

## Beyond Design – Effects of Surface Roughness on High-speed PCBs

by Barry Olney | In-Circuit Design Pty Ltd | Australia

At frequencies below 1GHz, the effect of copper surface roughness on dielectric loss is negligible. However, as frequency increases, the skin effect drives the current into the surface of the copper dramatically increasing loss. When the copper surface is rough, the effective conductor length extends as current follows along the contours of the surface up and down with the topography of the copper surface. At high frequencies, the effective resistance of the copper increases relative to the additional distance over which the current must transverse the contours of the surface. The total loss comprises of the sum of the conductor loss and dielectric loss.

Whilst it may be possible to manufacture copper foil with a perfect mirror-smooth finish, the foil to resin adhesion would be compromised. This would considerably increase the possibility of delamination during the thermal stress of the PCB fabrication and assembly processes. For this reason, a reduced oxide coating is applied to the inner core layers to promote adhesion of the prepreg resin as it flows under the applied heat and pressure to cure.

Skin effect is the tendency of an alternating current to become distributed within a conductor such that the current density is largest near the surface, and decreases with greater depths in the conductor. The higher the frequency, the greater the tendency for current to take the path of lower inductance on the outer surface of the conductor. The skin depth is given by:

$$\delta = \sqrt{\frac{2}{2\pi f \mu \sigma}}$$

where  $\delta$  is the skin depth in microns,  $f$  is the frequency in MHz,  $\mu$  is the magnetic permeability ( $4\pi \times 10^{-7}$  H/m) and  $\sigma$  is the copper conductivity, typically ( $5.6 \times 10^7$  S/m).

The skin depth (um) can be approximated by:

$$\delta = 66 \sqrt{\frac{1}{f}}$$

Looking at this equation, it is apparent that skin depth decreases with increased frequency. Figure 1, shows the skin depth compared to frequency. At low frequency (1MHz), the skin depth is 66um but this decreases to 0.66um at 10GHz. So at 10GHz, only the very outer surfaces of the trace carry the current. Also, the red horizontal lines represent the trace copper weight and thickness. This shows that at about 10MHz, a signal traveling in a ½ oz (17.78um) copper trace would not use the entire trace cross-section but rather the skin effect would be dominant.

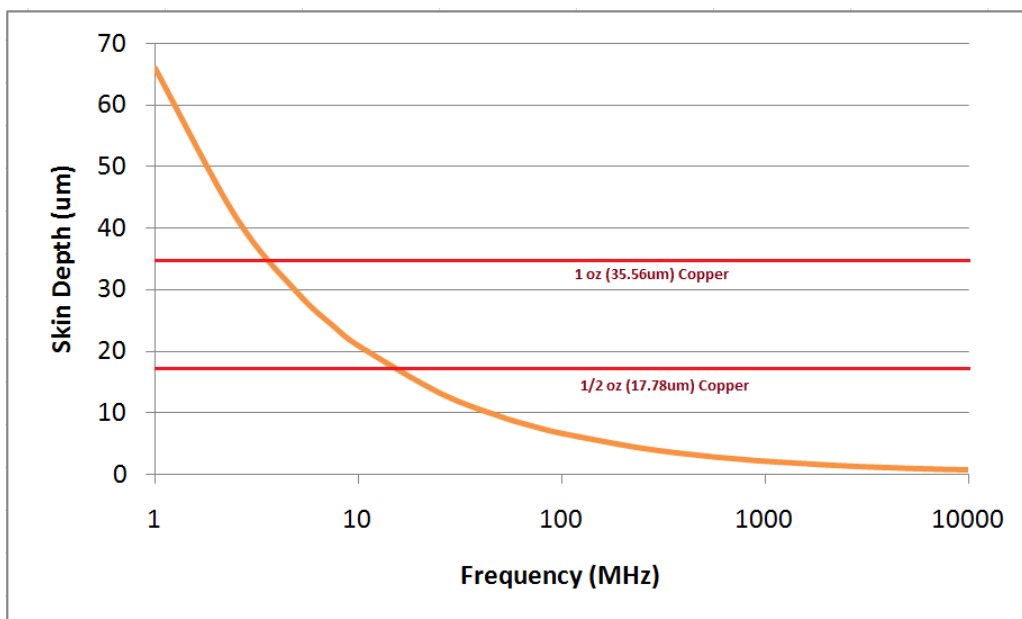


Figure 1 – Skin Depth (um) vs Frequency (MHz)

In a previous column, [Beyond Design: Surface Finishes for High-Speed PCBs](#), I pointed out that the nickel content of ENIG surface finish has a ferromagnetic property that can adversely affect electromagnetic fields in the high frequency domain. One could argue that since the nickel is plated on top of the microstrip surface, that it would have little effect on properties of the trace. And that due to the skin effect, the current will travel the path of least inductance, which is on the lower surface of the copper closest to the reference plane. However, it has been found that at approximately 2.7 GHz, the resonant behavior of the nickel component in ENIG, increases insertion loss. It is for this reason that solder mask over bare copper (SMOBC) processing should be considered for all high-speed designs.

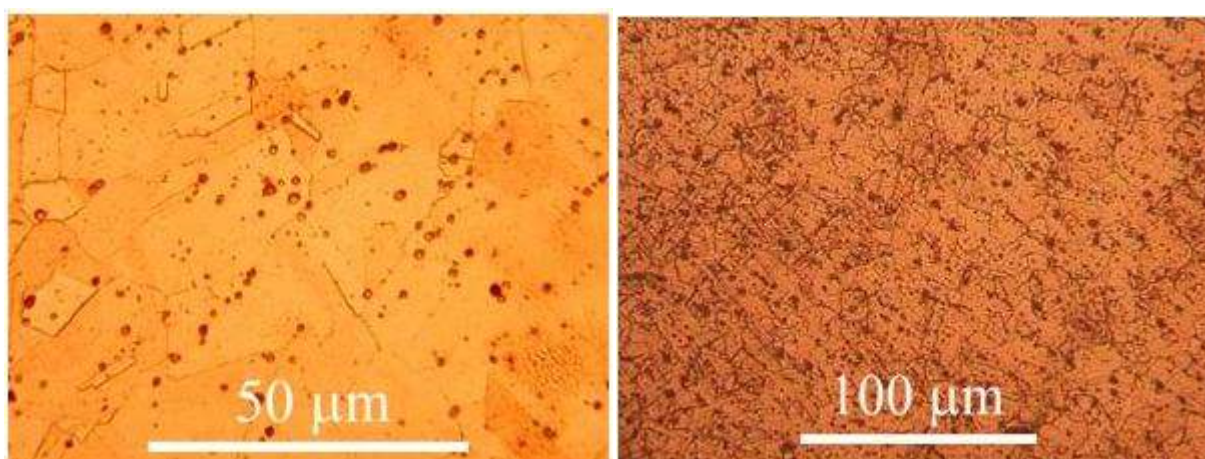


Figure 2 – Rolled Annealed copper (left) and etched copper (right) under an electron microscope (courtesy of University of Cambridge)

Most substrates are copper clad with either Rolled Annealed (RA) copper, Electrodeposited Copper (ED) or Reverse Treated Foil (RTF). RA copper is both smooth and consistent in thickness, but is the most expensive foil. ED copper has the roughest surface and depending on the application and speed requirements, may be perfectly adequate. RTF copper is smoother, and is much the same cost as ED.

However, it does exhibit poor peel strength and is prone to delamination. So it is a trade-off between performance and price.

Electrodeposited copper foil is the standard copper used in the laminate industry. ED foil is deposited from a copper solution, at a specific DC voltage, onto a moving polished titanium drum which forms the cathode. The foil is subsequently stripped from the drum. The grain construction formed by this process forms the dendritic “tooth” of the copper on the “bath side” of the copper. The drum side takes on the smooth texture of the polished drum surface onto which it is plated. Figure 3, illustrates a typical inner layer trace cross-section showing the roughness of both the upper and lower copper surfaces.

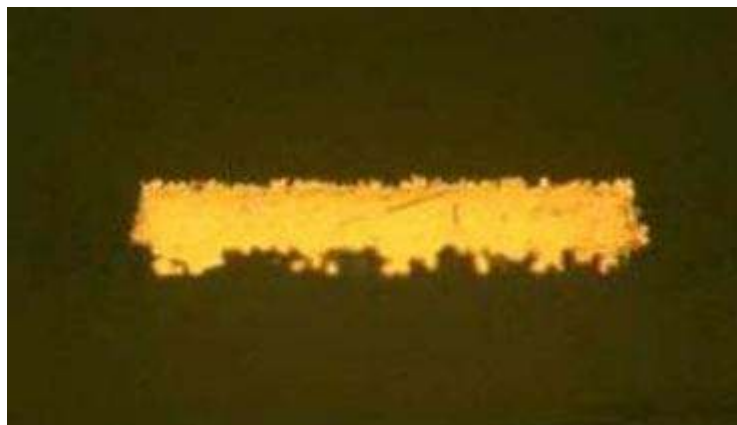


Figure 3 – Inner layer trace cross-section<sup>3</sup>

Rolled copper is made by running a copper strip through successively smaller and smaller gaps in a rolling mill until it reaches the desired thickness. Rolled copper is smoother and can be made very flexible by annealing. Because it is smooth, its bond to laminates is totally dependent on the quality of the treatment it receives and the adhesive properties of the resin system employed. RA copper also has a different grain structure than ED copper and will etch at a different rate. Much of the RA copper in the laminate industry is used in flexibly circuits, typically bonded to a polyimide film with an acrylic adhesive.

Reverse treated foils involve the subsequent treatment of the smooth side of the electrodeposited copper. Treatment layers are thin, rough coatings that improve adhesion of the base foil to the dielectric material.

To the naked eye, copper clad laminate appears smooth but at the microscopic level, all materials exhibit surface irregularities. If the average incline of the “teeth” of the conducting surface is 60°, forming an equilateral triangle, then the increase in surface resistance would be approximately twice that of a dead flat surface. Less severe geometries induce smaller effects. However, a better measure of the surface roughness is the root-mean-square (RMS) height ( $h_{RMS}$ ) of the surface bumps, since the exact profile cannot be established for a working design. Taking the worst case equilateral ridge geometry as a guide, one would expect the RMS roughness to be in the order of 0.29 times the average peak to valley roughness.

The onset frequency ( $\omega$ ) of the RMS surface roughness effect is given by:

$$\omega = \frac{2}{\mu \sigma h_{RMS}^2}$$

where  $\mu$  is the magnetic permeability ( $4\pi \times 10^{-7} \text{H/m}$ ) and  $\sigma$  is the copper conductivity ( $5.98 \times 10^7 \text{ S/m}$ ) and  $h_{\text{RMS}} = \text{Average bump ht (0.000006m)} \times 0.29$  for ED copper.

Therefore, inserting the numbers into the above equation, the onset frequency ( $\omega$ ) of the RMS surface roughness effect is 1.28GHz for ED copper. The smoother the copper surface, the higher the frequency at which surface roughness takes effect.

Also, the effective dielectric constant and hence capacitance is increased due to the increased surface area of the teeth of the rough conductor. This in turn, lowers the characteristic impedance slightly. The capacitance increases by about 5% for microstrip and 10% for stripline traces that exhibit more roughness. So the effect on impedance is -2% to -5% respectively.

Although the surface roughness is not generally stated in material manufacturer's datasheets, typical values are 3 $\mu\text{m}$  for the outer surface and 6 $\mu\text{m}$  for the inner surface. For example, Panasonic's high-performance laminate, Megtron 6 core material, has a dielectric constant (Dk) of 3.4 and loss tangent (Df) of 0.004 at 18GHz. This material is available in standard ED, VLP, SVLP and HVLP (very/super/hyper low profile) foil with average surface roughness of 7-8, 3-4 and 1.5-2 $\mu\text{m}$  respectively.

Isola use mostly VLP type coppers for their HSD product offerings. The RTF coppers that Isola offer have roughness values of 4-8 microns. This is standard for FR408HR and IS415 products. VLP2 (Isola designation) copper is incorporated in high end products that require the best insertion loss. The roughness for this copper is 2 microns.

So the smoothest surface HVLP material with 1.5 $\mu\text{m}$  average surface roughness, will therefore not exhibit any noticeable surface roughness effect up to 20GHz. Consequently, one would be well advised to take note of the surface roughness properties, if your design is running over 1GHz to ensure you choose an appropriate material for the application.

#### Points to Remember:

- At speeds below 1GHz, the effect of copper surface roughness on dielectric loss is negligible.
- As frequency increases, the skin effect region drives the current into the surface of the copper dramatically increasing loss.
- When the copper surface is rough, the effective conductor length extends as current follows along the contours of the surface up and down with the topography of the copper surface.
- Smooth surfaces considerably increase the possibility of delamination during the thermal stress of the PCB fabrication and assembly processes.
- Skin effect is the tendency of an alternating current to become distributed within a conductor such that the current density is largest near the surface.
- Skin depth decreases with increased frequency.
- The nickel content of ENIG surface finish, has a ferromagnetic property that can adversely affect electromagnetic fields in the high frequency domain.
- At approximately 2.7 GHz, the resonant behavior of the nickel component in ENIG increases insertion loss. It is for this reason, that SMOBC processing should be considered for all high-speed designs.
- Most substrates are copper clad with either Rolled Annealed (RA) copper, Electro Deposited Copper (ED) or Reverse Treated Foil (RTF).
- To the naked eye, copper clad laminate appears smooth but at the microscopic level, all materials exhibit surface irregularities.
- The onset frequency of the RMS surface roughness effect is 1.28GHz for ED copper.
- Typical values of surface roughness are 3 $\mu\text{m}$  for the outer surface and 6 $\mu\text{m}$  for the inner surface.



- The smoothest surface HVLP material with 1.5um average surface roughness, will not exhibit any noticeable surface roughness effect up to 20GHz.

**References:**

[Beyond Design: Surface Finishes for High-Speed PCBs](#) – Barry Olney  
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 Roughness Characterization for Interconnect analysis – Yuriy Shelepnev, Chudy Nwachukwu  
 Signal and Power Integrity Simplified – Eric Bogatin  
 High-speed Signal Propagation – Howard Johnson  
 For information on the ICD Stackup and PDN Planner, please go to [www.icd.com.au](http://www.icd.com.au)

**Bio:**

Barry Olney is Managing Director of In-Circuit Design Pty Ltd (ICD), Australia. The company developed the ICD Stackup Planner and ICD PDN Planner software, is a PCB Design Service Bureau and specializes in board level simulation.

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