Non-Contact Measurement of Conformal Coating Thickness Using Chromatic Confocal Microscopy

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ABSTRACT

Conformal coating is designed to provide protection and long-term reliability to printed circuit boards (PCB) in harsh environments where high humidity, high temperature, corrosive gases, or salt spray may be present. The coating uniformity and correct thickness is necessary to prevent inadequate coating properties, coating defects, heat entrapment, and long-term reliability issues. Traditional methods for measuring coatings thickness are separated into wet and dry methods. Currently, wet thickness is measured using a wet film gauge, whereas, dry thickness can be measured using micrometer, eddy current, and ultrasonic techniques. However, these methods have disadvantages such as user dependent inconsistencies, requiring a ground plate, and measuring a coupon rather than the board itself. This study aims to highlight the application of chromatic confocal microscopy (CCM), an optical technique used to characterize 2D/3D surfaces, for measuring wet and dry conformal coating thickness.

In this work, conformal coating wet and dry thicknesses were measured using CCM and traditional methods. FR4 boards with varied color solder masks and components were created for realistic use cases. For wet coating thickness, CCM and wet film gauge measurements were taken immediately after application. For dry coating thickness, micrometer and eddy current measurements were taken before application and after full cure, along with CCM measurements. Compared to traditional methods, CCM as a non-contact measurement technique was found to be highly accurate, have lower variability, and have expanded possible thickness measuring locations with a smaller measurement diameter. Therefore, it was concluded that CCM can be used as a powerful alternative to standard methods for measuring conformal coating thickness.

Key words: conformal coating; conformal coating thickness; thickness measurement; optical measurement; chromatic confocal microscopy; non-contact; quality control

INTRODUCTION

Conformal coatings are thin polymer films applied to the surface of printed circuit boards (PCB) as a protective measure against moisture, chemicals, temperature, and other environmental conditions. Conformal coating is designed to "conform" to the shape of PCBs and its components, providing coverage in all areas with a uniform thickness [1]. The correct coating thickness is critical to ensure long-term reliability. According to IPC-CC-830, the recommended thickness for most standard conformal coatings range from 30 – 130µm or 210µm depending on the specific type [2]. Standard coatings applied thinner than the recommended specifications may not have the full protective properties detailed by the manufacturer. Coatings applied too thick can lead to risks of defects such as coefficient of thermal expansion (CTE) mismatch, heat entrapment, cracking, etc. [2]. Therefore, it is necessary to control conformal coating thickness on all areas of a PCB.

Traditional methods to measure conformal coating include wet film gauge, micrometer, and eddy current methods. These are largely manual processes where operator proficiency can impact the reliability of measurements. These instruments also require direct contact, which can scratch and damage the coating layer. As a result, manufacturers commonly use a representative test coupon to obtain an estimate of the coating thickness, however, the actual thickness on the PCB may differ due to component layout or material changes. Traditional methods are also not capable of measuring the thickness on top of components or on component leads. Measuring the thickness in these areas are commonly only achieved by destructive cross-sectioning of desired components. This is a time-consuming and expensive process if multiple components or boards need to be evaluated.

This study evaluates the use of chromatic confocal microscopy (CCM) as a powerful alternative to traditional methods to measure conformal coating thickness. Since CCM is a non-contact method, wet and dry thickness can be measured. CCM measurements were compared with micrometer, eddy current, wet film gauge measurements, and component cross-sectioning for accuracy and variability.

Chromatic confocal microscopy

CCM is a well-established technology used in the semiconductor, glass, medical, automotive, and plastics industry for process control [3]. Its uses include, measurements of the thickness of glass and plastics, as well as the 3D surface topography of silicon wafers [3]. As an optical measurement technique, CCM uses white light to measure the distance from a surface of a material or the thickness of transparent materials. White light produced by a spectrophotometer is split into a series of monochromatic light that converges at varying distances away from the sensor. This allows individual wavelengths of light to be in focus on the surface at a time. Different wavelengths of light are associated with specific physical distances, which provides a relationship between the surface height and the detected wavelength [4]. A schematic is shown in Figure 1.

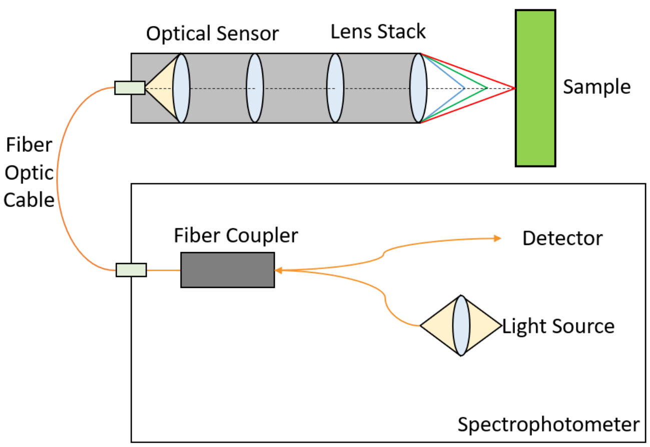

Figure 1. Schematic of chromatic confocal unit

When light passes through a transparent layer such as conformal coating, the light path is bent due to the refractive index of the coating as shown in Figure 2. The refractive index of a material is the ratio of the velocity of light in a vacuum to that in another material with higher density [5]. This occurs in conformal coating because the light impacts the atoms within the coating's polymer structure, causing it to slow down. Generally, the denser the material, the more the velocity of light is reduced and the higher the refractive index [5].

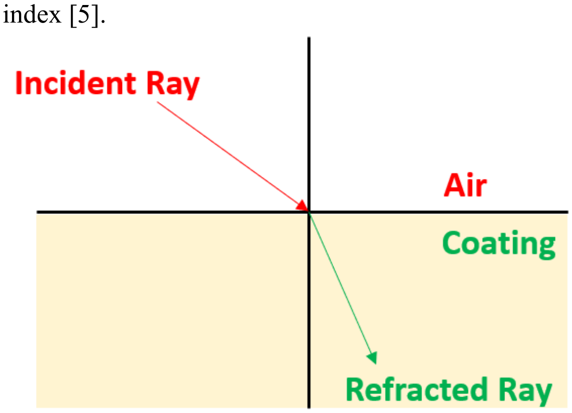

Figure 2. Bending of light through conformal coating

Monochromatic light is reflected into the spectrophotometer in two places: the top and bottom of the coating layer as shown in Figure 3. Since the reflected light at each interface is of a single wavelength, the light intensity is higher compared to other wavelengths. In the detector, this produces two light intensity peaks that correspond to the two surfaces in focus.

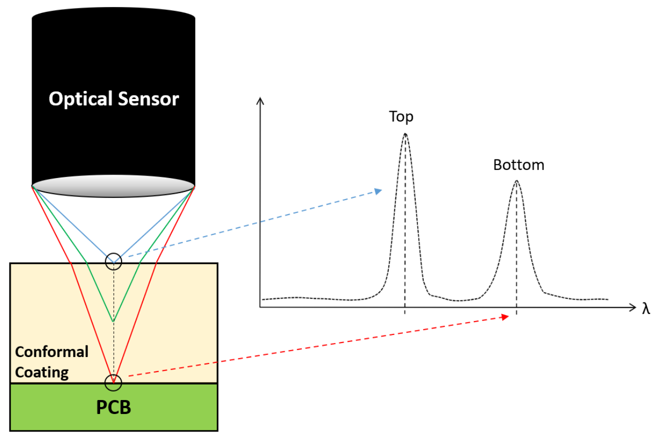

Figure 3. Light intensity peaks produced from the top and bottom of a transparent layer [4]

The two peaks are centered at individual wavelengths of light which correspond to differences in physical distance. Using the refractive index of a conformal coating, the thickness of the coating layer can be calculated using Equation 1.

$$T = Z_1 - Z_2 \frac{\eta}{\eta'} \quad (1)$$

Where T is the thickness of the coating layer, Z_1 is the location of the upper coating interface, Z_2 is the location of the lower coating interface, η is the refractive index outside the coating (typically unity in air), and η' is the refractive index of the conformal coating [4].

MATERIALS AND METHODS

Sample Preparation

A custom test coupon was designed to allow for thickness measurements using various measuring methods to be used in specified locations for the most accurate comparison, as shown in Figure 4. The front side of the test coupon has silkscreened circles to designate three locations for micrometer, eddy current, and CCM measurements. The reverse side has four horizontal regions with silkscreened markers align with notches on a wet film. A copper plane was placed underneath the solder mask to allow for eddy current measurements. Coupons were prepared in seven different solder mask colors: red, yellow, green, blue, purple, black, and white. Test coupons were manually sprayed on the front and brush on the back side with a commercial polyurethane and commercial acrylic conformal coating, followed by curing based on manufacturer's specifications.

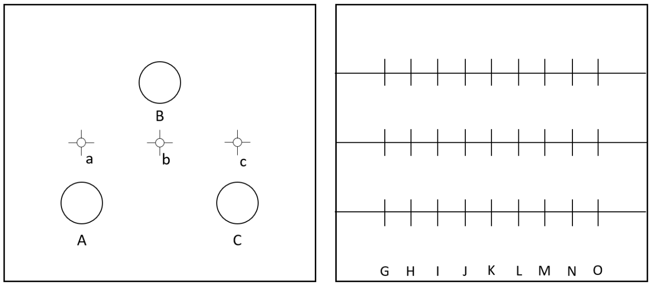

Figure 4. Front (left) and back(right) sides of test coupon

An IPC-7711/7721 test board (see Figure 5) was used for cross-sectioning of components in comparison to CCM. The test board was manually sprayed with the commercial polyurethane and cured following manufacturer's specifications.

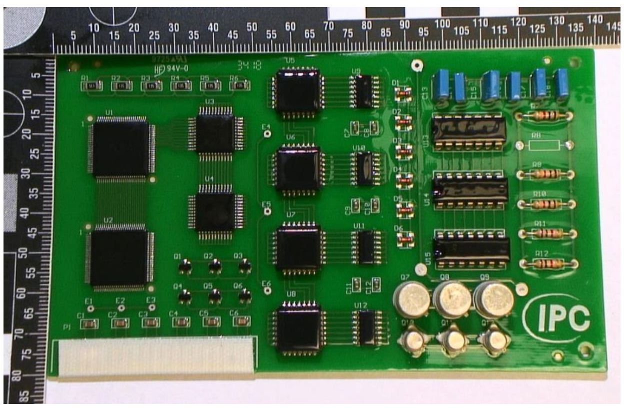

Figure 5. Test board sample used for cross-sectioning

Refractive Index Measurement

The refractive index of wet and dry conformal coating was measured using a refractometer shown in Figure 6.

Figure 6. Refractometer used for conformal coating measurements

Thickness Measurement Setup

Micrometer

Coating thickness was measured by a handheld micrometer with resolution down to 0.001mm shown in Figure 7. Five measurements were taken in the designated circles on the test coupon before application and after full cure of the coating. The coating thickness was calculated as the difference of the board thickness before and after application of coating at each location. The thickness uncertainty was determined by propagating the standard deviations of the board thickness at each location.

Figure 7. Handheld micrometer

Eddy Current

Coating thickness by eddy current was measured using a PosiTector 6000 and followed the same procedure that was used for micrometer measurements.

Wet Film Gauge

Wet film thickness measurements were performed using a notched wet film gauge, shown below in Figure 8. After application of conformal coating, the wet film gauge was placed and withdrawn perpendicular to the test coupon. The wet film thickness was determined by the last wetted and first unwetted tooth on the gauge using a UV light, resulting in a thickness range in which the true value lies. The wet thickness was reported as the interval between the last wetted notch and the first unwetted notch.

Figure 8. Wet film thickness gauge

CCM Apparatus

A chromatic confocal sensor with a measuring range of 0.3mm, 4nm resolution, and measurement diameter of 6μm was used. The sensor was mounted onto the stage of a stepper motor linear actuator. This allowed for precise movements in the vertical axis to bring the sensor into focus on the test coupons or components. Movement of the sensor allowed for accommodation of samples where vertical topography may differ (e.g., PCB populated with components). Five consecutive measurements were averaged for wet and dry thickness. A schematic of the measurement setup and a photograph of the equipment are shown in Figure 9.

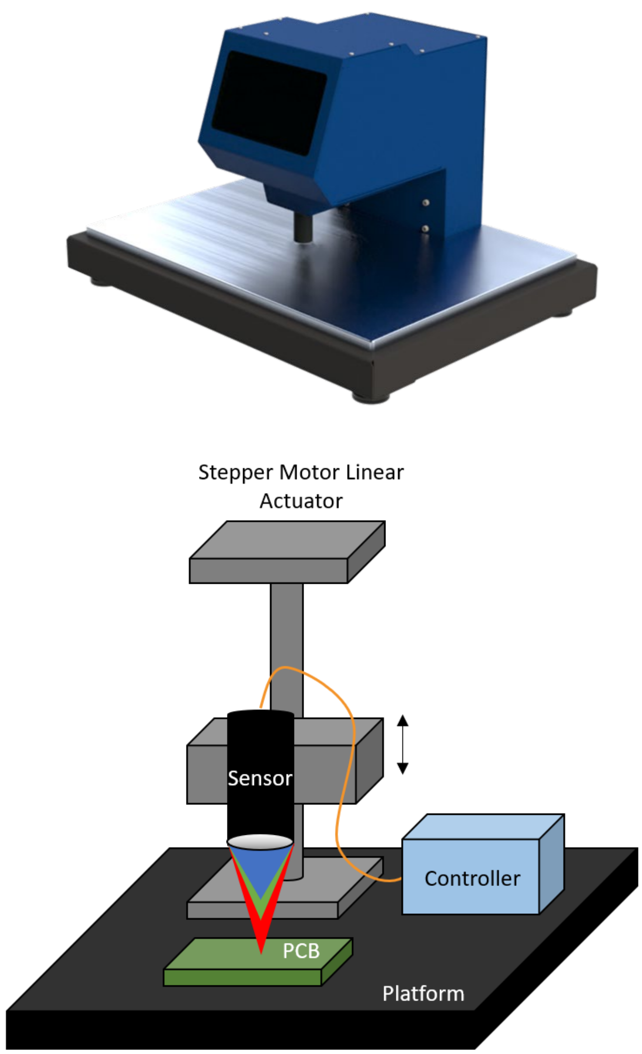

Figure 9. External (top) and internal (bottom) schematic of experimental testing setup

Cross-Sectioning

Cross-sectioning was performed by an independent lab on an 0805 capacitor and QFP44 on an IPC-7721 test board coated with a commercial polyurethane conformal coating. CCM measurements were performed on the top, lead, and leg of the QFP and across the center of the 0805 capacitor prior to cross-sectioning.

RESULTS AND DISCUSSION

Dry Thickness

The dry thickness of a polyurethane and acrylic conformal coating was measured using a micrometer, eddy current, and CCM. The full tabulated results are shown in Table 1 and Table 2. As can be seen, the measured thicknesses between the three methods are comparable with one another; however, the most accurate and repeatable measurements were made with the CCM method. Thicknesses measured by the micrometer tends to be slightly larger compared to the other two methods due to its larger measurement area. The large, flat measurement area of the micrometer is affected by non-uniformity and peaks in coating topography that can result in a larger measured thickness, illustrated in Figure 10. The eddy current gauge will provide an average response based on the magnitude of the eddy currents produced in the copper layer. CCM is the most sensitive to non-uniformity in coating thickness due to an extremely small measurement area of 6–7μm.

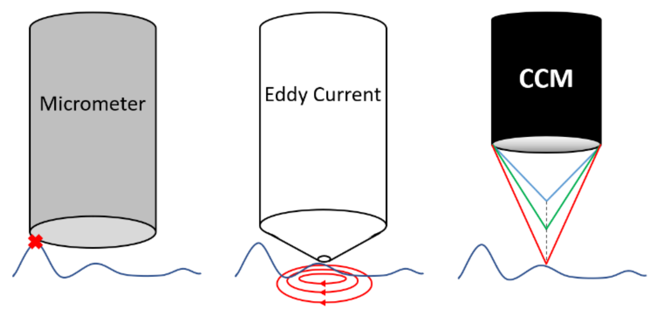

Figure 10. Sensitivity of instruments to coating topography

CCM also has the lowest amount of variation between consecutive measurements. Since only the optical sensor travelled in the vertical direction, repeated measurements in an exact location were possible, eliminating the chance of operator error positioning and contact with the coating surface. With the micrometer and eddy current, operator error and the compressibility of the coating are factors of variation, resulting in larger deviations for the two instruments.

The color of the solder mask also did not impact thickness measurements, only the intensity of reflected light. A black solder mask reflects slightly less light from the conformal coating – solder mask interface due to absorption of light. Inversely, a white solder mask or metallic substrate will reflect more light back into the sensor, creating clear peaks and allowing measurements down to thinner thicknesses.

Table 1. Measured Results for Dry Polyurethane Coating Thickness on Test Coupons

Table 1. Measured Results for Dry Polyurethane Coating Thickness on Test Coupons

Test Coupon Color	Location	Micrometer (µm)	Eddy Current (µm)	Chromatic Confocal (µm)
Red	A	77 ± 6	74.6 ± 1.3	74.23 ± 0.28
	B	123 ± 3	109.4 ± 2.7	109.27 ± 0.56
	C	127 ± 7	114.6 ± 3.2	113.23 ± 0.33
Yellow	A	31 ± 3	30.4 ± 1.3	31.52 ± 0.29
	B	66 ± 4	63.4 ± 1.4	64.44 ± 0.66
	C	137 ± 4	134.5 ± 1.2	133.45 ± 0.65
Green	A	42 ± 2	45.7 ± 1.4	42.92 ± 0.60
	B	80 ± 5	82.7 ± 1.8	83.47 ± 1.12
	C	156 ± 4	151.9 ± 1.9	151.86 ± 1.68
Blue	A	76 ± 3	76.5 ± 4.8	74.95 ± 0.31
	B	127 ± 4	118.5 ± 1.7	116.73 ± 0.87
	C	178 ± 4	162.6 ± 1.8	161.69 ± 0.35
Purple	A	63 ± 2	61.8 ± 1.6	59.67 ± 1.12
	B	110 ± 4	108.3 ± 1.3	109.83 ± 0.39
	C	65 ± 2	69.9 ± 5.1	67.14 ± 1.23
Black	A	79 ± 3	81.5 ± 2.7	79.27 ± 0.32
	B	62 ± 3	58.2 ± 2.0	59.61 ± 0.54
	C	154 ± 2	146.6 ± 2.0	145.8 ± 0.05
White	A	22 ± 4	23.9 ± 0.7	21.23 ± 0.02
	B	96 ± 3	90.7 ± 1.2	92.37 ± 0.05
	C	145 ± 4	139 ± 3.9	142.15 ± 0.02

*Each entry is an average of five measurements (average ± standard deviation)

Table 2. Measured Results for Dry Acrylic Coating Thickness on Test Coupons

Test Coupon Color	Location	Micrometer (µm)	Eddy Current (µm)	Chromatic Confocal (µm)
Red	A	91 ± 4	84.6 ± 1.6	83.82 ± 0.53
	B	81 ± 3	81.2 ± 1.9	81.81 ± 0.70
	C	100 ± 3	99.1 ± 2.4	99.68 ± 0.82
Yellow	A	93 ± 3	93.0 ± 1.7	92.37 ± 0.54
	B	95 ± 2	86.6 ± 2.7	89.50 ± 0.35
	C	92 ± 3	85.6 ± 3.1	88.72 ± 0.24
Green	A	80 ± 4	78.4 ± 1.3	82.21 ± 0.51
	B	96 ± 2	94.5 ± 1.6	93.82 ± 0.40
	C	88 ± 3	85.7 ± 3.8	88.39 ± 0.36
Blue	A	31 ± 3	33.8 ± 1.5	91.98 ± 0.34
	B	38 ± 4	38.0 ± 2.5	40.40 ± 0.21
	C	66 ± 2	60.4 ± 1.8	64.74 ± 0.16
Purple	A	148 ± 2	139.7 ± 1.5	144.31 ± 0.44
	B	120 ± 3	115.6 ± 5.6	118.24 ± 0.39
	C	79 ± 3	80.6 ± 1.7	84.14 ± 0.52
Black	A	93 ± 3	93.2 ± 4.8	92.60 ± 0.33
	B	81 ± 2	79.7 ± 1.5	80.77 ± 0.74
	C	66 ± 4	66.3 ± 1.7	67.32 ± 0.63
White	A	61 ± 3	58.4 ± 2.4	62.61 ± 0.18
	B	66 ± 3	64.3 ± 1.0	66.73 ± 0.16
	C	71 ± 3	70.0 ± 0.9	71.09 ± 0.39

*Each entry is an average of five measurements (average ± standard deviation)

Wet Thickness

The wet thickness of two commercial conformal coatings were measured using CCM and compared to measurements using a wet film thickness gauge. Since color did not have a significant impact previously for dry thickness, only a black and white test coupon was used. The results are summarized in Table 3 and Table 4. Using CCM, exact values of the wet thickness were possible, and all measurements fell within the range measured by the wet film gauge. The variability in wet thickness measurements is larger than in dry thickness due to the high volatility of solvents and coating flow from slight adjustments in positioning.

Table 3. Measured Results for Wet Polyurethane Coating Thickness on Test Coupons

Sample	Wet Film Gauge Range (µm)	CCM Thickness (µm)
Black	178 – 203	191.85 ± 4.96
	203 – 229	215.35 ± 1.64
	178 – 203	183.12 ± 6.76
White	203 – 229	202.12 ± 3.82
	356 – 406	366.29 ± 0.79
	305 – 356	336.42 ± 4.47

Table 4. Measured Results for Wet Acrylic Coating Thickness on Test Coupons

Sample	Wet Film Gauge Range (µm)	CCM Thickness (µm)
Black	102 – 127	113.20 ± 1.93
	102 – 127	125.80 ± 1.51
	178 – 203	197.00 ± 2.46
White	178 – 203	182.16 ± 1.38
	203 – 229	213.80 ± 2.00
	279 – 305	281.12 ± 3.44

Thickness on Components

CCM allows for thickness measurements on many locations on a PCB. This is made possible by the fact that CCM is non-contact and has a small measurement area. A wide range of measurement locations are made possible such as in-between components, on top of components, and on top of leads using CCM.

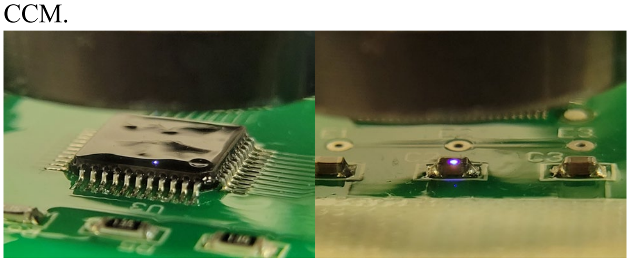

Figure 11. CCM measurement on top of components

Two components, a QFP44 and an 0805 capacitor (see Figure 11) were measured using CCM and compared to cross-sectioning thickness measurements by an independent lab. The QFP44 was measured on the top edge of the component, the top of the lead, and the leg of the lead, shown in Figure 12. The 0805 capacitor was measured across the center of the component, shown in Figure 13.

Table 5. Measured Thickness of QFP44 using CCM vs. Cross-sectioning

Location	CCM (µm)	Cross-section (µm)
A	34.18	31.1989
B	36.16	33.9187
C	102.25	100.3815

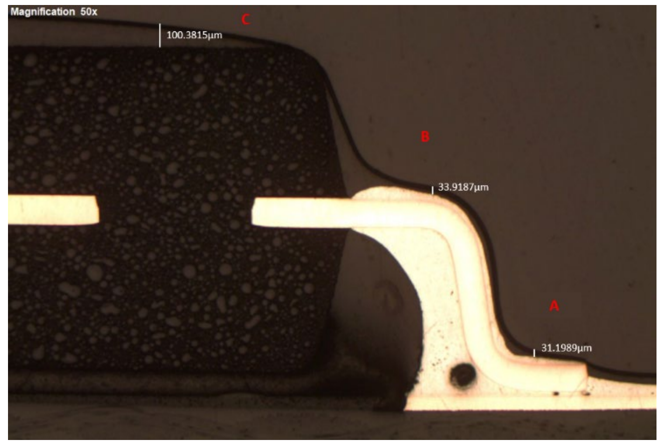

Figure 12. Cross-section of QFP44

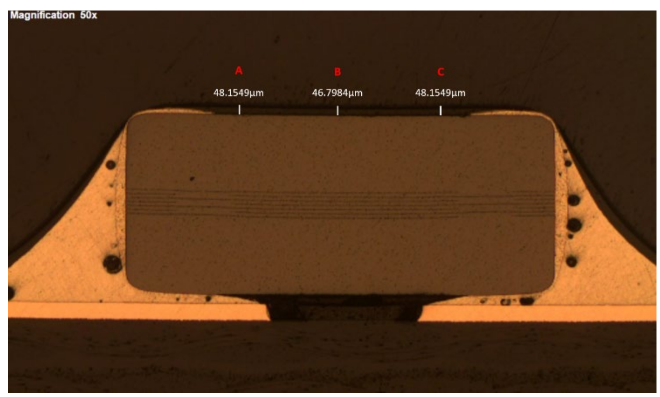

Figure 13. Cross-section of 0805 capacitor

On the QFP44, CCM measured thickness was accurate and comparable to cross-section values, differing by only a few microns. On the 0805 capacitor, the average coating thickness on top of the dielectric layer by CCM was 38.35µm compared to 47.70µm by cross-sectioning. The cause of the larger discrepancy is due to slight variations in the measured plane by CCM vs. the cross-sectioning plane and not measurement error of the CCM instrument. Since the component was polished manually during cross-sectioning, the exact measurement plane may have been offset. The coating was thicker towards each edge and slightly depressed in the center, so a polished plane that is off-center can result in a higher thickness compared to the desired plane.

CONCLUSION

This research provides insight into the capabilities of chromatic confocal microscopy as a powerful alternative to traditional thickness measurement instruments. Micrometer, eddy current, wet film gauge, and CCM methods were used to compare thicknesses of a commercial polyurethane and acrylic coating. CCM also allowed for measurements on top of components and leads that could be compared with cross-sectioning.

The dry thickness of conformal coating measured by micrometer, eddy current, and CCM were mostly comparable with one another. However, micrometer and eddy current measurements are affected by coating topography. Micrometer measurements may result in higher thickness readings because the measurement gauge stops when it touches the highest point of the coating. Eddy current measurements calculate the average thickness which can result in higher or lower thickness readings depending on uniformity. CCM had much lower variations in measurements compared to the other two methods, with most standard deviations measuring below 1µm. This is a significant improvement compared to the micrometer and eddy current, whose standard deviations can vary based on factors such as operator skill, coating compressibility, and measurement location. The color of the solder mask also did not appear to impact CCM measurements.

The wet thickness of conformal coating measured by CCM agreed with that measured by a notched wet film gauge. The variability in wet thickness measured by CCM was higher than in dry thickness measurement due to high volatility of solvents and the coating was susceptible to flow from slight movements. CCM was able to provide an exact value of wet thickness whereas the wet film gauge can only provide a range of thicknesses.

Compared to cross-sectioning, CCM measurements of the top of a 0805 capacitor and the lead of a QFP44 were comparable. CCM was able to take accurate measurements on top of the lead, leg, and top of the QFP44. In addition, the measurements were within a few microns of the cross-sectioning data. On the 0805 capacitor, CCM was within 10µm to the cross-sectioning data. This larger variation was mainly due to slight differences in the planes where CCM measurements were taken and where the component was polished down during cross-sectioning. Using CCM offers the ability to measure coating thickness on components which is critical to ensure proper coverage and thickness.

The results of this study demonstrate the advantages and improvements of chromatic confocal microscopy over traditional thickness measurement tools. This non-contact, optical technique allows for direct measurements on any component on a genuine assembly without the need for a test coupon. Using CCM can offer tighter process controls to ensure long-term reliability of PCBs.

REFERENCES

[1] M. Szuch, A. Lewis and H. Pulido, "New Coating Technologies and Advanced Techniques in Conformal Coating," in SMTAI, 2006.

[2] IPC, "Guidelines for Design, Selection and Application of Conformal Coatings," in IPC-HDBK-830A.

[3] Precitec, "Chromatic Confocal Technology," [Online]. Available: https://www.precitec.com/optical-3d-metrology/technology/chromatic-confocal-sensors/.

[4] R. L. (Ed.), Optical Measurement of Surface Topography, Springer, 2011.

[5] M. W. Davidson, "Refractive Index (Index of Refraction)," MicroscopyU, [Online]. Available: https://www.microscopyu.com/microscopy-basics/refractive-index-index-of-refraction.

[6] F. Argentiero, "Single AOI Scans Measure the Thickness of Conformal Coating," U.S. Tech. [Online].