Semi-Automatic Copper Foil Surface Roughness Detection from PCB Microsection Images

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Abstract— Characterization of surface roughness of printed circuit board (PCB) conductors is an important task as a part of signal-integrity analysis on high-speed multi-GHz designs. However, there are no methods to adequately quantify roughness of a signal trace or a power/reference plane layer within finished PCBs. Foil roughness characterization techniques currently available can only be applied to the base foil, prior to its incorporation into a finished board. In a finished PCB, a foil surface is not directly accessible, as it is embedded in the dielectric of the board, and attempting to expose the surface will damage the board and the surface of interest. In this paper, a method of surface roughness quantification from microsectioned samples of PCBs is presented. A small, non-functional area, e.g., a corner of the PCB, can be removed, and the surface roughness of the circuit layers can be assessed without impairing the function of the PCB. In the proposed method, a conductor (a trace or a plane) in the microsectioned sample is first digitally photographed at high magnification. The digital photo obtained is then used as an input to a signal- and image-processing algorithm within a graphical user interface. The GUI-based tool automatically computes and returns the surface roughness values of the layer photographed. The tool enables the user to examine the surface textures of the two sides of the conductor independently. In the case of a trace, the composite value of roughness, based on the entire perimeter of the trace cross-section, can be calculated.

I. INTRODUCTION

Signal attenuation in transmission lines due to skin effect loss and surface roughness in copper conductors on printed circuit boards (PCBs) is a well-documented issue, confronting in particular designers of high-speed (>10 Gb/s) circuits [1]-[4]. Knowledge of copper roughness on PCBs is important for high-speed electronics, where accurate separating and modeling of conductor and dielectric losses at the design stage determine quality of the performance of designs [5], [6]. To minimize the variation in channel loss within a large population of PCBs built by multiple board shops over an extended period of time and on a variety of different laminate materials, it has become a standard practice at many Original Equipment Manufacturers (OEMs), to attempt to control the surface roughness of copper foils through specification of the roughness grade on the fabrication drawing. Maximum roughness values for PCB circuit foils are governed by the appropriate industry specification for metal foils, IPC-4562A [7]. However, as is demonstrated in [8] and [9], the roughness profile of an inner-layer trace is influenced not only by the grade of copper foil used on the laminate core material, but also by the oxide or alternative-oxide inner-layer treatment process applied by the PCB fabricator.

![Image](https://example.com/image.png)

Fig. 1. Typical photos of cross-sections: (a) optical photo, (b) SEM picture.

Existing measurement methods for conductor surface roughness may be applied to raw copper foil or a sheet of copper-clad core material, either in its original form or following circuitization (including inner-layer treatment). The traditional measurement method used in the PCB industry for over thirty years has been stylus profilometry, in which the movements of a mechanical stylus dragged in a straight line across the sample are used to calculate values of roughness [10]. Modern non-contact commercially available techniques...
include laser profilometry, atomic force profilometry, and white light interferometry, which generate a 3D image of the sample’s target area, and are thus more representative of the surface profile than the linear measurement generated by a stylus.

However, all of these methods have an important prerequisite: the surface to be studied must be exposed (directly accessible) to the test instrument. Unfortunately, in many cases, the first indication of a possible issue with copper surface roughness appears only in a finished board—the designers notice unexpectedly high channel loss and signal-integrity test failure. While high channel loss results not only from conductor roughness, a complete root-cause failure analysis requires that the surface roughness of the trace(s) under test should be accurately determined, so that excessive roughness can be eliminated.

Additionally, in the case of a finished and assembled PCB, the circuit layers of concern are laminated within the board, and thus their roughness cannot be assessed by the commercial methods mentioned above. The abovementioned methods are applied today only to PCB components (raw foil and inner-layers) prior to the layer lamination step. Even if one attempts to separate and peel apart a laminated PCB to access the target layers, the surface micro-features of the inner-layer copper will be filled with the dielectric resin to which the foil was previously bonded, and measurement by the above methods will represent the residual resin adhering to the foil rather than the surface of the actual copper foil.

The only practical method of accessing an internal layer on a PCB is through micro-sectioning, a quick and inexpensive technique universal throughout the PCB industry. Microsectioning, recognized as an industry-standard technique, has been used for decades as a part of quality assurance in assessing PCB attributes such as quality of holes, trace/dielectric dimensions, and plating thickness [11]. The ability to use microsectioned slugs cut from a board to determine surface roughness of the inner-layers would thus be highly useful, building upon a capability already resident at the majority of PCB fabricators and electronics designers.

The measurement method described in this paper consists of a software tool which accepts as input a micro-photograph of a PCB microsection in, e.g., *.jpg format. The photograph may be generated either by optical or scanning electron microscope (SEM) [5]. The pictures may be either monochrome or color. The contour of the target object (signal trace or reference plane) is determined by contrast enhancement between the metal layer, which is lighter in color and/or more reflective, and the surrounding dielectric, which is less reflective. Using the tool, the user is able to select the area of interest within the microsection photograph, and may analyze the top or bottom surface of a copper layer independently, or select the entire periphery of a trace to obtain a composite roughness value. A graphical user interface (GUI) is provided to assist the user in selecting the target area, and to display the measured values using the statistical definitions of roughness most commonly encountered in the PCB industry, viz. $R_m$, $R_q$ (or $R_{rms}$), $R_v$, and $R_s$ [5], [12]. For this paper, we present the surface roughness parameters $R_m$, $R_q$, $R_v$, $A_s$, $A_r$, and $A_l/A_s$ (see Table 1).

$R_a$ is the arithmetical mean roughness is defined as

$$R_a = \frac{1}{n} \sum_{i=1}^{n} x_i.$$  \hspace{1cm} (1)

Herein, if $l$ is the length of the surface being analyzed, then $x_i$ is each sample point in the length. The total number of sample points is $n$.

$R_{rms}$ is the root-mean-square roughness and is defined as

$$R_{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} x_i^2}. \hspace{1cm} (2)$$

$R_s$ is the ten-point mean roughness value. If $Y_{pk}$ and $Y_{sk}$ is the $k$-th highest peak and the $k$-th highest valley (where $k=1, 2, 3, 4, 5$), along the length of the sample, then $R_s$ can be defined as

$$R_s = \frac{[Y_{p1} + Y_{p2} + Y_{p3} + Y_{p4} + Y_{p5} + Y_{v1} + Y_{v2} + Y_{v3} + Y_{v4} + Y_{v5}]}{5}.$$ \hspace{1cm} (3)

$A_r$ is somewhat similar to $R_s$, but includes all the peaks and valleys as compared to just five of them in case of $R_s$. It is defined as:

$$A_r = \frac{\sum_{i=1}^{m} Y_{pi} + \sum_{j=1}^{m} Y_{vj}}{pm + jv}, \hspace{1cm} (4)$$

where $Y_{pi}$ and $Y_{vj}$ are the $i$-th peak and $j$-th valley respectively. Also, from (4), $pm$ is the total number of peaks while $vn$ is the total number of valleys.

The surface roughness, strictly speaking, is a random function of coordinates in the cross-section and along the signal trace. However, in some models it is convenient to consider it as a quasi-periodic function. $\Lambda_r$, the quasi-period of the roughness function, is defined as

$$\Lambda_r = \frac{\Lambda^+ + \Lambda^-}{2}. \hspace{1cm} (5)$$

If $l$ is the length of the sample, then $\Lambda^+$ can be defined simply as $l/pm$, and $\Lambda^-$ can be defined as $l/vn$.

The proposed technique differs fundamentally from the currently-available image analysis software package [13], which operates by superimposition of perpendicular grid lines within the microsection photograph and measurement of the length of such, rather than by boundary detection within the image as in our case.

II. METHODOLOGY

The methodology includes two stages: (1) preparation of the samples to be photographed using the optical microscope (OM) or scanning electron microscope (SEM), and (2) surface roughness parameters extraction.
A. Sample Preparation

Samples for the analysis consist of fairly small (3-10 mm) slugs removed from a PCB by punching or routing. The X-Y coordinates of a slug are selected to capture target traces or planes as desired. The slug is encapsulated in an epoxy-based potting compound, so that the copper layers of interest are perpendicular to the plane of view in the finished microsection plug. The surface to be viewed is ground past the zone of mechanical damage from the punching/routing of the slug, then polished to a high degree to ensure that the metal layers are reflective (shiny) and all surface scratches removed.

The plug is then placed on an optical microscope, suitable for micro-photography to produce photos, e.g., in *.jpg format, of the target structures, utilizing the available lighting techniques (specular, diffuse, reflective, etc.) to maximize the contrast between the metal circuit feature and the surrounding dielectric. A typical optical microscope photo is shown Fig. 1(a). Following the optical analysis, or in some cases instead of it, the plug may then be sputtered with a conductive layer for SEM photography. A typical SEM picture of the board cross-section is presented in Fig. 1(b). The quality of the sample preparation and the microscope set-up affect the quality of the *.jpg photo generated. These aspects are discussed in detail in the subsequent sections of this paper. It should be noted that digital images need not be limited to *.jpg format, but may include lossless formats as well, such as *.bmp or *.png, or formats such as *.tif, which may be either lossless or compressed.

B. Roughness Measurement Technique

The image-processing algorithm realized in the tool for roughness analysis is schematically shown in Fig. 2. The *.jpg image is used as an input. The tool displays the photo on-screen, and requests the user to select the region of interest by using the cursor to draw a box around the target area. This step is intended to analyze the image based on the region of interest defined by a user, thereby reducing the computation time for the analysis. Alternatively, the user may select an object, either the metal trace or plane, whose roughness will be characterized. The area to be analyzed necessarily consists of light (metal) and dark (dielectric) regions, and the algorithm uses the contrast information within the image to predict the metal/dielectric boundary. If the user is interested in a plane layer, the analyzed area will consist of a light region and a dark region separated by a roughly horizontal boundary, as is seen in Fig. 1(b), where the lowest gray horizontal region spans across the image. If the user analyzes a trace, the boxed area will contain the roughly trapezoidal light-colored image of the trace surrounded entirely by the darker dielectric, as is seen in the center of Fig. 1(b).

The image-processing algorithm uses the pixel information (in grayscale format) embedded in the image to optimize the definable boundary between the light and dark regions. This is done by enhancing the contrast first, and then by analyzing the statistics (mean and variance) of the selected region. The contrast-enhanced image is shown in Fig. 3(a). An iterative boundary detection scheme is used to find the boundary, which separates the metal (brighter) and non-metal (darker) regions within the selected region. All gray pixels are thus forced to either pure white (metal), or pure black (non-metal), generating a binary black-and-white image. The boundary between these regions defines the surface texture of the target. This can be seen in Fig. 3(b), which shows the binary image obtained from the contrast enhanced image as in Fig. 3(a). After obtaining the binary image, the boundary line is extracted as a pixel map into Cartesian coordinate data, based on the input from the user. Each pixel creates one data point. A sample of a bottom surface selected by a user is shown in Fig. 3(b). Finally, a de-trending function is applied to eliminate any tilt present in the sample or photo.

The coordinate dataset thus generated from the user-selected surface, as the one shown in Fig. 4, is functionally analogous to datasets which could be generated by different techniques, e.g., a two-dimensional stylus measurement, or a three-dimensional data set generated by one of the non-contact measurement methods for a planar slice.
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The tool must be provided with a scale factor for the photo in order to tie the size of the peaks and valleys, in pixels, to actual measured distances in mils or microns. This may be in the form of the magnification factor for the *.jpg, typically known when the photo is taken, as is shown in the lower right corner of Fig. 1(b). An alternative method is to use the cursor to select or mark a scale bar incorporated into the *.jpg followed by inputting the known length of the bar.

As is shown in [12], [14], the parameters of peak-to-valley roughness $R_v$, average roughness $R_a$, and r.m.s. roughness $R_{rms}$ are all obtained by statistical manipulations applied to a base data set consisting of X-Y Cartesian coordinate data. This dataset is essentially a locus of measured points, which define an irregular line bearing numerous peaks and valleys.

III. RESULTS AND DISCUSSION

In this section, surface roughness values for some sample SEM images with foils of different types are provided in Table 1. Three different samples were evaluated under the SEM as STD (standard foil), VLP (very-low-profile foil), and HVLP (hyper-very-low-profile foils).

![](image)

**Fig. 4.** Selection of bottom surface (zoomed), following the binary conversion.

<table>
<thead>
<tr>
<th>Foil Type</th>
<th>$A_r$ ($\mu$m)</th>
<th>$\Lambda_r$ ($\mu$m)</th>
<th>$A_r/\Lambda_r$</th>
<th>$R_a$ ($\mu$m)</th>
<th>$R_v$ ($\mu$m)</th>
<th>$R_{rms}$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>7.15</td>
<td>15.22</td>
<td>0.47</td>
<td>1.59</td>
<td>8.07</td>
<td>1.93</td>
</tr>
<tr>
<td>VLP</td>
<td>3.43</td>
<td>10.3</td>
<td>0.33</td>
<td>0.76</td>
<td>4.24</td>
<td>0.95</td>
</tr>
<tr>
<td>HVLP</td>
<td>1.57</td>
<td>5.01</td>
<td>0.31</td>
<td>0.36</td>
<td>2.30</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The eye diagrams for the test vehicles with the same dielectric of fiber-glass filled epoxy resin system, and the different foils at 3 Gbps and 28 Gbps bit rates are shown below in Figs. 5-7. They were generated from the measured S-parameters on the test vehicles as those in [5] and [6] using link-path-analysis software.

![](image)

**Fig. 5.** Eye pattern of the test vehicle with STD foil at (a) 3 Gbps, (b) 28 Gbps

![](image)

**Fig. 6.** Eye pattern of the test vehicle with VLP foil at (a) 3 Gbps, (b) 28 Gbps

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TABLE I. SURFACE ROUGHNESS OF DIFFERENT FOILS
B is presented, in which measured-rn, difference-may be used in simulations of high-conductor surface roughness parameters on finished PCBs discussed.

Strategies for mitigating the known causes of variation are sample preparation and photographic technique. Some accuracy and repeatability of the method are affected by which standard definitions of s-PCB component mater-

The method is applicable to circuit layers within a finished PCB, whereas existing techniques may be applied only to PCB component materials prior to lamination. The method uses grayscale resolution to define the pixel border between the light (metal) and dark (dielectric) areas of the photo, and then extracts this data into a Cartesian coordinate plot, from which standard definitions of surface roughness are calculated. Accuracy and repeatability of the method are affected by sample preparation and photographic technique. Some strategies for mitigating the known causes of variation are discussed.

The primary motivation for developing the technique was to facilitate signal-integrity failure analysis on finished boards. There are also some additional uses for the tool. Accurate data of conductor surface roughness parameters on finished PCBs may be used in simulations of high-speed digital designs with different numerical, analytical, and semi-empirical models and tools to separate conductor loss from dielectric loss, e.g., as in [5], [6], [15]-[17].

First, the method can be used to verify that copper foil used in a given PCB corresponds to the roughness grade specified on the fabrication drawing, provided that the construction of the board calls for inner-layer cores of balanced copper foil construction. As the copper planes in the vast majority of high-speed designs are cut out near the edges of the PCB, the surface texture of the planes may be analyzed to verify that roughness-compliant foil was supplied, without waiting for the PCB fabricator to deliver retained microsection slugs or raw material traceability records. PCB fabricators, in turn, could use this method for the same purpose on microsections of copper-clad core material. Again, these could be small corner samples which would not render the panel unusable.

Second, the tool may be used to examine the roughness imparted to a board by the PCB fabricator’s oxide or oxide-alternative inner-layer treatment process. If the same part number is being built by multiple PCB vendors, an analysis (on non-functional areas as above) can be made to numerically characterize the degree of roughness difference within the supply base, as it is highly likely that the various PCB makers will be using different chemical systems or variations of such. Periodically checking the same supplier over time may reveal roughness variation due to a change in the inner-layer treatment chemistry, which might be otherwise unknown to the end-user.

ACKNOWLEDGEMENT

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REFERENCES

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