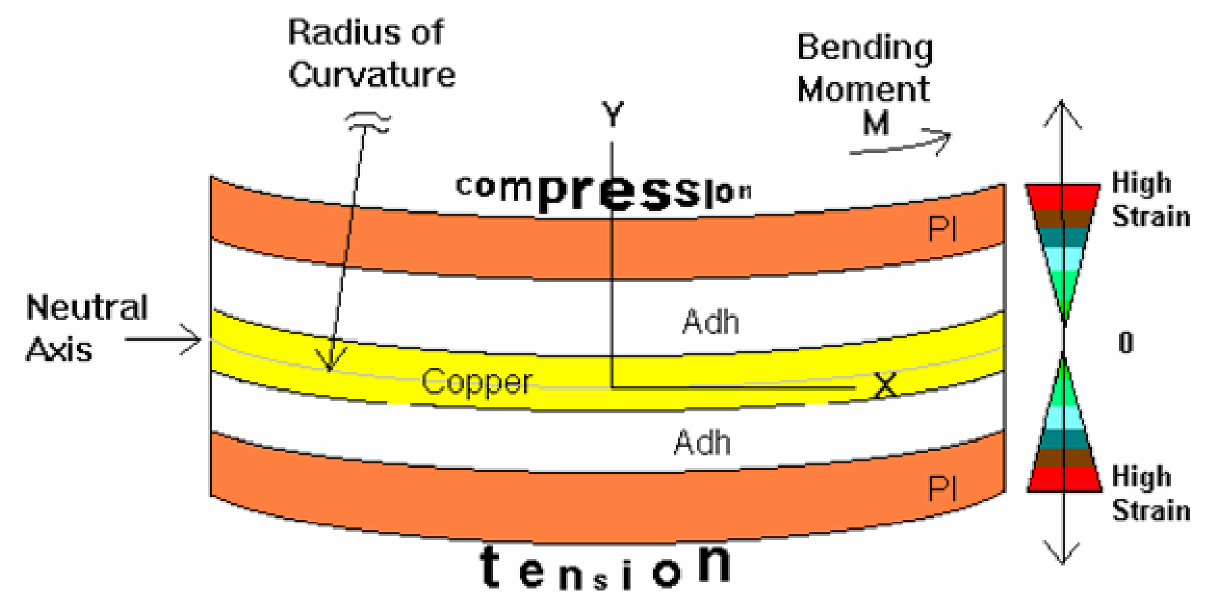
John Coonrod
Rogers Corporation

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

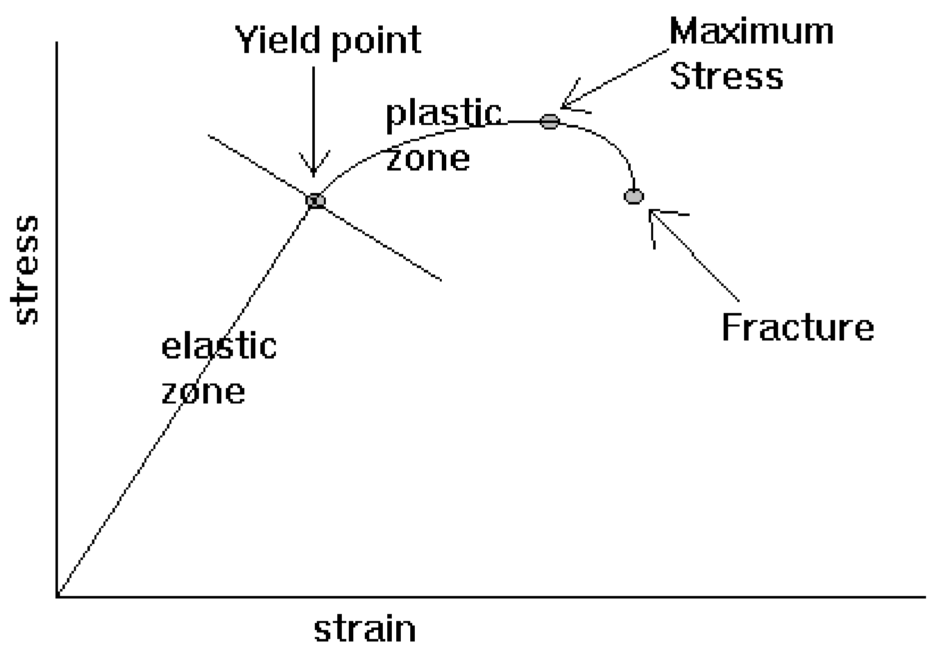
- Composite Beam theory
  - The 3 major topics associated with bending and flexing
    - Neutral axis location
    - Bend radius
    - Modulus of the materials that are used in the printed circuit

	Modulus	
	Gpa	Kpsi
Rolled Annealed copper	117.3	17,000
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

Materials with glass reinforcement are not considered here.

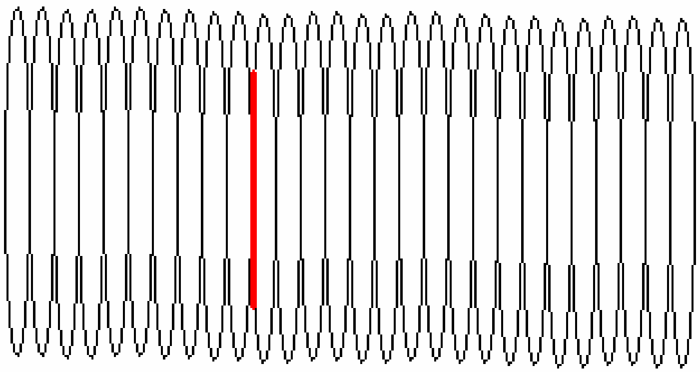
Bending, Forming and Flexing Printed Circuits

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

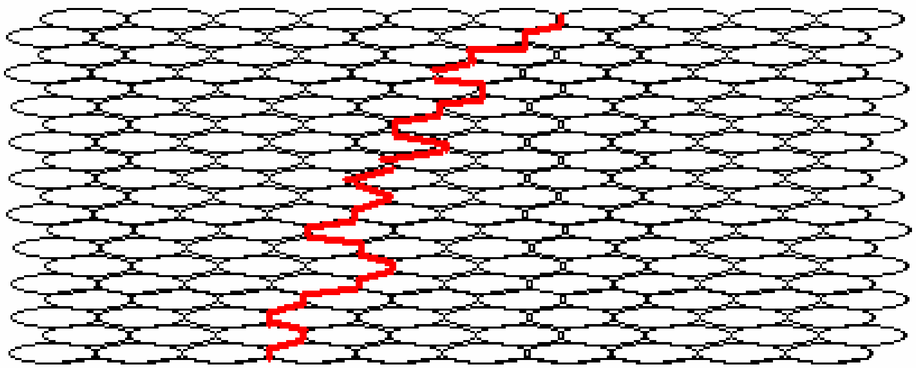


Bending, Forming and Flexing Printed Circuits

- 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



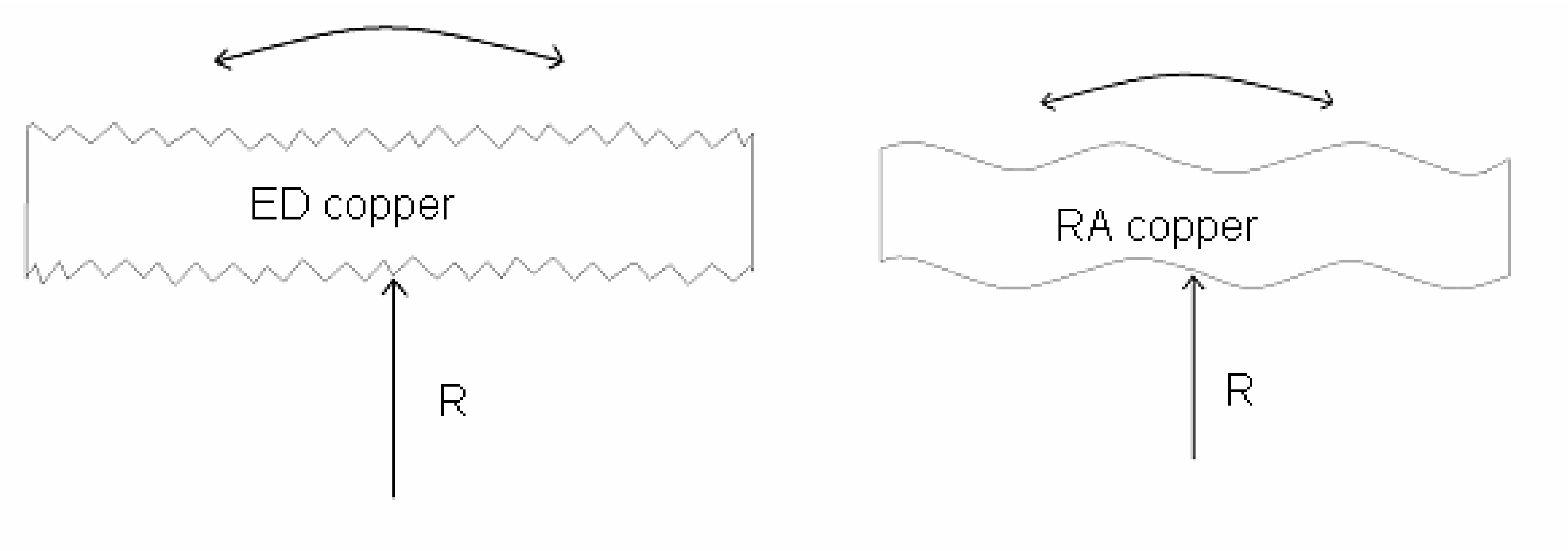
Electro-Deposited Copper grain structure



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



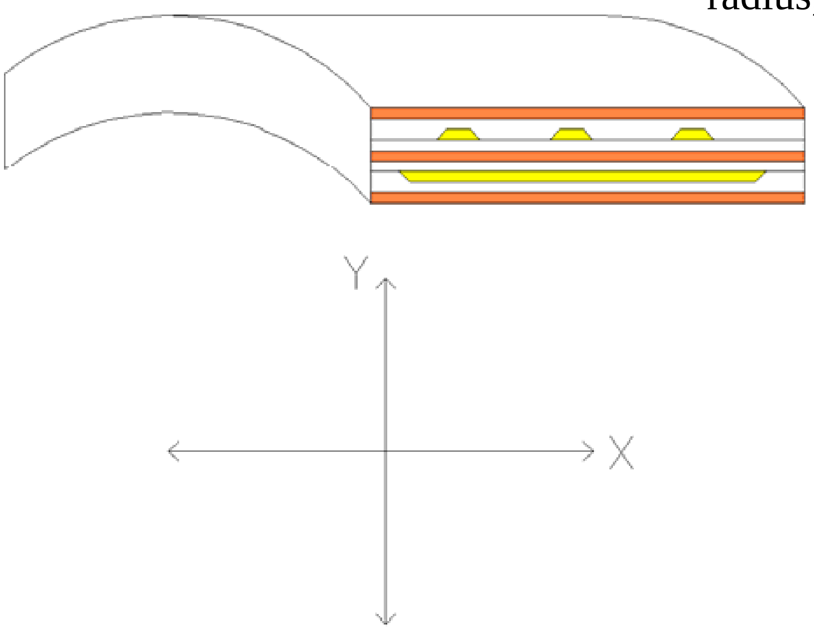
Bending, Forming and Flexing Printed Circuits

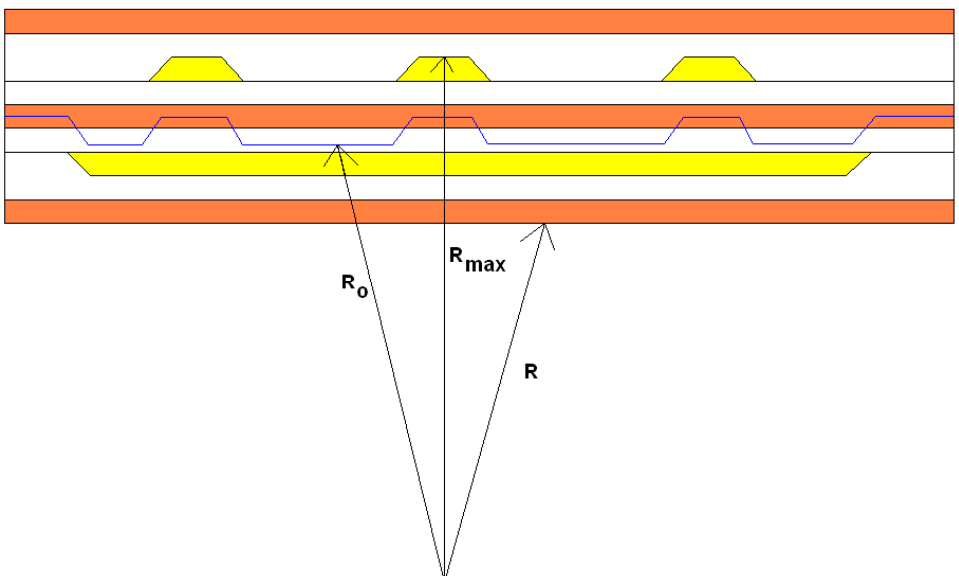
- Basic Theory
  - Calculation of neutral axis location
  - Calculation of strain as a percent elongation
  - Neutral axis location variation due to design
    - Neutral axis variation due to fabrication

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

$$R_{o} := R + \frac{\sum_{i=1}^{n} E_{i}\cdot Y_{i}\cdot A_{i}}{\sum_{i=1}^{n} E_{i}\cdot Y_{i}}$$

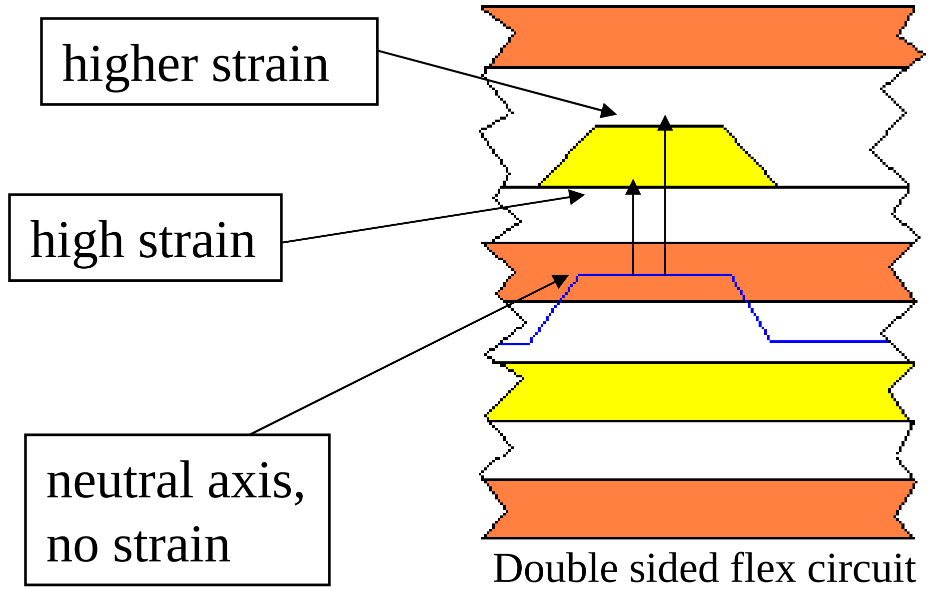
E is modulus, Y is mean distance from origin, A is area, R is bend radius, $R_{)}$ is neutral axis and R_{max} is the interface in question.



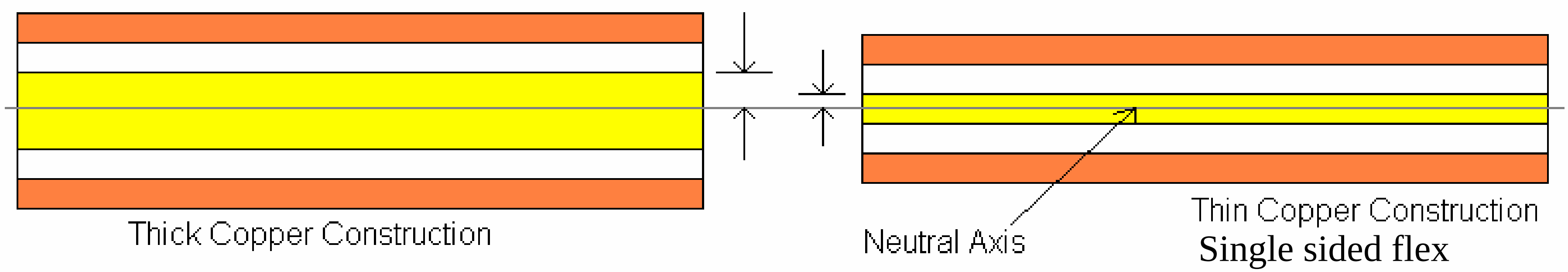


Bending, Forming and Flexing Printed Circuits

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



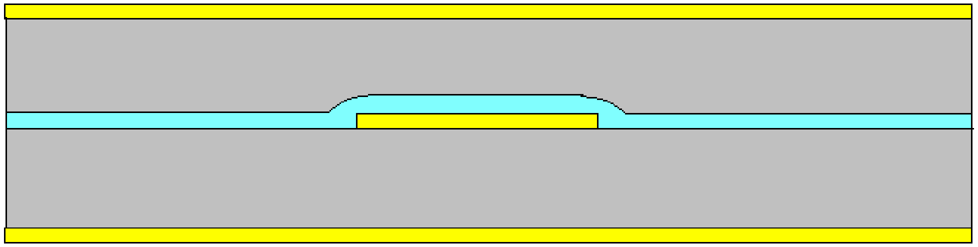
Double sided flex circuit



Single sided flex circuit

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

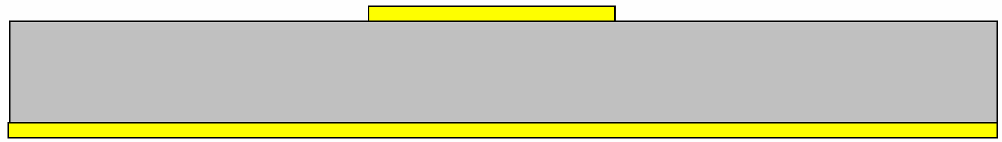
Bending, Forming and Flexing Printed Circuits

- 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 ~ 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
1/4oz - 5mil material	2.926	0.272	2.844

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