The Effect of Peak Count or Surface Roughness on Coating Performance

Putting a long-held assumption about surface profile to the test, the authors show this: profile peak count can be measured, it can be controlled, and it does make a difference in coating performance.

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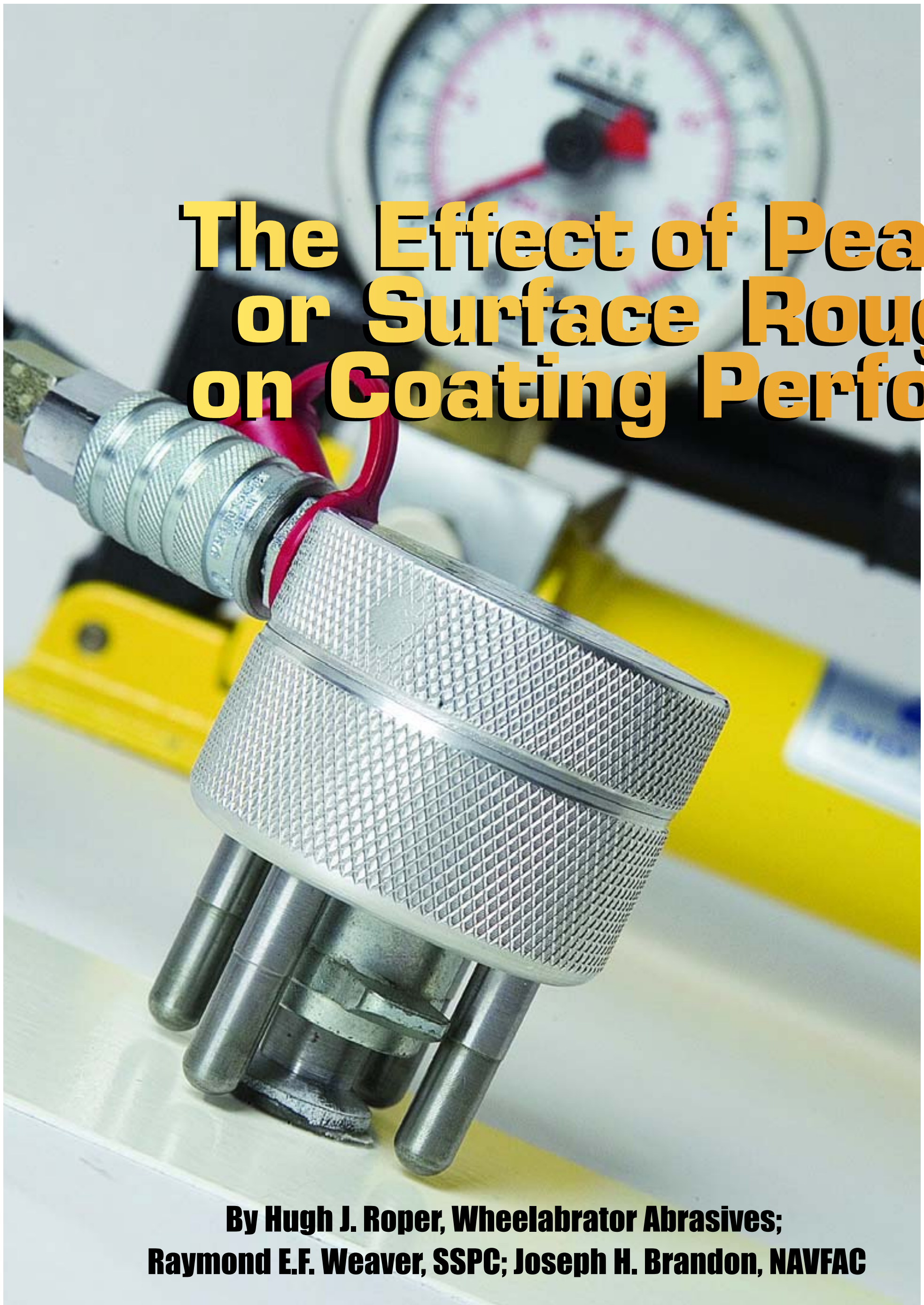


Coating adhesion was measured in accordance with ASTM D 4541 using a Type III GM 1, self-aligning tester. Courtesy of Elcometer

It is well accepted in the protective coatings industry that coating performance is related to the profile height of a steel substrate. Coating specifications can include a minimum and/or a maximum profile measured in accordance with ASTM D 4417, "Test Methods for Measurement of Surface Profile of Blast Cleaned Steel," usually using a comparator disk or replica tape. Some specifiers require an angular profile, i.e., steel grit rather than steel shot must be used for blast cleaning. This is certainly the case when applying a zinc or aluminum thermal spray coating. In the present study, the profile height was held constant and the peak count, or roughness, was varied. Coating performance was then measured by pull-off adhesion and scribe undercutting after exposure in accelerated test environments.

We have accumulated much anecdotal evidence over years of working with abrasives. A rule of thumb for coating adhesion is that the higher the peak count, the better the adhesion, provided the coating completely wets the surface. A rougher surface has better adhesion because the area between substrate and coating is increased. In addition, as the number of peaks increases, the steepness of the peaks increases, resulting in disbonding forces that are more shear and less tension.

To see if we can go beyond anecdotal evidence about the effect of peak count on coating performance, we conducted carefully controlled accelerated exposure tests using six coatings. Coating performance was evaluated using pull-off adhesion tests, and scribe undercutting measurements. The only profile variable was peak count (number of peaks per unit length). All panel preparation, exposure tests, and data collection were conducted by Hugh Roper or by participating coating company technicians under his direct supervision. This article will show that surface roughness, as determined by the number of peaks per unit length, has a measurable impact on adhesion and scribe undercutting resistance.

For a full evaluation of the effect of roughness, there must be a method to measure it objectively and quantitatively. Fortunately, portable stylus instruments exist for this specific task. Currently, at least four companies make this type instrument. New laser technology is being developed to replace the mechanical stylus and possibly enhance the characterization of blast cleaned surfaces.

In addition to simply measuring peak count, there must be a means to control it. By adjusting particle size, shape, and impact velocity, the peak count can be controlled independently from profile height. In summary, peak count can be measured, it can be controlled, and it makes a difference in coating performance.

Characterization and Measurement of Surface Profile Parameters

As early as 1974 Keane et al.[1] recognized that peak-to-valley distance alone could not completely describe a blast cleaned surface for painting. Scanning electron microscope (SEM) images clearly revealed that steel shot, steel grit, and nonmetallic abrasives each produce very different surface textures. What was qualitatively described then is quantified in this report.

Profile was measured with a portable stylus. Courtesy of Mahr Federal

Measuring Profile

Three parameters (Rmax, Rt, and Pc) were used to describe the blast profile, and all were measured with a Perthometer M4Pi manufactured by Mahr Federal. A fourth parameter, Rz (average maximum peak height), is included in an ASTM test method under development but was not considered in this study. The Perthometer operates by drawing a stylus at constant speed across a 0.22-inch (5.6-mm) length of the surface. The diamond point has a diameter of 0.2 mil (5 µm). The length of travel of the stylus is divided into 7 equal segments. The first and the last segments

Key Words

Sampling Length: *The length of a straight line trace of seven segments that is representative of the surface whose roughness is to be evaluated.*[1] The sampling length is the total length of travel of the stylus during one trace, 0.22 inch (5.6 mm).

Evaluation Length: *Consists of five segments, taken from the sampling length after discarding the first and the last segments, used for assessing the profile under evaluation.*[2] The evaluation length is the part of the stylus travel that is used in computing the surface profile parameters. It is five-sevenths of the length of travel of the stylus (5/7 · 0.22 = 0.16 inch or 4.0 mm).

Sampling Segment: One fifth of the evaluation length or one seventh of the length of travel of the stylus (1/7 · 0.22 = 0.031 inch or 31 mils or 0.8 mm).[3]

Rmax: *The largest peak to valley measurement in the five evaluation segments of the sampling length.*[4] The distance from the highest peak to the lowest valley within each sampling segment is measured. The largest of these five peak/valley distances is recorded as Rmax.

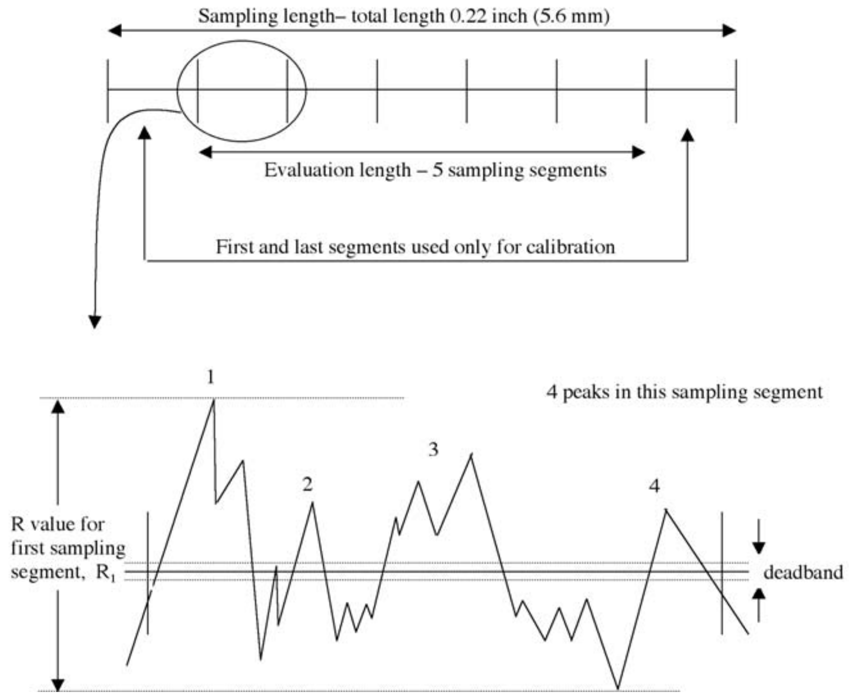
Rt: *The maximum peak to lowest valley measurement in the evaluation length.*[5] Unlike Rmax, when measuring Rt, it is not necessary for the highest peak and the lowest valley to lie in the same sampling segment.

Mean Line: A line half way between the highest peak and the lowest valley in the evaluation length and centered between the two lines defining the deadband.

Deadband: *That distance above and below the mean line that a continuous trace line must cross in both directions (up and down) to count as a single peak. The deadband disregards small, spurious peaks due to noise.*[6] The deadband width is usually adjusted to fall in the range from 0.04 to 0.05 mils (1.0 to 1.25 µm). The deadband was adjusted to 0.06 mils (1.5 µm) in this study to optimize noise reduction and repeatability.

Pc–Peak Count: *The number of peak/valley pairs per unit distance extending outside a "deadband" centered on the mean line. The width of a peak/valley pair is defined by the distance between crossings of the deadband region.*[7] Because the deadband width is so small compared to the size of the peaks and valleys encountered in coatings work, the deadband region is essentially the mean line. For all practical purposes, a peak would be registered if a continuous trace starts below the mean line, goes above it, and then below it.

1. Definitions are taken from a draft ASTM document "Standard Test Method for Measurement of Surface Roughness of Abrasive Blast Cleaned Metal Surfaces Using a Portable Stylus Instrument." Sampling length is defined as "Traversing Length" in ASME B46.1-2002.
2. Taken from a draft ASTM document "Standard Test Method for Measurement of Surface Roughness of Abrasive Blast Cleaned Metal Surfaces Using a Portable Stylus Instrument."
3. The five sampling segments within the evaluation length are defined as "Sampling Lengths" in ASME B46.1-2002.
4. Taken from a draft ASTM document "Standard Test Method for Measurement of Surface Roughness of Abrasive Blast Cleaned Metal Surfaces Using a Portable Stylus Instrument." Rmax is also called "Maximum roughness Depth" in ASME B46.1-2002.
5. Taken from a draft ASTM document "Standard Test Method for Measurement of Surface Roughness of Abrasive Blast Cleaned Metal Surfaces Using a Portable Stylus Instrument." Rt is also called "Maximum Height of the Profile" in ASME B46.1-2002.
6. Taken from a draft ASTM document "Standard Test Method for Measurement of Surface Roughness of Abrasive Blast Cleaned Metal Surfaces Using a Portable Stylus Instrument."
7. Taken from a draft ASTM document "Standard Test Method for Measurement of Surface Roughness of Abrasive Blast Cleaned Metal Surfaces Using a Portable Stylus Instrument." Pc is also called "Peak Density" in ASME B46.1-2002 and "Peaks Per Inch Count" in SAE J911.



- The vertical scale is distorted because for abrasive blast cleaned steel, the deadband is typically 0.04 to 0.05 mils (1 to 1.25 µm) while the R value is typically 2 to 4 mils (50 to 100 µm). The deadband for the instrument used in this study was set at 0.060 mils (1.5 µm). At 100 peaks per inch (40 peaks/cm), the average distance between peaks is 10 mils (250 µm).
- The distance from the highest peak to the lowest valley in the first segment of the evaluation length is R_1; the distance from the highest peak to the lowest valley in the second segment is R_2; and so on. The largest of R_1 to R_5 is defined as Rmax.
- The average value of R_1 to R_5 is defined as Rz.
- Rt is the distance from the top of the highest peak in the evaluation length to the lowest valley in the evaluation length. The highest peak and the lowest valley do not have to lie in the same sampling segment.
- The peak count, Pc, expressed as peaks per inch (peaks per centimeter), is computed from the number of peaks counted in the evaluation length (five evaluation segments). The "peak" to the left of peak #2 is not counted as a peak since it does not cross the deadband.
- When measuring Rmax, Rz, and Rt, "distance" is measured perpendicular to the mean line as shown in the figure.
- The mean line is half way between the highest peak and the lowest valley in the evaluation length and is centered between the two lines defining the dead band.

Figure 1: Schematic illustrating the profile parameters

are used only to set the internal calibration of the instrument. Data from the middle 5 segments are used by the internal software to compute the profile parameters. Other stylus instruments operate in a similar fashion.

The stylus (Type 150) used in this study has a maximum profile height range of 6 mils (150 µm). Although the Perthometer computes to the nearest 0.001 mil (0.04 µm), the data in this report are often rounded to a hundredth of a mil.

Terms used in this article are defined in the box titled "Key Words". Some parameters are illustrated in Fig 1.

Each trace yields a printout with the value for each of these parameters. Five traces were made on each 4 x 6 inch (10 x 15 cm) test panel. One trace was made in each corner, one inch from the edge, with the stylus moving parallel to the long axis of the panel. A fifth trace was made in the center of the panel with the stylus movement perpendicular to the other traces. Measurements made on the backs were essentially the same as those made on the fronts. Profile parameter measurements were very consistent from one panel to the next and from one batch to the next. The blast cleaning process was very tightly controlled for each of the three blasting conditions, as is evidenced by the uniformity of the data.

Test Details

The Substrate

All panels were cut from 4-inch-wide (10-centimeter-wide) bar stock that came from the same heat of low carbon structural steel. Final panel dimensions were 4 x 6 x ¼ inch (10 x 15 x 0.6 cm). All steel was rust condition A (intact mill scale). No oils were used in rolling or cutting the steel. All sharp edges were rounded by grinding. A hole was drilled in the center top of each panel so they could be hung on a hook during paint application and drying. Each panel was identified by notches cut into the top (identifying the peak count range) and the edge (identifying the number).

Surface Preparation

All panels were blast cleaned with a GB (50-55 Rockwell C) steel grit operating mix in a wheel machine at the Wheelabrator Abrasives test facility. The unit is a commercial machine run under normal operating conditions, not special laboratory conditions. The degree of cleaning was SSPC-SP 10, Near-White Blast Cleaning. The target profile height (Rmax) was 2.5 mils (63 µm) for all panels. After being blast cleaned, the panels were sorted, wrapped in VPI paper, and sealed in a plastic bag for distribution.

To keep the profile height constant and change the peak count density, three different controlled steel grit operating mixes of standard SAE abrasive sizes were used. Abrasive velocity (wheel speed) was adjusted to maintain the targeted profile depth. There were three different ranges of peak count—high, medium, and low. Small size grit will give many

Table 1: List of coatings used

Coating Code	Description	Color	Nominal DFT	
			mils	micrometers
A	Polyurethane hybrid	gray	20	500
B	Polyurethane 15 (modified)	black	20	500
C	Polyurethane 30 (modified)	white	20	500
D	Epoxy	gray	7	175
E	Phenolic high temperature for immersion	gray	15	375
F	Phenolic	cream	13	325

Coatings A, B, and C are from one manufacturer; Coating D from another manufacturer; and Coatings E and F from a third manufacturer.

Table 2: Number of test panels in each exposure environment and nominal exposure times for each test

Coating Code	Exposure	No. of Panels	Nominal times(1) (h) when panels were tested					
			@ Cure	1000	2000	3000	4000	5000
A	salt spray(2)	6	x	x	x	x	x	x
B	salt spray(2)	6	x	x	x	x	x	x
C	salt spray(2)	6	x	x	x	x	x	x
D	Prohesion/UV-con(3)	6	x	x	x	x	x	x
E(4)	salt spray(2)	6	x	x		x	x	
	salt water immersion	3	x	x		x	x	
F(4)	salt spray(2)	6	x	x		x	x	
	salt water immersion	3	x	x		x	x	

There were one or two panels for each coating - peak count - environment combination. After testing, the same panel was re-exposed for further exposure and testing.

(1) Exact evaluation times were determined by availability of the principal investigator and the testing laboratory.
(2) ASTM B 117, Practice for Operating Salt Spray (Fog) Apparatus
(3) ASTM D 5894, Practice for Cyclic Corrosion /UV Exposure of Painted Metal, (Alternating Exposures in Fog/Dry Cabinet and a UV/Condensation Cabinet)
(4) For Coatings E and F, pull-off data at cure were taken from replicate panels that were not subsequently exposed. Panels in immersion were not scribed.

peaks, but the velocity must be increased to achieve the desired profile height. Large sized abrasive at lower velocity will give fewer peaks with the same profile height. Both sides of each panel were prepared the same.

In air blast operations, the same profiling effects can be produced by varying the abrasive size, air pressure, nozzle type, and flow rate and by consistently maintaining the appropriate blasting angle and the appropriate nozzle-to-workpiece distance. Based on field experience, the most effective blast angles for recyclable abrasives are between 55 and 70 degrees; for non-recyclable abrasives, the optimum blast angle is 90 degrees.

The Coatings

The coating manufacturers (major companies) that participated in this study were granted anonymity because it was not the coatings that were to be compared to other coatings, but rather the effect of surface profile parameters on coating performance. There is no a priori reason to believe that the effect of peak count would be the same for all generic classes of coatings. Similarly, all formulations of a generic coating type may not necessarily exhibit the same response to peak count variations. The six coatings used in this study are described in Table 1.

Paint Application

Each coating was applied at its manufacturer's facility by in-house personnel. Blast cleaned panels were removed from the plastic bag, unwrapped, and immersed in methyl ethyl ketone (MEK) for 24 hours. The solvent was visually inspected for oil and other contamination. Some of the MEK was poured off before the panels were removed from the solvent. Panels were hung on hooks in the spray booth and allowed to air dry.

The panels were randomly checked for micronic backside contamination, i.e., minute dust particles (metallic and nonmetallic) that remain on the panels after they are blown down with air or vacuum cleaned. This type of contamination is referred to as "backside" because when an adhesion pull test is performed, the particles are visible on the backside of the coating. Scotch Magic Tape #810 from 3M was pressed onto the panels. After removal, the tape was mounted on a bright white surface where contamination picked up by the tape became visible using up to 200x magnification. This test (similar to ISO 8502-3[2]) showed all test panels to be extremely clean.

Both sides of all the panels were coated from the same mix. The coating was cured in accordance with the manufacturer's recommendations.

Exposures

All coatings were not exposed in all environments. Table 2 lists the exposures chosen for each coating type. The most common accelerated exposure environment was salt spray (ASTM B 117) with 5 percent sodium chloride. The two phenolic systems were also exposed in aerated synthetic sea

Table 3: Raw profile data for panels with high peak count to be coated with paint system A

Table 3a: Rmax (largest peak to valley measurement)

Panel ID	Rmax (mils)					
	1	2	3	4	5	Average
1-1-A	2.578	2.490	2.170	2.248	2.404	2.378
1-2-A	2.191	2.708	2.137	2.725	1.999	2.352
1-3-A	2.370	2.208	2.674	1.995	2.655	2.380
1-4-A	2.526	2.230	2.177	2.114	2.669	2.343
1-5-A	2.314	2.213	2.263	2.786	2.289	2.373
1-6-A	2.283	2.297	2.737	2.285	1.991	2.319
1-7-A	2.902	2.418	2.867	2.274	2.572	2.607
1-8-A	2.614	2.719	2.169	2.102	2.623	2.445

sample standard deviation 0.257
standard deviation of the means 0.091
Grand Average 2.400

Table 3b: Rt (maximum peak to lowest valley measurement)

Panel ID	Rt (mils)					
	1	2	3	4	5	Average
1-1-A	2.731	2.945	2.375	2.360	2.404	2.563
1-2-A	2.418	2.796	2.137	2.725	1.999	2.415
1-3-A	2.489	2.293	2.674	2.246	2.655	2.471
1-4-A	2.779	2.230	2.819	2.214	2.669	2.542
1-5-A	2.354	2.213	2.263	2.786	2.347	2.393
1-6-A	2.283	2.396	2.737	2.512	1.991	2.384
1-7-A	2.902	2.418	2.879	2.247	2.572	2.604
1-8-A	2.614	2.719	2.198	2.124	2.770	2.485

sample standard deviation 0.264
standard deviation of the means 0.082
Grand Average 2.482

Table 3c: Pc (peak count)

Panel ID	Pc (peaks per inch)					
	1	2	3	4	5	Average
1-1-A	125	119	131	144	146	133
1-2-A	131	119	125	119	131	125
1-3-A	156	126	144	119	109	131
1-4-A	138	144	125	113	106	125
1-5-A	131	131	156	113	119	130
1-6-A	113	125	113	131	125	121
1-7-A	119	138	138	136	138	134
1-8-A	131	143	119	144	138	135

sample standard deviation 12
standard deviation of the means 5
Grand Average 129

water immersion. The epoxy system was exposed in a prohesion/UV condensation cycle per ASTM D 5894. Accelerated exposures were conducted by the coating manufacturers. The principal investigator assisted each technician with the panel evaluations.

Pull-Off Adhesion Tests

Pull-off adhesion testing was conducted in accordance with ASTM D 4541 using a Type III GM 1, self-aligning hydraulic tester from Elcometer. All pulls were done with the same machine. Many pulls were done on each test panel. The dollies were prepared by abrasive blast cleaning with steel grit to a minimum profile of 2 mils (50 microns), then thorough cleaning with MEK solvent. They were attached to the test panels with LaPage's steel-filled epoxy adhesive to which a very small amount of #6 glass beads had been added to ensure an even layer of glue under each dolly. There were very few glue failures, and all glue failures were retested. If bare steel was exposed at the pull-off site, it was touched up with paint before the panel was re-exposed. Nothing was done to sites with 100% cohesive failure, and no rust appeared at these sites.

Scribe Undercutting Measurements

A 3-inch (75 mm) vertical scribe was centered on the front of each test panel. The maximum undercutting at any point along the scribe was measured from the center of the scribe.

Surface Profile Data

Profile Parameters

At least five traces with the stylus instrument were taken on each test panel. To show the consistency of the data, Table 3 gives raw profile data for Rmax, Rt, and Pc for panels coated with Paint A. Profile data for the other panel groups is similar.

The value assigned to Rmax for a single panel is the average of five traces. The average Rmax for these eight panels is 2.4 mils (˜60 µm). The minimum value of Rmax for any one panel was 2.3 (˜58 µm) and the maximum was 2.6 (˜66 µm). Similarly, the values for Rt ranged from a low of 2.4 to a high of 2.6 with an average of 2.5 mils (˜63 µm). One would expect Rt to be larger than Rmax because the highest peak and the lowest valley used to compute Rt do not need to lie in the same segment. The

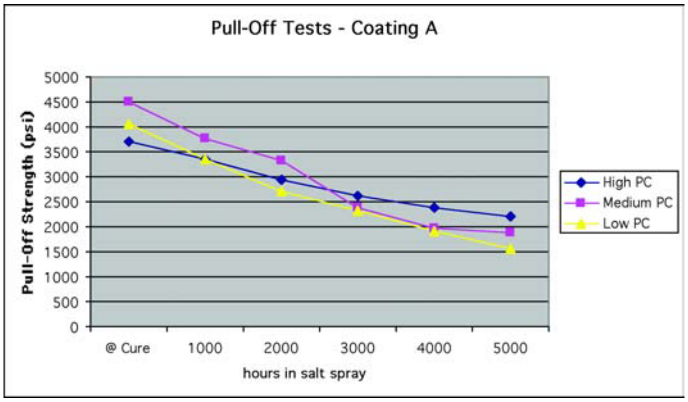


Figure 2: Comparison of pull-off data for Coating A for panels with high, medium, and low peak counts after exposure in salt spray. Each data point is the average of three pull-off readings. All pulls for the high and the medium peak count panels were cohesive failures within the coating itself. All three pulls at 5000 hours for the low peak count panel failed at the substrate, where about 50 percent was substrate failure and 50% was cohesive failure.

Table 4: Summary of statistical data on profile parameters for 144 panels

Peak Count Range	Rmax		Rt		Pc	
	mean	s	mean	s	mean	s
High	2.44	0.15	2.55	0.14	126	5
Medium	2.52	0.15	2.67	0.13	101	5
Low	2.51	0.13	2.68	0.15	56	4

s = standard deviation of the mean

Table 5a: Pull-off data in psi for Coating A exposed in salt spray – average of 3 pulls

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-3-A	High	3700	3367	2950	2617	2383	2217
2-3-A	Medium	4500	3766	3333	2383	1983	1883
3-3-A	Low	4067	3300	2700	2333	1917	1550

1000 psi = 6.895 MPa

Table 5b: Percentage of failure at the substrate for Coating A exposed in salt spray – 3 pulls per panel

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-3-A	High	0	0	0	0	0	0
2-3-A	Medium	0	0	0	0	0	0
3-3-A	Low	0	0	0	0-0-10	0-15-20	40-50-60

0 = no substrate failure
Multiple entries indicate the percent substrate failure for each of the three pulls; all other failures were cohesive.

closeness of Rt and Rmax indicates a very uniform surface profile height.

As with Rmax and Rt, the peak count value, Pc, assigned to a single panel is the average of five traces. The panel from this group with the highest peak count (135) and the one with the lowest peak count (121) are within 6 percent of the average (129). The standard deviation of all the traces was 12, which means that if another trace was made, there is a 68 percent probability that it would give a peak count of 129 ± 12, or between 117 and 141. The standard deviation of the means was 5; so if another panel was measured by averaging five traces, the average would have a 68 percent probability of falling within 129 ± 5, or between 124 and 134 peaks per inch. Other panel sets were also very consistent.

There were 144 panels blast cleaned for this project, 48 with each of the three peak count ranges. The statistical data attesting to the uniformity of the panels is given in Table 4. Of the 144 panels prepared for this study, 42 were exposed in an accelerated test, and six others were used for pull-off data at cure for Coatings E and F.

From the values of the surface profile parameters given in Table 4, it is evident that the panel preparation was well controlled. It is also evident that profile height as measured by Rmax or Rt is independent from peak count. The three panel sets all have essentially the same Rmax and Rt but very different peak counts.

Pull-Off Adhesion and Scribe Undercutting Data and Analysis

Coating A, Hybrid Polyurethane in Salt Spray

Each coating group was tested independently. Three pull-off adhesion readings were made after full cure before any accelerated exposure and at various intervals throughout the exposure time of 5000 hours. The average of the three pulls for each panel with Coating A (hybrid polyurethane) is given in Table 5a and the description of the mode of failure is given in Table 5b. Figure 2 is a plot of this data.

In order to show the level of consistency of the pull-off data, the value of each pull for Coating A is given in Table 6.

For exposures at 3000 hours and above, the trend is that the higher the peak count, the higher the pull-off strength. This is most pronounced at 5000 hours where the low peak count surface partially failed at the steel/coating interface. Prior to 5000 hours exposure, where adhesion failure is almost all cohesive, the peak count is not a factor. The downward slope of the lines in Figure 2 can be attributed to the weakening of the internal strength of the coating as it absorbs moisture and ages normally.

The panels with Coating A were scribed and exposed in salt spray per ASTM B 117. Scribe results are given in Table 7 and plotted in Figure 3. The maximum undercutting or

Table 6: Complete pull-off adhesion data in psi for Coating A (polyurethane) panels exposed in salt spray

Exposure Hours	Pull 1	Pull 2	Pull 3	Average	Range*
High Peak Count (Panel ID 1-3-A)					
@ cure	4100	3400	3600	3700	500
1000	3700	3100	3300	3367	400
2000	3250	2700	2900	2950	550
3000	2600	2450	2800	2617	350
4000	2450	2300	2400	2383	150
5000	2250	2150	2250	2217	100
Medium Peak Count (Panel ID 2-3-A)					
@ cure	4700	5200	3600	4500	1400
1000	4100	3900	3300	3767	800
2000	3600	3300	3100	3333	500
3000	2100	2600	2450	2383	500
4000	1800	2200	1950	1983	400
5000	1750	2000	1900	1883	250
Low Peak Count (Panel ID 3-3-A)					
@ cure	4600	4000	3600	4067	1000
1000	3300	3500	3100	3300	400
2000	2550	2750	2800	2700	250
3000	1800	2500	2700	2333	900
4000	2100	1900	1750	1917	350
5000	1700	1400	1550	1550	300

* Difference between highest and lowest pull
1000 psi = 6.895 MPa

creep from the center of the scribe was measured in millimeters. There was no creep evident until 3000 hours exposure. Scribes on panels with high or medium peak count were essentially the same. The panel with low peak count exhibited the most undercutting. This result is expected since more peaks mean the coating has to disbond along a longer microscopic path to affect a visually noticeable creep. Although the low peak count panel displayed 75% more undercutting than the panels with higher peak counts at 5000 hours (3.5 versus 2 mm), if the length were measured microscopically along the metal surface up and down the peaks, the distances may be comparable.

Coating B, Polyurethane in Salt Spray

Coating B, a modified polyurethane, was also exposed in salt spray. The pull-off data are given in Tables 8a and 8b. The low peak count surface performed worse than the other surfaces from early in the test. At 2000 hours and above, for Coating B, the lower the peak count, the lower the average pull-off strength. The difference was very pronounced by 5000 hours. There was not much difference in pull-off strength between the high and the medium peak count surfaces.

Scribe undercutting data for Coating B are given in Table 9. Peak count did not have an effect on scribe undercutting until 4000 hours. The effect became more pronounced at 5000 hours. Higher peak counts retard scribe undercutting for this modified polyurethane coating.

Coating C, Polyurethane in Salt Spray

Coating C, another modified polyurethane, was also exposed in salt spray. The pull-off data are given in Tables 10a and 10b. Unlike most of the other coatings tested in this study, the average pull-off strength of the medium peak count surface was consistently greater than that of the high peak count surface. Still, the panel with low peak count had by far the lowest pull strength. The low peak count surface also showed the highest percentage of failure at the steel/coating interface.

The scribe undercutting data for Coating C, Table 11, does not show an effect of peak count until 2000 hours. A direct correlation between all three peak count levels and scribe undercutting does not become evident until 4000 hours. This trend is more evident at 5000 hours. As expected, the higher the peak count, the less the scribe undercutting.

Coating D, Epoxy in Prohesion/UV

The pull-off data for Coating D, an epoxy, are given in Tables 12a and 12b. Two sets of Coating D panels were exposed in a prohesion/UV cycle per ASTM D 5894. At 2420 hours exposure and beyond, the panels with the lowest peak count had the lowest pull-off strength. As exposure time increases and as peak count decreases, there is definitely more failure at the steel/coating interface. The percent failure numbers are the average estimates of multiple observers.

With epoxy Coating D in the prohesion/UV cycle, scribe undercutting data, given in Table 13, do not show an effect of peak count until 2420 hours. The high and the medium peak count surfaces are similar until 5560 hours, at which time there is a definite correlation between peak count and scribe undercutting.

Coating E, Phenolic in Salt Spray and Salt Water Immersion

Pull-off data for Coating E, a high-temperature phenolic, exposed in salt spray, are given in Tables 14a and 14b. The pull-off strengths of the high and the medium peak count panels were essentially the same. The low peak count panel had

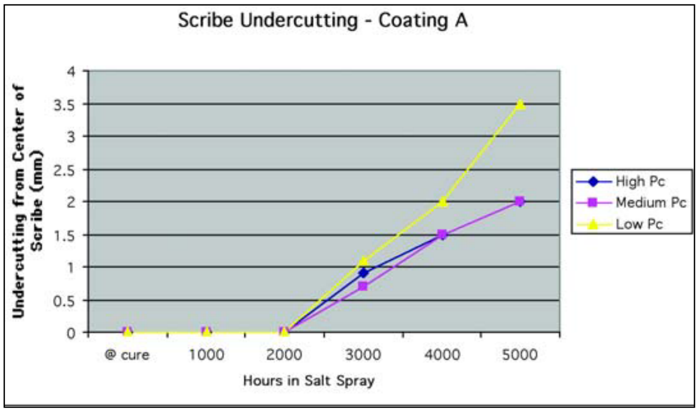


Figure 3: Comparison of scribe undercutting data for Coating A for panels with high, medium, and low peak counts after exposure in salt spray.

weaker pulls and exhibited substantial adhesion failure at the steel/coating interface after extended salt spray exposure.

Scribe undercutting data for Coating E is given in Table 15 and shows that undercutting increases as peak count decreases. For Coating E the undercutting was generally in the form of blistering at the scribe; hence, lower peak count correlated with larger blisters.

The size of a blister is directly related to the adhesion strength between the coating and the underlying substrate. A blister will continue to expand until the component of the force on the coating perpendicular to the surface at the point where the coating is attached is equal to the adhesion strength.

Consider this analogy. A horizontal line between two poles supports a weight hung from the center of the line. The line exerts a force pulling the poles together. If the line is allowed to sag and supports the same weight, the force on the poles is much less. A blister may form rather quickly in immersion and then not grow for years. Adhesion strength determines the equilibrium size of the blister—the stronger the adhesion, the smaller the blister.

The pull-off data for Coating E in salt water immersion are given in Tables 16a and 16b. The medium peak count panel had the highest pull strength. However, after extended exposure, failure at the steel/paint interface increased as peak count decreased. This is the second instance in this study where the medium peak count surface had higher pull-off strength than the high peak count surface, the other being Coating C in salt spray. In both of these cases, the low peak count surface still had the weakest adhesion.

A possible explanation why the medium peak count surface has the largest pull-off strength is that the coating did not completely wet the high peak count surface. It was known at the beginning of this project that Coatings E and F, both phenolics, had less wetting capabilities than Coatings A through D. When the peak count is very high, the valleys are very narrow. The effect of increased surface area due to high peak count is negated by the lack of complete wetting.

Coating F, Phenolic in Salt Spray and Salt Water Immersion

Pull-off data for Coating F, a phenolic, exposed in salt spray, are given in Tables 17a and 17b. Pull-off values did not appear to be a function of peak count. The only failure at the steel/paint interface occurred with the low peak count panel at the longest exposure time. Although scribe undercutting is greatest for the low peak count panel, it is only at the longest exposure time that undercutting correlates directly with peak count. Based on the fact that the other coatings in this study often did not exhibit a correlation with peak count until many hours of exposure, it is possible that Coating F would need to be exposed for a much longer time for similar trends to become evident.

Scribe undercutting data for Coating F are given in Table 18. There was not much difference in scribe undercutting between the high and the medium peak counts. However, at the longest exposure, the high peak count surface had the least scribe undercutting. After 1000 hours, the low peak count surface definitely showed the most scribe undercutting.

Cracking (or checking) of the coating after 4222 hours in the salt spray is directly related to peak count. The high peak count panel had no evidence of checking or cracking, the medium peak count panel had slight cracking with no rust, and the low peak count panel had definite cracking with scattered rusting.

Cracking (to the substrate) or checking is caused by internal stress in the coating caused by shrinking. Thermal expansion and contraction should be able to be discounted because the salt fog is not that warm and is held at constant temperature. The only thermal cycling is when the panels cool to room temperature during the rating process. Clearly, the low peak count surface had more cracking than the high peak count surface.

A possible explanation of why cracking is dependent on peak count follows. As the coating tries to pull apart (i.e., crack), the “handles” grabbing the coating are the highest peaks. With fewer peaks, the distance between anchor points increases. When the coating finally fractures, the gap will be large, hence, visible. If the peaks are close together, the fracture will be microscopic and not readily visible. The width of the crack is proportional to the distance between the anchor points because the shrinkage is a percentage of the distance between two points on the coating. Adhesion to the substrate is so good that no flaking or disbondment occurs.

Table 7: Maximum undercutting (mm) from center of scribe for panels with Coating A exposed in salt spray

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-5-A	High	0	0	0	0.9	1.5	2
2-5-A	Medium	0	0	0	0.7	1.5	2
3-5-A	Low	0	0	0	1.1	2	3.5

Table 8a: Pull-off data in psi for Coating B exposed in salt spray – average of 3 pulls

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-3-B	High	2000	2116	1967	1933	1833	1817
2-3-B	Medium	2200	2166	1850	1750	1733	1667
3-3-B	Low	2133	1700	1366	1250	1083	958

1000 psi = 6.895 MPa

Table 8b: Percentage of failure at the substrate for Coating B exposed in salt spray – 3 pulls per panel

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-3-B	High	3 of 18 pulls showed from 5 to 10% substrate failure					
2-3-B	Medium	4 of 15 pulls showed from 8 to 15% substrate failure					20-20-25
3-3-B	Low	13 of 18 pulls showed substrate failure; 10-15% early; up to 50% mid test					70 to 80

Multiple entries indicate the percent substrate failure for each of the three pulls; all other failures were cohesive.

Table 9: Maximum undercutting (mm) from the center of the scribe for Coating B exposed in salt spray

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-5-B	High	0	0	0	2	2.5	3
2-5-B	Medium	0	0	0	1.5	3.5	4.5
3-5-B	Low	0	0	0	2	6	8

Table 10a: Pull-off data in psi for Coating C exposed in salt spray – average of 3 pulls

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-3-C	High	1483	1450	1216	1300	1034	900
2-3-C	Medium	1817	1900	1750	1417	1216	1233
3-3-C	Low	1500	1400	1150	900	684	450

1000 psi = 6.895 MPa

Pull-off data for Coating F in salt water immersion is given in Tables 19a and 19b. Peak count only becomes a factor for the low peak count panel at the longest exposure time. As with coating E in immersion, the effect of peak count for Coating F may only become prominent after many more hours of exposure. If there was incomplete wetting of the high peak count surface, it is possible that with continued exposure, the medium peak count surface will still have the best performance.

Conclusions

In this study a portable stylus instrument was able to objectively measure surface profile parameters. The parameters corresponding to peak height, Rmax and Rt, were independent from the parameter for roughness as measured by peak count, Pc. These parameters are controllable using standard commercially available abrasives in a standard type of wheel-blast machine. (Similar control should be possible with air nozzles.) Data showed that if profile height is kept constant, peak count can affect the performance of a coating as measured by pull-off adhesion strength, scribe undercutting, and in some cases cracking. The inference is that once this relationship between peak count and paint performance is fully documented, it may behoove owners to specify a range for peak count as well as a range for peak height.

A common thread woven through all this data is that over time, the adhesive strength between the substrate and the coating will become less than the cohesive strength within the coating itself. This point is reached sooner on surfaces with a low peak count. Data from the longest exposure for each exposure test are summarized in Table 20. As expected, surfaces with higher peak counts form a stronger bond with the coating. The assumption in this statement is that the coating is able to completely wet the surface, as was the case for Coatings A through D used in this study. Coatings E and F, both phenolics, were included knowing that their wetting and flow characteristics may not result in complete wetting of the bottoms of the narrowest or deepest valleys.

For all six coatings tested in this study, eventually, the panel with the lowest peak count exhibited the poorest performance. Sometimes it took 5000 hours of accelerated exposure for this difference to manifest itself. This trend was always evident with pull-off adhesion and scribe undercutting, and for Coating F, even cracking. The pull-off strength for Coating E in immersion and Coating F in salt spray were slightly higher for the low peak count than for the high peak count surfaces, but they were essentially equal when experimental uncertainty is considered. Examination of the mode of pull-off failure, however, clearly shows failure at the substrate on only the low peak count surface.

There are two possible explanations why peak count had less effect on performance for Coatings E and F. First, these two phenolic coatings had less wetting capability than the other four coatings. If the valleys were not completely wetted, microscopic sections of the substrate would not contribute to adhesion strength. Second, Coatings E and F were only exposed for 4222 hours; so perhaps the trend may have been better defined had the test continued for an additional 1000 hours or so.

High peak count surfaces performed better than low peak count surfaces for all three accelerated environments: ASTM B 117 salt spray, ASTM D 5894 Prohesion/UV, and salt water immersion. The last column of Table 20 indicates the percentage increase in performance of the high peak count surface compared to the low peak count surface.

Further research is needed to quantify the relationships among profile height, peak count, degree of cleaning, paint, DFT, exposure environment, mode of failure, and expected lifetime of a coating system.

Future Work

This study certainly does not answer all the questions related to the effect of profile on coating performance. The authors' vast experience in this field has led to other relationships or theories that still need to be verified by testing. Additionally, the authors have sufficient personal experience and other evidence to indicate that these theories are valid for many common conditions, but not necessarily all conditions.

Table 10b: Percentage of failure at the substrate for Coating C exposed in salt spray – 3 pulls per panel

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-3-C	High	0	0	0	0-0-10	0-0-10	0-0-10
2-3-C	Medium	0	0	0	0-0-5	0-0-0	0-0-5
3-3-C	Low	0	0	0	0-5-30	0-20-30	0-50-50

Multiple entries indicate the percent substrate failure for each of the three pulls;
all other failures were cohesive.
0 = no substrate failure

Table 11: Maximum undercutting (mm) from the center of the scribe for Coating C exposed in salt spray

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-5-C	High	0	0	0	2	2.5	2.7
2-5-C	Medium	0	0	0	1.5	3.5	4.2
3-5-C	Low	0	0	2	5	7	9

Table 12a: Pull-off data in psi for Coating D exposed in prohesion/UV cycle – average of 2 pulls

Panel ID	Peak Count	Exposure Time (h) in Prohesion					
		@ cure	1220	2420	3700	4400	5560
1-4-D	High	3575	3400	3150	3025	2970	2815
1-5-D		3270	3170	3295	2825	2990	2783
2-4-D	Medium	3500	3011	3250	3050	2998	2800
2-5-D		3420	3370	3275	2850	2648	2605
3-4-D	Low	3350	3140	2950	2875	2620	2530
3-5-D		3250	3275	3150	2875	2685	2425

1000 psi=6.895 Mpa

Table 12b: Percentage of failure at the substrate for Coating D exposed in prohesion/UV cycle – 2 pulls per panel

Panel ID	Peak Count	Exposure Time (h) in Prohesion					
		@ cure	1220	2420	3700	4400	5560
1-4-D	High	0	0	0	0	0	0
1-5-D		0	0	0	0	0	0
2-4-D	Medium	0	0 – 5	0 – 5	0	0	5 – 8
2-5-D		0	0	0	0	12 – 17	8 – 10
3-4-D	Low	0	0 – 12	5 – 12	8 – 12	11 – 19	19 – 27
3-5-D		0	0 – 8	5 – 8	7 – 14	8 – 23	16 – 29

Multiple entries indicate the percent substrate failure for each of the two pulls
0 = no substrate failure

Table 13: Maximum undercutting (mm) from the center of the scribe for Coating D exposed in prohesion/UV cycle

Panel ID	Peak Count	Exposure Time (h) in Salt Spray					
		@ cure	1000	2000	3000	4000	5000
1-4-D	High	0	0	0.5	2	4	6
2-4-D	Medium	0	0	0.75	3	3	15
3-4-D	Low	0	0	2	8	16	35

Table 14a: Pull-off data in psi for Coating E exposed in salt spray – average of 2 pulls

Panel ID	Peak Count	Exposure Time (h) in Salt Spray			
		@ cure*	1027	2892	4222
1-3-E	High	2725	1275	1420	1076
2-3-E	Medium	2725	1960	1400	1031
3-3-E	Low	2600	1795	550	600

* At cure, the panel IDs were 1-3-E, 2-3-E, and 3-3-E.
1000 psi=6.895 Mpa

Table 14b: Percentage of failure at the substrate for Coating E exposed in salt spray – 2 pulls per panel

Panel ID	Peak Count	Exposure Time (h) in Salt Spray			
		@ cure*	1027	2892	4222
1-3-E	High	0	10 – 20	0	0
2-3-E	Medium	0	0	0	0
3-3-E	Low	0	0	100 – 100	50 – 60

* At cure, the panel IDs were 1-3-E, 2-3-E, and 3-3-E.
0 = no substrate failure
Multiple entries indicate the percent substrate failure for each of the two pulls

Table 15: Maximum undercutting (mm) from the center of the scribe for Coating E exposed in salt spray

Panel ID	Peak Count	Exposure Time (h) in Salt Spray			
		@ cure	1027	2892	4222
1-4-E	High	0	0	6	12
2-4-E	Medium	0	0	4.4	17.5
3-4-E	Low	0	0	16	30

Table 16a: Pull-off data in psi for Coating E exposed in salt water immersion – average of 2 pulls

Panel ID	Peak Count	Exposure Time (h) in Salt Water Immersion			
		@ cure*	1027	2892	4222
1-2-E	High	2725	1600	1290	875
2-2-E	Medium	2725	2200	1500	1013
3-2-E	Low	2600	2325	630	950

* At cure, the panel IDs were 1-3-E, 2-3-E, and 3-3-E.
1000 psi=6.895 Mpa

Theory 1: *A surface with a consistent profile height will provide better coating performance than a surface with an inconsistent profile height.*

Discussion: With a consistent profile height, the anchor points for the coating will be more uniform and will be more evenly dispersed, thereby distributing the internal stresses of the coating more evenly, which should lead to less cracking and improved adhesive characteristics.

According to a paper[3] by Yuly Korobov, high internal stresses may be created at uneven anchor points within a coating. These high unbalanced stresses can cause cracks to develop in the coating and also degrade the cohesive strength of the coating.

Theory 2: *Surfaces prepared to SSPC-SP 10 may have higher peak counts than surfaces prepared to SSPC-SP 5, all else being equal.*

Discussion: When the surface is blasted to obtain the White Metal (SP 5) finish expected by the inspector, the surface of the substrate can be overworked and the internal integrity of the substrate reduced. Therefore, overblasting can reduce the cohesive strength of the substrate to a point that it becomes weaker than the adhesive strength of the coating; thus, failures occur within the substrate. For a given abrasive and for a given set of blast parameters, as blasting continues, the peak count will decrease slightly as SP 10 approaches SP 5. To achieve SP 5 more abrasive must be thrown at the surface. Continued blasting over time will flatten more existing peaks than will be created, resulting in lower peak density. The maximum peak density for a given abrasive under fixed conditions occurs close to a cleaning level of SP 10.

Overblasting commonly occurs when inspectors attempt to match the color of a newly blasted surface with SSPC-VIS 1 photographs. This is particularly acute on previously coated steel, on heat treated steel, and on non-standard alloys.

Theory 3: *The optimum conditions for a wide range of standard coatings that will completely wet the surfaces are a 2.5 mil (65 µm) profile height and a peak density between 120 and 150 peaks per inch (50 and 60 peaks per cm).*

Discussion: The two independent mechanisms to regulate surface area are peak count and peak height. The greater the surface area for the coating to bond, the better. More peaks provide more surface area. If there are too many peaks, the valleys become too narrow for complete wetting. As peak count increases, for common industrial coatings, the valleys become so narrow that the finite size of the pigment particles and coating viscosity prevent complete wetting of the surface. The particles get stuck part way down the valley and may bridge over. Coatings perform better on high peak count surfaces as long as they can wet the surface.

Another way to increase the surface area without increasing the peak count is to increase the height of the peaks. However, for a given peak count, as the height increases, the slope of the peaks increases and the valleys become narrower. The minimum valley width limits the height at which a coating will perform adequately. The authors have collected a large amount of anecdotal data that indicates that 2.5 mils (65 µm) surface profile may provide the most effective adhesive properties for most coatings. Much of this data is from manufacturers that have tried many combinations of coatings and surface profile and have standardized on 2.5 mils (65 µm).

Theory 4: *Surfaces contaminated with micronic backside contamination are susceptible to premature coating failure.*
Discussion: Micron sized particles are inherent in the abrasive blasting process and can contribute significantly to the loss of adhesion. This dust can originate in the abrasive material or the surface to be blasted, or it can be generated during breakdown of the abrasive particles in the blasting process. Micronic dust may become attached to the substrate by electrostatic or magnetic forces or by being driven into the blast cleaned surface by the abrasive.

This dust may be seen without magnification, and is so tightly attached to the steel substrate that it is difficult to remove by blowing down, vacuuming, or even power washing. Momber et. al.[4] also showed micrographs illustrating how this dust could be mechanically trapped by peaks being bent over by subsequent abrasive blasting. According to this theory, for best coating adhesion, one should not blast any longer than is necessary and should use a non-friable low-dusting abrasive. Methods are needed to identify, evaluate its impact, and remediate micronic dust.

In this study, ultra-clean panels were used to minimize any effect of backside contamination caused by micronic dust. The only profile variable was peak count.

Theory 5*: Optimum performance will be obtained when the peak count is matched to the wetting characteristics of the primer.*
Discussion: For the best corrosion protection, the peak count should be chosen as high as possible, but not so high that complete wetting does not occur. Conversely, coatings should be formulated with maximum wetting properties so that high peak counts can be used. Surfaces with low peak counts and complete wetting can outperform surfaces with high peak counts and incomplete wetting. Wetability is determined by many factors such as solvent, fineness of grind of pigment, and temperature. Empirical testing may be required to determine the optimum peak count for a particular coating.

Table 16b: Percentage of failure at the substrate for Coating E exposed in salt water immersion – 2 pulls per panel

Panel ID	Peak Count	Exposure Time (h) in Salt Water Immersion			
		@ cure*	1027	2892	4222
1-2-E	High	0	10	0	0
2-2-E	Medium	0	0	0	1 – 20
3-2-E	Low	0	0	70	30 – 40

* At cure, the panel IDs were 1-3-E, 2-3-E, and 3-3-E.
0 = no substrate failure
Multiple entries indicate the percent substrate failure for each of the two pulls

Table 17a: Pull-off data in psi for Coating F exposed in salt spray – average of 2 pulls

Panel ID	Peak Count	Exposure Time (h) in Salt Spray			
		@ cure*	1027	2892	4222
1-3-F	High	2925	2900	2635	2175
2-3-F	Medium	3100	3150	3025	2650
3-3-F	Low	3150	2650	2475	2276

* At cure, the panel IDs were 1-3-F, 2-3-F, and 3-3-F.
100 psi=6.895 Mpa

Table 17b: Percentage of failure at the substrate for Coating F exposed in salt spray – 2 pulls per panel

Panel ID	Peak Count	Exposure Time (h) in Salt Spray			
		@ cure*	1027	2892	4222
1-3-F	High	0	0	0	0
2-3-F	Medium	0	0	0	0
3-3-F	Low	0	0	0	15 – 25

* At cure, the panel IDs were 1-3-F, 2-3-F, and 3-3-F.
0 = no substrate failure
Multiple entries indicate the percent substrate failure for each of the two pulls

Table 18: Maximum undercutting (mm) from the center of the scribe for Coating F exposed in salt spray

Panel ID	Peak Count	Exposure Time (h) in Salt Spray			
		@ cure	1027	2892	4222
1-4-F	High	0	6	15	16
2-4-F	Medium	0	2	10	23
3-4-F	Low	0	15	36	37

Notes

1. J.D. Keane, J.A. Bruno, and R.E.F. Weaver, *Surface Profile for Anti-Corrosion Paints,* Publication #74-01, SSPC: The Society for Protective Coatings, Pittsburgh, PA 15222
2. ISO 8502-3, Preparation of steel substrates before application of paint and related products—Tests for the assessment of surface cleanliness—Part 3: Assessment of dust on steel surfaces prepared for painting (pressure-sensitive tape method)

Table 19a: Pull-off data in psi for Coating F exposed in salt water immersion – average of 2 pulls

Panel ID	Peak Count	Exposure Time (h) in Salt Water Immersion			
		@ cure*	1027	2892	4222
1-4-F	High	2925	2875	2700	2700
2-4-F	Medium	3100	3000	3050	2750
3-4-F	Low	3150	3225	2725	2275

* At cure, the panel IDs were 1-3-F, 2-3-F, and 3-3-F
1000 psi=6.895 Mpa.

Table 19b: Percentage of failure at the substrate for Coating F exposed in salt water immersion – 2 pulls per panel

Panel ID	Peak Count	Exposure Time (h) in Salt Water Immersion			
		@ cure*	1027	2892	4222
1-4-F	High	0	0	0	0
2-4-F	Medium	0	0	0	0
3-4-F	Low	0	0	0	10 – 15

* At cure, the panel IDs were 1-3-F, 2-3-F, and 3-3-F
0 = no substrate failure.
Multiple entries indicate the percent substrate failure for each of the two pulls

Table 20a: Final pull-off data in psi

Coating (Exposure/Time)	Peak Count			% Improvement
	High	Medium	Low	Low to High
A (B 117/5000 h)	2217	1883	1550	43
B (B 117/5000 h)	1817	1667	958	90
C (B 117/5000 h)	900	1233	450	100
D (D 5894/5560 h)	2799	2703	2478	13
E (B 117/4222 h)	1076	1031	600	79
E (immersion/4222 h)	875	1013	950	-8
F (B 117/4222 h)	2175	2650	2276	-4
F (immersion/4222 h)	2700	2750	2275	19

1000 psi = 6.895 MPa

Table 20b: Maximum percent failure at the substrate on adhesion pulls

Coating (Exposure/Time)	Peak Count			% Improvement
	High	Medium	Low	Low to High
A (B 117/5000 h)	0	0	60	100
B (B 117/5000 h)	10	25	80	88
C (B 117/5000 h)	10	5	50	80
D (D 5894/5560 h)	0	10	29	100
E (B 117/4222 h)	0	0	60	100
E (immersion/4222 h)	0	20	40	100
F (B 117/4222 h)	0	0	25	100
F (immersion/4222 h)	0	0	15	100

Table 20c: Maximum undercutting (mm) from the center of the scribe

Coating (Exposure/Time)	Peak Count			% Improvement
	High	Medium	Low	Low to High
A (B 117/5000 h)	2	2	3.5	43
B (B 117/5000 h)	3	4.5	8	62
C (B 117/5000 h)	2.7	4.2	9	70
D (D 5894/5560 h)	6	15	35	83
E (B 117/4222 h)	12	17.5	30	60
F (B 117/4222 h)	16	23	37	57

3. Yuly Korobov Ph.D., "Stress Analysis as a Tool in Coatings Research," *MP*, Vol. 29, No. 4, April 1990, pp 30-35
4. A. W. Momber, S. Koller, and H.J. Dittmers, "Effects of Surface Preparation Methods on Adhesion of Organic Coatings to Steel Surfaces," *JPCL*, Nov. 2004, p. 44-50

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