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STATISTICAL AND TECHNICAL EVALUATION OF RAPID DRY FILM THICKNESS (DFT) MEASUREMENT TECHNOLOGIES

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ABSTRACT

Dry film thickness (DFT) is an important parameter of coating application, and both low and high DFTs can result in coating failures. Typically, DFTs are measured in accordance with SSPC-PA 2 Procedure for Determining Conformance to Dry Coating Thickness Requirements (1) or other similar standards. Recent advancements in technology have resulted in DFT probes capable of achieving a higher rate of DFT data collection than previous devices. However, current standards do not take full advantage of the technology and little is known of the effects of scanning probe wear on DFT accuracy and precision. In order to obtain higher confidence in DFT characterization of critically coated areas, a study has been completed to perform a statistical comparison of results obtained between the traditional non-scanning method and new scanning methods of DFT data collection. Results of this study have been used to develop recommendations for field implementation procedures to take full advantage of this technology.

INTRODUCTION

As a proposed alternative to the SSPC Paint Application Standard Number 2 (SSPC-PA 2) method, rapid scanning procedures to measure DFT using handheld electronic devices were examined to verify whether any losses in precision, and thus fidelity, of the data resulted from the use of the new scanning method. A study was conducted to investigate these issues and verify whether the use of new technology constitutes a loss in fidelity in terms of the information collected from proper application of the DFT device.

Background

DFT is an important parameter of coating application, and both low and high DFTs can contribute to premature coating failures. Typically, DFTs are measured in accordance with SSPC-PA 2 or other similar standards as dictated by the contract language of the awarded application procurement. Based on the requirements established in these standards, a minimum number of DFT measurements are made due to time constraints placed on the inspectors as well as limitations of the devices used to conduct the inspections. The ability of an inspector to capture larger DFT datasets within the defined parameters may result in lower statistical variation of the data and higher confidence in the results. This should lead to fewer coating failures resulting from improper DFTs, thereby reducing maintenance costs.

Recent advancements in technology have resulted in DFT probes capable of achieving a higher rate of DFT data collection than previous devices. However, current standards do not cover the implementation of these new probes. The National Shipbuilding Research Program’s Surface Preparation and Coatings Panel (NSRP SP-3) recently conducted a study to demonstrate this new technology (2). The project’s final report detailed a comparison between a conventional Type II DFT gauge, a fixed calibration Type II gauge, and a conventional Type II DFT gauge with scanning probe capabilities. According to the NSRP report, calculating DFT using the scanning instrument was more than three times faster than the current method used by Naval Sea Systems Command (NAVSEA) as outlined in the SSPC-PA 2 procedure noted within NAVSEA Standard Item (NSI) 009-32. The report also claimed that scanning technology would reduce the labor cost of a DFT inspection by almost 70%, and that scanning technology has a lower standard deviation than current DFT readings taken using the procedures outlined in SSPC-PA 2.

Objective

The primary objective of this assessment was to verify the efficacy of using scanning probe technology to conduct DFT measurements in accordance with SSPC-PA 2 and to develop testing recommendations to modernize the collection of DFT measurements outlined in the SSPC-PA 2 procedure of NSI 009-32 using DFT scanning technology. This study also investigated the possibility of statistical improvements achieved with higher sampling rates obtained from DFT scanning probe technology. Large area samples were coated with US Navy coatings in a laboratory setting and characterized using traditional spot measurement DFT gauges and new gauges equipped with scanning probe technology. Sampling was based on established standards, such as SSPC-PA 2, as well as more robust plans that included larger data sets to improve statistical significance. Laboratory findings were used to develop recommendations for the use of DFT scanning probe technology in the field. The technology was also demonstrated in various spaces onboard US Navy surface ships to ensure the viability of the new DFT scanning technique protocol. Laboratory testing was conducted at the Naval Research Laboratory.

EXPERIMENTAL PROCEDURE

Two DFT instrument types (conventional Type II DFT gauge and conventional Type II gauge with scanning probe capabilities) were evaluated to compare the reliability of scanning probe technology compared to DFT standards established within NSI 009-32 and SSPC-PA 2.

Test Plan Development

Eight 4 ft. by 4 ft. by 3/16 in. steel panels were prepared using a NAVSEA approved epoxy, manually applied, for a total of twelve laboratory specimens. Coating thicknesses of 5, 10, 20, and 40 mils were used for laboratory testing. A coating thickness of 5 mils was applied to each test specimen prior to the start of DFT measurements. Upon completion of testing with the appropriate test method probe of coatings at 5 mils, an additional coating thickness of 5 mils was added to each test specimen, and the DFT measurements were repeated. This process was repeated with the addition of 10 and then 20 mils until a coating thickness of 40 mils was achieved. Drawdown test samples were used for a probe wear analysis and were coated in accordance with ASTM D823, “Standard Practices for Producing Films of Uniform Thickness of Paint, Varnish, and Related Products on Test Panels” (3). Three 6 in. by 12 in. by 1/4 in. steel drawdown panels with various coatings were used for a DFT probe wear analysis.

Conventional Probe DFT Measurements

DFT measurements taken using a conventional Type II gauge were done in accordance with SSPC-PA 2. Prior to DFT measurements and before each test specimen, gauge accuracy was measured through a two-point adjustment in accordance with Appendix 8 of SSPC-PA 2. For the 4 ft. by 4 ft. by 3/16 in. flat surface test panels, five DFT spot measurements were taken with the conventional Type II gauge randomly spaced throughout the test specimen. In accordance with SSPC-PA 2, spot DFT measurements were composed of the average of three gauge readings within a 1.5 in. diameter circle. DFT measurements on the 4 ft. by 4 ft. by 3/16 in. test panels were no less than 1/2 in. from any surface edge and 1 in. from any other spot measurements. Figure 1 illustrates the conventional DFT measurement patterns on the 4 ft. by 4 ft. by 3/16 in. test panels.

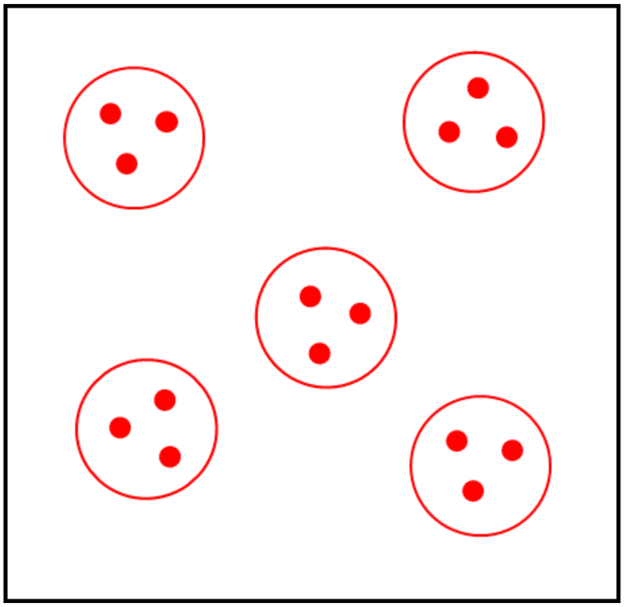

Figure 1: Conventional DFT measurement pattern

Scanning Probe DFT Measurements

Scanning probe DFT measurements are taken by running a specialized probe tip across the surface of a material and measuring numerous DFT readings without breaking contact with the coated surface. DFT measurements taken using a Type II gauge with a scanning probe were done in a manner similar to SSPC-PA 2. Prior to DFT measurements and before each test specimen, gauge accuracy was measured through a two-point adjustment in accordance with Appendix 8 of SSPC-PA 2. For the 4 ft. by 4 ft. by 3/16 in. test panels, five randomly spaced DFT scan measurements were taken with each scanning Type II DFT gauge. DFT measurements were collected in batch sizes of 12, 24, 36, and 48. Scanning DFT measurements on the 4 ft. by 4 ft. by 3/16 in. test panels were no less than 1/2 in. from any surface edge and 1 in. from any other scan measurements. Figure 2 illustrates the DFT measurement patterns on the 4 ft. by 4 ft. by 3/16 in. test panels using the Type II gauge with a scanning probe.

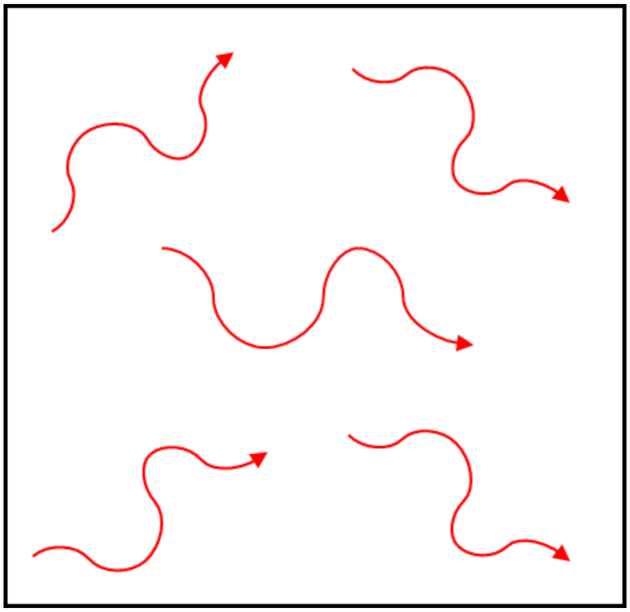

Figure 2: Scanning probe DFT measurement pattern on a large steel panel

Statistical Measurement Methodology

DFT data collected using the traditional SSPC-PA 2 method and the rapid scanning method were statistically analyzed by examining each test specimen's sample mean DFT, 95.0% and 99.9% individual confidence intervals for each mean, and margins of error for each method from the 99.9% individual confidence intervals. Sample mean DFT values were collected on each test sample in batches of 12, 24, 36, 48, and the traditional SSPC-PA 2 method.

SSPC-PA 2 Method

The SSPC-PA 2 method uses 5 spot measurements, which are themselves the averages of 3 measurements taken at that specific spot. Defined mathematically, for any given spot measurement x_i with an accompanying 3 measurements at the ith spot $y_{i,j}$ which comprise it,

$$x_i = \frac{1}{3}\sum_{j=1}^{3} y_{i,j}. \qquad (1)$$

Then, the arithmetic mean of the 5 spot measurements are taken to determine the overall average $\bar{x}$:

$$\bar{x} = \frac{1}{5}\sum_{i=1}^{5} x_i = \frac{1}{5}\sum_{i=1}^{5}\left(\frac{1}{3}\sum_{j=1}^{3} y_{i,j}\right). \qquad (2)$$

It is important to note that the SSPC-PA 2 method indicates that the 3 measurements that comprise any of the 5 spot measurements are fundamentally measurements of the same quantity (location); which is to say, they are not independent measurements. This is acknowledged implicitly in the technique due to the overall average being calculated as the average of the 5 spot measurements, as opposed to the average of the 15 total readings. While these quantities are mathematically equivalent, the sample size is different. The SSPC-PA 2 technique implicitly uses a sample size of $n = 5$ independent observations (the 5 spots).

Scanning Method

The scanning method operates by moving a probe across the panel surface, taking measurements at fixed batch intervals as the probe is moved. The batch size is set by the operator and is the total number of measurements taken. Defined mathematically, for any given scanning method batch which takes n measurements (i.e., batch size of n) with an individual measurement defined as z_k, the arithmetic mean $\bar{z}$ can be calculated as

$$\bar{z} = \frac{1}{n}\sum_{k=1}^{n} z_k. \qquad (3)$$

Thus, the sample size n for the scanning method is simply the batch size set by the operator, with n independent observations taken across the panel surface due to the movement of the probe across the surface (rather than in-place measurements). It should also be noted that scanning technology can also be utilized to perform equivalent data collection to the SSPC-PA 2 method, where three averaged readings from the same location are taken at five different spots. Thus, the scanning technology can also be used to output results of equivalent sample size ($n = 5$) to the SSPC-PA 2 method, if desired.

Statistical Analysis Methodology

To examine the precision of the two measurement techniques, statistical terminology was established and defined. Let μ be defined as the population parameter of interest (i.e., the arithmetic mean dry film thickness), and μ is a fixed, unknown constant. Because a true value of μ is unknown to analysts, μ must be estimated by the collection of a sample. The sample's arithmetic mean, defined as $\bar{x}$, can be understood to be an estimate of μ. Likewise, some true population parameter indicating the variation for observations taken in a sample is the standard deviation σ. Much like the mean, the standard deviation has a true, constant value that is unknown and is also estimated through the collection of a sample. This sample-based estimate of the standard deviation is defined as s.

The sample's arithmetic mean $\bar{x}$, unlike μ, is not a fixed constant and has inherent randomness contained within estimations. By estimating the variability within $\bar{x}$, also known as the standard error, the precision of $\bar{x}$ in estimating μ can be analyzed. While the standard deviation estimates the variation of individual observations within the collected sample, the standard error estimates the variation in the sample mean and thus is an indicator of how well the sample mean $\bar{x}$ estimates the population mean μ. The standard error depends on the sample size n. As n increases, the standard error decreases, and thus, the precision increases.

In summation, a sample is collected to calculate $\bar{x}$ (the estimate of the true mean DFT μ) and s (the estimate of the true standard deviation σ). These quantities can also be used to estimate the standard error, which indicates how well the collected sample mean $\bar{x}$ "performs" in relation to the true mean DFT μ.

The statistical analysis refers explicitly to the fidelity of DFT data collection as it pertains to the two measurement techniques. Issues such as operator error, mechanical failure of a device, and probe wear were not taken into consideration for the statistical analysis. Rather, this statistical analysis was meant to be an examination of the fundamental mathematical processes underlying the methods and the fidelity of the resultant data.

Monte Carlo Simulation

DFT data was collected on 2 sample panels: a 4 in. by 6 in. panel with an approximate DFT of 20 mils and a 6 in. by 12 in. panel with an approximate DFT of 3 mils. Measurements were collected on both panels using the SSPC-PA 2 method (taking 3 readings at 5 different spots, repeated for 5 batches per panel; $n = 5$) as well as the rapid scanning technology (taking 10 measurements per batch, repeated for 5 batches per panel; $n = 10$). Across all batches, these results were used to compute estimates of the population mean DFT μ and the standard deviations for both the SSPC-PA 2 and scanning methods. After these quantities were estimated, bootstrap simulations of the techniques were performed under the assumption of normality to estimate the variation around the computed sample means (the standard errors).

DFT Scanning Technique Verification of Accuracy

In order to understand the effects of probe wear on gauge accuracy during the DFT scanning process, a scanning probe wear test was conducted. A scanning DFT gauge was mounted above a coated 6 in. by 12 in. by 3/16 in. steel test specimen, see Figure 3. Two DC brush motors and a mechanical RC servo motor were used to move the scanning probe over various coated steel test specimens in a pattern that mimics the DFT scanning technique. Three coatings of varying surface roughness were chosen to test the effects of probe wear on gauge accuracy. An epoxy polyamide coating (MIL-DTL-24441, Type III, Formula 151) was chosen to represent a smooth coating surface, and an epoxy polyamide zinc rich primer (MIL-DTL-24441, Type III, Formula 159) was chosen to represent a coating with intermediate surface roughness. In order to create an extremely rough coating surface, an alumina aggregate was added to an epoxy polyamide coating (MIL-DTL-24441, Type III, Formula 151). The alumina aggregate epoxy polyamide coating was designed to mimic a worst-case field scenario for the DFT scanning technique. Prior to DFT data collection and before each test specimen assessment, the scanning DFT gauge was calibrated

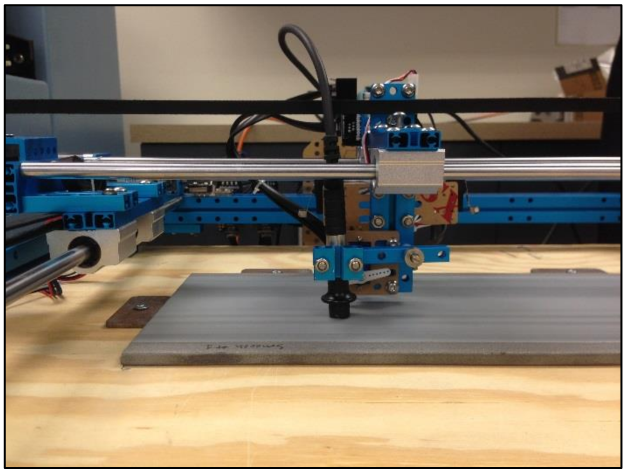

Figure 3: Scanning probe DFT wear testing apparatus

through a two-point adjustment in accordance with Appendix 8 of SSPC-PA 2.

Twenty simulations of the probe wear test apparatus were run for each DFT scanning probe. Each simulation of the probe wear test collected 10 batches of scanning DFT measurements, and each DFT scanning batch consisted of 255 DFT measurements. The same calibration conducted at the beginning of each probe wear test was used for all 20 simulations in order to see a progression of probe wear. For each simulation, a total of 2,550 DFT measurements were taken continuously over a coated surface equating to 50.98 ft.^{2} (15.54 m^2) of coated surface. A total of 51,000 DFT measurements were taken on each DFT scanning probe, equating to a total linear distance of 1019.6 ft. (310.8 m) scanned by each probe cap. The scanning probe tips were analyzed with microscopic and vertical scanning interferometer imagery before and after wear testing. DFT data collected during probe wear testing was also analyzed for statistical trends in order to understand the effects of the DFT scanning process on gauge accuracy.

DATA ANALYSIS

Statistical data suggests that greater precision of DFT measurements can be obtained using the scanning method over the traditional SSPC-PA 2 method. Increases in DFT precision were noted during statistical simulations, indicating a greater level of DFT measurement precision during rapid DFT scanning methods. Increases in confidence intervals and decreases in margin of errors were also noted during laboratory testing, indicating greater increases in precision during rapid scanning operations. However, due to mechanical friction, great care must be taken during the scanning process to diminish the effects of probe wear on reading precision and accuracy. During the scanning process, frequent calibration verification of the DFT instrument is paramount to DFT measurement accuracy and precision.

Monte Carlo Results

Visually, the precision of the simulation results can be seen by examining a plot of 100 bootstrap Monte Carlo trials with estimates and 95% confidence intervals for the mean using the calculations for the SSPC-PA 2 method, the scanning method with a batch size of 10, and the scanning method with a batch size of 25, as seen in Figure 4. The intervals become narrower as the batch size increases, indicating more precise estimations of the sample mean from the scanning technology in comparison to the SSPC-PA 2 method. The dispersion around the sample mean,

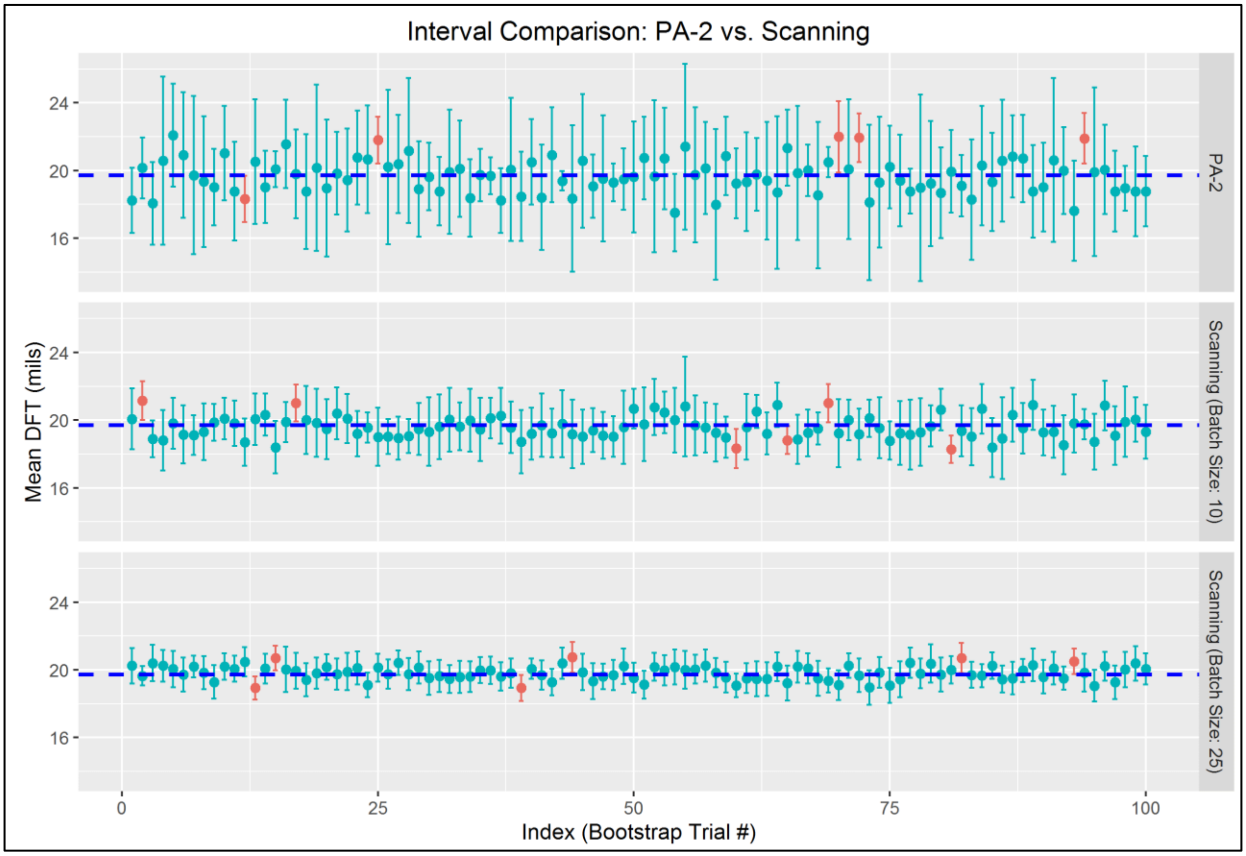

Figure 4: Conventional us. scanning interval comparison (bootstrap estimates of size 100)

and thus the precision, can also be seen visually in histograms and density plots of the distribution generated from a bootstrap sample of size 10,000, see Figure 5 and Figure 6.

Finally, from the bootstrap estimates, the average size of the interval around the estimate of the mean was computed for the 3 different scenarios. The findings are summarized in Table 1. Bootstrap simulation estimates indicate that, on average, the 95% confidence intervals around the estimated sample means were ±14.43% using the SSPC-PA 2 method, ±10.51% using the scanning method with a batch size of 10, and ±6.18% using the scanning method with a batch size of 25. In other words, for the bootstrap sample, the scanning method represents a 27% decrease in interval size from the SSPC-PA 2 method with a batch size of 10 and a 57% decrease in interval size from the SSPC-PA 2 method with a batch size of 25. Consequently, the scanning method represents an estimated average increase in precision of 37% over the SSPC-PA 2 method with a batch size of 10, and an average increase in precision of 133% with a batch size of 25. These simulations were repeated with the data from the approximately 20 mil panel and indicated even larger increases in precision (48% and 70% reductions in interval size from the SSPC-PA 2 method and 93% and 229% increases in precision with batch sizes of 10 and 25, respectively).

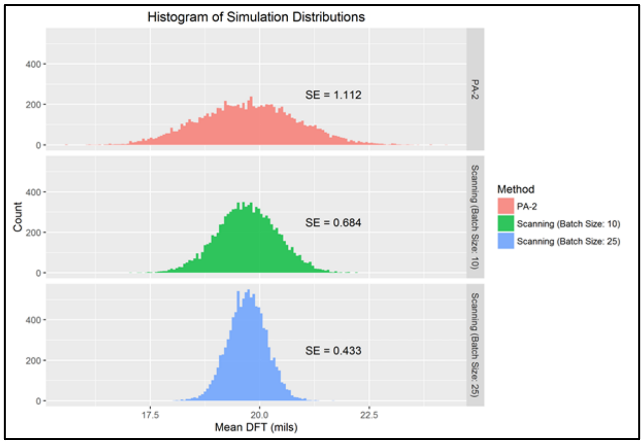

Figure 5: Histogram of simulation distributions (bootstrap estimates of size 10,000)

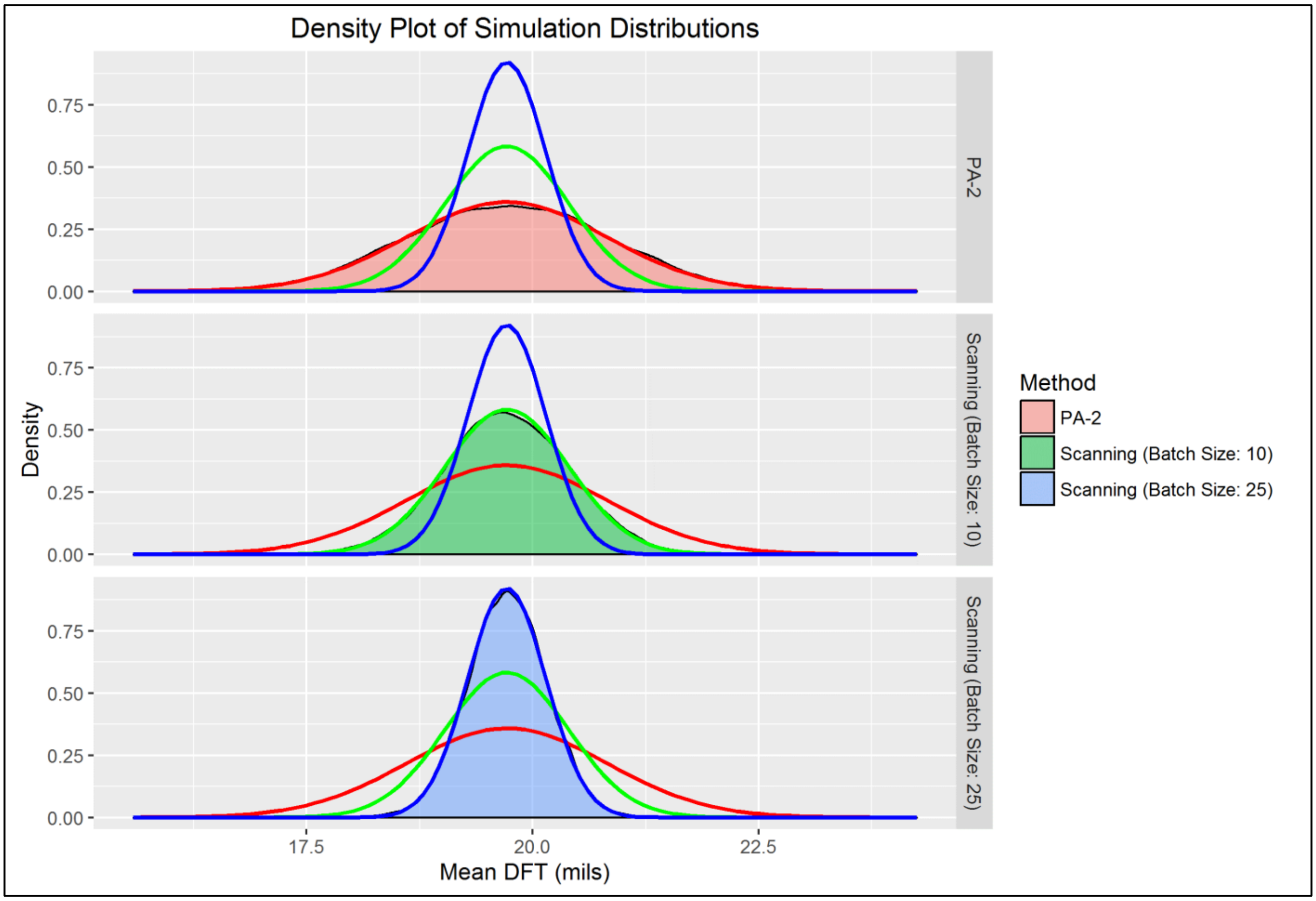

Figure 6: Density plots of simulation distributions (bootstrap estimates of size 10,000)

Table 1: Average interval size around the estimated mean (bootstrap estimates of size 10,000)

Method	Interval size around mean
SSPC-PA 2	±14.43%
Scanning (Batch Size 10)	±10.51%
Scanning (Batch Size 25)	±6.18%

It should be noted that these simulations were designed to provide preliminary estimates of the precision of each method. A check of the bootstrap simulations using collected data from large panels was then performed using fully-coated 4 ft. by 4 ft. steel panels with varying coating thicknesses.

Laboratory Steel Panel Results

DFT data collected from the coated steel panels was analyzed at a statistical level to provide fundamental comparisons of the SSPC-PA 2 method to the rapid DFT gauges at varying batch sizes. An analysis of variance (ANOVA) indicated significant interaction effects ($p < .05$) between the method of data collection (random batches of size 12, 24, 36, and 48; the full panel scans; and the SSPC-PA 2 method) and the experimental panel at all approximate thickness levels except for the approximately 40 mil thickness panels. Since a significant interaction effect was present, the omnibus test was not used, and instead further analyses were performed to examine the simple main effects for each panel. In other words, the data was separated into per-panel subsets rather than combining all data together, and each panel's sample mean DFT was calculated for each of the different analysis methods.

Panel DFT Confidence Intervals

To supplement the sample mean calculation and provide an estimate of the precision of the techniques, confidence intervals were calculated for each of the means. The confidence interval can be considered a range of plausible values within which the true underlying population mean might lie. Since a comparison of various gauge manufacturers was not the intent of the analysis, the number of simultaneous hypotheses being tested per approximate thickness level was 48 (6 methods per panel, with 8 panels total). To account for the increased probability of committing a type I error due to the number of simultaneous tests, a Bonferroni correction was applied such that the targeted level of significance for each individual test was calculated as $1 - \frac{.05}{48} = 99.9\%$. In other words, to maintain an overall type I error rate of 5%, each individual confidence interval generated for the mean DFT was generated at a 99.9% confidence level.

The intervals for the full panel scans are the most precise, given that they are comprised of 2,300 observations per panel, see Figure 7 and Figure 8. As can be seen in Figure 9, the precision of the confidence interval results tends to be in good agreement. In other words, the intervals for each analysis method tend to overlap. It should be noted that the rapid scans, even with the small batch size of 12, provide a greatly increased amount of precision to the mean estimation over the SSPC-PA 2 method due to the rapid DFT's much larger sample size of 60 (five batches of size 12 each) compared to the SSPC-PA 2 method's sample size of 5. This can be seen visually by the large width of the SSPC-PA 2 method's confidence interval compared to the width of the batch size 12 intervals. As an additional note, while the batch sizes of 24, 36, and 48 all offer increased precision over the batch size of 12, there is an element of diminishing returns where the decreases in the width of the confidence interval

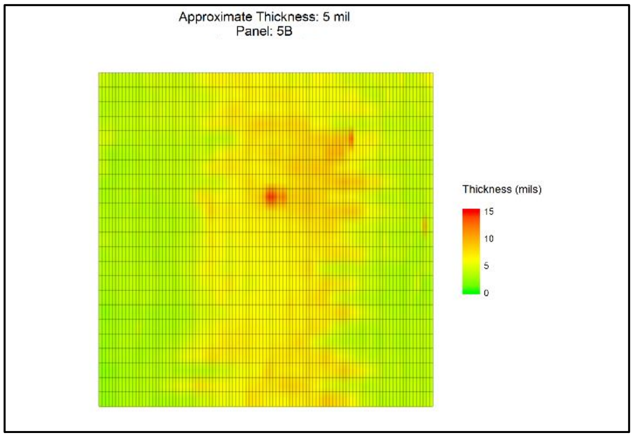

Figure 7: 5 mil full panel scan consisting of 2,300 DFT measurements

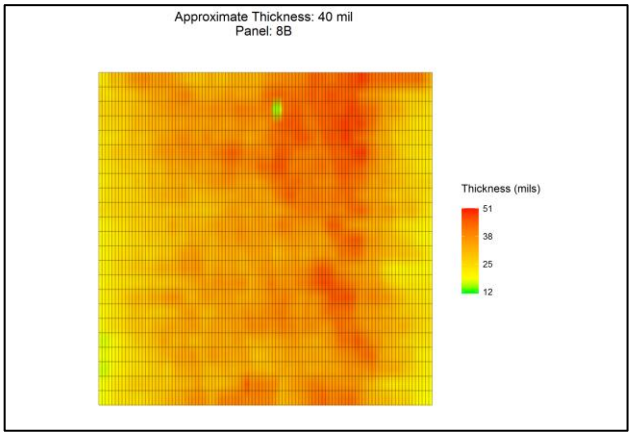

Figure 8: 40 mil full panel scan consisting of 2,300 DFT measurements

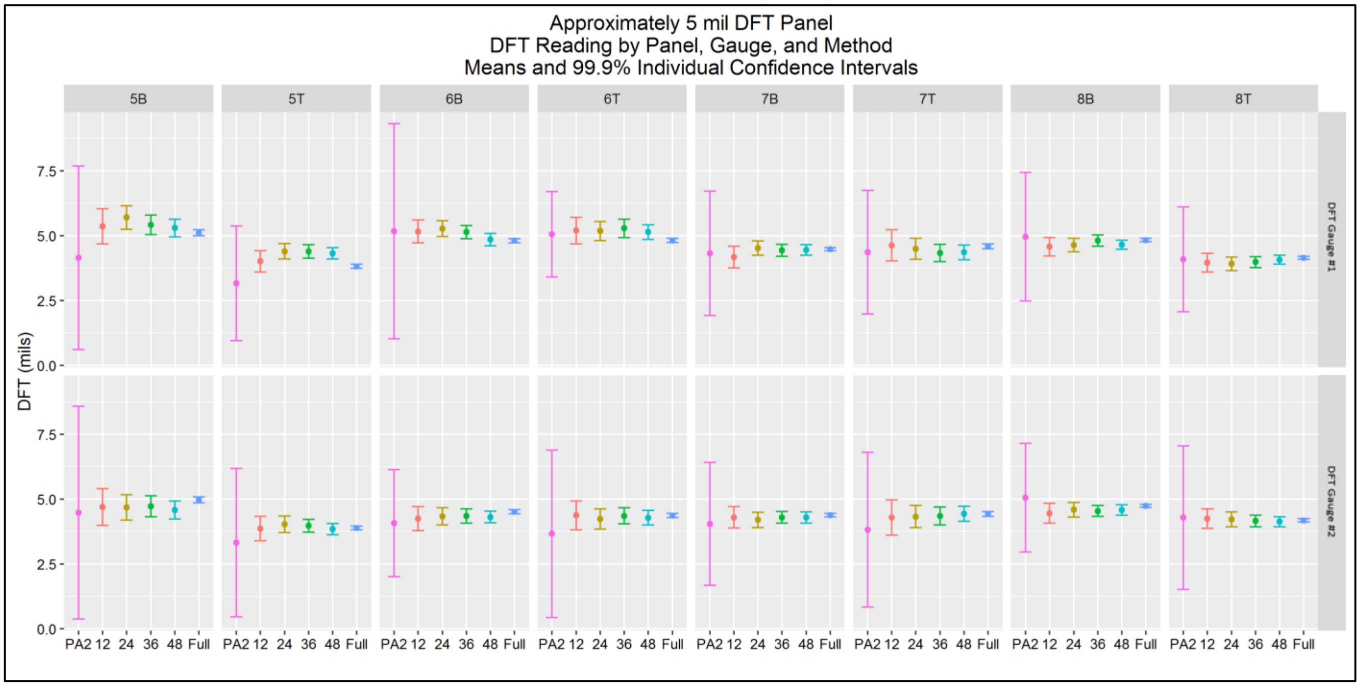

Figure 9: Panel 5 mil 99.9% confidence intervals

are of a smaller magnitude than the difference between the SSPC-PA 2 method and the rapid scanning method.

Panel DFT Margins of Error

To provide a quick comparison of the uncertainty around a result, margins of error were also calculated for each of the methods from the 99.9% confidence intervals. These margins of error give an indication as to the uncertainty around each calculated sample mean. For example, if the sample mean was 10 mils and the margin of error was ±4 mils with a 99.9% confidence for the individual interval, the panel's true mean DFT would be estimated to be somewhere between 6 mils and 14 mils.

As can be seen in Figure 10, the data once again indicate the difference between the SSPC-PA 2 method and the rapid DFT gauges in terms of margin of error.

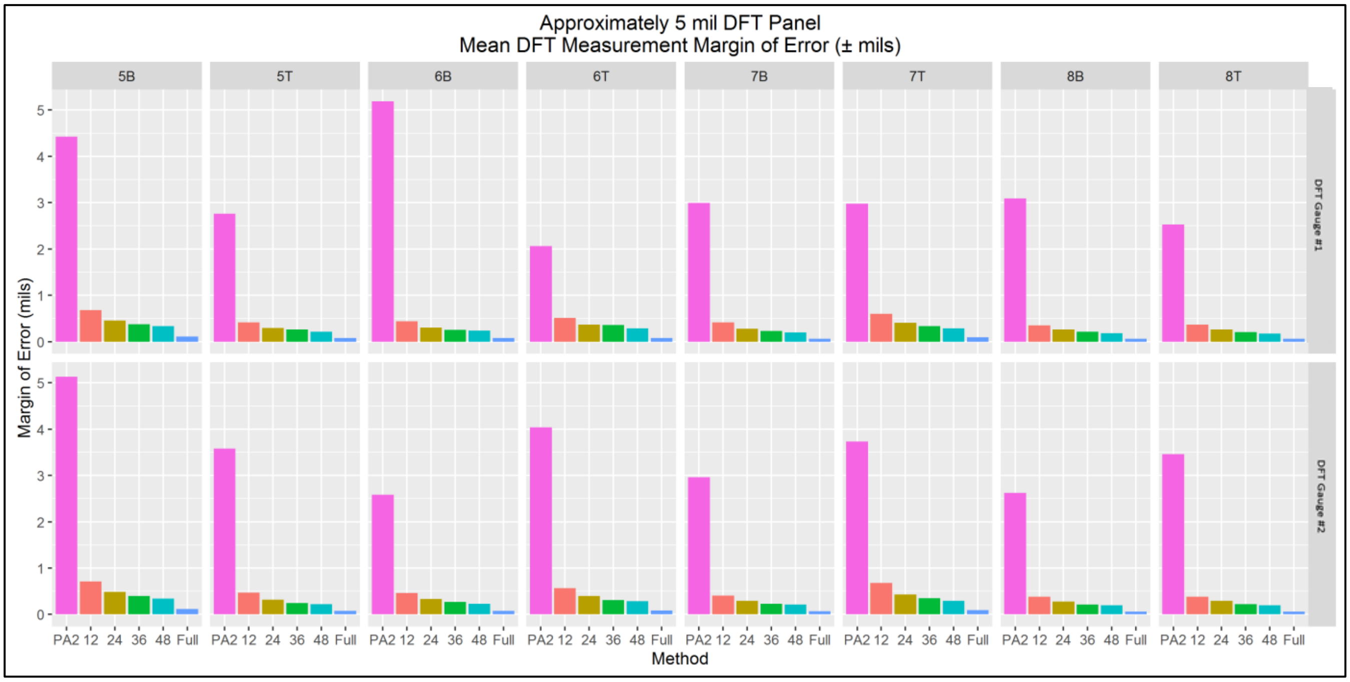

Figure 10: Panel 5 mil mean DFT margins of error

The margins of error for the SSPC-PA 2 method are substantially larger than those from the rapid DFT gauges, indicating that there is a large amount of uncertainty in the SSPC-PA 2 measurements, particularly when compared to those measurements taken from the rapid scanning DFT gauges.

Probe Wear Analysis

Probe wear test results indicate that degradation due to mechanical friction of probe tips during DFT scanning operations can have significant effects on the accuracy and precision of scanning DFT measurements. Depending upon the type of coating measured, the severity of drift in accuracy and precision of scanning DFT measurements ranged from minimal (smooth coating surfaces) to severe (rough coating surfaces). As can be seen in Figure 11, the mean DFT scanning values taken with the same instrument calibration over a rough coating surface decreased approximately 10 mils during probe wear testing. The large standard deviations of the rough coating DFT measurements can be attributed to the differential surface feature heights created by the alumina aggregate in the epoxy polyamide coating. For the smooth and intermediate roughness surfaces, the mean DFT scanning values decreased approximately 0.5 mils and 2 mils, respectively, during probe wear testing.

Smooth Panel Probe Wear Test

After 51,000 scanning DFT readings on a steel panel coated with an epoxy polyamide primer (MIL-DTL-24441, Type III, Formula 151), the scanning DFT probe tip experienced minimal mechanical wear with mean DFT values decreasing from 13.195 mils to 12.677 mils. For all 20 simulations of wear testing on the smooth panel, the standard deviation and coefficient of variation both remained fairly consistent at 0.7 mils and 5.4%, respectively.

A surface characterization of the MIL-DTL-24441, Type III, Formula 151 coating revealed a relatively smooth coating surface. Vertical scanning interferometer imagery was used to detail the coating surface of the smooth panel used during probe wear testing. As can be seen in the vertical scanning interferometer imagery in Figure 12, surface features are relatively smooth and sparsely distributed throughout a 25 mm² section of the test panel. An average surface feature height of 19.6 µm was observed on the 25 mm² section of test panel used during probe wear testing.

There was evidence of minimal mechanical wear on the scanning DFT probe tip used on the MIL-DTL-24441, Formula 151 coated test panel. Concentric rings placed on the scanning DFT probe tip during manufacturing were for the most part still intact and

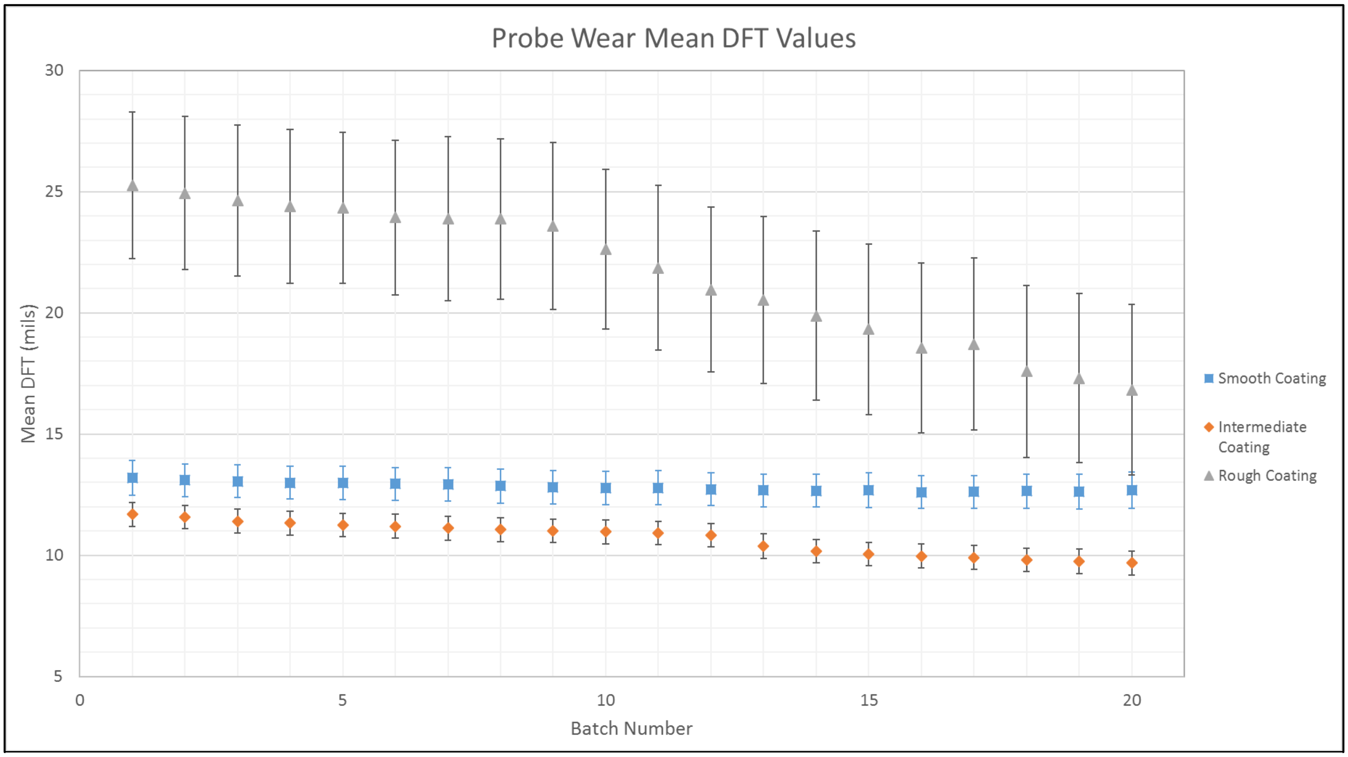

Figure 11: Probe wear mean DFT values

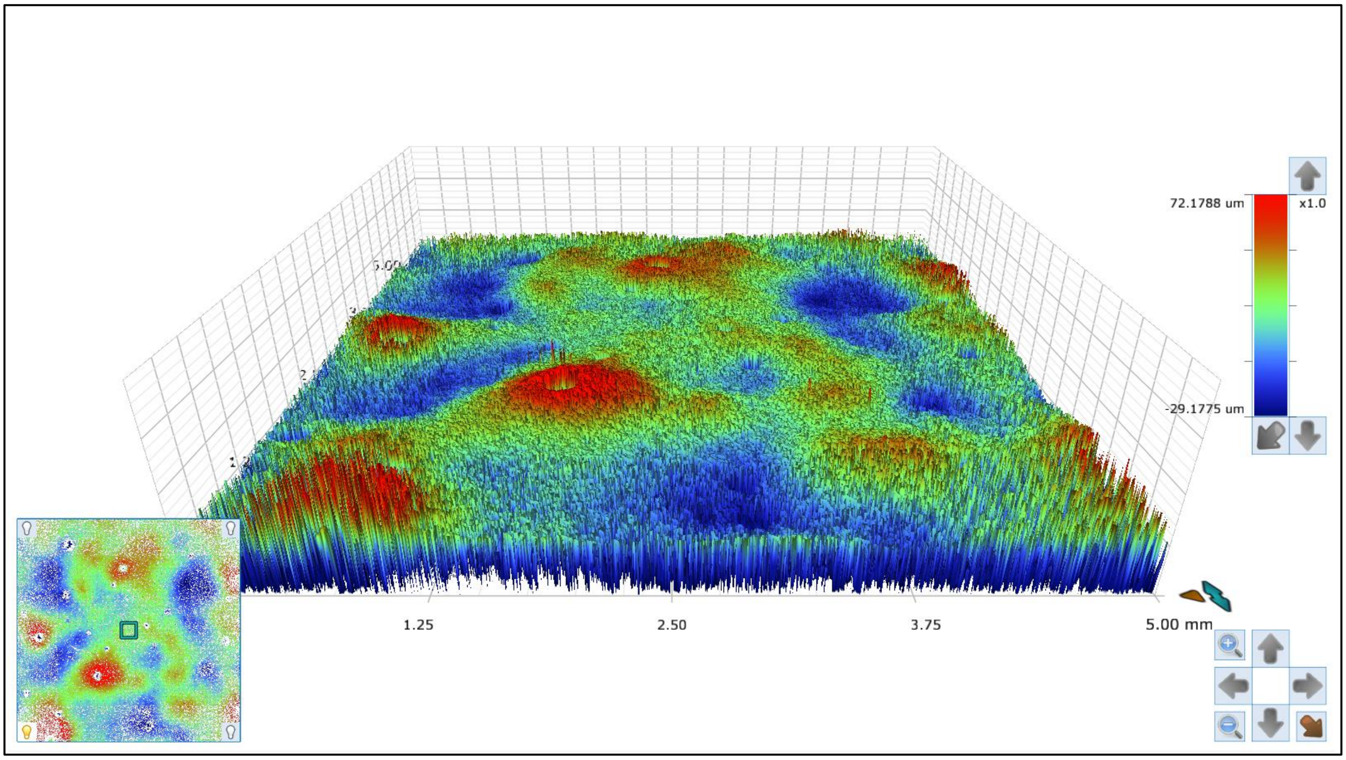

Figure 12: Smooth panel surface profile

can be seen in vertical scanning interferometer imagery (Figure 13).

Intermediate Roughness Panel Probe Wear Test

After 51,000 scanning DFT readings on a steel panel coated with an epoxy polyamide zinc rich primer (MIL-DTL-24441, Type III, Formula 159), the scanning DFT probe tip experienced moderate mechanical wear with mean DFT values decreasing from 11.686 mils to 9.683 mils. For all twenty batches of wear testing, the standard deviation and coefficient of variation both remained fairly consistent at 0.5 mils and 4.7%, respectively.

A surface characterization of the MIL-DTL-24441, Type III, Formula 159 coating revealed a relatively jagged coating surface. Microscopic and vertical scanning interferometer imagery were used to detail the coating surface of the intermediate roughness

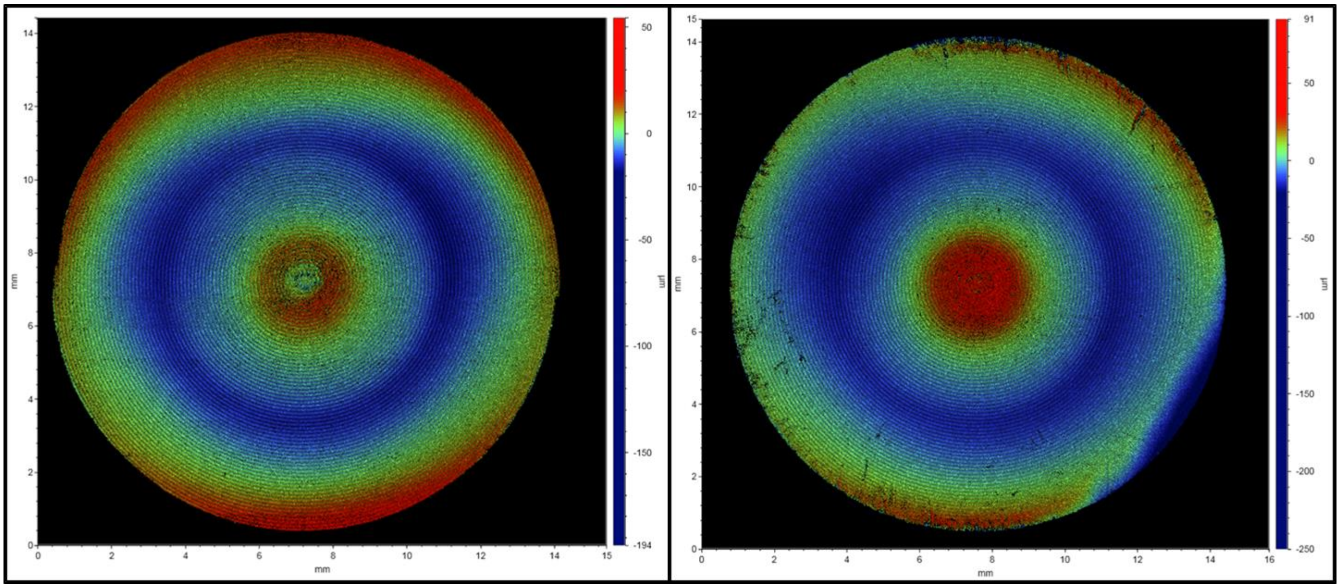

Figure 13: Smooth probe VSI imagery before probe wear (left) and after probe wear (right)

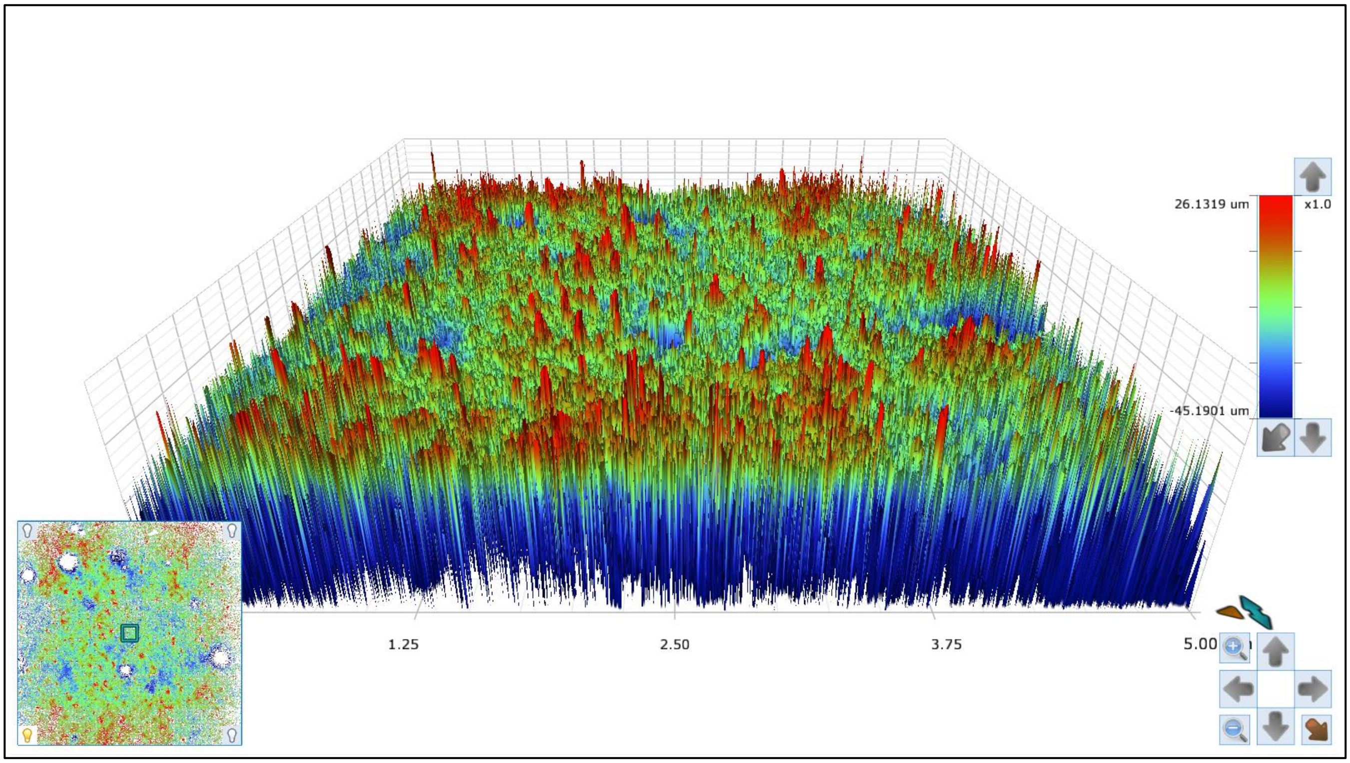

Figure 14: Intermediate roughness panel surface profile

panel used during probe wear testing. As can be seen in Figure 14, surface features are relatively jagged and abundantly distributed throughout a 25 mm² section of the test panel. An average surface feature height of 18.3 µm was also observed on the 25 mm² section of test panel used during probe wear testing.

There was evidence of moderate mechanical wear on the disposable scanning DFT probe tip used on the MIL-DTL-24441, Formula 159 coated test panel. Concentric rings placed on the disposable probe tip during manufacturing have been completely worn off of a 2 mm diameter circle located at the center of the disposable probe and can be seen in vertical scanning interferometer imagery (Figure 15). The 2 mm diameter circle located at the center of the disposable probe is where the actual probe makes contact with the disposable probe tip during the collection of scanning DFT measurements. Linear gouges in the concentric rings were also seen sparsely distributed on the disposable probe tip at the completion of wear testing.

Rough Panel Probe Wear Test

After 51,000 scanning DFT readings on a steel panel coated with an alumina aggregated epoxy (MIL-DTL-24441, Type III, Formula 151), the scanning DFT probe tip experienced severe mechanical wear with mean DFT values decreasing from 25.265 mils to 16.831 mils. The standard deviation increased from 3.029 mils to 3.514 mils, and the coefficient of variation increased from 12% to 20.9%.

A surface characterization of the MIL-DTL-24441, Type III, Formula 151 with alumina aggregate coated

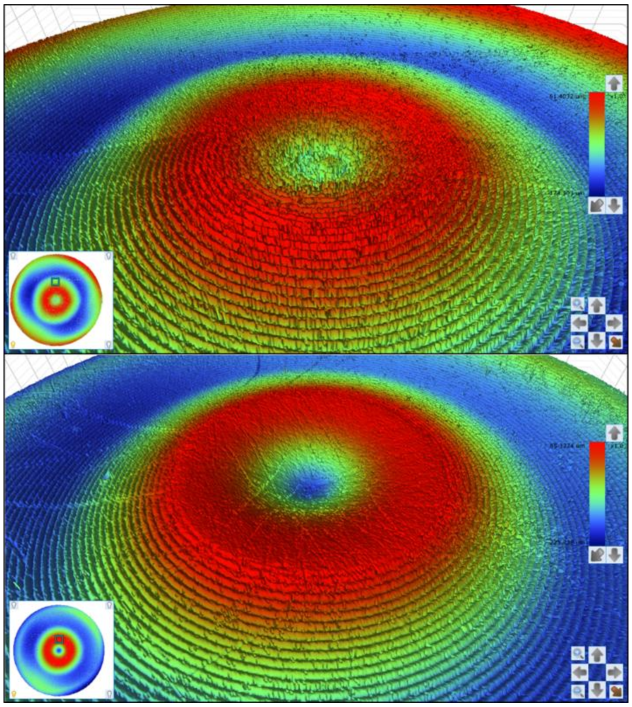

Figure 15: Intermediate probe tip VSI imagery before probe wear (top) and after probe wear (bottom)

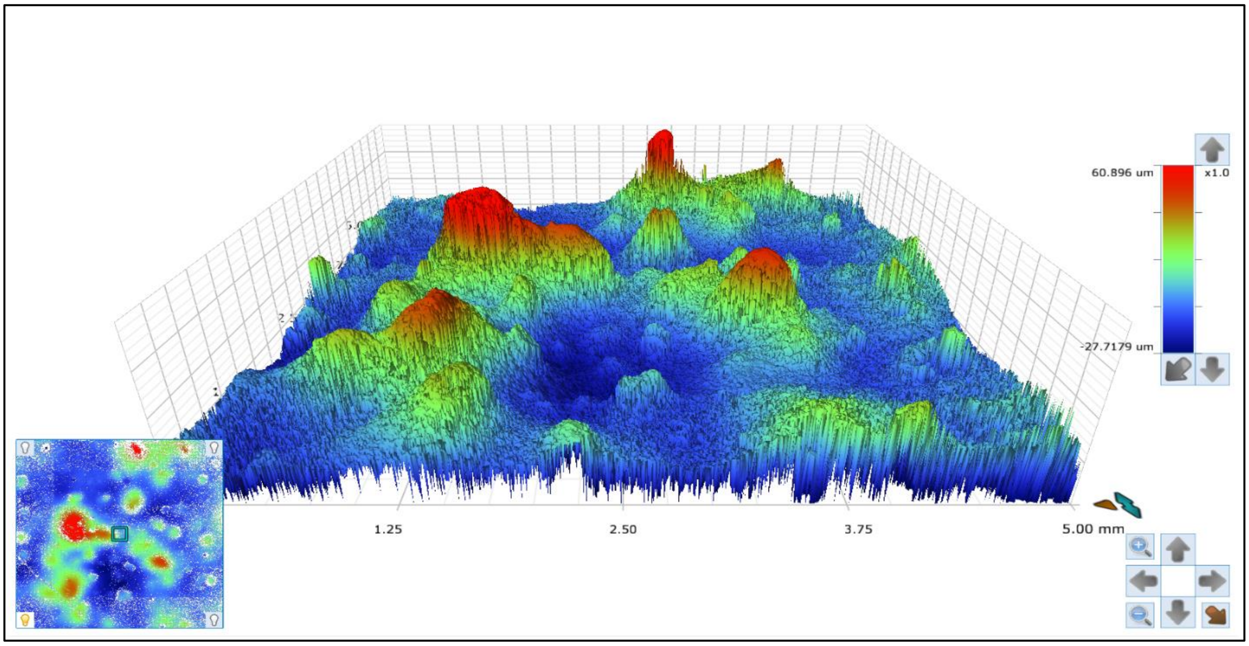

Figure 16: Rough panel surface profile

test panel revealed a relatively jagged coating surface. Vertical scanning interferometer imagery was used to detail the coating surface of the rough panel used during probe wear testing. As can be seen in Figure 16, surface features are relatively jagged and moderately distributed throughout a 25 mm² section of the test panel. An average surface feature height of 55.6 μm was also observed on the 25 mm² section of test panel used during probe wear testing.

There was evidence of severe mechanical wear on the scanning DFT probe tip used on the MIL-DTL-24441, Formula 151 with alumina aggregate coated test panel. As can be seen in Figure 17, concentric rings placed on the disposable probe tip during manufacturing were completely worn off the entire disposable probe tip and a 1 mm diameter hole developed at the center of the disposable tip. Microscopic and vertical scanning interferometer imagery detail the severe mechanical wear on the disposable probe tip. Numerous linear gouges could also be seen in the disposable probe tip at the completion of wear testing.

CONCLUSIONS

Statistical data suggests that greater precision of DFT measurements can be obtained using the scanning method over the traditional SSPC-PA 2 method. Increases in DFT precision were noted during statistical

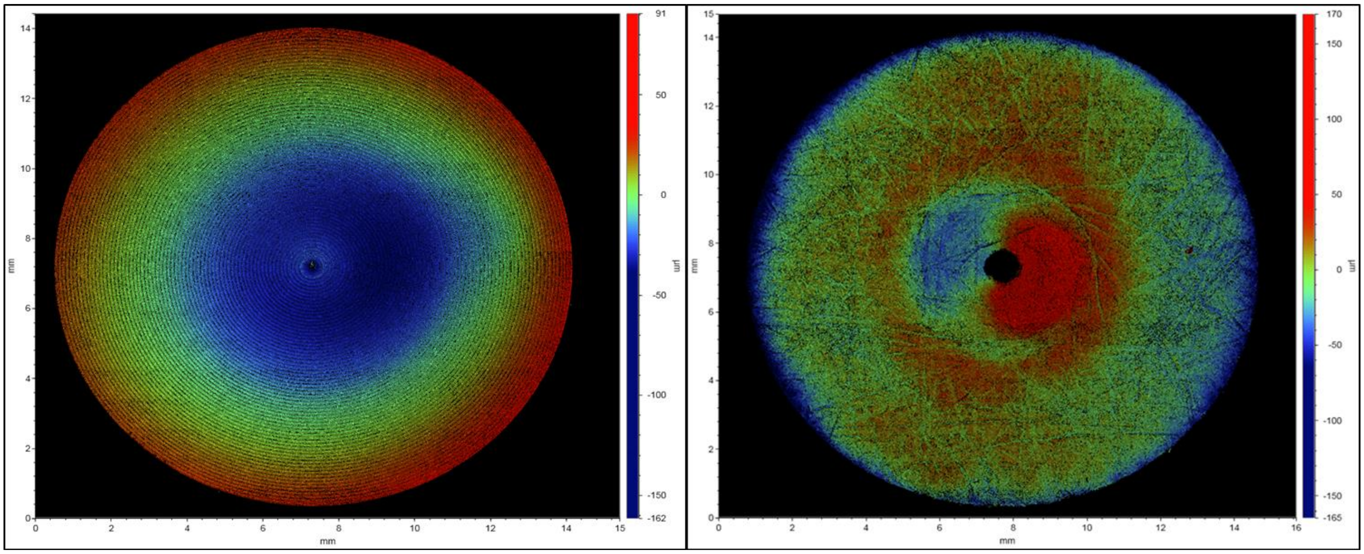

Figure 17: Rough surface probe tip VSI imagery before probe wear (left) and after probe wear (right)

simulations indicating a greater level of DFT measurement precision during rapid DFT scanning methods. Also, rapid DFT scanning technology enables an operator to collect a larger number of measurements in a shorter time frame than the SSPC-PA 2 method, validating results obtained in the NSRP SP-3 report. As a result of the increased number of observations collected, better estimates of the sample mean were obtained through increased precision. Statistical data suggests the increase in precision of rapid scanning DFT measurements over traditional SSPC-PA 2 methods can be substantial.

For bootstrap Monte Carlo simulations, the results indicated a substantial increase in estimated precision utilizing the rapid scanning method. Bootstrap Monte Carlo simulations estimated average increases in DFT precision ranging from 37% to 133% with scanning batch sizes of 10 and 25, respectively. Increases in DFT precision were also validated by data collected in the laboratory.

DFT data collected from each coated steel test specimen was analyzed at a statistical level to provide fundamental comparisons of the SSPC-PA 2 method to the rapid DFT scanning method at varying batch sizes. The DFT data was separated into per-panel subsets rather than combining all the data together, and each sample's mean DFT was calculated for each of the different analysis methods. To supplement the sample mean calculation and provide an estimate of the precision of each technique, confidence intervals were calculated for each of the means. Even with a small batch size of 12, rapid DFT scans provided a greater increase in the amount of precision to the mean estimation over the SSPC-PA 2 method.

The increase in precision can be attributed to the rapid DFT's much larger sample size of 60 (5 batches of size 12 each) in comparison to the SSPC-PA 2 method's sample size of 5. This can be seen visually by comparing the width of the SSPC-PA 2 method's confidence interval to that of the batch size 12 intervals. While batch sizes of 24, 36, and 48 all offered increased precision over a batch size of 12, there is an element of diminishing returns. Decreases in the width of the confidence intervals are of a smaller magnitude compared to the difference between the SSPC-PA 2 method and the rapid scanning method. To provide a quick comparison of the uncertainty around a resultant, margins of error were calculated for each of the methods from the 99.9% confidence intervals.

The SSPC-PA 2 method's margins of error are substantially larger than those of the rapid DFT scanning method, indicating there is a large amount of uncertainty in the SSPC-PA 2 measurement method in comparison to the rapid DFT scanning method. Although scanning DFT measurements provide more precise readings than traditional SSPC-PA 2 methods, special attention must be taken to ensure the accuracy and precision of scanning DFT measurements due to the effects of probe wear created by mechanical friction.

Probe wear test results indicate that degradation of probe tips during DFT scanning operations can have significant effects on the accuracy and precision of scanning DFT measurements. Depending upon the type of coating measured, the severity of drift in accuracy and precision of scanning DFT measurements ranged from minimal (smooth surfaces) to severe (rough surfaces). The mean DFT scanning values taken with the same instrument calibration over a rough coating surface decreased approximately 10 mils during probe wear testing. The large standard deviations of the rough coating DFT measurements can be attributed to the differential surface feature heights created by the alumina aggregate in the epoxy polyamide coating. For the smooth and intermediate roughness surfaces, the mean DFT scanning values decreased approximately 0.5 mils and 2 mils, respectively, during probe wear testing. Due to probe wear created by mechanical friction during the scanning process, DFT gauge calibration is a key component of the DFT scanning process.

The following recommendations have been made to increase the precision of DFT data collection:

- **Implement scanning DFT measurements into SSPC-PA 2 and NSI 009-32**. Increases in precision of DFT measurements can be achieved with the implementation of rapid scanning techniques. Statistical data suggests that increases in confidence intervals and decreases in margins of error can be achieved with rapid scanning DFT techniques.
- **Develop and implement scanning DFT calibration schedules for greater DFT data precision**. DFT probe calibration schedules will vary significantly depending upon the type of coating being measured. Rougher coating surfaces will require more frequent DFT probe calibration, and smoother coating surfaces will require less frequent DFT probe calibration. DFT scanning probe calibration schedules should be established to limit drift in probe precision and assist DFT gauge operators in the field.
- **Use larger batch sizes within reason**. The larger the scanning batch size, the greater the precision of DFT measurements. A minimum batch size should be established depending upon the level of precision desired, time constraints, and the risks associated with coating failure.

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