Low Cost Optical Thickness Measurement of Conformal Coatings

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Abstract
Conformal coatings are used in high reliability electronics to protect the circuits from environmental contaminants. They are applied by a variety of methods, and in varying thicknesses. Confirming that the thickness meets specifications called out by documentation or customer can be problematic. Mechanical, ultrasonic, electrical (capacitive, eddy current), and various optical techniques are available, but all involve incurring significant limitations/penalties in capability, capacity or cost.

For optically transparent, and some translucent coatings, it is possible to accurately measure the thickness using optical (focal) techniques. This paper presents data on an innovative coating measurement process based on commercially-available low-cost optical equipment modified to make the measurements. The modified equipment is capable of making measurements on films as thin as 25µm (0.001”) and thicker than 1000µm (0.040”) with high repeatability. The method does not require a free edge and is not dependent on before/after coating differential measurement. The process has been fully developed and is used in a production environment.

The paper presents an overview of the equipment and method, Gage R&R data for the process, as well as comparative information on other available techniques. The focal technique is applicable to measurement of all types of optically clear coatings and films, and is appropriate for moderate-volume measurement applications where direct, non-contact measurement of coated parts is desirable and where measurement in small areas is required.

Background
Current practice for measurement of the thickness of conformal coating typically involves measurement with a mechanical gauge with a least count of 25µm (0.001 inches) or 12.5µm (0.0005 inches). The technique is generally unreliable for the following reasons:

- The gauges have a very coarse resolution ; typical gauge resolution of 25µm (0.001 inches) is approximately equal to the lower spec limit for the coating process
- Strong operator dependency
- Must measure total board thickness change (two sides) and divide by two if coating is applies to both sides.
- Must measure before & after or rely on masking an area. Hitting exactly the same spot for a before/after measurement is nearly impossible

While the mechanical gauge and the procedure associated with it could be improved, the method would always be subject to the final three points above, and would be very unlikely to be capable of meeting traditional definitions of acceptable gauge accuracy & repeatability.

Given that the manual application of conformal coating is a variable process, it was imperative that a capable measurement technique be made available to assess the process performance. There are many available techniques for measuring coating thickness, but most were found to have significant limitations that made them unworkable or very limited for production conformal coating measurement. Some newer optical techniques showed great promise but had equipment costs exceeding $25,000 USD. The target for this investigation was set to implement a technique that met the following goals:

- Implemented cost less than $10,000 USD
- Capable of repeatable measurement to $\pm$ 2.5µm ($\pm$ 0.0001 inches)
- Able to access small areas, <1mm by 1mm (0.040 inches square) was preferred
- Able to measure over varied substrate materials (metals, ceramics, organic materials)
- Measurement directly on boards and/or components (no requirement for separate test coupons)
- Measurement time < 1minute
- Non-contact measurement preferred

Proof-of-Concept Tests
An initial survey of turn-key metrology techniques was undertaken. The results of this survey indicated that there were available techniques, but the measurement constraints and/or cost of equipment made them less than ideal solutions. For example, eddy current electrical measurements are possible but rely on availability of an area approximately 12mm (0.5 inches) in diameter of continuous coating over ground plane, without intervening solder mask. After comparing the off-the-

shelf equipment with a proposed manual technique based on basic optical microscopy, it was decided to evaluate the manual technique using the following approach:

- Conduct proof-of-concept testing on the optical technique at a 3rd-party lab
- If proof-of-concept tests showed the technique to be viable, then purchase equipment to do in-house testing
- Validate the technique on in-house, on equipment specifically configured for the technique
- Train operators and transition production to new technique

The proposed optical technique was based on the ability of a metallurgical microscope to selectively focus on either the coating surface or the substrate, and on the ability to monitor the position of the microscope stage z-axis motion. A metallurgical microscope could be configured to meet these needs. The scope of the proof-of-concept testing was to:

- Provide data showing the technique was actually practical
- Assess the effects of operator, coating type and substrate with relation to measurement repeatability
- Identify specific equipment configuration requirements for the microscope and gauge

The proof-of-concept testing was performed at the Chemistry & Materials Lab at Rockwell Automation in Milwaukee, WI, using a Zeiss inverted metallographic microscope in bright field mode. Magnification was varied to meet the needs of individual measurements. The fine focus knob on the microscope was marked in microns, so the z-axis movement of the stage could be tracked by taking the difference between position readings of the fine focus dial, including number of turns of the dial for large displacements. This manual process required two operators to avoid error.

The experiment was a full-factorial test with three replications. Table 1 shows the variables considered and their levels. The *operator* variable refers to the person doing the observing/focusing. The operator not performing the focusing task observed the focus adjustment and recorded readings. Prior to taking actual test readings, the z-axis calibration was verified by optically measuring a metal shim of known thickness. During testing, the operator positioned the sample, then focused on the substrate. The person recording data then recorded the focus knob reading, and the operator re-focused on the coating surface. The focus knob final position was recorded, and the difference calculated to yield the raw height difference.

Table 1: Variables & Levels

Variable:	Levels:		
Operator	CG	FB	
Coating	Type UR	Type AR	
Location	XTAL	Via Edge	SOIC
Repetition	1	2	3

In order to compensate the raw measurement data for the refractive indices of the coatings used, it was necessary to experimentally determine the indices, because reliable information on the refractive indices was not available form the coating manufacturers. The conformal coatings, despite being in the broad class of Urethane (Type UR)[1] or Acrylic (Type AR), had proprietary chemistries and therefore generic published properties were not reliable. That said, small errors in refractive index would result in errors in thickness of like magnitude, and the expected range of refractive indices of the coatings was small, ranging from approximately 1.50 to 1.60. Using a generic compensation factor of 1.55 would therefore be expected to yield an error of <± 3.5% due to error in refractive index. This level of error would be acceptable in a production environment where the upper specification level for thickness is twice the lower specification level.

The experimentally measured refractive indices for the materials were 1.54 for the type AR coating, and 1.60 for the type UR coating. These values fell within the expected range for the material types. In the second phase of testing, a set value of 1.55 was used as a correction factor, to simplify application on the factory floor.

Once the data for the proof-of-concept test were accumulated and compensated, the results were analyzed using ANOVA to determine the sources of variation. Shown below in table 2 and Figure 2 are the ANOVA results in tabular and graphical form. The "real" variation in the data should ideally have come from only the ***Coating*** and ***Location*** variables. Each reading for the same coating/location should have been identical. In practice, 95.6% of the variation present was due to these two factors and their interaction term. In contrast, less than 1% of the variability was due to inter-operator differences. Location 1 had a higher observed variability than other locations, and this was attributed to the difficulty of focusing on the specific substrate at that location with the equipment available; the microscope used for the proof-of-concept testing was not capable of dark-field observation, and it was known prior to conducting the test that dark field would be useful for eliminating the contrast-reducing effect of reflections off the coating surface when focusing through the coating on the substrate.

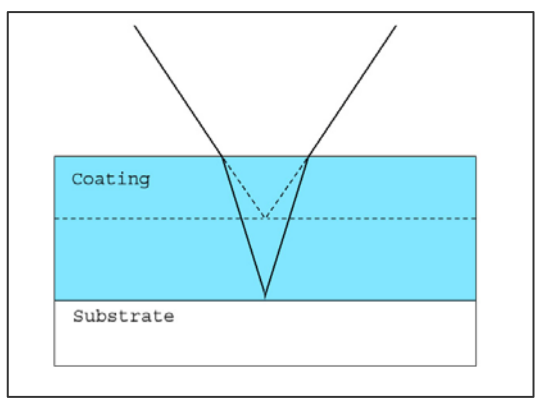

Figure 1: Refraction through Coating

ANOVA: Thickness versus Operator, Coating, Location, Repetition & Interactions					

Table 2: ANOVA Results for Proof of Concept Test

Source	DF	SS	MS	F	P
Operator	1	1195.8	1195.8	16.06	0.001
Coating	1	108794.4	108794.4	1461.42	0.000
Location	2	5377.5	2688.7	36.12	0.000
Repetition	2	1033.9	517.0	6.94	0.007
Operator*Coating	1	450.9	450.9	6.06	0.026
Operator*Location	2	616.1	308.0	4.14	0.036
Operator*Repetition	2	76.9	38.4	0.52	0.606
Coating*Location	2	13531.9	6766.0	90.89	0.000
Coating*Repetition	2	260.9	130.5	1.75	0.205
Location*Repetition	4	1067.9	267.0	3.59	0.029
Error	16	1191.1	74.4		
Total	**35**	**133597.2**			

Based on the success of the initial test, equipment was purchased to run a production trial. In order to minimize cost, a used microscope was purchased. An upright metallograph was selected, because that configuration allowed the board to be laid

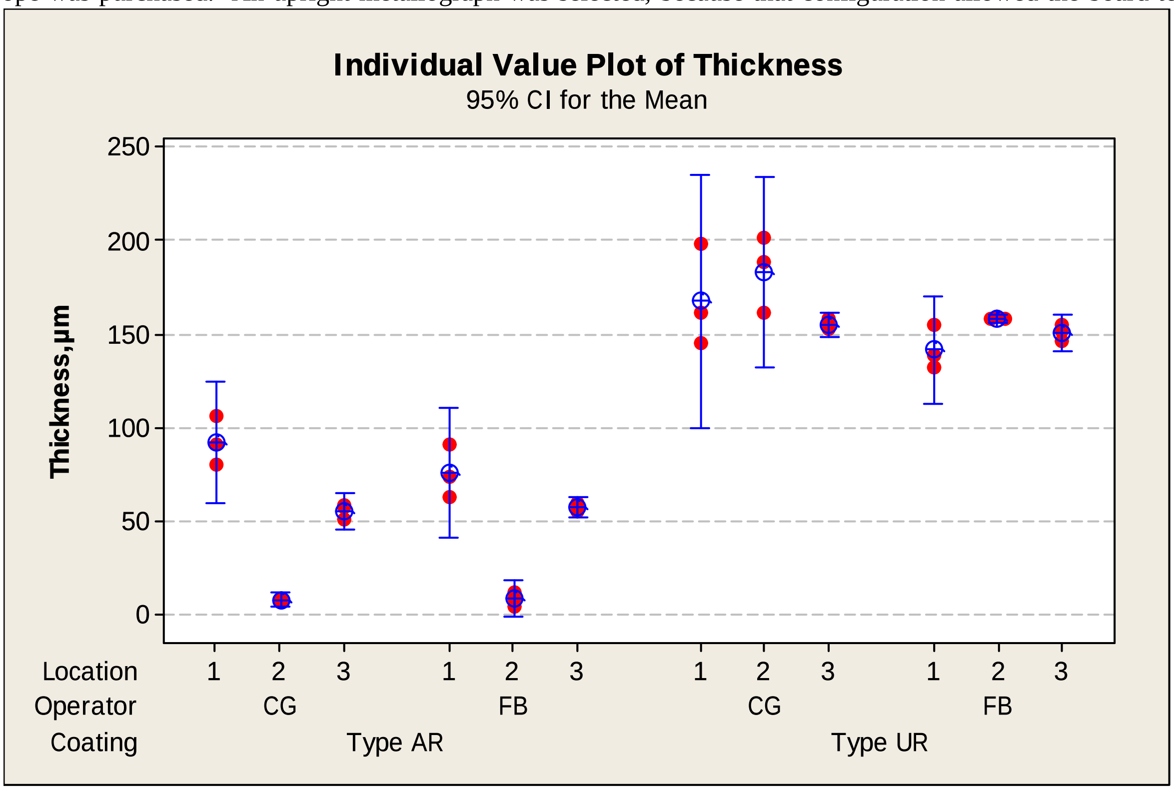

Figure 2: Graphical Results for Proof-of-Concept Test

flat on the stage and observed from the top. An inverted metallograph would require the board to be laid upside down on the stage, with the microscope looking up through a hole in the stage. The inverted configuration would be ideal for small, flat samples, but not for large samples with variation in height.

Production Implementation

The microscope selected for the production implementation is shown in Figure 3. It was a Nikon Optiphot 150 upright metallographic microscope. The microscope was equipped for both bright field and dark field observation. Both modes were required for production measurement of coating thickness. The objectives used for coating thickness measurement were 10x (0.30 Numerical Aperture) and 20x (0.46 Numerical Aperture). The numerical aperture (NA) of the objective used determined the sensitivity of the technique. The operator was asked to focus precisely on a surface, that is, to put the surface within the depth of field (DOF) of the microscope. The DOF can be calculated per Equation 1:

$$DOF_{TOT} = \frac{\lambda n}{NA^2} + \frac{n}{M \cdot NA} e$$ [2]

In Eq. 1, λ is the wavelength of the light, n is the refractive index of the medium between the lens and object (1.0 for air), NA is the numerical aperture of the objective, M is the magnification of the objective, and e is the resolution available at the objective image plane. The first term in Equation 1 is essentially wave or diffraction limited DOF. The second term is the optical geometric DOF. In practice, the first term dominates, so DOF is inversely proportional to NA^2. A large NA was therefore desirable in order to generate a small DOF. Working backward from a desired repeatability of 2.5µm (0.0001 inch), a DOF of 2.5µm or less required an NA approaching 0.5, assuming λ of 0.55µm and n of 1.00.

Figure 3: Nikon Optiphot 150 and Z-axis DRO

The standard bright-field/dark-field (BD) objectives for the Optiphot 150 are shown in Table 3. The 20x objective had the best combination of NA and working distance (the distance from the sample to the glass on the objective) to yield precise measurements with a working distance long enough to give reasonable access to typical assembly surfaces. It should be noted that the apparent DOF when observing through the eyepieces was expected to be larger than the calculated DOF shown in Table 3 because of visual accommodation (focusing) of the operator's eyes. The expected effect was a broadening of the error band.

The 50x objective was found to be usable where there was access to lower the objective to the board or component, but the added precision was not required; in fact the surface roughness of the substrate and other factors, e.g. local variation in coating thickness, substrate roughness, etc., made the added precision of little value. There were long-working-distance versions of some objectives available that may have provided additional benefits in accessing difficult areas, but at the cost of a reduction in NA, implying worse sensitivity.

Table 3: Nikon CF BD Objective Properties

Objective	NA	Working Distance	DOF
CF Plan BD 5x	0.13	10 mm	32.8 µm (0.0013 inches)
CF Plan BD 10x	0.30	6.5 mm	6.2 µm (0.00024 inches)
CF Plan BD 20x	0.46	3.1 mm	2.6 µm (0.0001 inches)
CF Plan BD 50x	0.80	0.54 mm	0.9 µm (0.00004 inches)
CF BD Plan 100x	0.90	0.39 mm	0.7 µm (0.00003 inches)

For production measurement, the two-operator approach taken during the concept work was considered non-viable. It was critical that operator dependence, the time required to make the measurement, and the complexity of the task all be minimized for the production measurement process. To this end, an electronic DRO (Digital Read-Out) was purchased and mounted on the z-axis of the microscope. The gauge provided the ability to monitor the vertical position of the microscope stage to better than 1μm repeatability. The gauge also provided the ability for one-touch zeroing of the readout and for serial (RS-232) communication for data collection. Together, the features of the gauge greatly streamlined and simplified the measurement process and eliminated the necessity to hand-write readings. The gauge also provided the capability to scale readings to account for the refractive index, however scaling was not implemented. Instead, the readings were compensated after collection, leaving the gauge accurate for general-purpose z-axis measurement in air.

In order to validate the production tool, a study was undertaken involving three operators, three measurement points and three repetitions. The results were analyzed suing ANOVA to determine the sources of variation. The ANOVA results are shown in Table 4, and the graphical results are shown in Figure 4.

Table 4: ANOVA for Production Process Validation

ANOVA: Thickness versus Operator, Location, Trial					
Source	**DF**	**SS**	**MS**	**F**	**P**
Operator	2	12.46	6.23	1.09	0.381
Location	2	8348.06	4174.03	731.65	0.000
Trial	2	6.33	3.17	0.56	0.595
Operator*Location	4	176.28	44.07	7.72	0.007
Operator*Trial	4	15.34	3.84	0.67	0.629
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Error	8	45.64	5.70		
Total	26	8619.45			

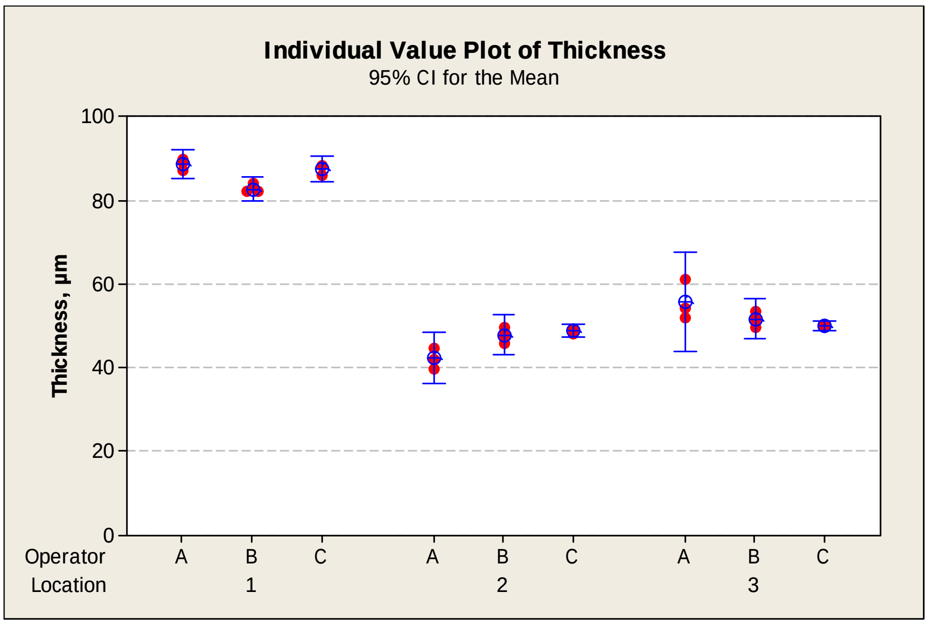


Figure 4: Validation of Production Measurement Process

The results of the multi-operator study validated the approach; 96.9% of the variation present was due to the real differences in coating thickness between locations. Only 0.1% of variation was due to differences between operators. The *Operator* by *Location* interaction accounted for 2.0% of the total variation. This can be seen in Figure 4; there were slight systematic differences in how the individual operators measured at the different locations. This can be attributed to differences in precisely where the operators decided to focus the microscope. As such, the differences may in part have been real differences, but the expectation is that they were mainly due to technique. Overall, the approach yielded data with coefficients of variation generally below 5% for individual operators. The variation is somewhat overstated, because of the small sample sizes.

Finally, a single-operator test was run, making 15 measurements alternately at each of two locations. The chosen locations were known to have significantly different thicknesses, corresponding very roughly to the center and top of the industry standard thickness range for the type UR coating used [3]. Figure 5 shows the results of this test. The standard deviation for each of the locations was between 2.0µm and 2.3µm (0.0008 to 0.0009 inches). The range of values for location 1 was between 86µm and 92µm (0.0034 to 0.0036 inches), and the range for location 2 was between 51µm and 59µm (0.0020 to 0.0023 inches). The measurements were performed using a 20x objective. The calculated DOF for this objective of 2.6µm (0.0001 inches) suggested an expected focus error of ± 12µm (± 0.0005 inches). The somewhat larger observed error probably was attributable to additional error induced by repositioning the sample as well as eye accommodation (broadening of the DOF). Nonetheless, the system closely approached the target repeatability of ± 2.5µm (0.0001 inches). Greater precision was obtainable with higher magnification, but was not found to be useful, because the real point-to-point variation in actual coating thickness was found to be much greater than this error.

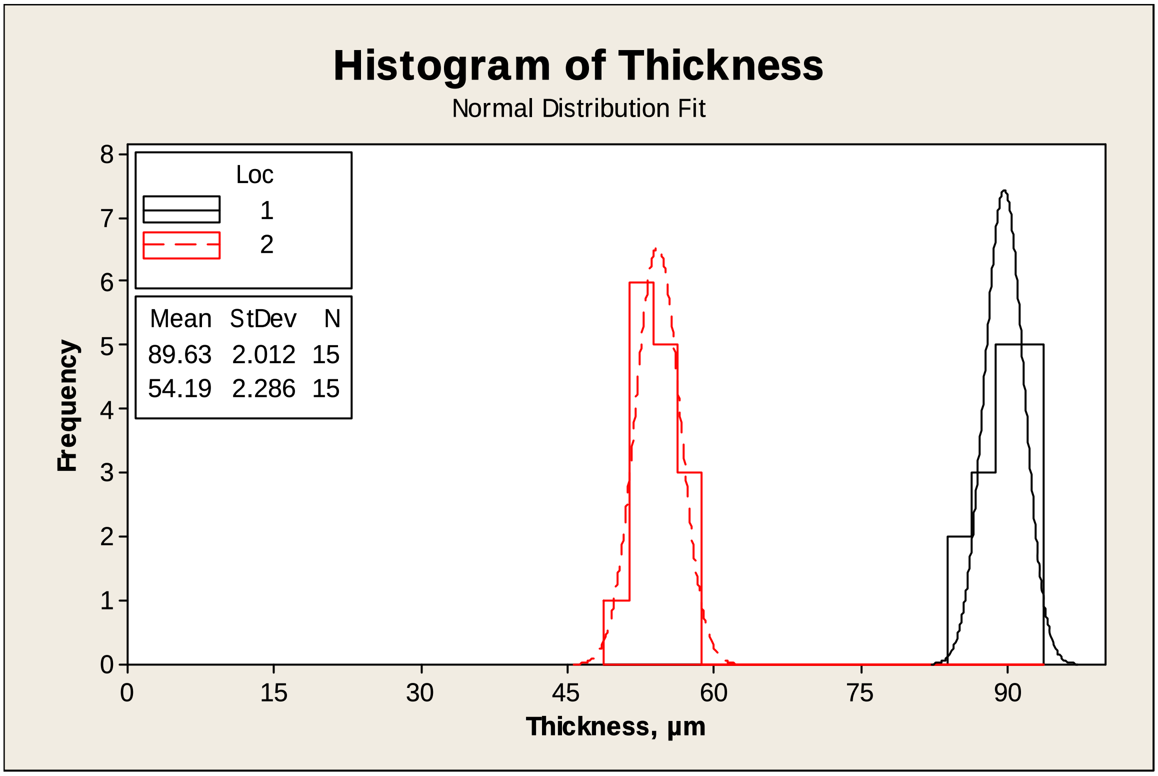


Figure 5: Validation of Production Measurement Process

Limitations of the Technique

The technique was found to be primarily limited by the operator's ability to focus on the surfaces involved. The characteristics of the surfaces, as well as the characteristics of the coating material affected the ability to accurately focus. The operator's visual accommodation (focus) also impeded the technique slightly because the perceived DOF was broadened.

Substrate properties affected ability to measure. Surface roughness of the substrate impacted the ability to obtain repeatable readings, because the coating tended to level over small imperfections. If a measurement was made to the top of a peak on the substrate, a lower value was obtained than when measuring to a valley. Optically translucent substrates were also troublesome; solder mask surfaces were difficult to focus on because they were both translucent and had optical refractive indices close to the coating. Under these conditions, the surface became nearly invisible. Many of the substrate issues were easily and quickly avoided by using opaque substrate features such as legend ink, lands, etc., as focusing aids and avoiding measurement on uninterrupted solder mask surfaces. Coating was also easily measured on the horizontal (top) surfaces of many components, where etched or painted markings provided excellent focusing aids for measurement. Dark field observation was always used to focus on the substrate, since this operational mode almost completely eliminated direct reflection from the coating surface. Bright field observation was always used to focus on the coating surface; the direct illumination highlighted any imperfections that then accurately revealed the position of the surface.

The properties of the coating surface also affected measurement. Coatings with extremely smooth surfaces were very difficult to focus on, even in bright field mode. Normally, any surface imperfection such as a fine scratch, or particle as small as 1µm would easily reveal the surface, but in very clean environments where the coating was very smooth and pristine, the surface was found to be hard to resolve. In these cases, a light rub with a lint-free wipe in the area to be measured was usually all that was necessary to generate submicron scratches that enabled repeatable focusing on the surface.

Finally, the coating material's optical transmission properties were found to affect measurement. The majority of coating materials are optically transparent and thus measurable with this technique. Even some translucent materials were acceptable candidates for measurement, as long as they allowed for focusing through them on the substrate. Some materials that scattered light from fine filler materials, however, were nearly impossible to measure due to the strong scattering from the fine fillers. This was the case for an elastomeric urethane that contained finely divided silica as a viscosity modifier.

Conclusions

Measurement of conformal coating thickness by focal-based optical techniques was implemented at low cost (approx. $8000 USD). The technique proved to be highly capable, relatively fast, and able to measure over a wide variety of substrates…

The technique had several advantages over the current, mechanical technique and over available turn-key techniques:

- Lower cost than any turn-key technique
- Not dependent on overall board thickness (double-sided measurement)
- Small spot size and non-contact measurement. Potential to measure in very small areas
- Measurement capability extends from below to above the thickness specification of the coating materials
- Able to measure a relatively wide range of thicknesses, from less than 25µm to more than 750µm

The technique also was found to have some disadvantages:

- Not an industry-standard technique, but will be submitted to IPC
- Requires knowledge of refractive index for the coating material being tested, but index can be determined empirically
- Access to measurement area is limited by microscope stage size. For the Optiphot 150, complete access to all areas was possible for PWBs with a minor dimension smaller than 25cm (10 inches)
- Some learning curve for operator. Approximately 1 hour was required to train and to assess operator capability

References

1.) IPC. (2002, August). IPC-CC-830B *Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies, Section 1.3*. Northbrook, IL, USA: IPC.

2.) Nikon. (n.d.). *Basic Concepts and Formulas in Microscopy*. Retrieved October 21, 2008, from MicroscopyU: http://www.microscopyu.com/articles/formulas/formulasfielddepth.html

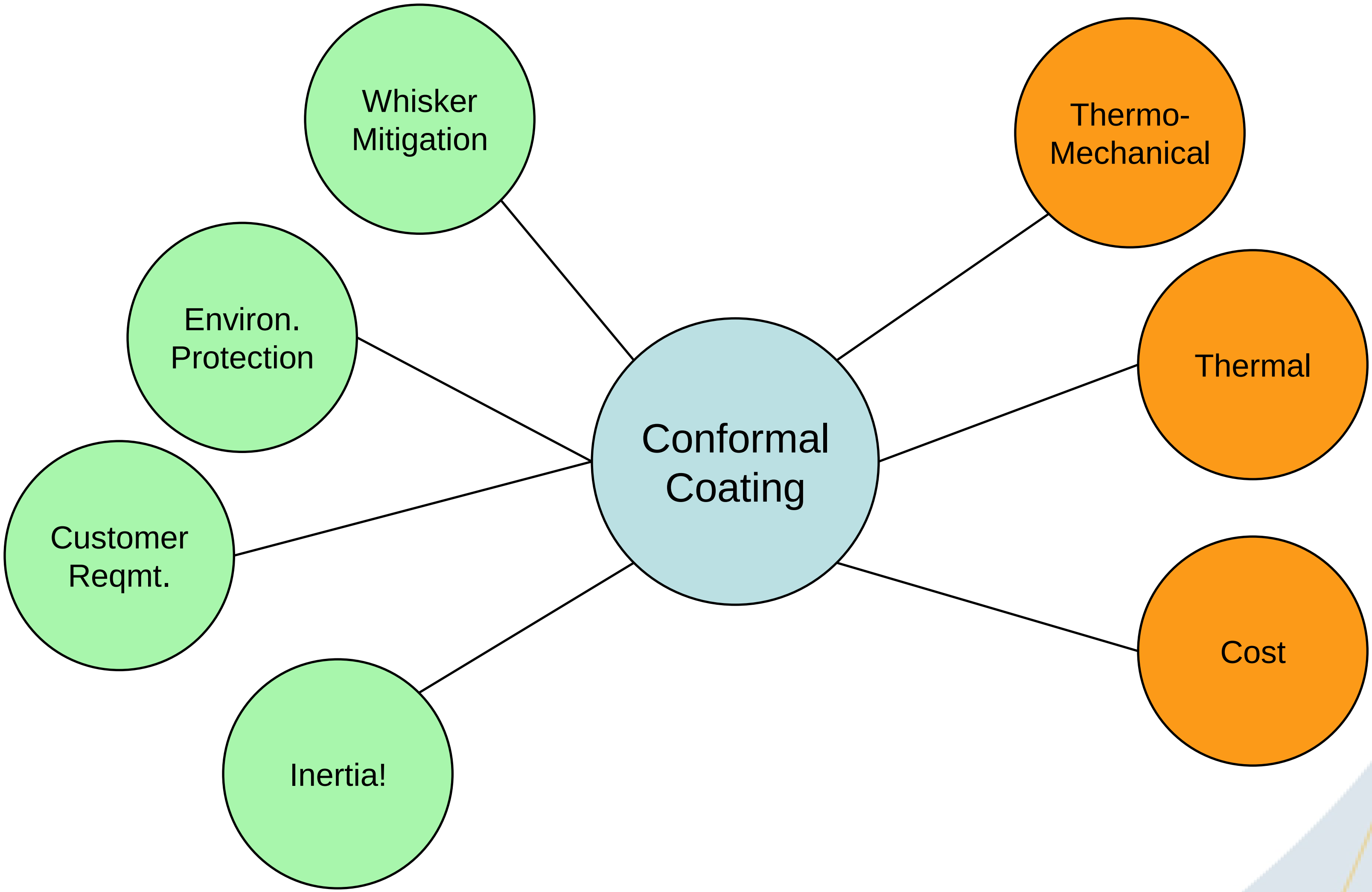
3.) IPC. (2002, August). IPC-CC-830B. *Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies* . Northbrook, IL, USA: IPC.

Low-cost Optical Thickness Measurement for Conformal Coatings

APEX 2009, Las Vegas, NV

Fritz Byle

CC Benefits & Impacts



Why We Control Thickness

- Mechanical Stresses
  - Excess thickness drives thermo-mechanical failure of components and/or solder joints
- Thermal impact
  - Thermal impedance of film rises with thickness
- Cost
  - Increased cost of materials (important for some coatings)
  - Increased cost of rework
- Customer specifications
  - Contractual requirements rule even if there are no demonstrated reliability impacts
- Process Impacts
  - Curing issues, cosmetic defects, mechanical interference…

Industry Guidance

- IPC CC-830
  - Specifies thickness requirements for qualification samples
- Material suppliers
  - Material specifications – limitations based on curing, application processes, etc.
- Customer’s testing (or internal testing)
  - Limits based on specific knowledge of how coatings interact with products

Available Technology

- Mechanical
  - Single-sided gauging (requires edge)
  - Double-sided gauging (before/after)
- Electrical
  - Capacitive, eddy current (require ground plane)
- Ultrasonic
  - Depends on reflection from discontinuity at substrate surface
- Weight
  - Average thickness can be calculated if pre-coated weight known; multiple confounding factors
- Optical
  - Laser, focal, diffractive
- Nuclear (!)

Targets

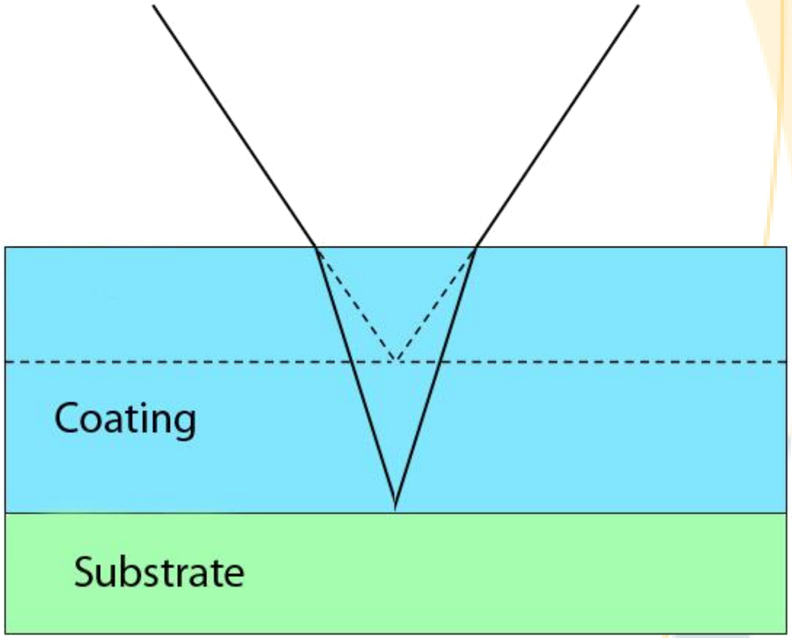
- Cost <=$10k USD
  - Implemented cost of technique
- Repeatability <=1µm
- Measurement range of <25µm to >250µm on optically clear coatings
- Measure over varied substrates
- Measure cured film in one step (no before/after correlation required
- Measurement time < 1 minute

Overview of Focal Technique

- Depends on the narrow depth of field of an optical microscope
- Standard metallurgical microscopes lack only a DRO for tracking stage position
- Must compensate raw measurements for index of refraction of coating

Compensation for *n*

- Actual thickness is larger than apparent thickness
  - Apparent thickness must be multiplied by *n* to get actual thickness
- *n* may be determined empirically
  - Measure near edge
  - Peel film & measure



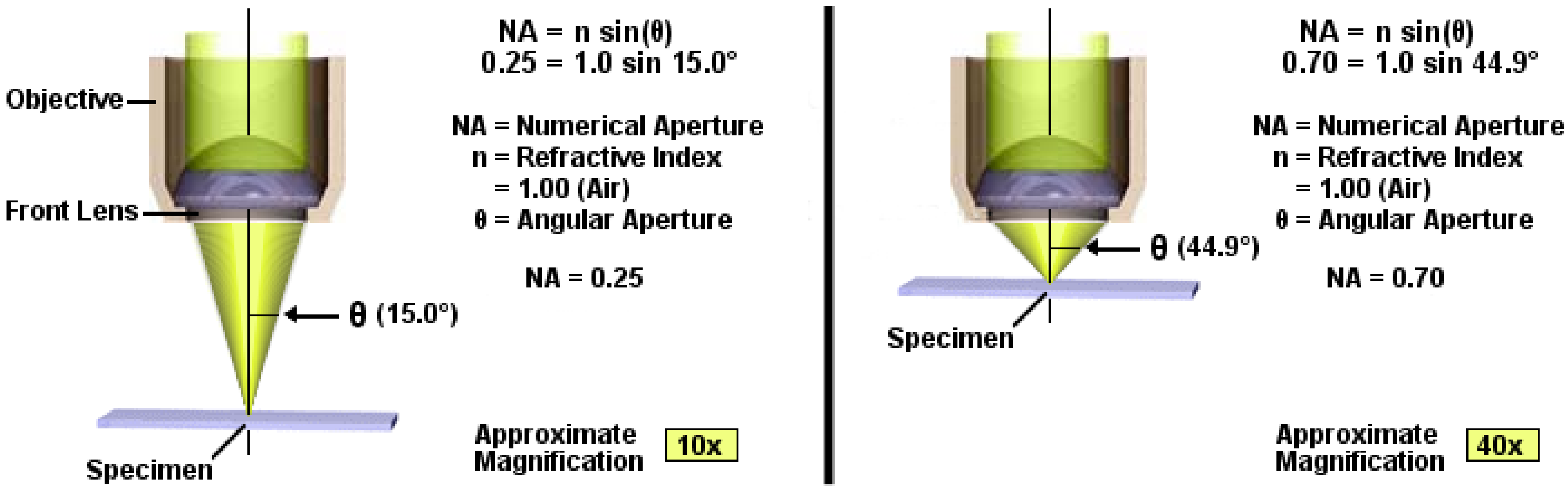
DOF of Optical Microscopes

- First term is wave or diffraction limited DoF
- Second term is optical geometric DoF
- In practice, the first term dominates
  - DoF inversely proportional to NA^2

$$DOF_{TOT} = \frac{\lambda n}{NA^2} + \frac{n}{M \cdot NA} e$$

λ	= wavelength of the light (550nm)
N	= The refractive index of the medium between the lens and object
M	= The magnification of the objective in use
NA	= The numerical aperture of the objective
e	= The resolution available at the objective image plane

Numerical Aperture Defined



NA = 0.25

NA = 0.70

http://www.microscopyu.com/tutorials/java/objectives/nuaperture/index.html

Microscope Objectives

Objective	NA	Working Distance	DOF
CF Plan BD 5x	0.13	10 mm	32.8 µm (0.0013 inches)
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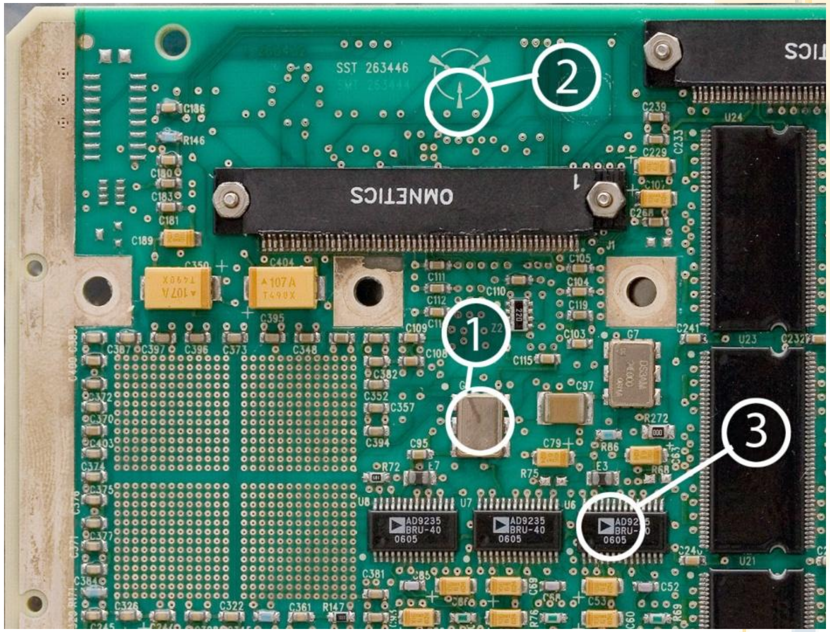
Implementation Strategy

- Proof of Concept
  - Use existing equipment to show that measurements can be made
- Source and configure a system
  - Used metallurgical microscope
  - Add DRO for z-axis (0.1µm resolution)
- Conduct gauge study to validate system performance
  - Operator, location, magnification, trial…
- Implement system in production
  - Automation for data collection to reduce error potential (transcription error)

Proof of Concept Test

- Two scrap boards
  - One coated with type UR
  - One coated with type AR
- Two operators
- Three locations
  - Varying substrates
- Zeiss inverted metallograph (Rockwell Automation)



ANOVA for Proof of Concept

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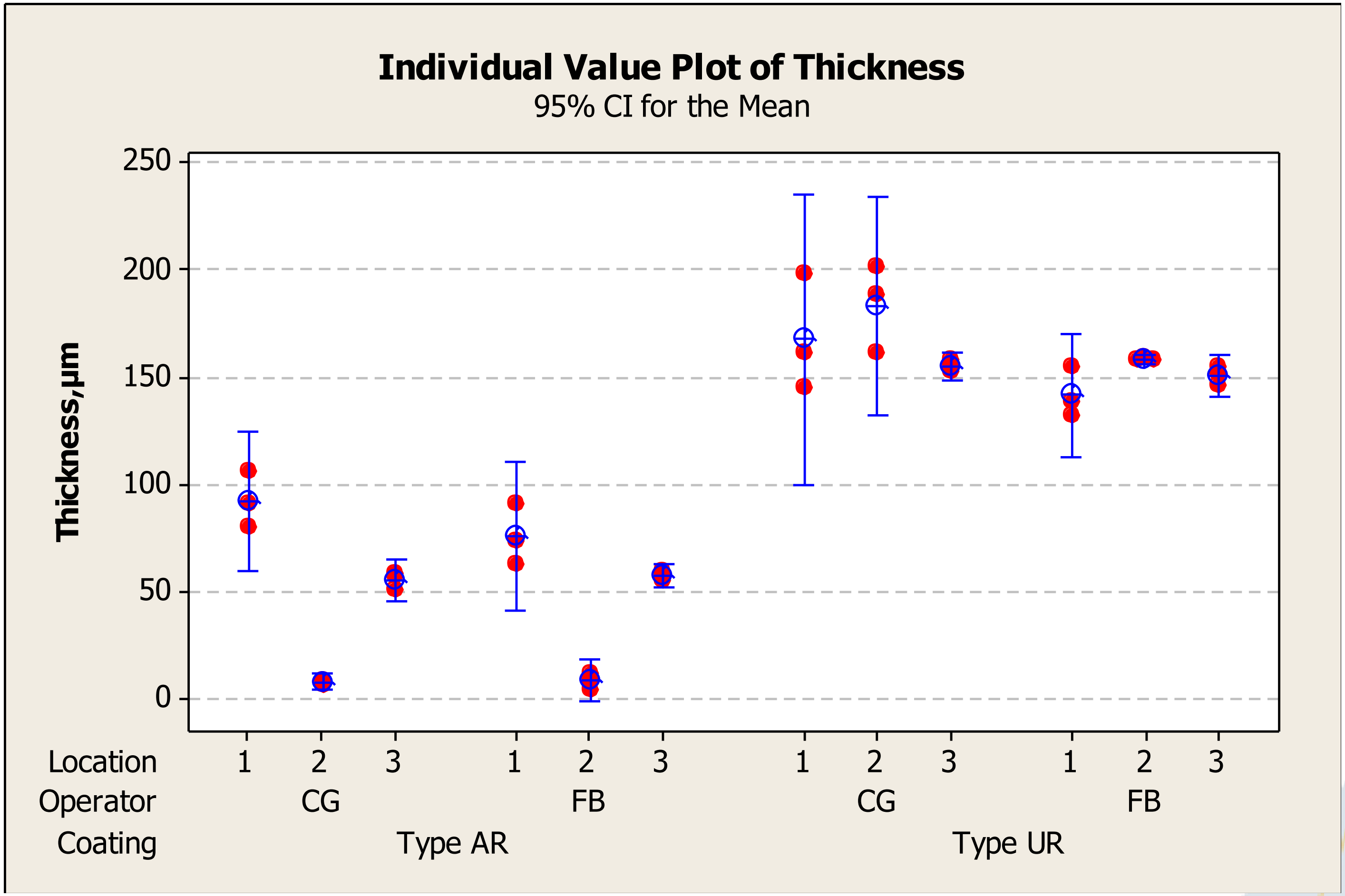
Results, Proof of Concept

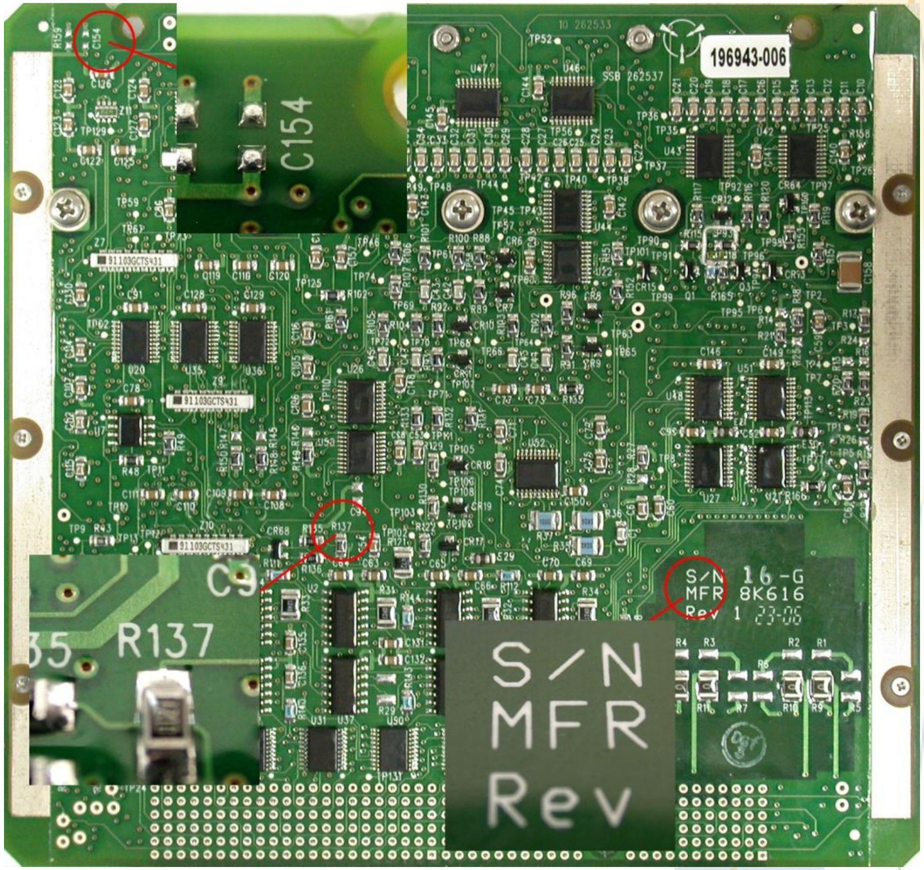


Equipment Configuration

- Nikon Optiphot 150
  - Equipped with BF & DF mode
  - Episcopic illumination
- Metronics QC100 single-axis DRO
  - 0.10 µm resolution
  - 30 mm travel

Production Validation Test

- Single PWA with type UR coating
- Three locations defined
- Three operators
- Three trials per operator



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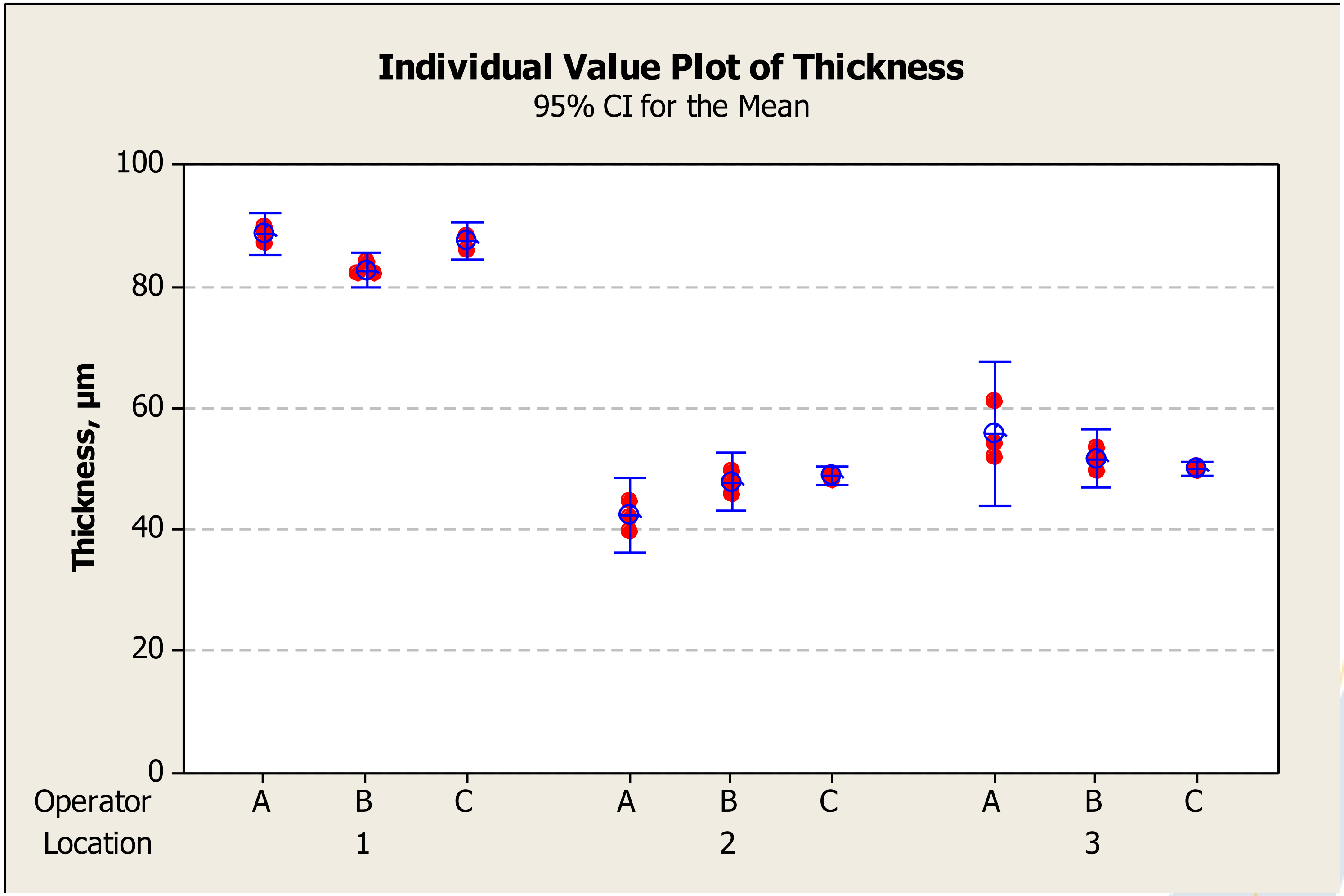
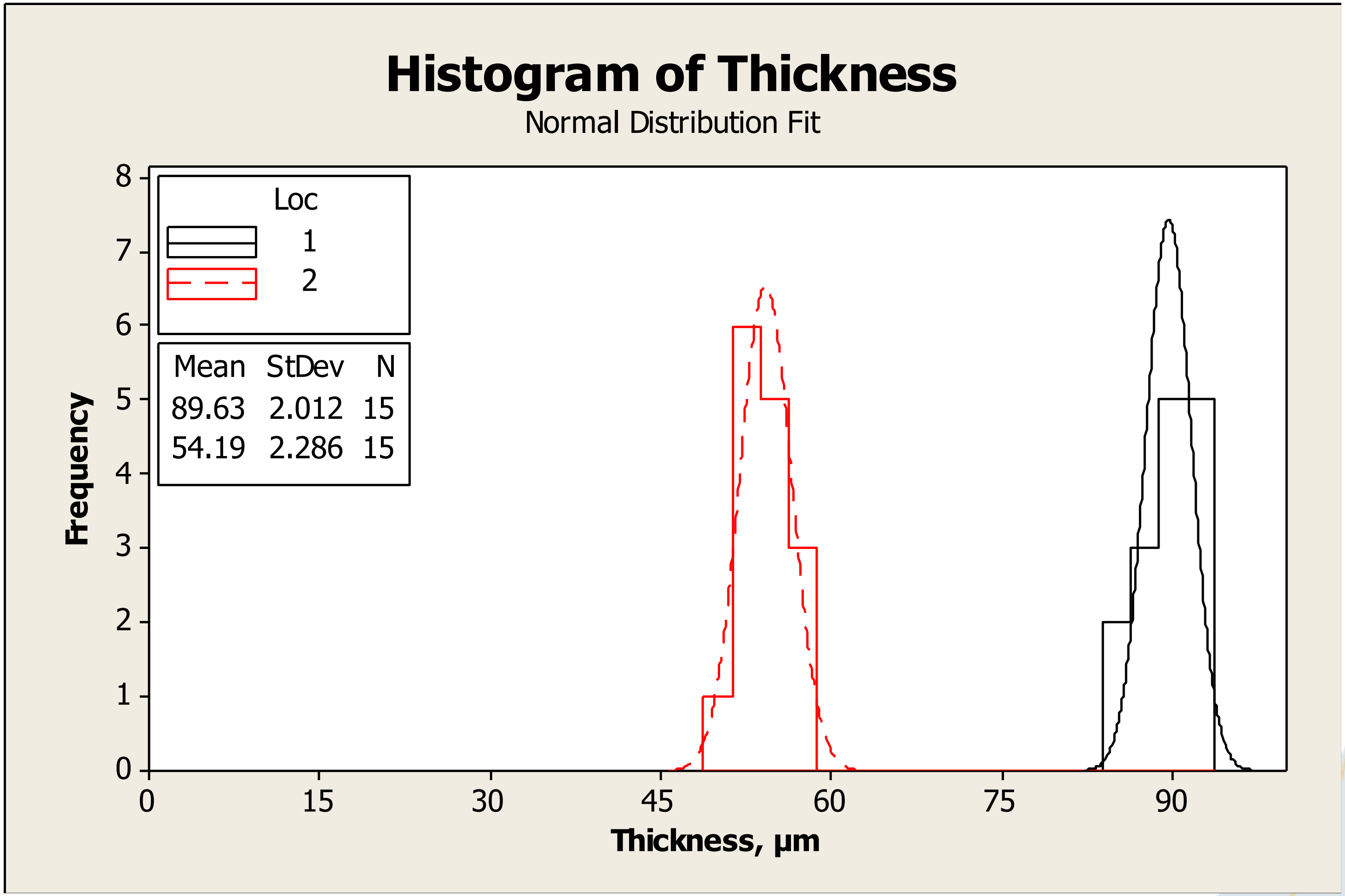
Total	26	8619.45			

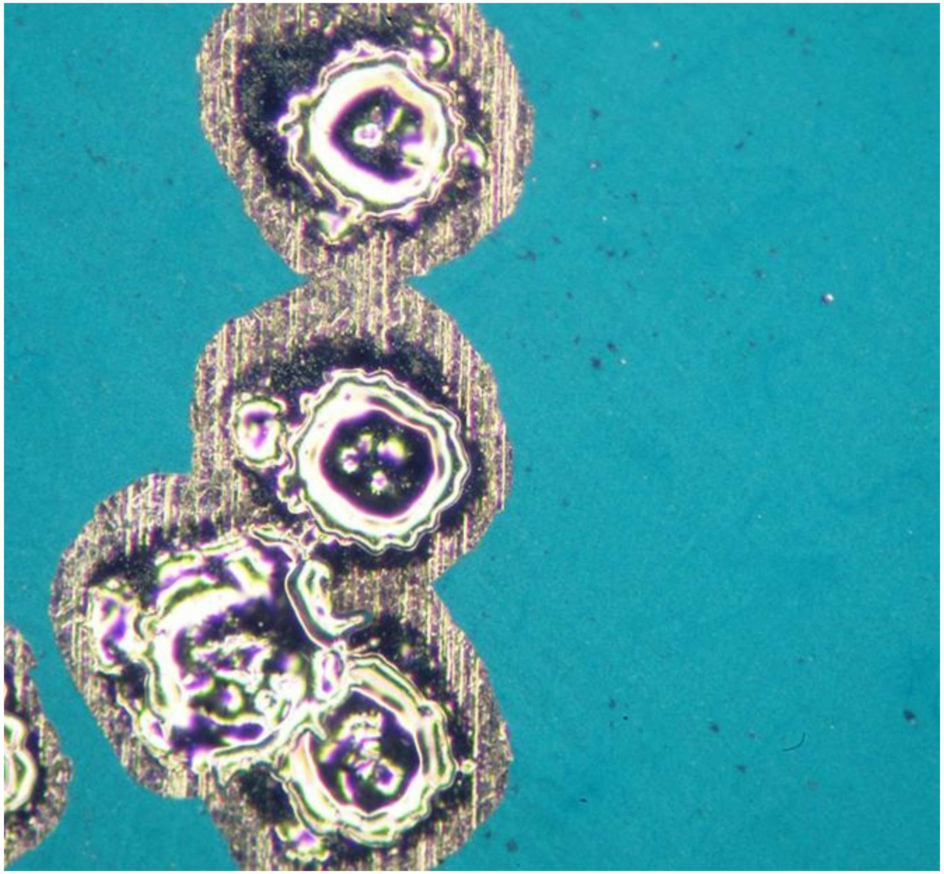
Validation Test Results



Validation Test Results



Focus Demo



Dark Field Imaging

Bright Field Imaging

Conclusions

- Optical (focal) thickness measurement is practical for production thickness measurement
  - Covers desired materials and thickness range
  - Extensible to thinner materials (higher NA) but with smaller working distances
  - Repeatability and throughput meet goals for a capable measurement technique
- Equipment may be leveraged for other uses
  - Also may be used to make general height measurements
  - Microscope can be leveraged for general analytical work
- Process can be implemented for <$10k USD
  - Cost <$10k requires used equipment; plenty of used microscopes available
  - DRO cost $2800 USD
- Process has some potential limitations
  - Optically clear or translucent coatings only
  - Not at this point an industry-standard technique
  - Requires knowledge of refractive index of coating