Improvements To The Replica Tape Test Method (ASTM D4417C / NACE SP287 / ISO 8503-5)

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ABSTRACT

The Replica Tape method is a trusted method used by inspectors worldwide for decades to measure surface profile height. Previous studies have shown the method to be highly precise and accurate, but an intricate burnishing technique and requirement to average two different grades of replica tape in some measurement ranges made the method challenging for some users. This paper details two proposed changes to the method: an updated burnishing tool and linearized measurement scale to eliminate the need for averaging. A study was conducted to determine the accuracy and precision of this updated method, involving measurements performed by 15 users of varied experience on a range of test panels blasted with varying media and profile heights.

Key words: Inspection, Coating Inspection, Testex Tape, Replica Tape, Burnishing, Surface Profile, Surface Roughness, ASTM D4417, NACE SP0287, ISO 8503-5

INTRODUCTION

Prior to applying an industrial protective coating, the substrate is prepared by abrasive or mechanical blasting. Blasting removes mill scale and corrosion from the substrate, while providing additional surface area and mitigation against sheer force through the generation of a complex pattern of peaks and valleys[1].

These additional peaks and valleys, known as the surface profile, vary based on factors such as abrasive size, abrasive shape, abrasive composition, blasting pressure, blast nozzle orifice size, and the position the blast nozzle is held with respect to the surface.

Ensuring that a sufficient surface profile has been created has been a common quality control requirement for decades. Historically, panels with a desirable surface profile were created at the beginning of a job and used by inspectors as a benchmark for tactile and visual comparison. Commercially-prepared comparator panels were subsequently introduced, featuring a range of standardized sample surface profiles for comparison. While the commercial comparators represented a significant improvement over previous methods, they were a qualitative method, relying on the judgment of the inspector to make a determination.

In the 1970's, an alternative method for measuring surface profile was introduced: Testex Replica Tape. Replica tape consists of a compressible foam adhered to an incompressible mylar substrate, which itself is adhered to an adhesive label with a hole to allow access to the foam/mylar. The replica tape is adhered to the blasted surface, and a handheld tool with a spherical ball on one end is pressed against the mylar side of the foam/mylar, pushing the foam into the surface and ultimately creating a negative replica. The replica tape is then removed from the surface, and the height of the foam/mylar is measured. By subtracting the thickness of the mylar substrate, the height of the foam replica can be determined, therefore establishing the peak-to-valley surface profile height.

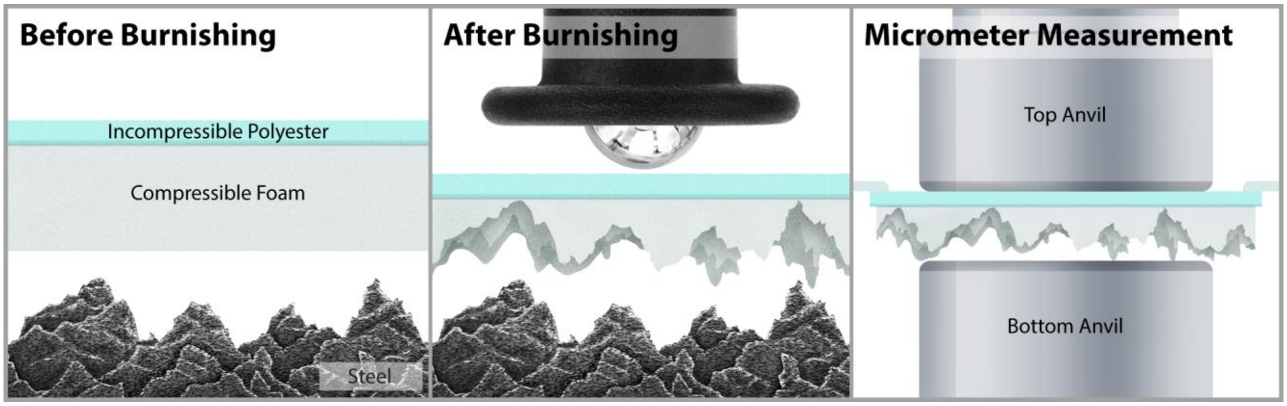

Figure 1: An overview of the burnishing process

The replica tape process provided a fast, inexpensive, quantitative, method that could be used in the field. It quickly gained popularity, and 50 years later remains among the most popular surface profile measurement methods.

There are three 'grades' of replica tape commonly used in the protective coatings industry: Coarse, for profiles between 20 – 50 µm (0.8 – 2 mils), X-Coarse for profiles between 40 – 115 µm (1.5 – 4.5 mils), and X-Coarse Plus, for profiles between 70 – 150 µm (4 – 6 mils).

Historical Attempts to Determine the Accuracy of Replica Tape

Attempts to determine the accuracy and precision of replica tape date back to 1987, when a panel of experts was convened by the National Association of Corrosion Engineers (Subsequently NACE International, Subsequently AMPP)[2]. The 1987 study compared replica tape measurements preformed on 14 panels by 7 operators, to measurements captured using a microscope focused on the peaks and valleys of the surface profile. Replica tape and focusing microscope measurements agreed within their 95 % confidence limits (two standard deviations) in 11 of 14 cases. The average difference between the two types of measurement technique was 4.5 µm (0.18 mils). The average standard deviation for the measurements made by the operators was 5.4 µm (0.21 mils), for a 95% confidence interval of ±10.8 µm (0.42 mils).

In 2012, a follow-up round-robin study was performed by the ASTM D01.46 subcommittee, with the goal of establishing the repeatability and accuracy of replica tape used in accordance with ASTM D4417[3]. Five panels were measured by three operators at eleven laboratories, for a total of 33 replica tape measurements per panel. The repeatability (95% confidence interval) of the measurements was between ±5 and 10 µm (0.2-0.4 mils) depending on the panel.

Determining accuracy is a challenge, because no traceable surface profile measurement standard exists. By their very nature, blasted profiles are random, making any attempt to generate a traceable standard impractical. The D01.46 subcommittee therefore decided to use D4417 Method D, the drag stylus, as the reference method. The drag stylus profilometer is an industry-standard method for measuring surface morphology, and more importantly, is traceable and can be calibrated using reference standards. These instruments are highly accurate, generally being specified at accuracies below 1 μm (0.04 mils).

Figure 2: Drag Stylus Profilometer

The drag stylus profilometer utilizes a fine-pointed stylus that penetrates into the surface profile. By dragging this stylus across the surface and recording measurement data, a 2D trace of the surface profile can be captured. Various mathematical functions can be performed on that 2D trade to yield a number associated with the morphology of the profile; ASTM D4417 Method D specifies Rt, the distance between the highest peak and lowest valley along a 12.5mm (1/2”) evaluation length, as the appropriate parameter.

Due to the random nature of blasted profiles the precision of this method is low, since the profile encountered along a thin line is a limited representation of the overall surface. However, this precision can be improved by taking an average of several measurements.

Using this ‘relative accuracy’ method, the accuracy of the replica tape method was determined to be about ±8 μm (0.3 mils).

In 2023, an attempt was made by this author to replicate the results of the 2012 study. While highly experienced users of replica tape were able to replicate the results to a reasonable degree, inexperienced users had significant difficulty replicating the results.

Linearization

It has long been known that replica tape responds non-linearly at the lower end of its range - where the foam becomes fully compressed - and at the upper end of its range - where the peak heights are greater than the foam's thickness.

As the tape's response becomes increasingly non-linear, measurements become increasingly inaccurate. Testex addresses this by setting conservative limits on the tape's useful range. For "X-Coarse" this range is 63um to 115um (2.5 to 4.5 mils). For "Coarse" the range is 20 to 38 um (0.8 to 1.5 mils). Small inaccuracies appear at the upper (115 um, or 4.5 mils) of "X-Coarse" and lower (20 um, or 0.8 mils) end of "Coarse". In the overlap region between the two grades an inconvenient averaging procedure must be applied, where readings are taken with “Coarse” and “X-Coarse” tape and averaged.

This averaging procedure utilizes materials and practices that are already part of the apparatus, but reduces accuracy and precision, as shown in the ASTM round robin. It also is inconvenient and confusing for some inspectors, causing a heightened risk of measurement error.

Experiments conducted by the manufacturer, based on an analysis of the ASTM round robin data and subsequent study, showed that the linearity error of replica tape was highly correlated with the surface profile being measured. For example, a panel with a measured Rt of 50 µm (2.4 mils) will consistently yield a measurement of 64 µm (2.6 mils) when measured using replica tape. By taking a significant number of measurements over a wide range of blasted profiles, this linearity error could be quantified across the measurement range of replica tape, yielding a correction factor that could be applied to readings to enhance accuracy, and eliminate the need for the cumbersome averaging procedure.

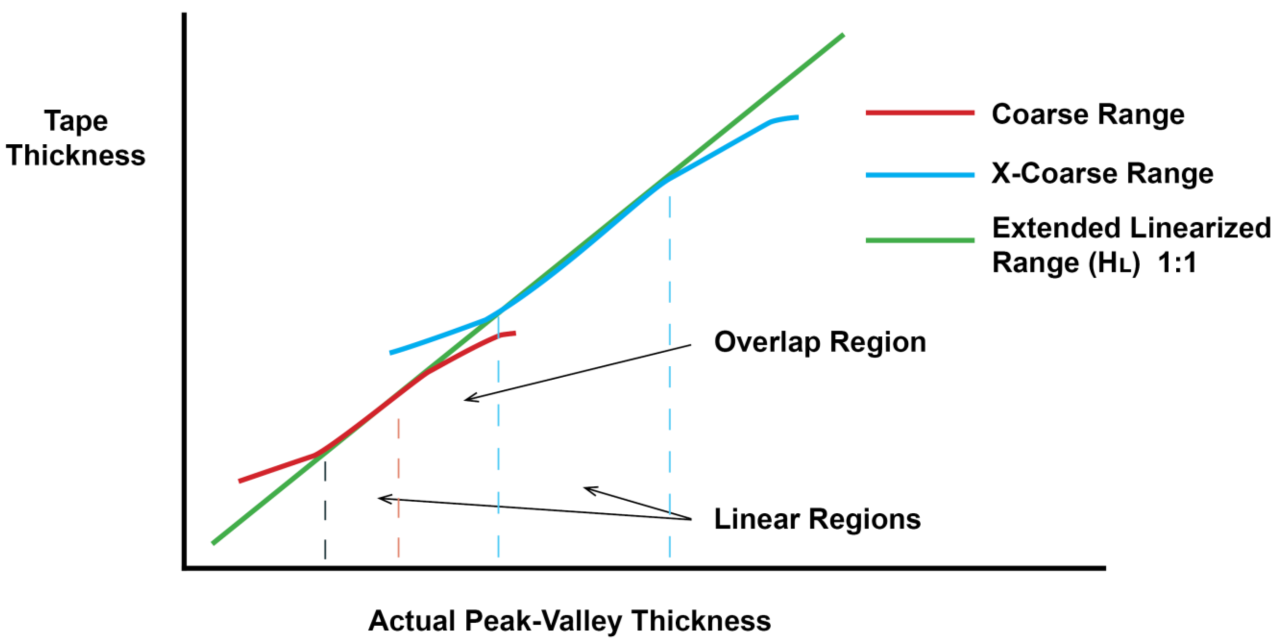

Figure 3: A graphical illustration of the linearization correction

Burnishing Tool

The replica tape method involves the use of a burnishing tool to press the mylar/foam into the blasted profile. The burnishing tool is a simple and inexpensive tool for applying pressure, but requires correct operator technique to properly burnish the replica tape. If sufficient force is not used, uncompressed areas of foam remain and an erroneously high result is measured. If excessive force is used, the peaks of the surface can penetrate past the foam into the Mylar backing, causing erroneously low results. While seasoned operators can learn to use a consistent and correct amount of force, the burnishing process remains challenging and inconsistent for new and existing inspectors.

Figure 4: The burnishing tool currently used for the replica tape method

To provide greater accuracy for users of all experience levels, a precision burnishing tool was created, and is pictured in Figure 5. It consists of an outer plastic housing containing a spring-loaded ball. The spring is calibrated to apply a known, consistent, force on the ball when the tool is pressed against the surface.

Similar to the existing method, the tool is placed on the replica tape as shown in Figure 6, and is moved in an alternating pattern until the replica foam is fully compressed, as evidenced by a consistent ‘pebble grain’ appearance. There should be no streaking or marks on the replica tape once burnished.

Figure 5: The revised precision burnishing tool, bottom view.

Regardless of the force applied by the operator, the steel burnishing ball applies a consistent amount of force, eliminating the risks of over-compressing the replica tape and driving the peaks of the surface profile into the backing material. So long as the entire area of the replica tape is burnished and the bottom face of the tool is in contact with the replica tape while burnishing, the risk of under-burnishing is also eliminated.

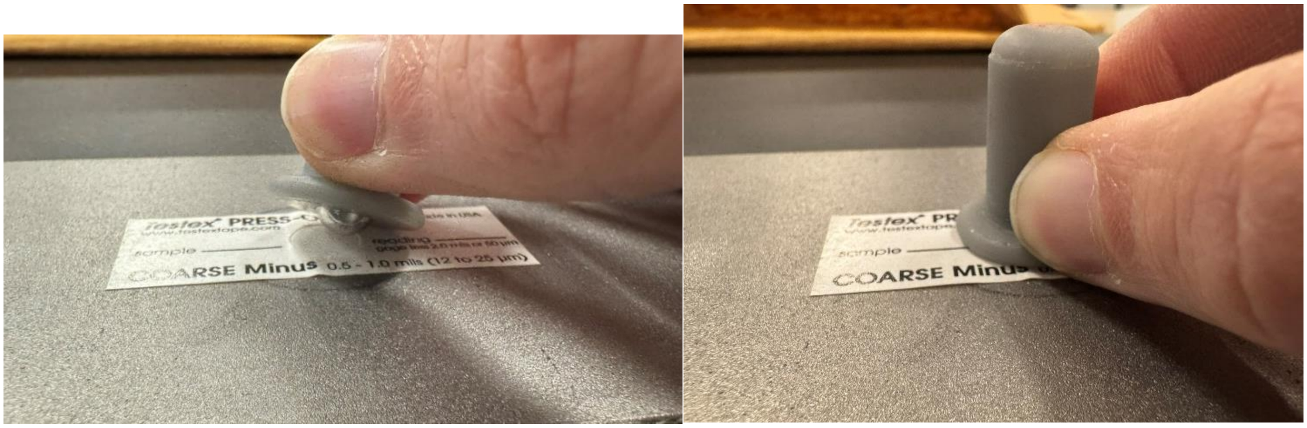

Figure 6: The revised precision burnishing tool being used to burnish replica tape

OBJECTIVE

The objective of this study is to determine the accuracy of the Replica Tape method, augmented by a precision-force burnishing tool and linearization/correction factor, in measuring Rt (peak-to-valley profile height) using a traceable reference method (the drag stylus profilometer).

EXPERIMENTAL PROCEDURE

To ensure the study was completed with test samples blasted under realistic field conditions, a set of 38 3" x 5" steel panels was commissioned from a commercial source for standardized panels . Four sets of eight panels were blasted with Shot, Steel Grit, Coal Slag, and Garnet, and six panels were blasted with Aluminum Oxide. Each set of panels was blasted with a range of abrasives, in an effort to generate a range of blast profiles. Two aluminum panels and two steel panels were also blasted using superoxalloy abrasive at lower pressure using a hobby-grade blasting setup, in an effort to create fine profiles suitable for testing the low range of Coarse grade replica tape, below the range typically used for industrial applications. Upon arrival at the laboratory, a preliminary evaluation of each panel was conducted using eight measurements of Rt with the stylus profilometer (Mitutoyo SJ-201 S/N 801624) in accordance with ASTM D4417 Method D.

Based on the preliminary evaluation, 22 panels that represented a range of Rt values and abrasive types were selected for the study and designated with a letter. Rt was then measured on each panel an additional 12 times using the stylus profilometer to increase the statistical confidence in the Rt measurements:

ID	Media Type	Rt
S	AM40/70-50	0.7
T	AM40/70-50 (Al Panel)	0.9
V	AM40/70-50 (Al Panel)	1.2
C	Stainless Steel Shot ES-300	1.6
F	Coal Slag 30/60	1.6
I	MG 25 Grit	2.0
O	Stainless Steel Shot ES-300	2.1
B	Stainless Steel Shot ES-300	2.3
R	Coal Slag 30/60	2.7
K	Garnet 30/60	2.9
H	MG 25 Grit	3.0
Q	Garnet 30/60	3.1
E	Coal Slag 12/40	3.8
J	Garnet 30/60	3.9
L	Coal Slag 12/40	4.0
N	MG 25 Grit	4.2
A	Steel Shot S230	4.5
M	Coal Slag 12/40	4.8
P	MG 25 Grit	5.1
D	Coal Slag 12/40	5.4
G	MG 25 Grit	5.7
X	Coal Slag 12/40	5.8
W	Alum. Oxide 16 Grit	7.4

Table 1: The test panels used for the study

To perform the testing, 17 test subjects were recruited from among the author’s colleagues. Effort was made to represent a range of demographics and experience using replica tape. Several participants had never used replica tape prior to this study:

Participant ID	Replica Tape Usage Prior to Study
11	> 500
12	> 500
13	25-50
14	25-50
15	25-50
16	10-25
17	0
18	25-50
19	50-100
20	10-25
21	0
22	0
23	0
24	0
25	0
26	10-25
27	10-25

Table 2: An overview of the study participants and their experience levels

The study was divided into two parts, to reduce the length of time the operators were engaged in the study at one time. 15 panels were measured with X-Coarse tape in part one of the study. In the second part of the study, 6 panels were measured with Coarse replica tape, and 6 panels were measured with X-Coarse Plus replica tape. (Some panels were used for multiple grades of tape). X-Coarse tape was the focus of the testing because it is the most popular grade, featuring a range capable of measuring commonly-encountered blasted profiles.

A station, pictured in Figure 7, was furnished with all materials required for testing, including the test panels, replica tape of the desired grade, burnishing tools, micrometer, laptop (for viewing instructional video and recording results), wax paper (for saving burnished pieces of replica tape), and paper (for cleaning micrometer anvils, as required)

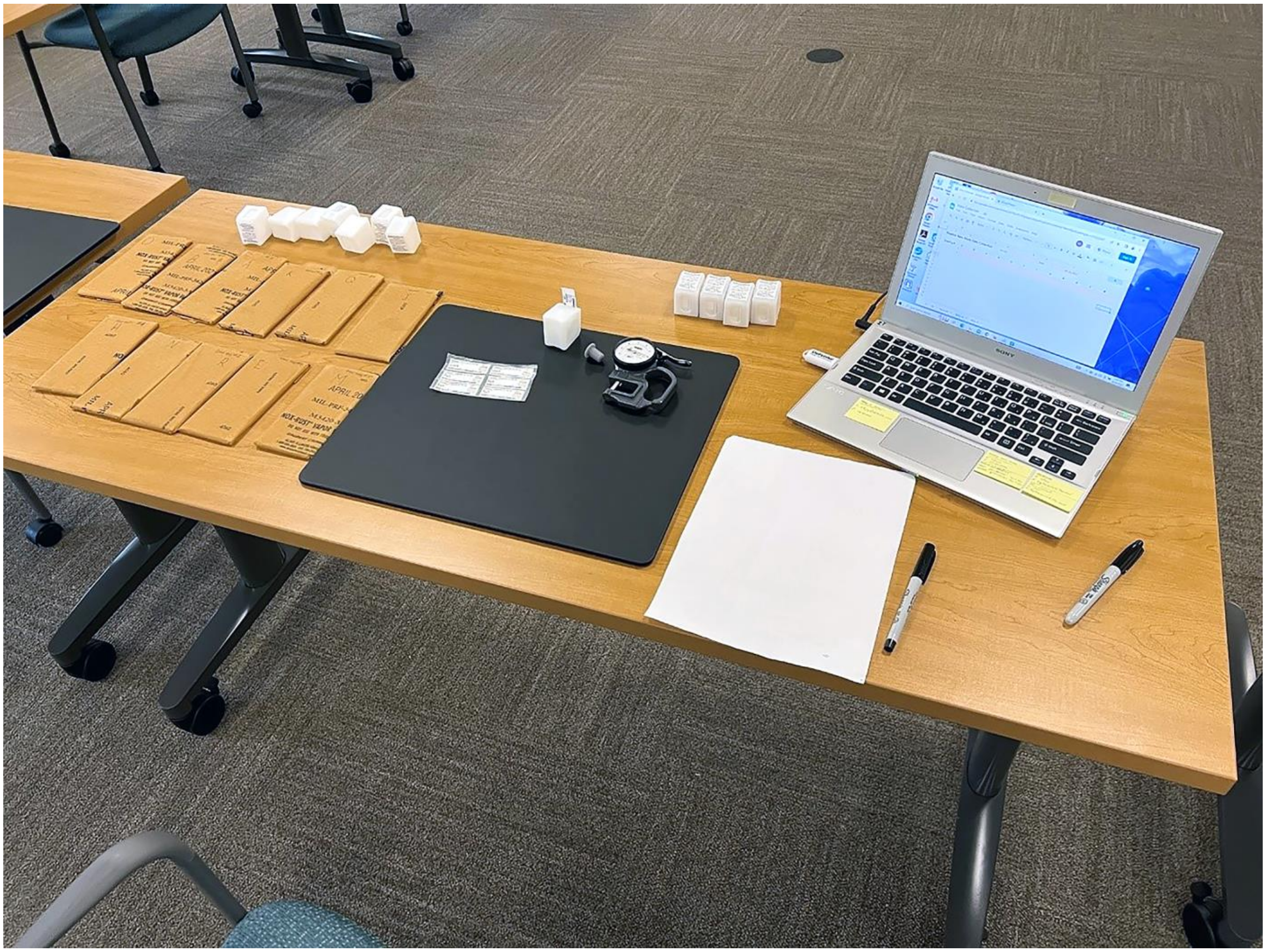
Figure 7: The station where the study was performed

For consistency, an 11-minute instructional video was recorded by the author of this study:

- One minute to review the apparatus
- One minute to review the principle of operation of replica tape
- One minute to review the operation and cleaning of the analog micrometer
- One minute to review the spreadsheet and data entry process
- One minute to explain how to open, handle, and store the test panels
- Two minutes to explain the burnishing tool and burnishing process
- One minute to explain how to measure the burnished replica tape
- Three minutes to review the process by repeating the measurement.

Testing was performed in accordance with ASTM D4417 Method C, except for the linearization and modified burnishing tool mentioned previously. Each participant was instructed to burnish the replica tape until a consistent grey pattern was attained, with no white spots or marks from burnishing. Sample pieces of burnished tape were provided to show examples of properly and improperly burnished replica tape. Two pieces of replica tape were burnished on an identified region of the panel, and measured using the micrometer. Those measurements were later averaged by the author during the data processing stage, in accordance with the manufacturer's instructions. Per the existing manufacturer's instructions, if two readings differed by more than 5 microns (0.2 mils), a third measurement was taken and averaged with the most similar of the original two measurements.

Results

X-Coarse Grade Replica Tape

In total, 510 pieces of replica tape were burnished, for a total of 255 measurements. The measurements from the X-Coarse replica tape portion of the study are summarized in Figure 8 below. The yellow band represents the 95% confidence interval for linearized measurements, and each operator's measurements are indicated with a specific color.

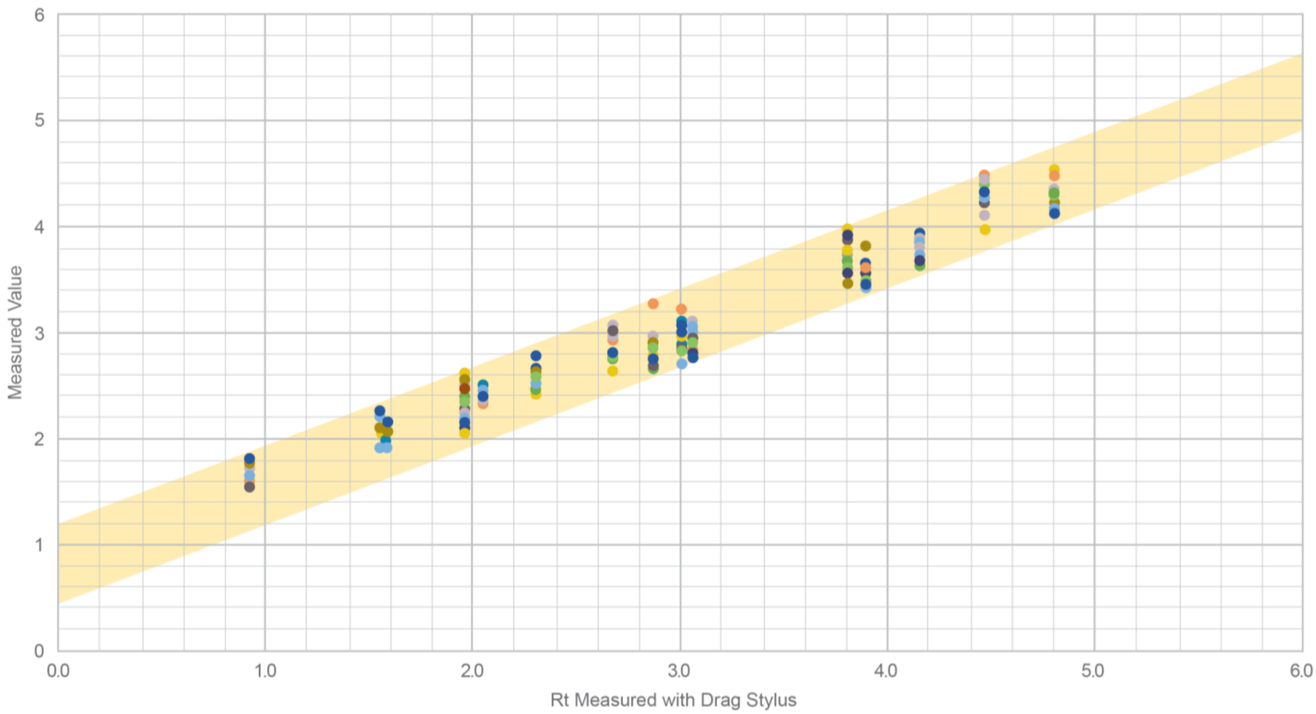

Figure 8: Measurement results from each study participant plotted against Rt values from the Drag Stylus, with the linearization curve and 95% confidence interval shaded in yellow.

The standard deviation and standard error (versus measured Rt) provide a measure of the repeatability between operators for a given panel, and the overall measurement bias for each panel, respectively.

ID	Media Type	Drag Stylus Rt µm (mils)	Replica Tape St. Deviation µm (mils)	Replica Tape Standard Error µm (mils)
T	AM40/70-50 (Al Panel)	23 (0.9)	2.7 (0.11)	2.8 (0.11)
C	Stainless Steel Shot ES-300	41 (1.6)	3.0 (0.12)	2.3 (0.09)
F	Coal Slag 30/60	41 (1.6)	2.8 (0.11)	0.5 (0.02)
I	MG 25 Grit	51 (2.0)	4.2 (0.17)	3.0 (0.12)
O	Stainless Steel Shot ES-300	53 (2.1)	1.2 (0.05)	1.0 (0.04)
B	Stainless Steel Shot ES-300	58 (2.3)	2.1 (0.08)	0.8 (0.03)
R	Coal Slag 30/60	69 (2.7)	2.9 (0.11)	2.5 (0.10)
K	Garnet 30/60	74 (2.9)	3.5 (0.14)	2.8 (0.11)
H	MG 25 Grit	76 (3.0)	3.2 (0.13)	2.3 (0.09)
Q	Garnet 30/60	79 (3.1)	3.0 (0.12)	2.0 (0.08)

E	Coal Slag 12/40	97 (3.8)	3.5 (0.14)	2.5 (0.10)
J	Garnet 30/60	99 (3.9)	2.6 (0.10)	2.8 (0.11)
N	MG 25 Grit	107 (4.2)	2.4 (0.09)	4.1 (0.16)
A	Steel Shot S230	114 (4.5)	2.1 (0.08)	3.8 (0.15)
M	Coal Slag 12/40	122 (4.8)	3.3 (0.13)	2.8 (0.11)
All Panels			**2.8 (0.11)**	**4.0 (0.16)**

Table 3: The standard deviation and standard error (versus Rt as measured by the drag stylus) for each panel

These results indicate an average precision, defined as twice the average standard deviation, of ±5.6 µm (0.22 mils). This is a representation of how similar the results were between the operators, and is also referred to as 'reproducibility'.

The standard measurement error was ±4.0 µm (0.16 mils).This is a representation of how close the results were to the traceable drag stylus measurements. The 95% confidence interval was therefore ±8.0 µm (0.32 mils)- typically considered the accuracy of the test method. Notably, each of the 255 measurements was inside the ±8 µm (0.32 mils) range.

Coarse Grade Replica Tape

For the Coarse Grade portion of the study, 177 pieces of replica tape were burnished, for a total of 89 measurements. The measurements are summarized in Figure 9 below. The yellow band represents the 95% confidence interval for linearized measurements, and each operator's measurements are indicated with a specific color.

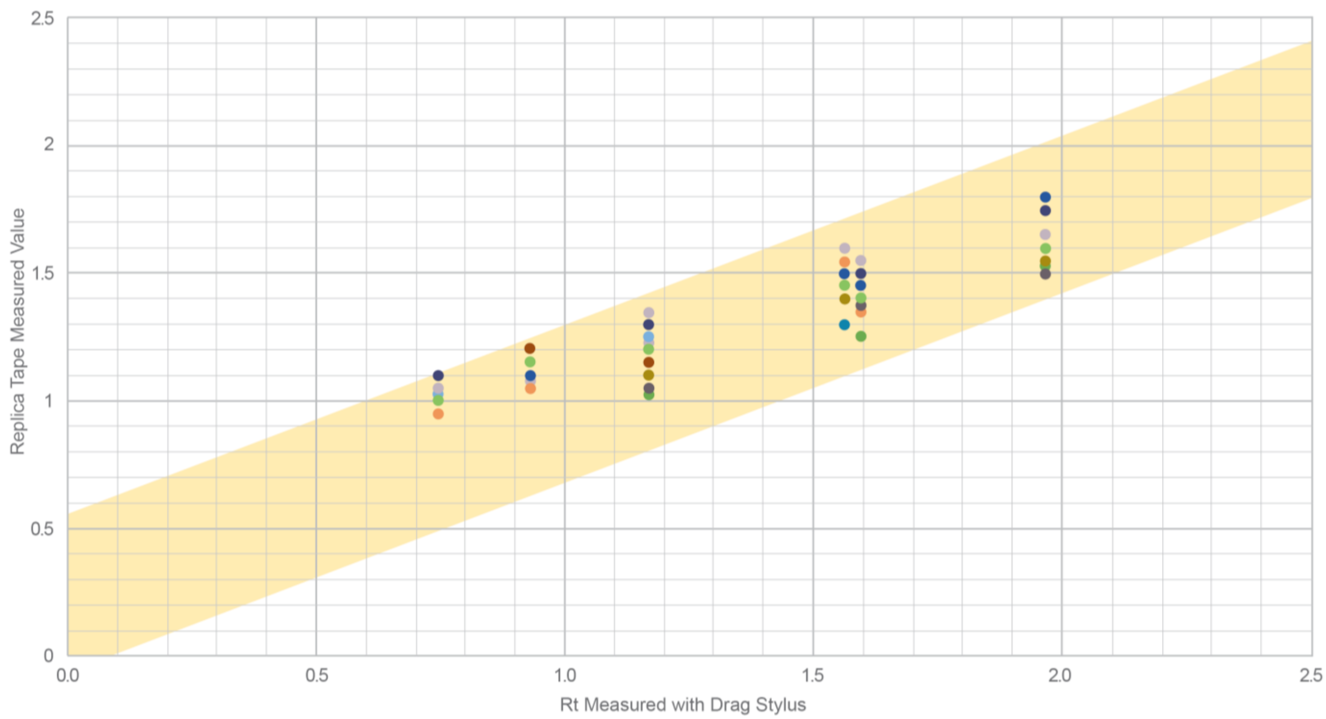

Figure 9: Measurement results from each study participant plotted against Rt values from the Drag Stylus, with the linearization curve and 95% confidence interval shaded in yellow.

The standard deviation and standard error (versus measured Rt) provide a measure of the repeatability between operators for a given panel, and the overall measurement bias for each panel, respectively.

ID	Media Type	Drag Stylus Rt µm (mils)	Replica Tape St. Deviation µm (mils)	Replica Tape Standard Error µm (mils)
S	AM40/70-50	19 (0.7)	1.3 (0.05)	5 (0.2)
T	AM40/70-50 (Al Panel)	24 (0.9)	1.3 (0.05)	2.8 (0.11)
V	AM40/70-50 (Al Panel)	30 (1.2)	2.4 (0.09)	1.2 (0.05)
C	Stainless Steel Shot ES-300	40 (1.6)	2 (0.08)	0.8 (0.03)
F	Coal Slag 30/60	41 (1.6)	1.9 (0.08)	0.5 (0.02)
I	MG 25 Grit	50 (2.0)	2.3 (0.09)	1.3 (0.05)
All Panels			**1.9 (0.07)**	**3.7 (0.14)**

Table 4: The standard deviation and standard error (versus Rt as measured by the drag stylus) for each panel

These results indicate an average precision, defined as twice the average standard deviation, of ±1.9 µm (0.07 mils). This is a representation of how similar the results were between the operators, and is also referred to as 'reproducibility'.

The standard measurement error was ±3.7 µm (0.14 mils).This is a representation of how close the results were to the traceable drag stylus measurements. The 95% confidence interval was therefore ±8 µm (0.32 mils)- typically considered the accuracy of the test method. Notably, each of the 89 measurements was inside the ±8 µm (0.32 mils) range.

X-Coarse Plus Grade Replica Tape

For the X-Coarse Plus grade portion of the study, 210 pieces of replica tape were burnished, for a total of 105 measurements. The measurements are summarized in Figure 10 below. The yellow band represents the 95% confidence interval for linearized measurements, and each operator's measurements are indicated with a specific color.

Panel W was included in this phase of the study despite having at Rt of 189µm (7.4 mils), which exceeds the maximum 150µm (6.0 mils) range of X-Coarse Plus replica tape. Despite significant effort, it was difficult to procure panels with an Rt in the 6.0-7.0 range, and it was decided to evaluate panel W, which had the next-highest profile. Since panel W was far outside the range of X-Coarse Plus replica tape, the measurements were not included in the overall precision or accuracy figures. The results from panel W indicate that the maximum range of X-Coarse Plus replica tape is likely greater than 150µm (6.0 mils), but further study is needed with panels in that range to determine the exact maximum range.

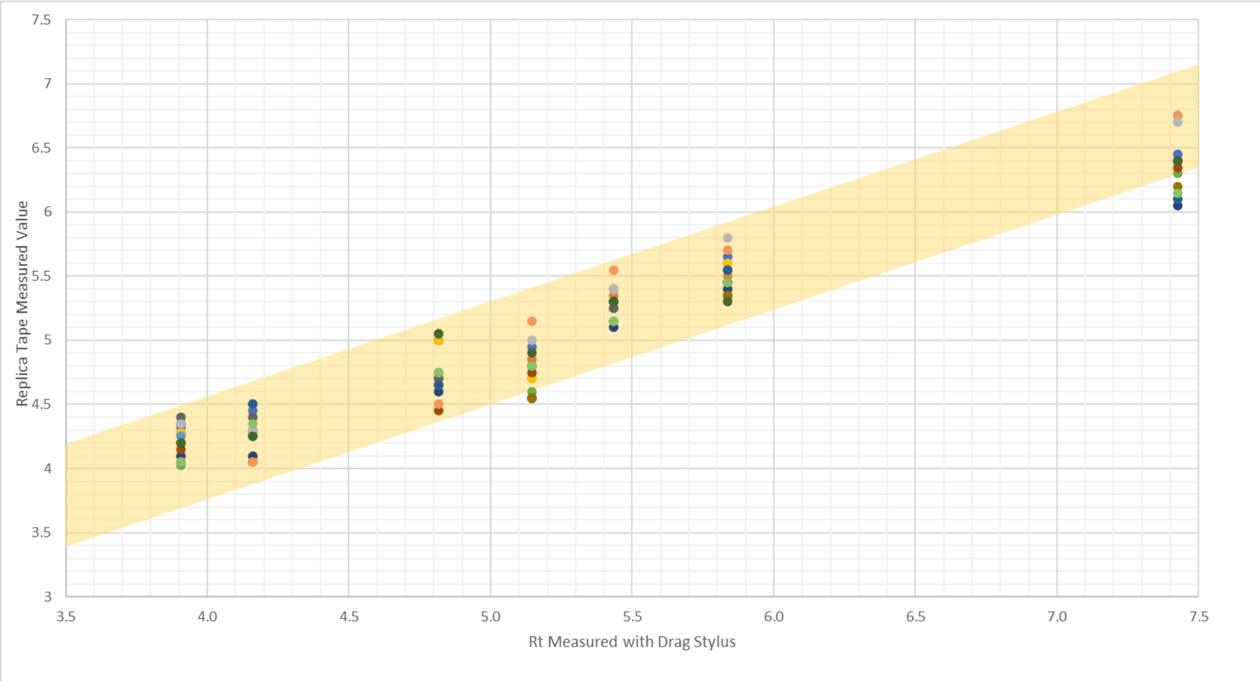

Figure 9: Measurement results from each study participant plotted against Rt values from the Drag Stylus, with the linearization curve and 95% confidence interval shaded in yellow.

The standard deviation and standard error (versus measured Rt) provide a measure of the repeatability between operators for a given panel, and the overall measurement bias for each panel, respectively.

ID	Media Type	Drag Stylus Rt µm (mils)	Replica Tape St. Deviation µm (mils)	Replica Tape Standard Error µm (mils)
J	Garnet 30/60	99 (3.9)	3.2 (0.13)	3.1 (0.12)
N	MG 25 Grit	106 (4.2)	3.8 (0.15)	2.1 (0.08)
M	Coal Slag 12/40	122 (4.8)	5.0 (0.20)	3.6 (0.14)
P	MG 25 Grit	131 (5.1)	4.8 (0.19)	9.5 (0.37)
D	Coal Slag 12/40	138 (5.4)	3.3 (0.13)	2.4 (0.09)
X	Coal Slag 12/40	148 (5.8)	3.3 (0.13)	1.5 (0.06)
W	*Alum. Oxide 16 Grit*	*189 (5.8)*	*5.7 (0.23)*	*11.8 (0.47)*
All Panels Excluding W			**3.9 (0.15)**	**4.9 (0.19)**

Table 4: The standard deviation and standard error (versus Rt as measured by the drag stylus) for each panel

These results indicate an average precision, defined as twice the average standard deviation, of ±7.8 µm (0.30 mils). This is a representation of how similar the results were between the operators, and is also referred to as 'reproducibility'.

The standard measurement error was ±4.9 µm (0.19 mils).This is a representation of how close the results were to the traceable drag stylus measurements. The 95% confidence interval was therefore ±10 µm (0.38 mils)- typically considered the accuracy of the test method. 100 of the 105 measurements were inside the ±10 µm (0.38 mils) range.

CONCLUSIONS

Slight updates to the Replica Tape method for measuring surface profile, namely the use of an updated burnishing tool and a linearization method for correcting measurement results, were evaluated in this study. Those two updates appeared to improve the accuracy and precision of the test method, despite a much less experienced roster of operators than in previous studies.

The results in this study are similar, but compare favorably to, the results of the previous ASTM ILS testing preformed by D01.46 committee. It is hypothesized that the revised burnishing tool more than offset the relative inexperience of the operators (there was no statistically significant difference between the results obtained from new and experienced operators), reducing overall variability. It is also hypothesized that the linearization process improved repeatability and accuracy at the upper and higher ends of the replica tape range.

Based on this study, the following accuracy and precision statements are suggested:

Replica Tape Grade	Precision	Accuracy
Coarse	±2 µm (0.1 mils)	±8 µm (0.3 mils)
X-Coarse	±6 µm (0.2 mils)	±8 µm (0.3 mils)
X-Coarse Plus	±8 µm (0.3 mils)	±10 µm (0.4 mils)

ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance of KTA-Tator in preparing the test panels used for this study.

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