Measurement of Adhesion Properties Between Topcoat Paint and Metallized/Galvanized Steel with Surface Energy Measurement Equipment

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Prepared for
The New England Transportation Consortium
September 23, 2013
NETCR93 Project No. 05-5

ACKNOWLEDGMENTS

The followings are the members of the Technical Committee that developed the scope of work for the project and provided technical oversight throughout the course of the research:

Jerry McMahan, Vermont Agency of Transportation, Chairperson

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Special thanks for the generous help and advice from persons outside the technical committee:

Michael Hewins, Massachusetts Highway Department

Michael Sock, Rhode Island Department of Transportation

Richard Brown, Dept. of Chemical Engineering, URI

The authors thank the following individuals for their valuable advices in editing the text of this report.

Jerry Zoller, New Hampshire Department of Transportation

Jerry McMahan, Vermont Agency of Transportation

Amanda Hanaway-Corrente, New England Transportation Consortium, UVM

.Technical Report Documentation Page

1. Report No.	2. Government Accession No.:	3. Recipient's Catalog No.
NETCR93	N/A	N/A

4. Title and Subtitle:	5. Report Date:
Measurement of Adhesion Properties Between Topcoat Paint and Metallized/Galvanized Steel with Surface Energy Measurement Equipment	September 23, 2013
	6. Performing Organization Code: N/A

7. Author(s):	8. Performing Organization Report No.:
Sze C. Yang, Kang-Won Wayne Lee, Maureen Mirville, Chen Lu, Anthony Pahram	NETCR93

9. Performing Organization Name and Address:	10. Work Unit No. (TRAIS):
University of Rhode Island Department of Chemistry, Department of Civil and Environmental Engineering 51 Lower College Rd., Kingston, RI 02881	N/A
	11. Contract or Grant No. N/A

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
New England Transportation Consortium University of Vermont – Transportation Research Center 210 Colchester Avenue Burlington, VT 05405	Final Report
	14. Sponsoring Agency Code NETC05-5. A study conducted in cooperation with U.S. DOT

15. Supplementary Notes

N/A

16. Abstract

The objectives of this research project are: (1) Compare the adhesion properties of NEPCOAT-approved topcoat paint over metallized or galvanized steel. Use "surface-energy" measuring technique to characterize the wetting properties of the liquid paint on the profiled zinc surfaces. Explore correlation between the adhesive strength and the liquid paint wetting properties. As control the adhesion properties of topcoat paint over zinc primer painted steel substrates will also be measured. (2) Investigate various factors affecting the adhesion of topcoat paint over galvanizing. (3) Report and recommend practices that produce the best adhesion of NEPCOAT-approved topcoat paints over metallized and particularly galvanized steel surfaces. We prepared four different types of test panels coated with five different commercial paint systems. The paint systems include four systems adapted from the NEPCOAT list of intermediate and top paints qualified for bare steel, and one system of epoxy sealer for metallized surface. Four types of substrates were used for fabricating the test panels: (1) galvanized steel with mechanical grinding to produce rough surface, (2) galvanized steel with blast profiling to produce rough surface, (3) galvanized steel stored indoors for two weeks before blast profiling and painting, and (4) metallized steel with inherent roughness due to the thermal spray process. We recorded, as a function of time, the contact angle of droplets of freshly prepared liquid paints on the replicas of the substrate used for spray painting. The cured test panels were subject to pull-off strength tests according to the ASTM D4541 standard, and the X-cut tape tests according to Method A of ASTM D3359 standard. Images of the pull-off test break surfaces were photographed and examined. We analyzed the correlation between the pull-off strengths and the contact angles. The correlation provided insight on the relative adhesive strengths of the different paint-substrate pairs. We concluded that (1) the NEPCOAT paints could be used for galvanized and metallized steel to obtain comparable adhesion performance as that of the zinc-rich organic primer coated steel, (2) although the NEPCOAT intermediate paint on the metallized surface has adequate pull-off strength to pass the inspection, it is highly recommended that the state DOT specification of the use of sealant is strictly followed, (3) although the exposure to atmosphere after galvanizing is commonly recognized as a problem for paint adhesion, we found that a time delay of two weeks between galvanizing and profiling/painting is permissible if the galvanized steel is stored in the normal indoor dry atmosphere, (4) we think a refined quantitative correlation between pull-off strength and contact angle could be useful for optimizing the paint-to-substrate match.

17 Key Words	18. Distribution Statement
Duplex Paint, Galvanize, Metallize, Coating, Adhesion, Surface Profile	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19 Security Classif. (of this report):	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	536	N/A

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Unit Conversions

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Source: http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol4/sicf.htm

ABSTRACT

The objectives of this research project are: (1) Compare the adhesion properties of NEPCOAT-approved topcoat paint over metallized or galvanized steel. Use "surface-energy" measuring technique to characterize the wetting properties of the liquid paint on the profiled zinc surfaces. Explore correlation between the adhesive strength and the liquid paint wetting properties. As control the adhesion properties of topcoat paint over zinc primer painted steel substrates will also be measured. (2) Investigate various factors affecting the adhesion of topcoat paint over galvanizing. (3) Report and recommend practices that produce the best adhesion of NEPCOAT-approved topcoat paints over metallized and particularly galvanized steel surfaces.

We prepared four different types of test panels coated with five different commercial paint systems. The paint systems include four systems adapted from the NEPCOAT list of intermediate and top paints qualified for bare steel, and one system of epoxy sealer for metallized surface. Four types of substrates were used for fabricating the test panels: (1) galvanized steel with mechanical grinding to produce rough surface, (2) galvanized steel with blast profiling to produce rough surface, (3) galvanized steel stored indoor for two weeks before blast profiling and painting, and (4) metallized steel with inherent roughness due to the thermal spray process.

We recorded, as a function of time, the contact angle of droplets of freshly prepared liquid paints on the replicas of the substrate used for spray painting. The cured test panels were subject to pull-off strength tests according to the ASTM D4541 standard, and the X-cut tape tests according to Method A of ASTM D3359 standard. Images of the pull-off test break surfaces were photographed and examined.

We analyzed the correlation between the pull-off strengths and the contact angles. The correlation provided insight on the relative adhesive strengths of the different paint-substrate pairs. We concluded that (1) the NEPCOAT paints could be used for galvanized and metallized steel to obtain comparable adhesion performance as that of the zinc-rich organic primer coated steel, (2) although the NEPCOAT intermediate paint on the metallized surface has adequate pull-off strength to pass the inspection, it is highly recommended that the state DOT specification of the use of sealant is strictly followed, (3) although the exposure to atmosphere after galvanizing is commonly recognized as a problem for paint adhesion, we found that a time delay of two weeks between galvanizing and profiling/painting is permissible if the galvanized steel is stored in the normal indoor dry atmosphere, (4) we think a refined quantitative correlation between pull-off strength and contact angle could be useful for optimizing the paint-to-substrate match.

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The New England Transportation Consortium
NETC Project No. 05-05

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1 Introduction

For many highway transportation steel structures, a zinc coating is added to the structural steel to act as a sacrificial layer for corrosion protection. Zinc is applied to steel in three ways – by zinc primer paint, by metallizing (where hot zinc is sprayed onto the steel surface), or by galvanizing (where the steel part is immersed in a molten zinc bath and a zinc layer metallurgically forms on the steel). Paint topcoats are often applied to roughened zinc-coated steel surfaces to provide additional protection and an aesthetic color finish.

The adhesion performance of these topcoats appears to vary considerably for coatings applied over galvanizing versus metallizing, and is dependent on the processes for roughening the zinc surface. The effectiveness of different zinc coatings with topcoat paint applications can be quantified by measuring adhesion properties between the topcoat paint and zinc-coated steel. In the fabrication process of the painted structures the organic liquid paints are spray-painted on the roughened zinc surfaces. The liquid paint wetting properties of the roughened zinc surfaces can be characterized by liquid paint droplet contact angles on the surface.

Questions of interest include the adhesive strengths of paints on zinc-coated steel surfaces for surfaces roughened by different methods, and the correlation between the wetting properties of the liquid paints and the adhesive strengths.

2 Objectives of the Research Project

a) Compare the adhesion properties of NEPCOAT-approved topcoat paint over metallizing to topcoat paint over galvanizing using specialized “surface-energy” measuring lab methods. As control the adhesion properties of topcoat paint over zinc primer painted steel substrates will also be measured.
b) Investigate various factors affecting the adhesion of topcoat paint over galvanizing.
c) Report and recommend practices that produce the best adhesion of NEPCOAT-approved topcoat paints over metallized and particularly galvanized steel surfaces.

3 Review of Relevant Literatures

3.1 Wetting of a liquid on Surfaces

The wetting properties of a liquid on a surface are determined by the relative surface energies (the surface tensions) between a liquid and the contacting metal surface. The basic concepts of the interaction between the liquid droplet contact angle and the wetting properties have been summarized in a 1964 review paper by W. Zisman [1]. The contact angles of liquids (e.g., water) on rough surfaces have been a subject of current research interest. For example, the blast roughened and lithographically etched surfaces have demonstrated to show "lotus effect" and "hemi-wicking" phenomena.

3.2 Measurement of liquid wetting: Contact Angles

In this study the contact angles of liquid paint droplets were measured with a goniometer (Model 200, Reme-Hart Instrument Company). The steel panels were either galvanized or metallized freshly on the same day and within 30 minutes of painting on the panels. As each of the 4 or 5 paints were freshly formulated for spray painting, a portion of the liquid paint was brought to a test room where we performed the contact angle measurement. We placed a small droplet of the liquid paint (Volume V is about 1 micro–Liter, μL) on the roughened zinc surface. We measured the contact angle as a function of time after the droplet is in contact with the profiled zinc surface. We also separately recorded the images of the droplet as a function of time. Figure 2 shows the basic parameters for a droplet measured are the contact angle θ, the diameter d of the liquid cap at the liquid / solid interface, and the height h of the liquid cap.

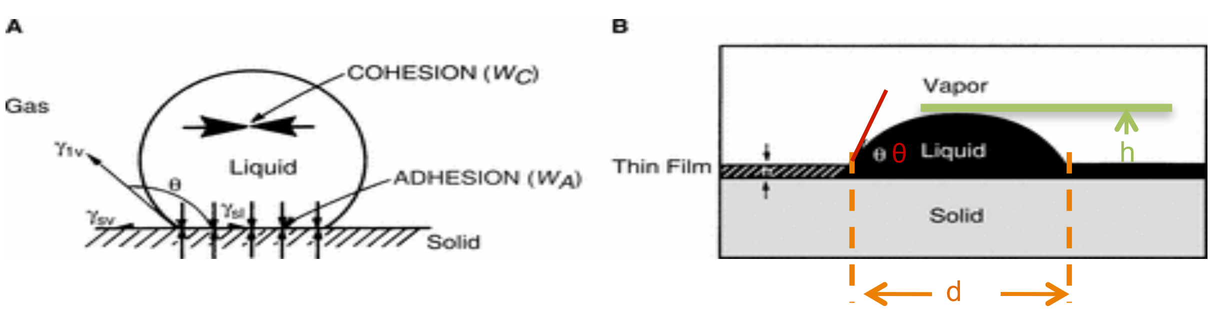


Figure 1. The shape and the contact angle of a liquid droplet is the result of the balance of forces, or equivalently, the minimization of the free energy of the system. This figure introduces the parameters measured during the experiment.

The contact angle for a droplet of liquid paint on the profiled zinc surface reflects the balance of the forces of cohesion and adhesion. The attractive force among the molecules in the liquid droplet is a cohesive force that tends to "ball-up" the droplet to reduce the liquid/air and the liquid/zinc interfaces. For a given amount of liquid, a strong cohesive force will make the contact angle higher. The attractive force between the liquid molecules and the molecules on the zinc surface (a mixture of metallic zinc, zinc oxide, zinc hydroxide, and surface contaminants) is the adhesive force. The adhesive force tends to increase the interfacial area between the liquid droplet and the zinc surface. A strong adhesive force tends to flatten the droplet to decrease the contact angle θ. The balance of the forces can be derived with the thermodynamic principle that minimizes the Gibb's Free Energy of the system. The relevant material properties are the surface tensions for three different interfaces, γ_{LV} for the liquid/vapor interface, γ_{SV} for the solid/vapor interface, and γ_{SL} for the solid/liquid interface. The "spreading coefficient, S_{LS}" which is an index for flattening and spreading of the liquid droplet, and the contact angle θ are related to these three interfacial tensions as the following.

$$S_{LS} = \gamma_{SV} - \gamma_{LV} - \gamma_{SL} \xrightarrow[\gamma_{SV}-\gamma_{SL}=\gamma_{LV}\cos\theta]{\text{Younge equation}} \gamma_{LV}(\cos\theta - 1) \quad (1)$$

Equation (1) shows that wetting of the surface is favored when the value of the surface tension γ_{LV} for the liquid-vapor interface is small, and the contact angle θ is small.

When a droplet has a contact angle θ larger than 90^o it is not wetting the surface. For example, a water droplet on a flat Teflon surface has a contact angle of 107^o. Water does not wet the Teflon surface. A drop of mineral oil on the surface of Teflon has a contact angle of 14^o. Oil wets the Teflon surface.

3.3 Effect of Surface Roughness on Contact Angle

All the primer paints used in our study wet the zinc surface (i.e., with $\theta < 90^o$). But on rare occasions, we observe an initial contact angle larger than 90 degree. The near spherical droplets are a consequence of the "lotus effect" [2] due to the interfacial interaction between the liquid paint and the roughened zinc surfaces.

Contact angle on a rough surface.

The equations listed in the above are derived for a molecularly flat surface. For a surface with an index of roughness r (the ratio of the rough surface area to the area projected normal to the panel), the last equation is modified according to the Wenzel model for rough surfaces [3].

$$Cos\ \theta_W = r\ Cos\ \theta_{smooth} \quad (2)$$

In equation (2) θ_W is the measured contact angle on a rough surface according to the Wenzel model, and θ_{smooth} is the contact angle for a perfectly smooth surface. The roughness r= $A_{contour}/A_{project}$ is the ratio of the contour surface area, $A_{countour}$, to the projected surface area, $A_{Project}$.

If a liquid droplet has a contact angle less than 90^o (wetting), the contact angle on a rough surface of the same material will have an angle smaller than 90^o. For example, if $\theta_{smooth}=80^o$ then $\theta_W=30^o$ for a surface with roughness index of r=5. This means that if a paint droplet can wet a smooth surface, it will show stronger wetting on a rough surface.

On the other hand, if a liquid droplet has a contact angle larger than 90^o (poor wetting), the contact angle on a rough surface of the same material will have an angle θ_W larger than that of the already large θ_{smooth}. For example, if $\theta_{smooth}=100^o$ then $\theta_W=150^o$ for a surface with roughness index of r=5. This means that if a paint droplet poorly wets a smooth surface, it will show poorer wetting on a rough surface.

Equation (1) applies to liquid droplet on smooth surface (Young type wetting). See figure 2a. Equation (2) applies to a rough surface with homogeneous wetting of the entire contour of the rough surface. See figure 2b.

There are other types of wetting of the rough surface. Figure 2c shows a droplet wetting only the top of the rough surface and leaving air pockets trapped underneath the liquid droplet. A theoretical model by Cassie and Baxter [4] for this type of wetting leads to equation 3 for the contact angle.

$$Cos\ \theta_{CB} = f \cos \theta_W + (f - 1) \qquad (3)$$

In figure 3c there is a fraction f of the area of liquid droplet that is in actual contact with the rough surface. The remaining fraction, 1-f, of the area is in contact with the air pocket underneath the droplet. As an example for r = 1.5, f = 0.01, a liquid with contact angle on a smooth surface of $\theta = 60^o$ will give a contact angle on the rough surface of 104^o for a Cassie-Baxter type surface.

If the contact angle for a liquid on smooth surface is sufficiently small, the liquid will spread and be absorbed by the surface due to the wicking effect of the capillary action. This situation is shown in Fig. 2e.

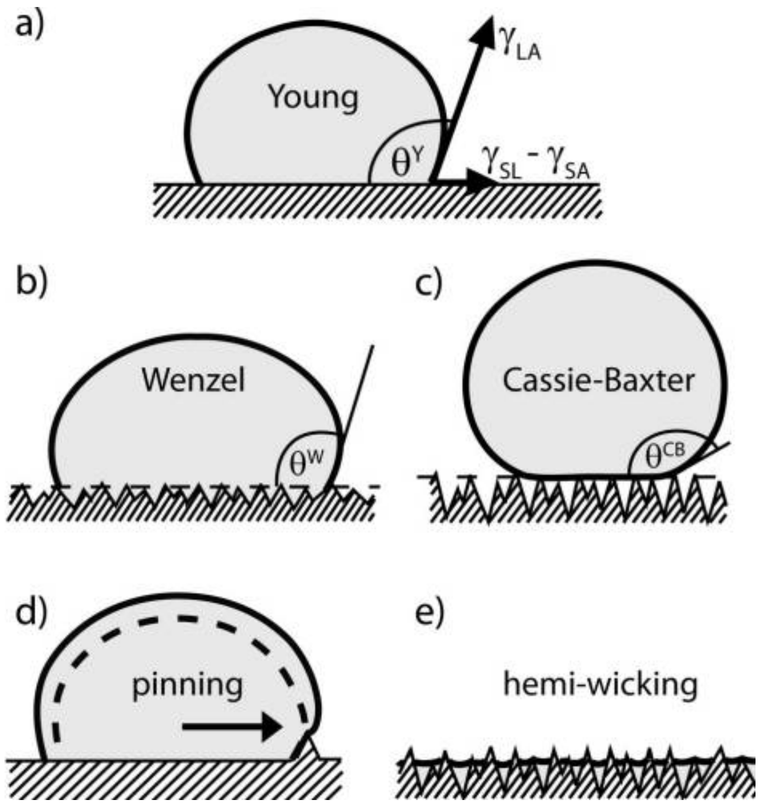


Figure 2. Different types of interactions between a liquid droplet and a rough surface.

3.4 Proposal for Experimental Verification of the Wetting-Adhesion Correlation.

We hypothesize that it is possible to devise a measurement method to verify the correlation between the wetting of the liquid paint on a zinc coated surface and the adhesion of the cured dry paint on the surface profiled substrates.

Although such a correlation is expected of a single component liquid adhesive, it is not obvious that a quantitative correlation exists for the system we are interested in this study. The metal substrate is roughened by either blast profiling, by mechanical grinding, or due to the thermal spray process. This type of surface has local variations in roughness and the chemical composition (zinc, zinc oxide, or zinc hydroxide). The paint is not a simple liquid. First of all, it is a complex mixture of organic solvents, polymeric resins and reactive hardeners. Secondly, the rheological properties of the paint liquid changes over time (within a time window of about 1 hour after mixing) due to the chemical cross-linking reactions of two parts of the epoxy paint. Furthermore, the organic solvent in the paint formulation begins to evaporate after the paint is applied to the surface and the viscosity of the liquid paint begins to rise.

We propose to use the liquid contact angle as a measure of the wetting property and use the pull-off strength as a measure for the paint adhesion. Knowing that multiple variables could obscure the correlation we intend to measure, we set up the test in a way that would minimize the external variables and try to obtain a quantifiable correlation between wetting and adhesion.

4 Test Panel Preparation and the Work Plan

The Test Panel specifications, the methods for panel preparation and the Work Plan are described in detail in Appendix A. In this section we outline the procedures and describe the naming conventions used to label the test panels.

4.1 Steel Base Panels

The steel plates with dimension of 4”x6”x1/8” were purchased from KTA-Tator Corp., Pittsburgh, PA. Two types of base panels are used for this study. Type A panel is a steel plate with a U-shaped “channel” welded perpendicularly at one end of the panel to emulate a structure with welded joints. Each panel has a ¼ “ mounting hole located near the top end of the panel. Panels are identified via three-digit number inscribe (or stamped) in the panel, top front face. Type B base panel is a flat rectangle plate.

The diagrams showing the design for the steel base panels are shown in Fig. 3.
Both types of steel panels undergo the following processes for coating with zinc metal and for profiling the surface: (1) they were coated with metallic zinc by either galvanizing or metallizing, and (2) the galvanized plates were roughened by either blasting or by mechanical grinding to produce a profiled zinc surface. After the surface profiling is completed, the Type A and Type B panels are used for different purposes. The Type A panels were painted with 4 different commercial paint systems to produce panels for adhesion strength tests. The Type B panels were used for the measurement of the wetting property of liquid paint on the profiled zinc surface.

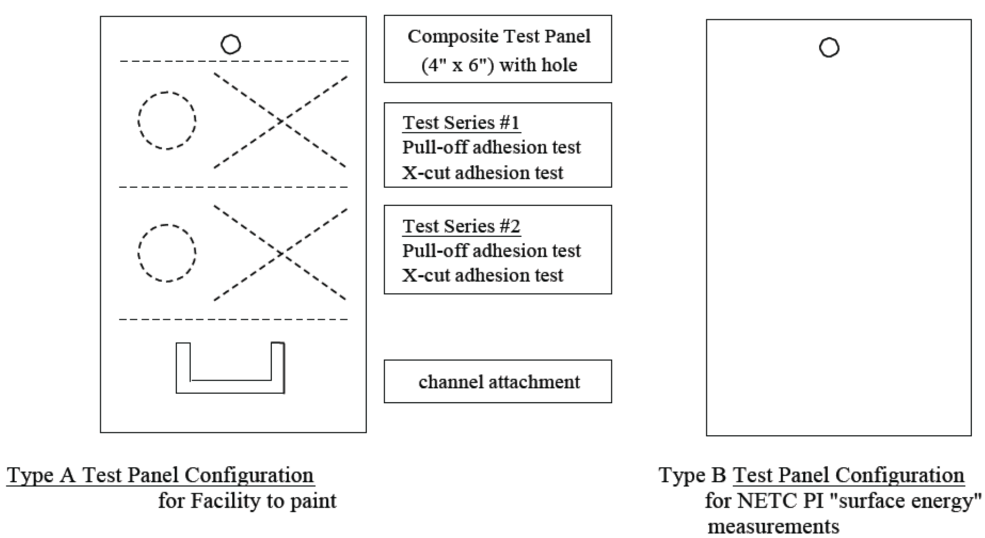


Figure 3. Diagrams show design for Type A and Type B steel test panels.

4.2 Zinc Coating on Steel Test Panels

Zinc coatings on the steel panels are applied by galvanizing, metallizing or organic zinc primers.

Galvanized test panels are prepared per ASTM A123. Metallizing is performed per SSPC-CS23.00/AWS C2.23M/NACE No. 12 Specification for the “Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc and Their Alloys and Composites for the Corrosion Protection of Steel”.

In addition to the of test panels we prepared a control group of test panels named as Group Z. The Group Z panels are not galvanized or metallized but are painted with zinc rich organic primers as the zinc containing layer. The organic zinc primers were selected from the list of NEPCOAT approved list of primers for bare steel. The organic zinc primers were applied on the control steel panels according to the technical specification from the zinc primer paint manufacturers.

Figure 4. Rough zinc surfaces produced by different methods. Left: Galvanized steel surface profiled by mechanical grinding. Right: Zinc metallized steel produced by thermal spray.

4.3 Code names for different groups of zinc coated test and control panels

Five different methods for preparing roughened zinc surfaces were used for producing the test panels. We gave each group of test panels a code name. The code names for these five groups of test panels are given in the following list. The meanings of the code names are described in parentheses.

(1) G0b (Galvanized / no delay / blast prep)

(2) G0m (Galvanized / no delay / mechanical grinding)

(3) M0 (Metallized / no delay)

(4) G2b (Galvanized / 2 week delay / blast prep)

(5) Z (Zinc-rich primer paint over blasted steel surface)

The first letter in the code name indicates the method used for Zinc coating on Steel panels. The code names started with “G” are galvanized steel panels. The code name started with “M” is for metallized surface. The code name started with Z is for organic zinc primer coated control panels.

The number in the middle of the code name signifies the time delay between zinc metal coating and the process of surface profiling/painting. The number in the code name “0” signifies that the zinc surface profiling and the painting of epoxy were done on the same day of the galvanizing or metallizing process. Here “0” signifies “zero time delay” between surface profiling and painting of the primer. The number “2” signifies a “two week time delay” between galvanizing/metallizing and profiling/painting.

The third letter in the code signifies the method for surface profiling of the galvanized steel. In the code, “b” stands for blast profiling, and “m” stands for surface roughening by mechanical grinding.

4.4 Preparation of surface profiled zinc metal substrates.

The photographic images of the Type A test panels after the pull-off and x-cut adhesion tests are collected in Appendix D.

4.4.1 Test panel group G0m.

The G0m group of zinc coated metal substrates are galvanized steel profiled by mechanical grinding of the zinc surface to produce surface roughness. This type of grinding produces circular scratch tracks on the zinc surface. These tracks are visible in the panel shown on the left side of figure 4.

The galvanizing and mechanical profiling of zinc surface was performed by Duncan Group, Everett, MA. The galvanizing and mechanical profiling of the surface were performed on the same day.

This group of test panels were labeled as group G0m, where “G” signifies “Galvanizing”, “0” signifies zero delay, and “m” signifies “mechanical profiling”.

4.4.2 Test panel group G0b.

G0b is a group of galvanized steel profiled by sweep blasting to produce rough surfaces. The galvanizing and blast profiling process were performed by V&S Galvanizing, Taunton, MA, using aluminum oxide grit to produce a profile of 1-2 mils.

Galvanizing and blasting were performed on the same day (less than 3 hours of delay). We give this group of test panels an abbreviated group name “G0b”. In this group name, “G” signifies galvanizing as the process of coating zinc, “0” signifies zero delay (within the same day, less than 3 hours) between galvanizing and profiling of the surface, and “b” signifies the use of blasting as a means for surface roughening.

4.4.3 Test panel group M0

The group of M0 zinc coated steel substrates was produced by thermal spray of molten zinc particles on steel. Since the surface of the zinc metallized steel is rough and porous there is no further surface profiling required. The zinc metallized steel test panels were processed by Falmer Thermal Spray, Salem, MA, using 99.99% zinc wire thermal sprayed over steel panels blasted with aluminum oxide grit to produce a 2 mil profile.

We give an abbreviated code name “M0” for this group of test panels, where “M” signifies the “metallizing”, and “0” signifies zero delay in surface profiling. There is zero delay for profiling because the rough surface is an inherent property of the metallized surface.

Figure 4 shows a photograph to contrast the freshly prepared G0m and M0 surfaces. The G0m base panel at the left of figure 4 is shinny with circular scratched tracks due to the mechanical grinding process. The M0 base panel at the right of figure 4 does not reflect light because of the porous nature of the thermal sprayed zinc surface.

4.4.4 Test panel group G2b.

G2b is a group of metal base panels of galvanized steel profiled by sweep blasting to produce rough surfaces. The galvanizing and blast profiling process were performed by V&S Galvanizing, Taunton, MA.

For this group of test panels there is a 2-week delay time between galvanizing and blast profiling. Here the “2” in the group label “G2b” signifies the 2-week delay time. The galvanized steel panels were stored indoors with surfaces exposed to ambient air for two weeks before they were blast profiled and painted.

4.4.5 Test panel group Z

We prepared a set of panels containing organic zinc rich primer as a reference for comparing with the galvanized and the metallized steel test panels. The steel panel were white blasted before application of the zinc-rich primer. We give a code name "Z" signifying "Zinc rich organic primer" for this group of test panels.

4.5 Fabrication of the galvanized and metallized test panels.

URI researchers delivered the steel panels (including Type A and Type B panels, see Fig. 3) to the zinc coating facilities on the day prior to the zinc coating event. Duncan (Everett, MA) and V&S galvanizing (Taunton, MA) performed the galvanization in the morning following the date of steel panel delivery.

For test panel groups G0m, and G0b, the galvanizers performed the mechanical or blast profiling on the same morning of galvanizing. URI researchers picked up the zinc-coated panels before noon on the day of the coating event. URI researchers then transported the zinc coated and surface profiled metal plates to Boyd Coatings Research at noon of the same day. Workers at Boyd Coatings Research started mixing of the two-part epoxy paints and begin spray painting on the Type A zinc coated metal substrates in the early afternoon of the same day. Portions of the freshly mixed liquid paints were brought to a room in Boyd Coatings Research where the URI researchers measured the wetting and spreading properties of small paint droplets (with volume about 1 μL) on zinc coated and profiled Type B test panels prepared from the same batch of galvanizing or metallizing process. The shape parameters of the droplets were measured as a function of time using a model 200 goniometer made by Reme-Hart Instrument Company . The parameters recorded include the contact angle, the height and the diameter of the liquid/solid contact area.

For test panel group M0, a metallizer (Falmer) coated zinc metal on Type A (see Fig. 3) steel substrates by thermal spray during the morning. The URI researchers picked up the metallized panels at noon time and brought them to Boyd Coatings Research at noon of the same day.

For test panel group G2b, the galvanizer (V&S) performed the blast profiling two weeks after the galvanizing event took place at the same galvanizer. Immediately after galvanizing, the zinc coated but not yet profiled test panels were stored indoors for two weeks in a room at URI (Room 315 Pastore Hall) with panels spread out on tables in ambient atmosphere (no air conditioning). After the two week storage, the panels were brought to the galvanizer for blast profiling and for the same-day painting of the primer at the paint facility (Boyd Coatings Research).

4.5.1 Data related to the fabrication process of the galvanized and metallized test panels.

Appendix B of this report contains the coating thickness and other parameters recorded during the galvanizing and metallizing process. Not all galvanizers provided complete data. In those cases, the galvanizer assured that PI that the process and the coating parameters conform within the specifications of the Work Plan.

4.6 Application of Paints on Metal Substrates

4.6.1 Paint Systems Coated on the Test Panels

Five systems of commercial paints were applied to the Type A test panels. The components of these 5 paint systems are described in the following table. We use the code names C, I, S1, S2 and S3 as the abbreviations for the paint systems.

TABLE 1 - Paint Systems for Galvanized or Metallized Test Panels

a. Paint System C, produced by Carboline Company

Primer:	(galvanizing, or mtallizing, or Carbozinc 859)
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

b. Paint System I, produced by International paint.

Primer:	(galvanizing or metallizing, or Interzinc® 52)
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

c. Paint System S1, produced by Sherwin Williams

Primer:	(galvanizing or metallizing, or Zinc Clad III)
Intermediate:	Macropoxy 646 Fast Cure Epoxy
Finish:	Acrolon 218 HS Acrylic Polyurethane

d. Paint System S2, produced by Sherwin Williams

Primer:	(galvanizing or metallizing, or Zinc Clad III)
Intermediate:	Recoatable Epoxy Primer Series B67
Finish:	High Solids Polyurethane Series B58

e. Paint System S3, produced by Sherwin Williams.

Primer:	Metallizing
Intermediate:	Macropoxy 920 Sealer
Finish:	Acrolon 218 HS Acrylic Polyurethane

Note: The paint system S3 was applied to substrate M0 only. It was not used for other metal substrates.

4.6.2 Paint Systems Coated on the Control Panels

The control panels have the same systems of the Intermediate and the Finish (Top) paints as those used for the test panels but use an organic Zinc-Rich Primer from the NEPCOAT approved list of primers for bare steel. The zinc rich primers used for control Panels are listed in Table 2. The coated control panels are labeled with a code starting with Z signifying the zinc-rich primer on steel surface. We label the control panels as Z-C, Z-I, Z-S1, and Z-S2 signifying the paint system used for fabricating the test panels

TABLE 2 - Paint Systems for Control Panels

a. Test panels subgroup Z-C

Primer:	Carbozinc 859 Organic Zinc Rich Epoxy Primer
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

b. Test panels subgroup Z-I.

Primer:	Interzinc® 52 Epoxy Zinc Rich (Green)
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

c. Test panels subgroup Z-S1

Primer:	Zinc Clad III HS Organic Zinc Rich Epoxy Primer
Intermediate:	Macropoxy 646 Fast Cure Epoxy
Finish:	Acrolon 218 HS Acrylic Polyurethane

d. Test panels subgroup Z-S2

Primer:	Zinc Clad III HS Organic Zinc Rich Epoxy Primer
Intermediate:	Recoatable Epoxy Primer Series B67
Finish:	High Solids Polyurethane Series B58

4.7 Work plan and Test Matrix.

4.7.1 The Work Plan

A Work Plan for the NETC 05-5 project is attached as Appendix A of this report. This document was constructed in June 2009 by the NETC 05-5 Technical Committee. The content was based on a workshop with paint industry representatives, consultation with galvanizing operators, and three NETC Technical Committee meetings during the period of March to June 2009.

The NETC 05-5 Work Plan in Appendix A contains specifications for the galvanizing, metallizing processes, the painting processes, and the adhesive strength measurement.

The test parameters outlined in the Work Plan are summarized in Part 4 of Appendix A in the format of a Test Matrix.

4.7.2 Test Matrix

The Work Plan contains a Test Matrix that shows the different parameters and specifications for all the test and control panels. Here, in Table 3, we insert the test panel codes into the Test Matrix to correlate the Test Panel Labels with the parameters and the specifications.

The test panels are labeled with a composite of the two identifiers connected by a hyphen "-". The first identifier signals the type of zinc coated metal substrate, e.g. G0m, G0b, M0, G2b, and Z. The second identifier signals the type of paint system used, e.g. C, I, S1, S2 and S3.

The total number of the painted type A test panel is 84 in this revised Test Matrix (it was 68 in the original Test Matrix).

Table 3. Test Matrix showing the tested panels and the subgroup names.

TEST MATRIX (Revised)	**1**					**2**		
NETC 05-05 Revised to reflect the actual tested panels. Process Variables (essential)	Duplex Galv steel - Paint	1	2	3	Con-trol	Duplex TS Metallize-Paint		
Test panel group name		**G0b**	**G2b**	**G0m**	**Z**		**M0**	**M0-S3**
Test piece, surface prep	none				paint	SP5	x	
Zinc over steel	Galv					Metallize		
Galvanizing (ASTM A123)		x	x	x				
Kettle process, dry or wet	dry							
Test piece, thickness (in.)	<1/4					<1/4		
Thickness of coating, mils (min)	3.0 (min)					8.0 avg	x	
Profilling steel					x	(6-10)	(6-10)	
Cleaning (ASTM D6386)								
5.2 Surface smoothing	as needed							
Profiling Zn (ASTM D6386, 5.4.1)								
Temperature of galv part	ambien t					ambient		
Abrasive sized to produce profile		x	x		x			
Abrasive hardness (Mohr)	record				Al Ox			
Low Nozzle pressure (psi)	record							
Profile (mils) - angular	1.0 - 3.0	x	x		x	>2.5	x	
Mechanical abrasion-grinding	record			x				
						Metal wire Zn 99.99%	x	
Time-coat steel after surf prep (max)	na					4 hrs		
Time-coat zinc after surf prep (max)	12 hrs	x		x		8 hrs	x	
ditto - max **DAYS**	14 days		x					
Facility - same galv & paint		no	no	no	yes		no	
Paint Selection Thickness (min)						Sealer		x
primer/intermediate/top 2-5 / 4-6 / 3-4 (mils)								
1. Carboline 859/888 / 133 LH	1 IT*	1 IT	1 IT	1 IT	1 PIT✚	Interm-Top	1	
2. International 52/345 /870 UHS	1 IT	1 IT	1 IT	1 IT	1 PIT	Interm-Top	1	
3. Sh Wm Zn Clad III / Recoat epoxy primer B67 / HS PU B58	1 IT	1 IT	1 IT	1 IT	1 PIT	Interm-Top	1	
4. Sh Wm Zn Clad III/646 /218HS	1 IT	1 IT	1 IT	1 IT	1 PIT	Interm-Top	1	
5. Sh Wm 920 /218HS						Interm-Top		1
(panels per test)	**4**	4	4	4	4	**4**	4	4
number of panels		16	16	16	16		16	4
number of test pieces	**64**					**20**		

Notes: * IT means Intermediate/Topcoat, ✚ PIT means Primer/Intermediate/Topcoat

4.7.3 Painted test panels.

In section 4.3 we identified 5 groups of zinc coated substrates (G0b, G2b, G0m, M0, and Z). In section 4.6 we identified 5 different paint systems (C, I, S1, S2 and S3). The combinations of different zinc surfaces and different paints are specified in the implemented Test Matrix in Table 3 of section 4.7.2. Using these abbreviations we now define a subgroup name for each particular pairing between a zinc surface and a paint system. The subgroup name is in the format of (Zinc coated substrate)-(paint system). For example, the subgroup name G0b-C means the test panel was galvanized with zero days of delay between galvanizing and profiling/painting, and the paint system C was used for coating over the zinc coated steel surface. The hyphenated code names are used for the subsequent discussions of the experimental designs and test results.

We further use stamped numbers on each steel substrate to identify the individual test panel. Each test panel has a number that is stamped on the steel plate or attached with a numbered metal tag.

In Appendix B of this report we collected the recorded painting conditions, spray coating parameters and paint thickness reported by Boyd Coatings Research, Hudson, MA.

In Appendix D of this report we display the photographic images of the test panels showing the pulled off dollies or the test spots, and the X-cut adhesion tests of each test panel.

During the metal substrate fabrication, and the subsequent painting process, each group of test panels was stored in a numbered cardboard box. The boxes were numbered and had labels identifying the metal-paint grouping and the tag numbers for the 4 or 5 panels contained in the box.

In Table 4 we display a list of the 84 painted test panels according to its subgroupings, with information about the Zinc coating, the method of profiling, the panel tag numbers and the box identification numbers that had been used for transporting and storing the test panels.

Table 4. The specification, the identifying panel numbers listed according to subgroups and the storage boxes.

1. ***Group G0m type A contains 4 subgroups. (G0m= Galvanized, same day, mechanical profiling.).***

a. Test panel subgroup G0m-C

Primer:	galvanizing followed by mechanical profiling
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

Test panel numbers G0m-C-253, 254, 255, 256, stored in box 1

b. Test panel subgroup G0m-I

Primer:	Thermal sprayed zinc metallizing coating
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

Panel numbers G0m-I-257, 258, 259, 260, stored in box 2

c. Test panel subgroup G0m-S1

Primer:	Thermal sprayed zinc metallizing coating
Intermediate:	Macropoxy 646 Fast Cure Epoxy
Finish:	Acrolon 218 HS Acrylic Polyurethane

Panel numbers G0m-S1-261, 262, 263, 264, stored in box 3

d. Test panel subgroup G0m-S2

Primer:	Thermal sprayed zinc metallizing coating
Intermediate:	Recoatable Epoxy Primer Series B67
Finish:	High Solids Polyurethane Series B58

Panel numbers G0m-S2-265, 266, 267 268, stored in box 4.

2. ***Group G0b type A contains 4 subgroups. (G0b = Galvanized, no delay, blast profile)***

a. Test panel subgroup G0b-C

Primer:	galvanizing followed by blast surface profiling
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

Test panel tag numbers: G0b-C-289, 290, 291, 292 stored in box 10.

b. Test panel subgroup G0b-I

Primer:	galvanizing followed by blast surface profiling
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

Test panel tag numbers: G0b-I-293, 294, 295, 296, stored in box 11.

c. Test panel subgroup G0b-S1

Primer:	galvanizing followed by blast surface profiling
Intermediate:	Macropoxy 646 Fast Cure Epoxy
Finish:	Acrolon 218 HS Acrylic Polyurethane

Test panel tag numbers: 297, 298, 299, 300, stored in box 12.

d. Test panel subgroup G0b-S2

Primer:	galvanizing followed by blast surface profiling
Intermediate:	Recoatable Epoxy Primer Series B67
Finish:	High Solids Polyurethane Series B58

Test panel tag numbers: G0b-S2-301 302, 303, 304, stored in box 13.

3. Group M0 type A contains 5 subgroups. (M0 = Metallized, same day, no need for profiling).

a. Test panel subgroup M0-C

Primer:	Thermal sprayed zinc metallizing coating
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

Panel numbers M0-C-269, 270, 271, 272, stored in box 5.

b. Test panel subgroup M0-I

Primer:	Thermal sprayed zinc metallizing coating
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

Panel numbers M0-I-273, 274, 275, 276, stored in box 6.

c. Test panel subgroup M0-S1

Primer:	galvanizing followed by blast surface profiling
Intermediate:	Macropoxy 646 Fast Cure Epoxy
Finish:	Acrolon 218 HS Acrylic Polyurethane

Test panel tag numbers: 281, 282, 283, 284, stored in box 8

d. Test panel subgroup M0-S2

Primer:	Thermal sprayed zinc metallizing coating
Intermediate:	Recoatable Epoxy Primer Series B67
Finish:	High Solids Polyurethane Series B58

Test panels M0-S2-277, 278, 279, 280, stored in box 7

e. Test panel subgroup M0-S3

Primer:	Thermal sprayed zinc metallizing coating
Intermediate:	Macropoxy 920 penetrating pre-primer
Finish:	Acrolon 218 HS Acrylic Polyurethane

Test panel numbers M0-S3-285 286, 287, 288, stored in box 9.

4. Group G2b type A contains 4 subgroups. (G2b = Galvanized, 2-week storage, blast profiled).

a. Test panel subgroup G2b-C
   Primer: (galvanizing or metallizing)
   Intermediate: Carboline 888 Epoxy
   Finish: Carboline 133 LH Aliphatic Polyurethane
   Test panel numbers 636, 637, 638, 639, stored in Box 14

b. Test panel subgroup G2b-I
   Primer: (galvanizing or metallizing)
   Intermediate: Intergard 345 Epoxy
   Finish: Interthane 870 UHS
   Test panel numbers 640, 641, 642, 643, stored in Box 15

c. Test panel subgroup G2b-S1
   Primer: (galvanizing) or (metallizing w/ and w/o Macropoxy 920 sealer)
   Intermediate: Macropoxy 646 Fast Cure Epoxy
   Finish: Acrolon 218 HS Acrylic Polyurethane
   Test panel numbers G2b-S1-644,645,646,647, stored in Box 16

d. Test panel subgroup G2b-S2
   Primer: (galvanizing or metallizing)
   Intermediate: Recoatable Epoxy Primer Series B67
   Finish: High Solids Polyurethane Series B58
   Test panel numbers G2b-S2-648,649,650,651, stored in Box 17

5. Group Z type A contains 4 subgroups. (Z = Zinc rich organic primer was coated on steel)

a. Test panels subgroup Z-C
   Primer: Carbozinc 859 Organic Zinc Rich Epoxy Primer
   Intermediate: Carboline 888 Epoxy
   Finish: Carboline 133 LH Aliphatic Polyurethane
   Test panels: ZC-43, ZC-305, ZC-3052, ZC-306, in Box 18

b. Test panels subgroup Z-I.
   Primer: Interzinc® 52 Epoxy Zinc Rich (Green)
   Intermediate: Intergard 345 Epoxy
   Finish: Interthane 870 UHS
   Test panels: ZI 307, 3072, 308, 3082, in Box 19

c. Test panels subgroup Z-S1
   Primer: Zinc Clad III HS Organic Zinc Rich Epoxy Primer
   Intermediate: Macropoxy 646 Fast Cure Epoxy
   Finish: Acrolon 218 HS Acrylic Polyurethane
   Test panels: ZS1 309, 3092, 310, 3102, in Box 20

d. Test panels subgroup Z-S2
   Primer: Zinc Clad III HS Organic Zinc Rich Epoxy Primer
   Intermediate: Recoatable Epoxy Primer Series B67
   Finish: High Solids Polyurethane Series B58

Test Panel numbers Z-S2-311, 3112, 312, 3122, in Box 21

4.7.4 A chronology of test panel fabrication, and the contact angle measurement.

The starting date of the fabrication process for each group of test panels is listed in the following. The contact angles were measured on the same day of the surface profiling and painting of the epoxy intermediate layer. The liquid paint used for the contact angle measurement is drawn from the same batch of freshly formulated epoxy paint prepared by Boyd Coatings Research. The contact angle measurements were performed within the period before the gelling of the fresh paint. The finish paints were applied after the intermediate paints were cured.

07/22/2009 Begun fabricating Group G0m type A panels. Duncan Group (Everett, MA) started galvanizing and mechanical grinding profiling process in the morning. We transported the freshly profiled panels from Duncan to Boyd Coatings Research at noon time. Boyd applied the epoxy intermediate paint to these panels. We performed contact angle measurements on the Group G0m type B panels in the afternoon at Boyd Coatings Research.

07/22/2009 Begun fabricating Group M0 type A panels. Falmer Thermal Spray (Salem, MA) started the metallizing process in the morning. We transported the freshly profiled panels from Falmer to Boyd Coatings Research at noon time. Boyd applied the epoxy intermediate paint to these panels. We performed contact angle measurements on the Group M0 type B panels in the afternoon at Boyd Coatings Research.

08/19/2009 Begun fabricating Group G0b type A panels. V&S Galvanizing (Taunton, MA) started galvanizing and blast profiling process in the morning. We transported the freshly profiled panels d from V&S to Boyd Coatings Research at noon time. Boyd applied the epoxy intermediate paint to these panels. We performed contact angle measurements on the Group G0b type B panels in the afternoon at Boyd Coatings Research.

01/05/2011 Galvanized Group G2b type A and type B panels. The panels were not profiled, but were taken back to URI for exposure to room air in Room 335 Pastore Hall, University of Rhode Island. The test panels were placed on a lab bench for 14 days before transporting them to V&S on 01/19/2011.

01/20/2011 The Group G2b type A and B panels galvanized on 01/05/2011 were blast profiled at V&S. We transported the profiled panels from V&S to Boyd Coatings Research at the noon time.

Boyd applied the epoxy intermediate paint to these panels. We performed contact angle measurements on the Group G0b type B panels in the afternoon at Boyd Coatings Research.

06/20/2011 Boyd Coatings Research blast cleaned the steel panels for Group Z and painted the zinc rich epoxy primers for Group Z. We obtained the formulated primer in liquid form during the afternoon. After the coatings were cured Boyd applied the intermediate and the finish coats. We picked up the finished Group Z panels on 07/11/2011.

5 Measurement of the wetting property of liquid paint on profiled zinc surfaces.

In section 3.5 we reviewed our proposal for measuring the wetting properties of a liquid paint and the potential for correlation with the adhesion strength of the dried paint on that same paint/zinc interface. In this section we first present in section 5.1 how the wetting property was measured and give a few examples to illustrate the process. In section 5.2 we show several wetting data that represent different categories of the wetting behavior. In section 5.3 we discuss the differences in the wetting properties among different paint/zinc surface pairs.

5.1 Measurement of contact angle of liquid paint on profiled surfaces of zinc galvanized and metallized steel.

It was discussed in Section 3.3 that the paint wetting parameters of a droplet of liquid paint consist the contact angle θ, the height h and the diameter d of the cap of a droplet (see figure 1). For some roughened surfaces, the liquid droplet spreads and penetrates into the void space in the profiled surface. This leads to observable change of the shape and the size of the droplets as a function of time. This phenomenon is generally characterized as the spreading and absorption of paint. Thus the information about the wetting property of a liquid paint on a zinc-coated surface is obtained by measuring the interfacial contact parameters (θ, h, d) of the droplets as a function of time. For some liquid/surface pairs a 10 seconds measurement is sufficient. For some other liquid/surface pairs, the useful data is contained in the parameters as a function of time for 20 minutes duration.

5.1.1 The contact angle measurement equipment

We used a Ramé-Hart Model 200 goniometer (made by Ramé-Hart Instrument Co., Succasunna, NJ) to measure the wetting properties. The apparatus is shown in Figure 5. At the center of the apparatus is a sample holder stage that allows fine adjustment of the position of the Type B test panels (see Fig. 2). During the test, we place a small droplet (about 1 μL of freshly formulated paint on the surface of a profiled Type B test panel. A beam of collimated parallel light is shined from the light source at the right of Figure 5 through the liquid/solid interface. A camera in the middle of Figure 5 is used to record the image of the droplet and the interface as a function of time. A software program “DROP” is used to analyze the shape of the contacting interfaces and to compute the best fit contact angle.

Figure 5. A goiniometer for measuring the liquid paint wetting of a profiled zinc surface*.*

5.1.2 Experimental protocols for minimizing systematic error.

In order for the wetting property measured to be relevant to the adhesion strength of the dried paint we need to be sure that the liquid paint we used for measuring the contact angle is as nearly as possible a replica of the liquid paint used for spray painting by the painter at the paint booth at Boyd Coatings Research.

It is not easy to have exact replicas of the paints for both the contact angle measurement and the painting operation. The paint viscosity and the wetting property change as a function of time after the paint is formulated at the paint booth. The aging of the primer paint is inevitable because of the nature of the chemical reactions and the physical property change involved in the curing process of the epoxy paint. The epoxy paint is formulated immediately before the painting process. The two parts of the epoxy paints (the resin and the hardener) are chemically cross-linked (the curing process) to result in hardened polymer. Although the paint manufacturer allows for a time interval (e.g. an hour) for useful painting process, we decided that we should try to minimize the effect of the extent of curing process.

From the above considerations, it is therefore recognized at our experimental design stage that the following three conditions are important for obtaining valid data aimed at establishing experimental correlations between the contact angle and the pull-off strength.

(1) The Zinc coated panels for painting (Type A panels) and for contact angle measurement (Type B panels) need to have nearly the same profiled surface. We prepared the galvanizing (or metallizing) and the surface profiling (mechanical abrasion, or blast roughening) in the same fabrication batch process.

(2) The paint used for coating and for contact angle measurement needs to have the same composition. We could not be sure that the same formulation prepared in separate batches would be good enough for the correlation between contact angle and pull-off strength. Thus we used the same epoxy paint prepared in the same batch of formulation for both the painting and the contact angle measurement.

(3) For the freshly prepared paint formulation, we measured the contact angle at approximately the same time (within a 20 minute window for completing the contact angle measurement) as the painter at Boyd Coating Research spray painted the same formulation at the paint booth. To accomplish this timing synchronization, we set up the goniometer in a room in Boyd Coatings Research adjacent to its painting facility with similar environment. As each paint system is formulated at the paint booth, a sample of the just formulated paint was given to the URI researchers. The URI researchers then measure the wetting parameter on the Type B panels that were in the same batch process of galvanizing/profiling (or metallizing). Some of the paints need to undergo a "sweat" time before spray painting. For this paint system, the contact angle measurement sample was taken from the batch of sweated paint formulation and was measured at approximately the same time as the paint booth work.

5.2 An Example of Contact Angle Measurement Result.

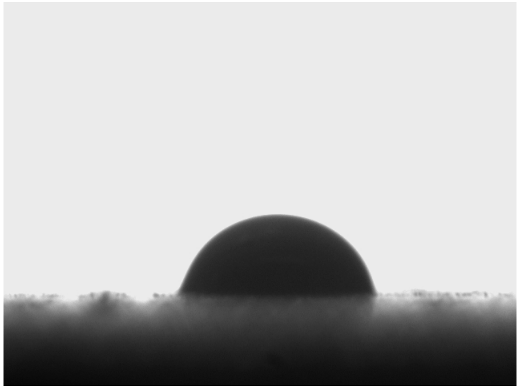
We first look at a typical example of the contact angle measurement. This initial discussion serves the purpose of familiarizing the reader with the measured data and their implications. Figure 6 shows a time sequence of the image of a droplet on a profiled zinc surface. In this example, we placed a droplet of the freshly mixed Carboline 888 epoxy liquid paint on a G0b surface (Galvanized, same day profiling/coating, blast profiled) at t=0 sec. The pictures show the image of the droplet at 2, 6, 12, 20 and 68 seconds respectively.

The figure shows that the contact angle is less than 45^o at t=5 sec which means significant attractive force between the liquid paint and the surface. We use the contact angle at t=5 seconds as a measure of the interfacial interaction. For some more viscous paints, the t=0 seconds droplet has not yet reached mechanical equilibrium immediately after the initial impact at the surface.

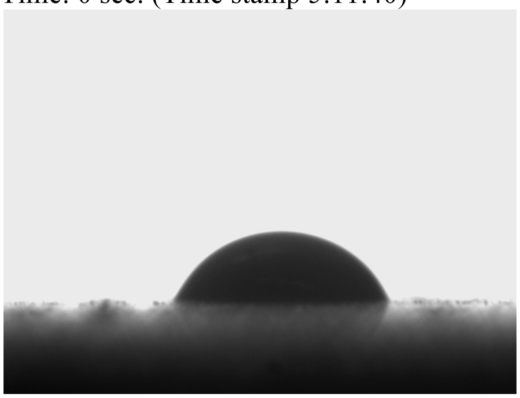
The contact angle and the droplet height h continue to decrease over time. The diameter of the cap expands. This time sequence informs us about another aspect of the wetting property, i.e., the spreading of the paint liquid on the surface. Using the h and d values we can calculate the volume of the liquid.

By measuring the height, the width and the contact angle simultaneously we are able to calculate the total volume of the liquid droplet as the liquid paint spreads. For the droplet shown in Figure 6 the volume of the droplet is nearly the same at t=68 sec as that at t=0 sec. This means that although the liquid paint is spreading, the paint is not absorbed by the surface voids. This implies that the profiled surface does not have microscopic channels that siphon away the paint by capillary action. Or, if there are microscopic cavities under the surface, the paint is not filling more of the cavities as time lapses.

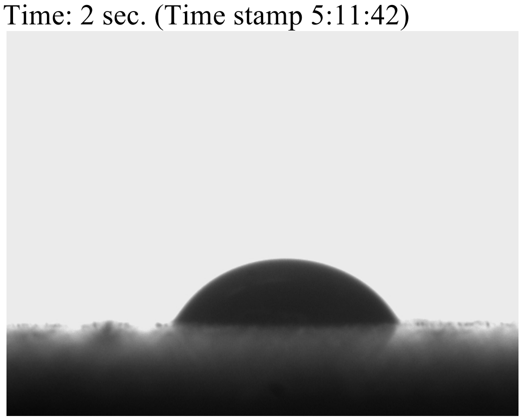
For droplets with slower rate of change, we photographed the images as a function of time and analyzed the wetting parameters using an image analysis program. For fast changing parameters we use the “auto run” mode that captures the change in the parameters without saving the images.



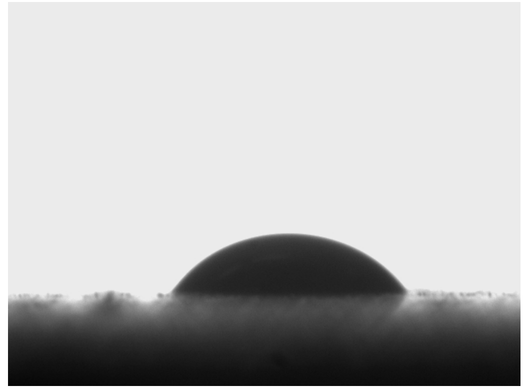
Time: 0 sec. (Time stamp 5:11:40)



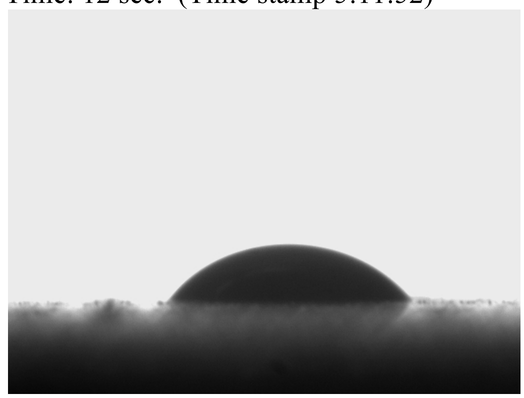
Time: 2 sec. (Time stamp 5:11:42)



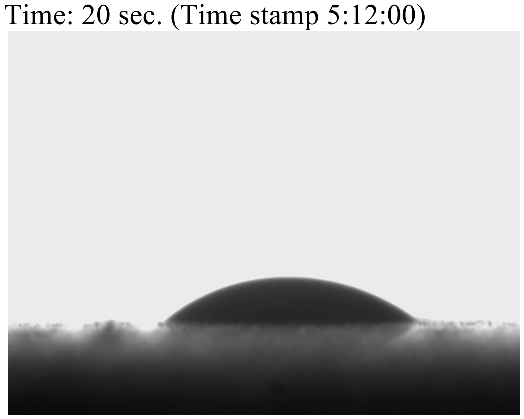
Time: 6 sec. (Time stamp 5:11:46)



Time: 12 sec. (Time stamp 5:11:52)



Time: 20 sec. (Time stamp 5:12:00)



Time: 60 sec.

Figure 6. Images of a droplet of liquid epoxy paint C on profiled surface G0b recorded as a time sequence. The contact angle decreases in time, the diameter d increased and the height h decreased. The last image was taken at 68 sec.

5.3 Examples of Paint Wetting Properties

In the following sections, we illustrate one example for each of the 4 different types of wetting phenomena observed when a droplet of the freshly formulated primer paint is in contact with the roughened zinc surfaces. We show one example for each typical case of wetting and spreading properties.

5.3.1 Case 1: Liquid paint wets metal surface without spreading or absorption.

Figure 7 shows the image of a droplet of paint primer I on galvanized steel roughened by blast abrasion.

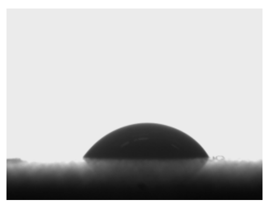


Figure 7. A droplet of epoxy primer I freshly formulated on galvanized steel surface roughened by blast abrasion. The contact angle does not change with time.

The contact angles for other samples of Gb-I are similar (ranging from 43 to 25^{o}) to that shown in figure 7. Since the contact angle is small, the droplet strongly wets the surface. This case is distinct from the other cases to be described later because the paint does not spread as evidenced from the constancy of the near constant (or slow changing) contact angle θ, the diameter of the base of the cap d, and the height of the droplet. An example of the time dependence of these measurable parameters is shown in figure 8. The volume of the observable cap of the droplet is calculated from the diameter d and the height h of the liquid cap according to equation 4.

$$V_{cap} = \frac{\pi}{6} h \left(3\left(\frac{d}{2}\right)^2 + h^2 \right) = 0.523598776(h)\left(0.75d^2 + h^2\right) \tag{4}$$

Figure 8 shows that all the measureable and calculable quantities are nearly constant for more than 2 minutes of continuous measurements. The slight drop in volume is consistent with the rate of the evaporation of the solvent used for the paint formulation.

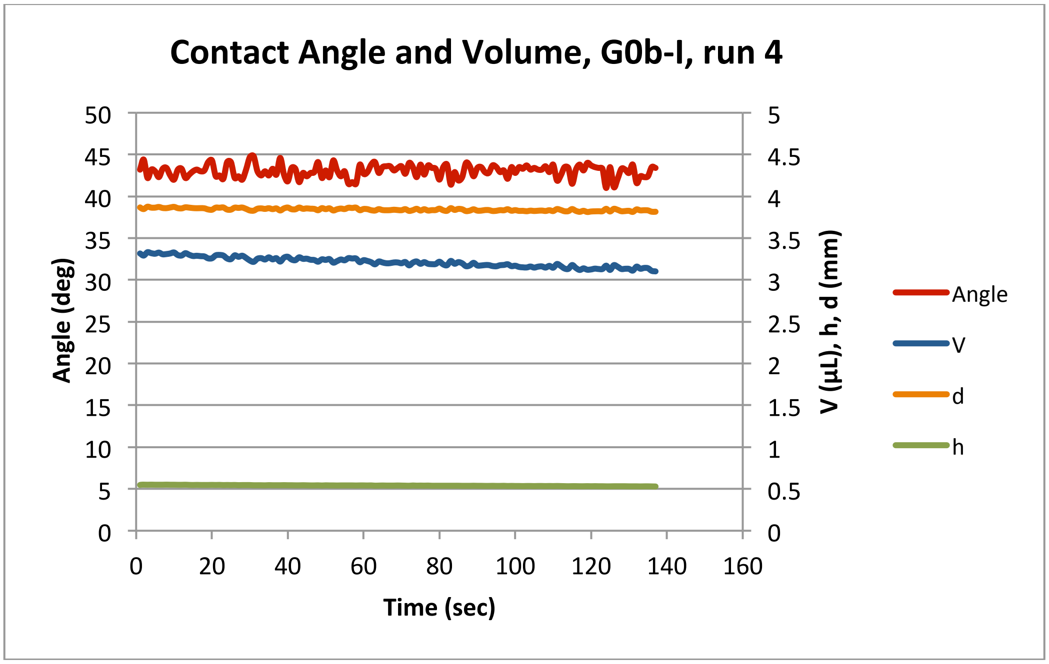


Figure 8. The contact angle and the size parameters of a droplet of epoxy primer I on G0b surface measured as a function of time.

Although the droplet is not spreading, it will form a liquid film by merging with other droplets when the sprayed primer droplets are dense enough and flowing.

5.3.2 Case 2: Paint liquid droplet wets the metal surface with moderate rate of spreading and paint absorption.

Figure 9 shows an example of a liquid paint droplet that wets the surface (initial θ=45o) like that of case 1. The time evolution in this case is, however, different from that of case 1 in the following manner:

(1) The contact angle decreases by a larger percentage. In case 1, the contact angle does not change during the first 100 sec. In case 2, the contact angle decreases by 38 % during the same period of 100 seconds.

(2) The height h of the cap decreases while the diameter of the base of the cap slightly increases during the same time of 100 seconds. This indicates that the droplet is spreading.

(3) The volume is decreasing at a faster rate than the evaporation loss. This implies that part of the liquid is absorbed to form a surface layer depicted as a thin flat film under the liquid cap shown in figure 2. Since the dimensions of the thin film are not measured as the height h or the diameter d in Figure 2, the height is decreasing because the liquid droplet is absorbed by the rough surface.

For this particular sample G0m-S2, the zinc surface has visible circular grooves produced by mechanical grinding with abrasive discs. The grooves are visible in figure 4 which compares the images of the galvanized and mechanically roughened surface. It is possible that the liquid epoxy primer is drawn into the channels cut into the zinc surface by the mechanical abrasion.

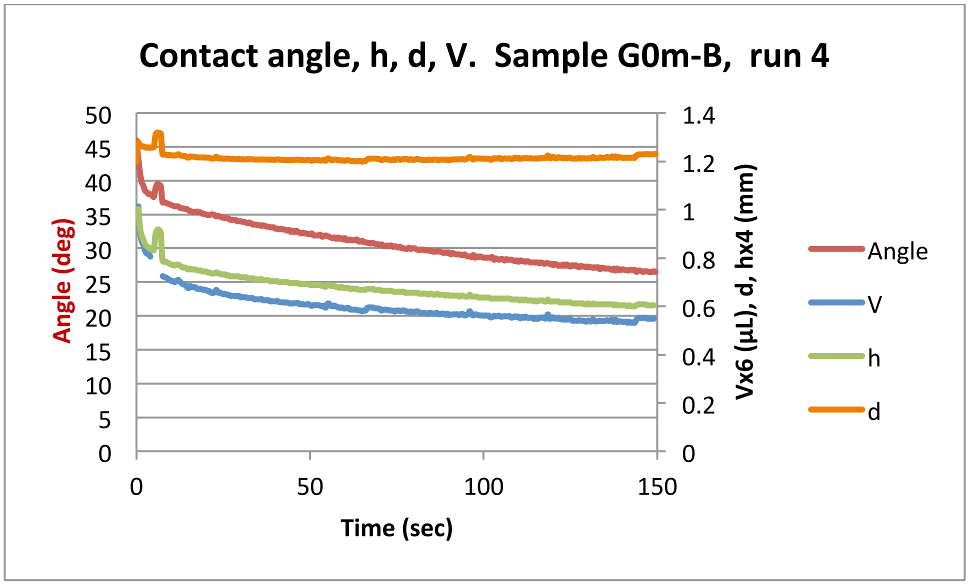
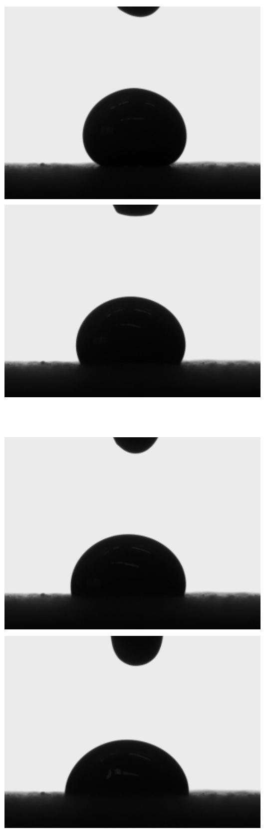


Figure 9. An example of case 2 phenomenon. Contact angle, height and volume decreases with time, while the diameter d is slightly increased.

5.3.3 Case 3: Paint liquid drop "balls up" with initial contact angle larger than 90°.

Figure 10 shows several image of an initially non-wetting droplet that eventually wets the surface.



t=0 sec, θ= 140°

t=10 sec, θ= 120°

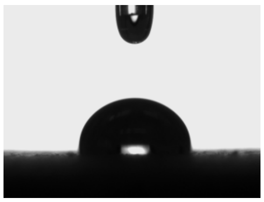
t=30 sec, θ= 100°

t= 120 sec, θ= 70°

Figure 10. Time sequence of change of droplet shape and contact angle for a liquid droplet on a roughened zinc surface.

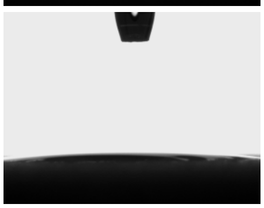
5.3.4 Case 4: Rapid spreading and absorption of a droplet of primer S3 on Metallized steel.

Figure 11 shows the images of a droplet of primer (sealer) S as a function of time after it is placed on a metallized steel. These images are in sharp contrast with those shown in Case 3. The initial contact angle is smaller than 90o for Case 4, while the contact angle is higher than 90o for Case 3.



t=0, θ= 70^{o}

t=0.5 sec, θ=10^{o}



t= 1.0 sec, θ= 7^{o}

Figure 11. Time-sequence Photos of sealant S3 liquid droplet rapidly spreading on zinc metallized surface.

Figure 12 shows that the contact angle, the height h and the volume V of the droplet are all decreasing at a rapid rate (decrease by 50% in less than 0.5 second), while the diameter d increases by 20% within the first 0.2 sec and decreases by 50% within the next 1 second. This indicates that the droplet spreads rapidly on the zinc metallized surface, and is penetrating into the porous zinc coating.

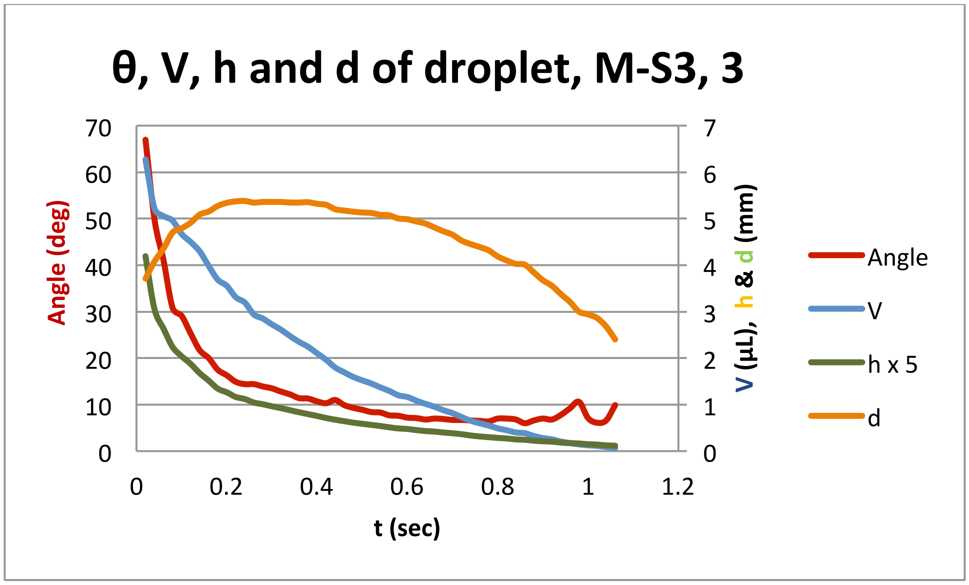


Figure 12. The contact angle, the diameter of the contact surface d, the height h and the volume V of a S3 droplet as a function of time t after contacting a zinc metallized surface. Notice the changes are mostly completed within 1 second.

5.4 Contact angles for different epoxy liquid paints on different zinc surface profiles

We measured the contact angles of droplets of 5 different primers on three different profiled surfaces and recorded the contact angle θ, the height of the droplet h and the diameter d of the liquid/solid contact area. These shape parameters provide the information of whether the paint primer wets the surface, how fast the droplet spreads and expands, and whether the primer liquid is absorbed and fills in the voids created by the roughening process during the deposition of zinc on steel. In the next section, we will tabulate one extracted data point from the θ vs. t curves. We use the contact angle θ at t=5 sec as a measure of the initial value of the contact angle. It is an index for the wetting property of the liquid paint on the solid surface.

The data for contact angles measurement are collected in Appendix C of this report. Selective images of the liquid droplets of the epoxy paints and the parameters relating to the wetting and spreading of liquid droplets on different profiled surfaces are plotted as a function of time in the manner exemplified in the plots of Section 5.3. The displayed wetting and spreading parameters include the droplet contact angle θ (in degree), the height h, and the width d, and the volume V of the droplet plotted as a function of time.

In this section we first give a qualitative discussion of the contact angle and the wetting process. We will then present a table of contact angles for different paint/surface pairs measured at an arbitrarily chosen time (t = 5 seconds) after the initial droplet to surface contact.

To highlight the characteristics of the observed liquid paint wetting on the test panels, we begin by contrasting our observed data with what is expected from an oversimplified model of paint/surface interaction. All paint formulations contain very similar organic solvents (typically a mixture of methyl ethyl ketone, acetone, xylene, toluene, etc.). An organic solvent droplet without the epoxy resin will have a very small contact angle (about 10-20o) on smooth metal surfaces. If the organic solvents were the dominant component in the paint formulation, the contact angles would be all very small and different paints with the similar organic solvents would all have the same low contact angles. Our data presented in Appendix C show, however, a wide range of contact angles for different paints on the different profiled surfaces. The contact angles θ we measured cover a wide range from 110^o to 0^o.

What are the factors that give a wide range of divergent θ values for the real paint/surface systems vs. the anticipated small and convergent angle (e.g. $\theta = 15^o$ for all paints) for the above mentioned (solvent dominant) imaginary paint system? The real system is different in two aspects:

(1) The paint has relatively low content of the solvent thus the contact angle is not entirely determined by the organic solvent.

(2) The surfaces of the zinc metal are not smooth. They were roughened in three different ways.

All NEPCOAT epoxy intermediate paints are high solid paints. Although enough organic solvents are incorporated in the paint formula to allow flowing, the paints have high solid content of organic epoxy oligomers and polymers. Collectively the organic solvents, the epoxy resin, and the amine hardener all contribute to the value of the initial contact angles. The viscosity of the paint and the affinity with the profiled zinc surface determine the spreading of the droplet.

Paint system S3 is an exception to the other paints. Paint S3 contains low viscosity epoxy in part A and low viscosity amine hardener in part B. There is no solvent added to S3, but the contact angle on metal surfaces is as low as that of the common organic solvent. Our data show that when a droplet of S3 is in contact with the metallized surface (M0) the liquid droplet is quickly absorbed within the first 1 second after the initial contact. At t = 5 seconds, the contact angle $\theta = 0^o$. The S3 system contains only low molecular weight epoxy and does not contain oligomer or polymer. This allows S3 to serve as a sealant.

The second reason for a wide range of the θ values for the tested paint/surface system is that the zinc surfaces are all roughened. Depending on whether the liquid paint wets only the tips of the roughened surface profile or the entire depth of the surface profile, the contact angles can be very different.

The contact angle θ for a liquid droplet on a smooth surface is determined by the interfacial tensions according to equation (1) of section 5. For a roughened surface the contact angle is determined by both the interfacial tensions and the degree of roughness. Equation (2) of section 5 shows that a liquid with small contact angle on smooth surface can attain much higher contact angle because of the degree of roughness r causes an amplification of the attainable contact angle. This phenomenon of very high contact is called “super hydrophobicity” or “lotus effect” in the contemporary research literature. The surface roughness of a lotus leaf is the reason for the common observation of near spherical shape of water droplets on the leaves after a rain shower. We believe that the “lotus effect” is the reason for the observation of high contact angles in some of the tested paint/surface pairs.

The values of measured contact angle are not always the same for the same paint on the same test panel. This is not surprising because the surface composition could slightly vary from spot to spot, and the surface roughness is not uniform to the microscopic scale. Lacking a more elaborate method for evaluating the variation in local chemical composition and the degree of roughness, we take the average of all measurements unless we have reason to doubt the validity of a specific measurement. In some of the measurements we suspect the fast auto-recording mode of the instrument was not working properly. If we did not do a calibration of the aspect ratio (using a standard sphere imaging) before the fast anto-recording data taking, we rely only on the data analyzed from the recorded photo images of the droplets. The following table (Table 5) is extracted from the contact angle data displayed in Appendices C1, C2, C3, and C4. We extract from the photographic images and the auto-recording charts the shape parameters of the liquid paint droplet at t = 5 seconds after the initial contact between the liquid drop and the test panel surface. We felt that the droplet shape parameter at t = 5 seconds is representative of the initial equilibrium at the liquid/solid interface. At t = 5 seconds, the liquid droplet has just reached mechanical balance between the gravitational force and interfacial tensions, but the slower process of paint spreading and paint absorption has not yet progressed.

Table 5: Contact angle θ (in degree) measured after 5 or 6 seconds after the liquid paint droplet was placed on the surface of a test panel.

Profiled surface	Paint	Measurement number	Contact angle Θ (degree)
G0b	C	1	32
G0b	C	2	40
G0b	C	3	31
G0b	C	4	47
G0b	I	1	37
G0b	I	2	32
G0b	I	3	40
G0b	I	4	37
G0b	S1	1	48
G0b	S1	2	44
G0b	S1	3	51
G0b	S1	4	41
G0b	S2	3	34
G0b	S2	4	74
G0m	C	1	114
G0m	C	3	82
G0m	I	2	40
G0m	I	3	32
G0m	S1	3	76
G0m	S2	1	32
G0m	S2	3	46
G0m	S2	4	38
M0	C	1	136
M0	I	2	75
M0	S1	2	81
M0	S1	1	125
M0	S2	2	58
M0	S2	3	58
M0	S3	2	0
M0	S3	3	0
M0	S3	4	0
M0	S3	7	0
M0	S3	8	0
G2b	C	1	35
G2b	C	2	41
G2b	C	3	33
G2b	C	4	30
G2b	C	5	35
G2b	I	1	38
G2b	I	3	35
G2b	I	4	31
G2b	I	5	35
G2b	I	6	30
G2b	I	8	38
G2b	I	9	29

G2b	I	10	38
G2b	I	11	38
G2b	S1	1	52
G2b	S1	2	55
G2b	S1	4	50
G0b	S1	6	40
G2b	S2	1	36
G2b	S2	3	38
G2b	S2	5	26
G2b	S2	7	35
G2b	S2	8	29
G2b	S2	9	35
G2b	G2b	11	37
G2b	G2b	12	36
G2b	G2b	13	31

For some of the panels exhibiting large contact angles (the "lotus effect") there are significant variations of the measured contact angles. Thus there will be a localized difference for paint wetting on the test panels.

For most test panels without "lotus effect" the contact angles are consistent from different independent measurements for the same surface/paint pairs.

In order to facilitate the analysis of the correlation between the contact angle and the pull-off strength, we need to calculate a representative average contact angle for each surface/paint pairs. We take the simplest approach of taking the average with equal weight for all the valid trials of the contact angle measurement for the same surface/paint interface. The data is shown in Table 6. A caveat should be noted that the simple algebraic average might not be the best way for assigning statistical weights to the data.

Table 6: Average contact angle for tested liquid paint droplets on profiled zinc surfaces.

Profiled surface	Liquid paint droplet	$\Theta_{Average}$ (degree)
G0b	C	37
G0b	I	37
G0b	S1	46
G0b	S2	54
G0m	C	82
G0m	I	36
G0m	S1	42
M0	C	87
M0	I	75
M0	S1	103
M0	S2	58
M0	S3	0
G2b	C	36
G2b	I	35
G2b	S1	49
G2b	S2	35

6 Measurement of paint adhesion on test panels.

The paint coated panels were tested for adhesion strength by two methods:

(1) Pull-off strength measurement according to ASTM D 4541 "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers"

(2) X-cut Tape Adhesion Test according to ASTM D 3359 Method A, "Standard Test Methods for Measuring Adhesion by Tape Test."

6.1 Test panel preparation

The test panels were prepared according to the Work Plan described in Appendix A. The test panel fabrication matrix is described in Table 3 of Section 4.7.2. The panel tag identifications are listed in Secion 4.7.3.

We mentioned in the earlier section that the coating of the epoxy Intermediate Paints for the galvanized or metallized substrates were performed at Boyd Coatings Research (Hudson, MA) on the same day as the liquid paint contact angle measurement. After the epoxy intermediate paints were cured for a duration of time according to the paint manufacturer specification, the polyurethane Topcoat was applied. After the Topcoat was cured, Boyed Coatings measured and recorded the dry film thickness. The URI researchers picked up the test panels from Boyd Coatings and stored the coated test panels indoors at URI for an additional two weeks before beginning the adhesion tests.

6.2 Adhesion test equipment and procedure

6.2.1 Pull-off Strength Test

We used two portable adhesion testers for paint adhesion pull-off strength measurement. The accuracy of the testers were certified by the equipment manufacturers.

(1) Elcometer Model 106-2 Adhesion Tester, with maximum pull-off pressure at 1000 psi. Manufacturer: Elcometer, Rochester Hills, Michigan. Figure 13 shows a photograph of this tester.

(2) PosiTest® AT-M Manual Adhesion Tester, with maximum pull-off pressure at 3000 psi. Figure 14 shows a photograph of this tester. The PI is grateful to Mr. Michael Sock of RIDOT for the loan of this equipment for this research project.

Fig. 13. Pull-off Strength tester, Elcometer Model 106, manufactured by Elcometer, Michigan.

Figure 14 Pull-off strength tester. PosiTest AT-M manufactured by DeFelsko, New York.

The following procedure was used for performing the test and for recording the test results.

(1) Dollies with diameter of 20 mm were used for the pull-off strength studies. Use fine sand paper to abrade the surface of dollies. Clean the surfaces the dolly with dry cloth.

(2) Use abrasive pad to roughen the topcoat surface. Clean the surface of the topcoat with dry cloth.

(3) Apply epoxy glue to both the dolly and the test spot surface and immediately clamp the dolly to the topcoat surface. Allow the epoxy glue to cure overnight.

(4) Perform pull-off test according to ASTM D 4541 "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers". Record the pull-off strength in the unit of psi

(5) Photograph the break interface at both the dolly and the test panel.

(6) Observe the nature of the break at the interface with estimated percentage of areas with cohesive or adhesive failure at the pulled-off coating interface. The abbreviations used for describing the break layers at the test spot are listed in Table 7.

Table 7. Abbreviations used to describe the break interface at the pull-off dolly and at the test spot.

Abbreviation for a layer	Description of the layer
St	Steel substrate
Zn-G	Galvanized zinc coating
Zn-M	Metallized zinc coating
Zn-P	Painted zinc rich organic primer
Int	Intermediate coat
Top	Top coat
Glue	Adhesive used to attach the dolly to the topcoat.

We describe the break as a "cohesive" or "adhesive" failure. A cohesive break is within the coating layer. An adhesive break is between two layers. In most cases the break surface is composed of more than one type of material. We estimate the percentage of coverage of each type of surface and report the estimated percentage coverage. We use the following examples to illustrate how these abbreviations are used in describing the interface of the pulled off break:

(1) If the break was between the dolly and topcoat and the break surface is within the glue layer, the notation is "100% Glue."

(2) If the pulled off dolly shows 100% surface area of the top coat while 100% of the area in the test spot of the panel shows the intermediate paint, showing an adhesive failure between the top and the intermediate paints, the notation is "100% adhesive between Top & Int".

(3) If the surface of both the dolly and the panel test spot showed 100% coverage by the Topcoat, signifying a cohesive failure of the Topcoat, the notation would be "100% cohesive within Top".

(4) If the dolly surface were covered 100% by the Intermediate paint and the panel test spot were covered 25% by the Intermediate paint with the remaining surface area showed bare galvanized zinc surface, the notation would be "75% adhesive between Int & Zn-G, 25% cohesive within Int."

(5) If the break was completely in the Zn layer the notation would be "100% cohesive within Zn-G."

6.2.2 The pull-off test result: an illustrative example.

The details of the pull-off test results are reported in Appendix D. In Appendix D, we presented the photographs of the test panels after the pull-off strength tests. We also took pictures of the dolly and the test spot after the test to show which layer of the coating interface broke apart from the pull force. We then describe the type of interfacial break, whether it is a cohesive failure within one layer of the coating or an adhesive failure between two different layers. We estimated the percentage area covered by each type of break. The pull-off test results on each type of the test panel are summarized in Tables in Appendix D.

We now use one example of the photograph to show how we report pull-off test results in Appendix D. Figure 15 shows a photograph of a test spot (at right) and the pulled-off dolly (at left) from Test 1 of Panel 641. The fabrication process of this panel involves the following: After galvanizing the panels were stored indoors in open air for 2 weeks before surface profiling by sweep blasting. The application of the epoxy paint was performed immediately (within 4 hours) after the surface profiling. This group of test panels is labeled as group "G2b" on the test panels. In this group label "G" stands for the galvanizing process, "2" stands for 2 weeks of indoor storage between the time of galvanizing and blast profiling / painting.

Figure 15. Photograph of the break surfaces on the Dolly (left) and the Test Spot for G2b-I, Test 1.

The Pull-off Strength was 2241 psi measured with the PosiTest Pull-off tester. The picture of the dolly at the left of figure 15 appears larger then the test spot on the right. The dolly was placed on the test panel near the test spot. Because the dolly surface is about ¾" closer to the lens of the camera, it appears to be larger than the test spot.

The picture in Fig. 15 shows the coexistence of two kinds of break interfaces. The green colored area, with about 80% of the dolly surface coverage, shows coherent break within the Top paint. The grey area on the left of the dolly surface and at the peripheral area of the island at the right of the dolly surface is judged as the cohesive break within the intermediate paint. The middle region on the island at the right shows spots of shiny reflection. This shiny and flat region that is the contacting interface between the Intermediate paint and the galvanized zinc surface. This shinny region (estimated to be about 10% of the surface of the dolly) is recorded as the adhesive break between the Intermediate paint and the Galvanized Zinc surface.

Figure 16 shows how the data for the test shown in Figure 15 were reported in Appendix D using the abbreviations described in Section 6.2.1.

Panel 641 G2b-I Test 1 Pull-off Strength: 2241 psi Break: 80% cohesive within Top; 10 % adhesive between Top and Int; 10% adhesive between Int and Zn-G Dolly at left.

Figure 16. An example of the pull-off data recorded in Appendix D. This data is associated with the G2b-I Test 1 photograph shown in Figure 15.

Figure 17 shows another example of the image of a Pull-off Test dolly and test spot for a zinc metallized steel substrate.

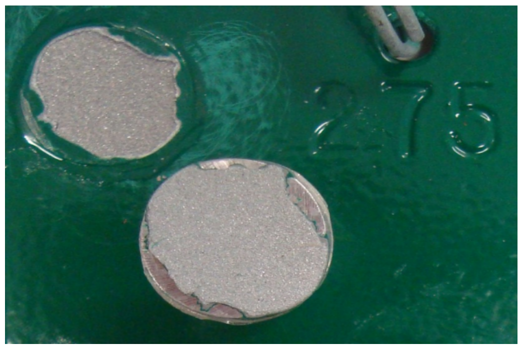


Figure 17. A painted panel after pull-off test. Upper left corner: exposed zinc surface after coating was pulled off. Lower middle: The top of the dally showing the primer in contact with zinc.

6.2.3 The X-cut Tape Test

We performed X-cut tape tests according to Test Method A of the ASTM D 3359 "Standard Test Methods for Measuring Adhesion by Tape Test."

The following procedure of the ASTM D3359 Method A was followed: An X-cut is made through the coating film with a sharp tip tool cut into the substrate. Pressure-sensitive tape is applied over the cut. Tape is smoothed into secure contact with the paint surface by using a pencil eraser over the area of the cut. Tape is removed by pulling it off rapidly. Adhesion is assessed on a 0 to 5 scale. The scale is defined in the following Table (Table 8).

Table 8. The correlation: Table of the scores of the ASTM D3359 X-cut tape test rating.

Score	Observation at the X-cut region after removal of tapes
5	No peeling or removal
4	Trace peeling or removal along incisions or at their intersection
3	Jagged removal along incisions up to 1/16 in. (1.6 mm) on either side
2	Jagged removal along most of incisions up to 1/8 in. (3.2 mm) on either side
1	Removal from most of the area of the X under the tape
0	Removal beyond the area of the X.

The photographs of the test panels after the X-cut and the scores of all the test panels are displayed in Appendix D. An example is shown in Figure 18.

Fig 18. A photograph showing the X-cut scores of 5 for Test panel #301 with G0b-S2 coating.

6.3 Pull-off Adhesive Test Results of Duplex Paint Panels.

All test panels listed in Table 4 of Section 4.7.3 were tested for the Pull-off Strength according to ASTM D4541. We have outlined the procedure for tests and discussed a few examples of data analysis in Section 6.2. We reported in Appendix D the photographs of the test panel, the pulled dolly and test spots, the description of the break interfaces, and the recorded pull-off strengths. The recorded pull-off strength values in the units of psi are tabulated in this section. The average value of the pull-off strength and the 95% confidence range for the uncertainty are listed at the end of each table. A bar chart is attached to graphically represent the pull-off strength and the distribution of the values.

6.3.1 Pull-off Test Results Tabulated with Statistics.

The pull-off strengths of all Test Spots are listed in the following Tables. Each Table collects the pull-off Strength of a particular subgroup of coating system (e.g., G0m-C, G0b-I, M0-S1 or G2b-S2, etc.) We used the combination the Panel Identification number (Panel #) and the Test Identification number (Test #) to label the Test spots. For example the 2nd test spot on Panel #257 is labeled as “257-2

The average value of the pull-off strength of each subgroup of coating and the uncertainty (95% confidence range of the mean value) of the average value are listed at the bottom of the Tables.

The Pull-off Strengths of the test spots for each coating group are graphically displayed in a bar chart.

Table 9. Pull off strength (in psi) for samples of organic coating systems on G0m-C test panels.

Pull-off Test	G0m-C
Panel#-Test#	Strength (psi)
253-1	1208
253-2	1811
253-4	600
254-1	1766
254-2	1134
254-3	2028
255-1	1752
255-2	1594
256-1	961
256-2	1379
256-3	872
Average	1373
Standard Dev	434
Confidence	256

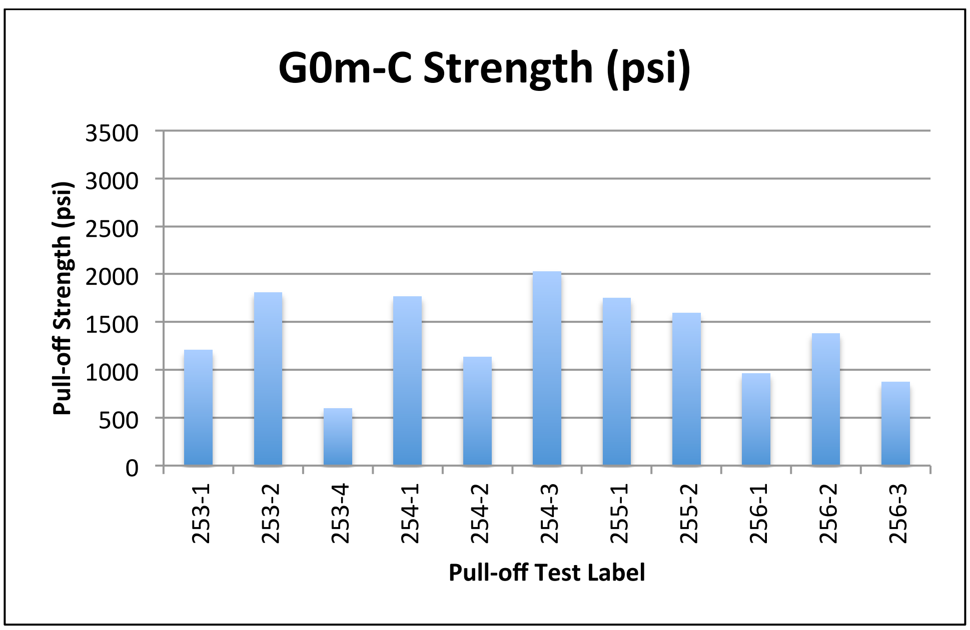


Table 10. Pull off strength (in psi) for samples of organic coating systems on G0m-I test panels.

Pull-off Test	G0m-I
Panel#-Test#	Strength (psi)
257-1	2844
257-2	2421
257-3	2770
258-1	2660
258-2	2912
258-3	2448
259-1	2423
259-2	2582
259-4	3170
260-1	680
260-2	2835
260-3	2551
Average	2525
Standard Dev	597
Confidence	338

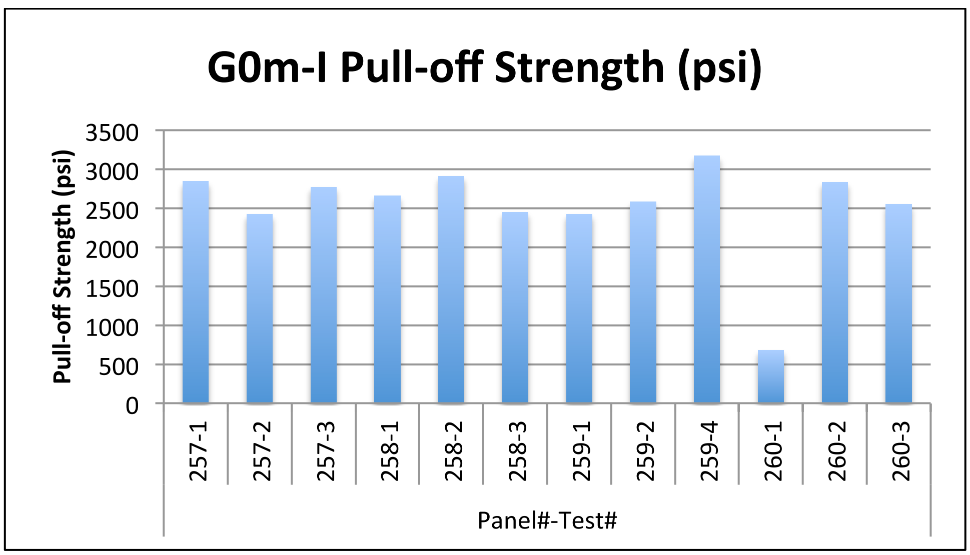


Table 11. Pull off strength (in psi) for samples of organic coating systems on G0m-S1 test panels.

Pull-off Test	G0m-S1
Panel#-Test#	Strength (psi)
261-1	1818
261-2	1987
262-1	1887
262-2	2511
263-1	1525
263-2	1506
264-1	1759
264-2	1456
264-4	400
Average	1818
Standard Dev	536
Confidence	338

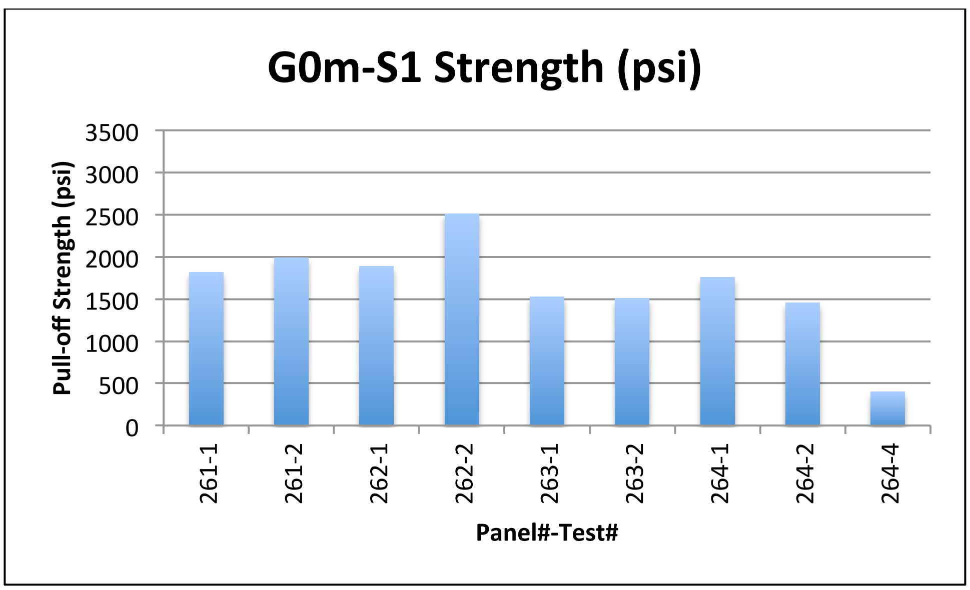


Table 12. Pull off strength (in psi) for samples of organic coating systems on G0m-S2 test panels.

Pull-off Test	G0m-S2
Panel#-Test#	Strength (psi)
265-1	1818
265-2	2222
266-1	2132
266-2	1884
267-1	2572
263-2	2072
267-3	2525
268-2	900
268-3	1767
Average	1988
Standard Dev	470
Confidence	307

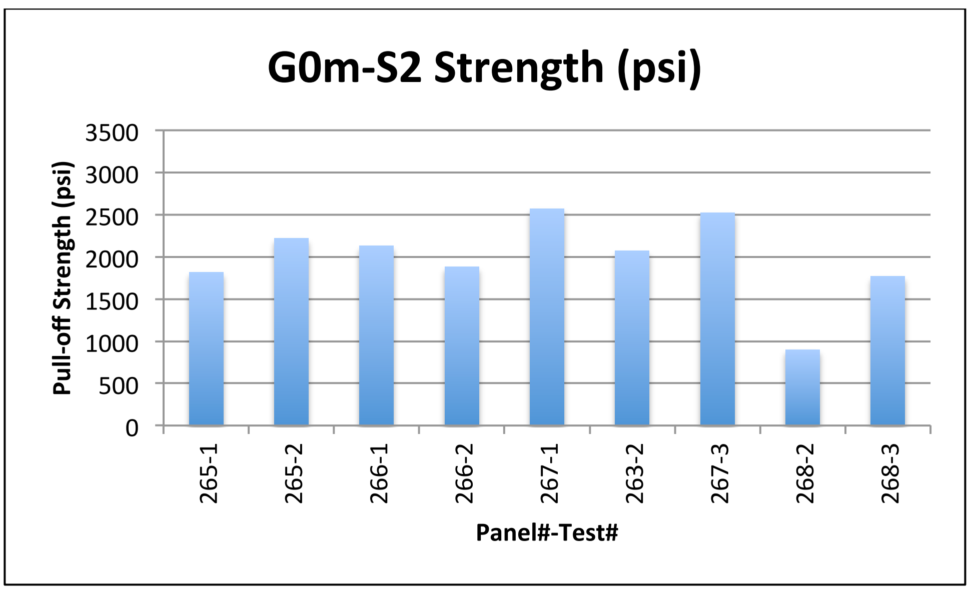


Table 13. Pull off strength (in psi) for samples of organic coating systems on G0b-C test panels.

Pull-off Test	G0b-C
Panel#-Test#	Strength (psi)
289-1	1865
289-2	2326
290-4	2333
290-1	2162
291-1	2398
291-2	2242
292-1	1561
292-2	1415
Average	2038
Stand Dev	354
Confidence	209

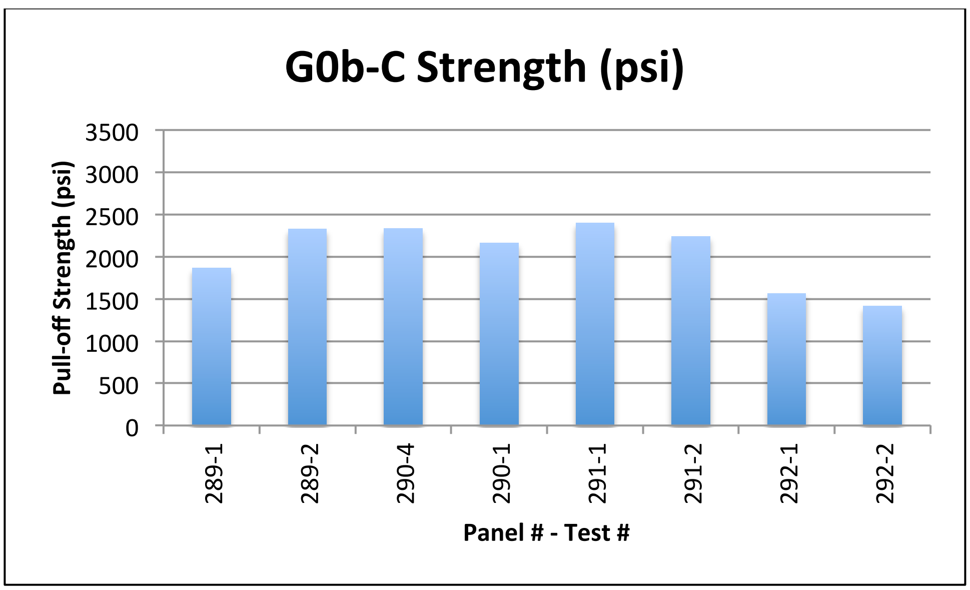


Table 14. Pull off strength (in psi) for samples of organic coating systems on G0b-I test panels.

Pull-off Test	G0b-I
Panel#-Test#	Strength (psi)
293-1	2606
293-2	2263
294-1	2689
294-2	2538
295-1	866
295-2	975
296-1	1629
296-2	2850
Average	2052
Stand Dev	740
Confidence	437

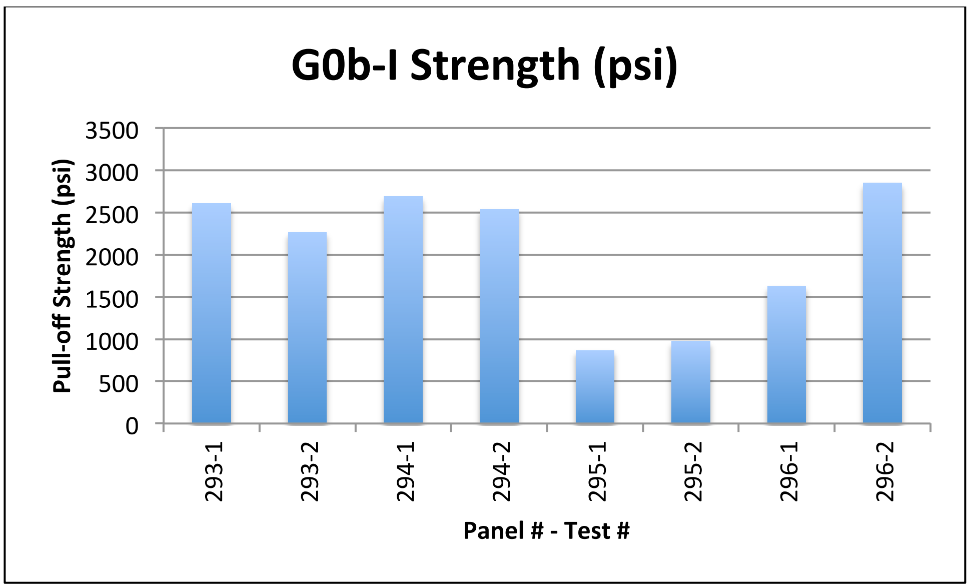


Table 15. Pull off strength (in psi) for samples of organic coating systems on G0b-S1 test panels.

Pull-off Test	G0b-S1
Panel#-Test#	Strength (psi)
297-1	1968
297-2	1653
298-1	1398
299-1	2578
299-2	975
300-1	1283
300-2	2850
Average	1815
Stand Dev	640
Confidence	474

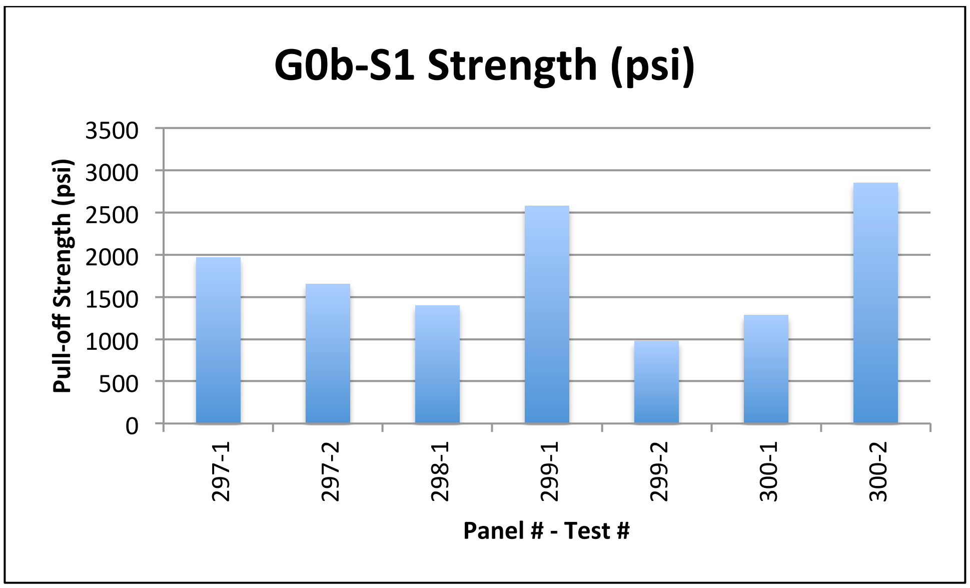


Table 16. Pull off strength (in psi) for samples of organic coating systems on G0b-S2 test panels.

Pull-off Test	G0b-S2
Panel#-Test#	Strength (psi)
301-1	1253
302-1	1236
303-1	1439
304-1	403
Average	1083
Stand Dev	400
Confidence	392

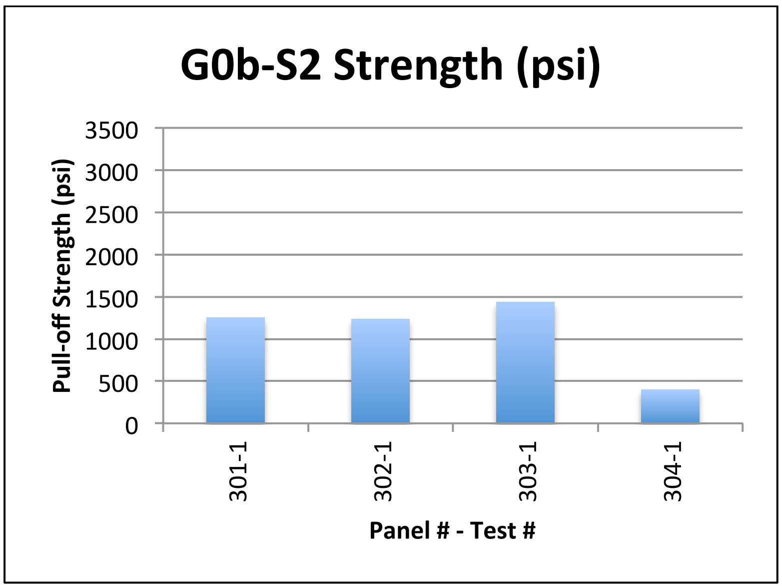


Table 17. Pull off strength (in psi) for samples of organic coating systems on M0-C test panels.

Pull-off Test	M0-C
Panel#-Test#	Strength (psi)
269-1	772
269-2	990
270-1	750
270-2	800
270-3	1382
271-1	1533
271-2	1220
272-1	1718
272-2	1437
Average	1178
Standard Dev	342
Confidence	224

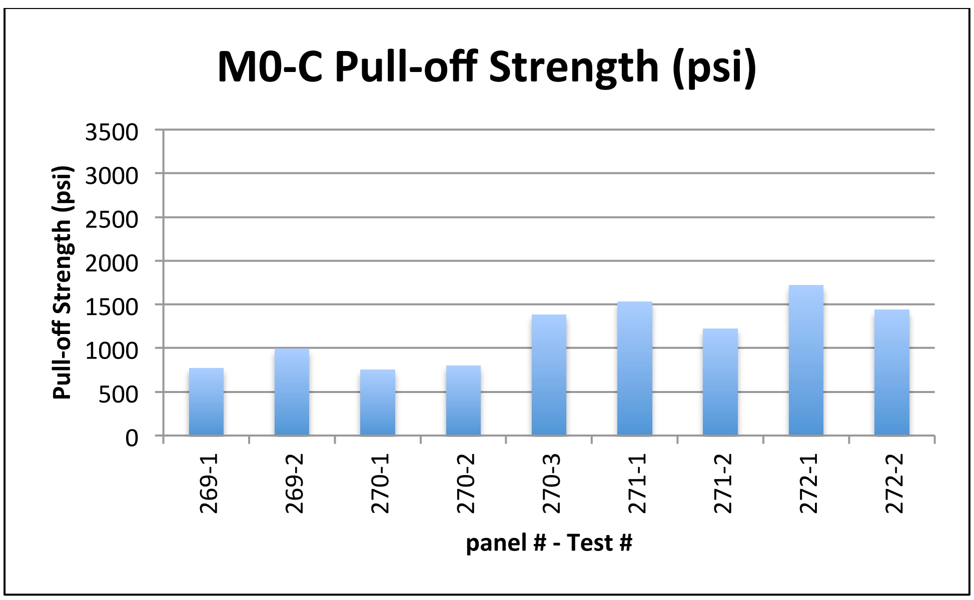


Table 18. Pull off strength (in psi) for samples of organic coating systems on M0-I test panels.

Pull-off Test	M0-I
Panel#-Test#	Strength (psi)
273-1	839
273-2	1075
274-1	1141
274-2	931
275-1	1263
275-2	1262
276-1	620
276-2	1568
Average	1087
Standard Dev	274
Confidence	190

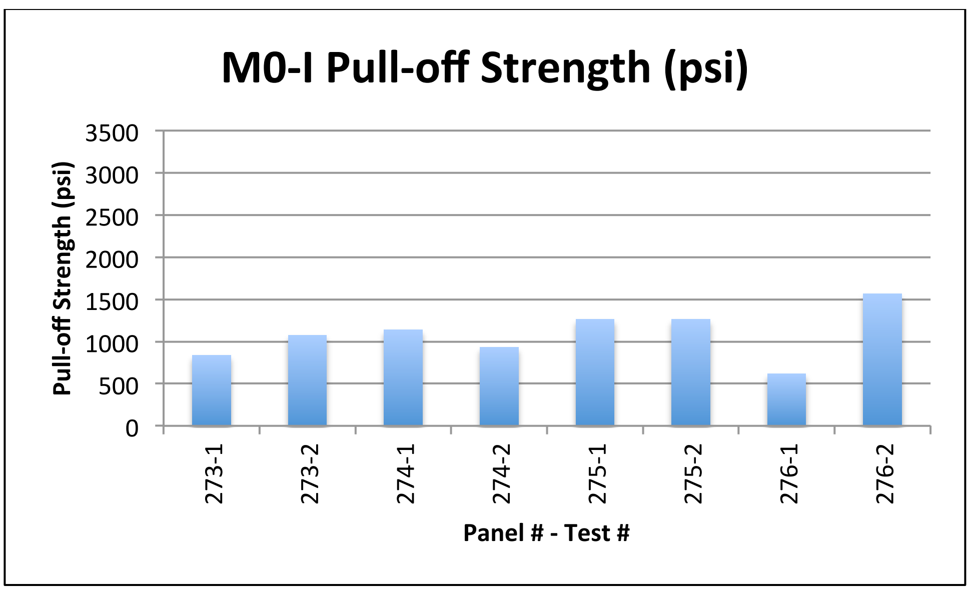


Table 19. Pull off strength (in psi) for samples of organic coating systems on M0-S1 test panels.

Pull-off Test	M0-S1
Panel#-Test#	Pull-off Strength (psi)
281-1	1266
281-2	1192
282-1	1179
282-2	1150
283-1	415
283-2	1010
284-1	1249
284-2	1172
Average	1079
Standard Dev	261
Confidence	181

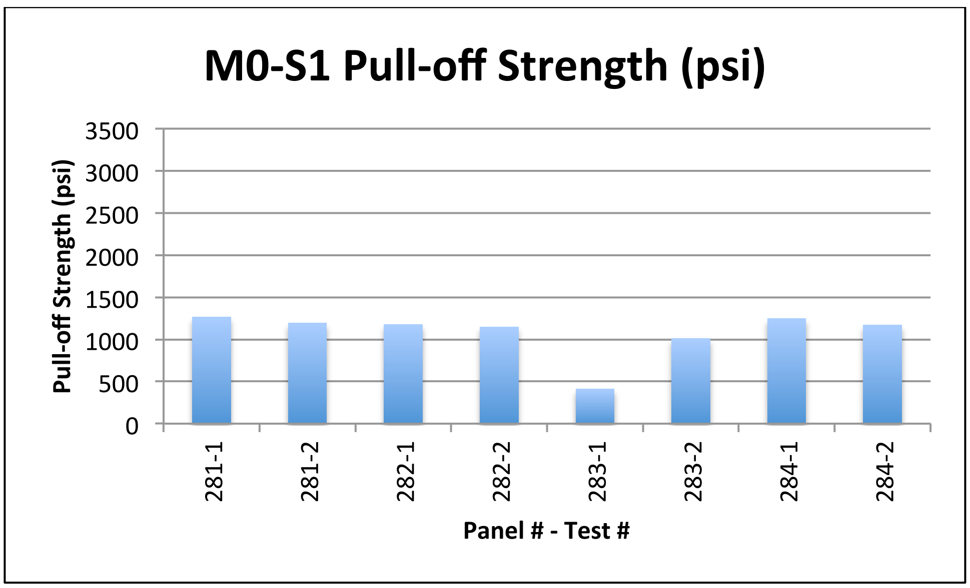


Table 20. Pull off strength (in psi) for samples of organic coating systems on M0-S2 test panels.

Pull-off Test	M0-S2
Panel#-Test#	M0-S2 Pull-off Strength (psi)
277-1	1063
277-2	1373
278-1	1297
278-2	1083
279-1	990
279-2	958
280-1	650
280-2	1408
Average	1103
Standard Dev	236
Confidence	163

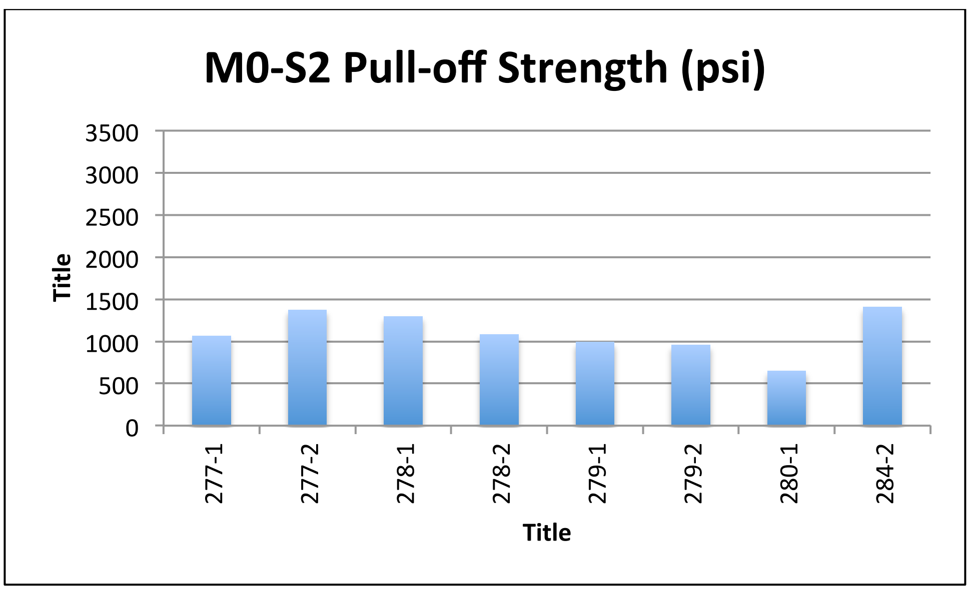


Table 21. Pull off strength (in psi) for samples of organic coating systems on M0-S3 test panels.

Pull-off Test	M0-S3
Panel#-Test#	M0-S3 Pull-off Strength (psi)
285-1	2182
285-2	2373
286-1	2227
286-2	2345
287-1	1811
287-2	3086
288-1	500
288-2	1658
Average	2023
Standard Dev	700
Confidence	485

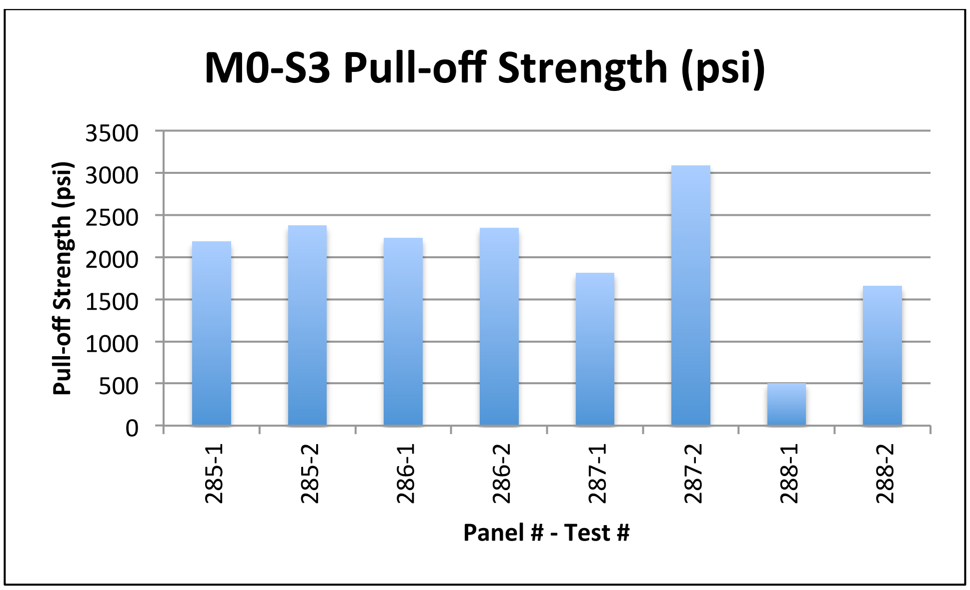


Table 22. Pull off strength (in psi) for samples of organic coating systems on G2b-C test panels.

Pull-off Test	G2b-C
Panel#-Test#	G2b-C Pull-off Strength (psi)
636-1	2410
636-2	2685
636-3	2380
637-1	2775
637-2	2687
637-3	2433
638-1	2527
638-2	2747
638-3	2360
639-1	2422
639-2	2447
639-3	2153
Average	2502
Standard Dev	179
Confidence	101

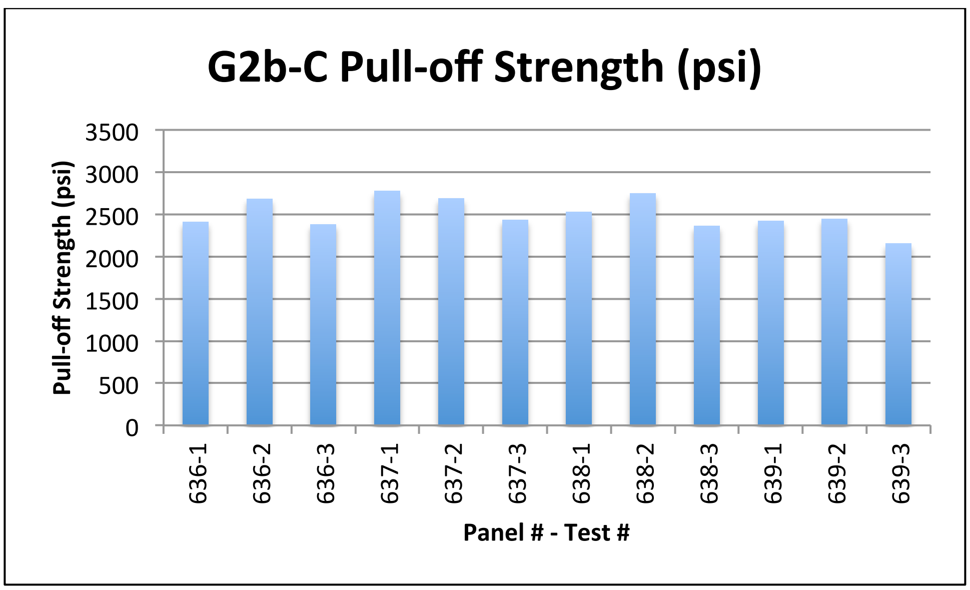


Table 23. Pull off strength (in psi) for samples of organic coating systems on G2b-I test panels.

Pull-off Test	G2b-I
Panel#-Test#	G2b-I Pull-off Strength (psi)
640-1	2326
640-2	2615
640-3	2210
641-1	2241
641-2	2207
641-3	1919
642-1	2161
642-2	2182
642-3	2484
643-1	2553
643-2	1882
643-3	2302
Average	2257
Standard Dev	214
Confidence	121

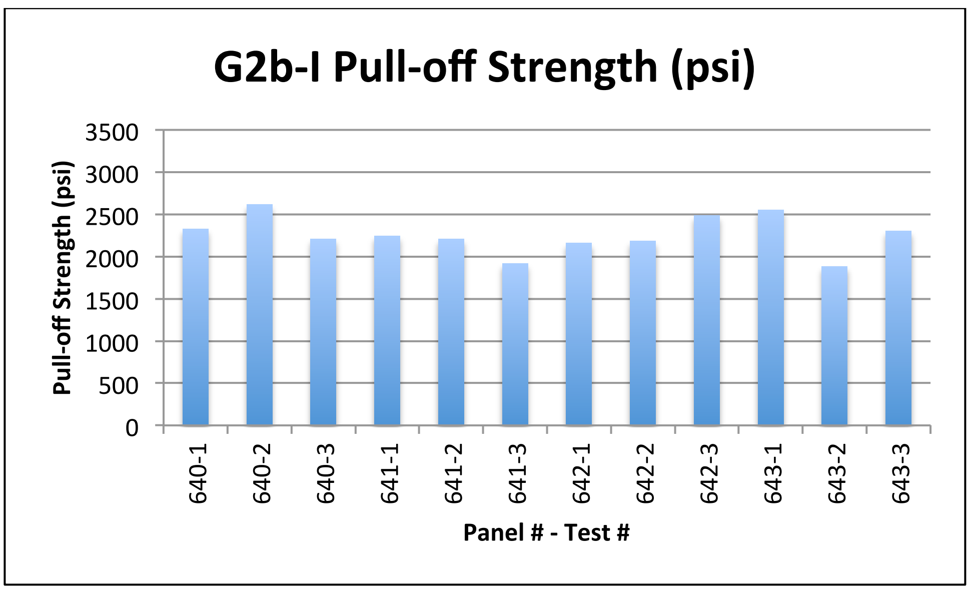


Table 24. Pull off strength (in psi) for samples of organic coating systems on G2b-S1 test panels.

Pull-off Test	G2b-S1
Panel#-Test#	G2b-S1 Pull-off Strength (psi)
644-1	2505
644-2	2320
644-3	3240
645-1	2335
645-2	1529
645-3	2466
646-1	2875
646-2	1740
646-3	2541
647-1	2959
647-2	2069
647-3	2088
Average	2389
Standard Dev	473
Confidence	268

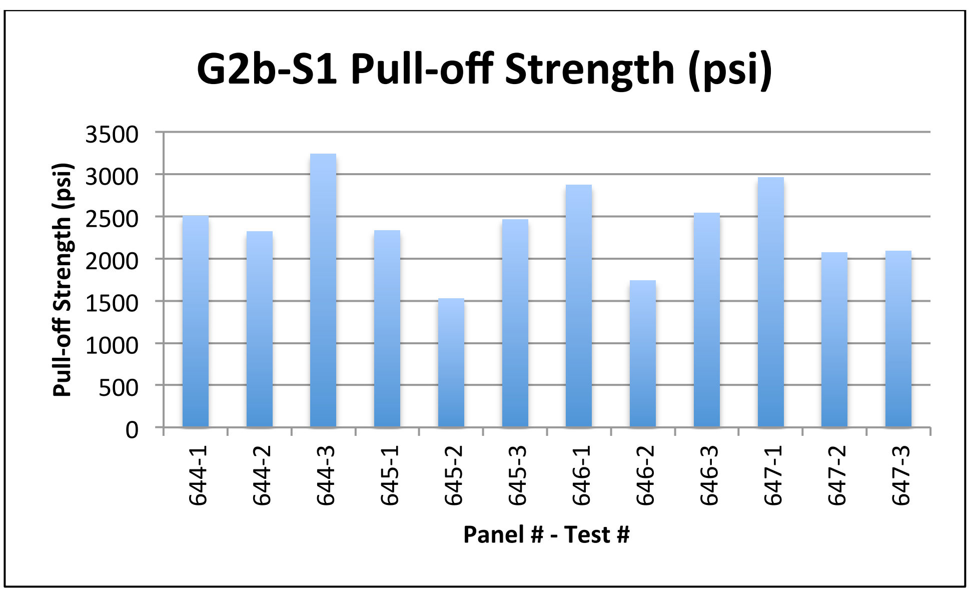


Table 25. Pull off strength (in psi) for samples of organic coating systems on G2b-S2 test panels.

Pull-off Test	G2b-S2
Panel#-Test#	G2b-S2 Pull-off Strength (psi)
648-1	1468
648-2	1481
648-3	1986
649-1	2055
649-2	1549
649-3	1424
650-1	2513
650-2	1894
650-3	2016
651-1	1785
651-2	1504
651-3	1232
Average	1742
Standard Dev	348
Confidence	197

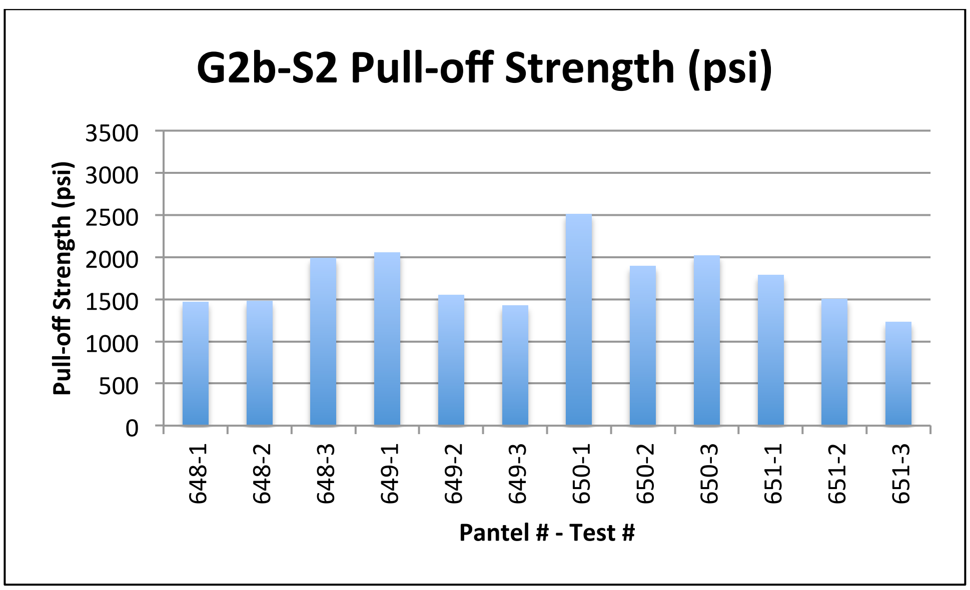


Table 26. Pull off strength (in psi) for samples of organic coating systems on Z-C test panels.

Pull-off Test	Z-C
Panel#-Test#	Z-C Pull-off Strength (psi)
43-2	1645
305-1	1309
305-2	1543
306-1	1415
306-2	1502
3052-1	1561
3052-2	200
Average	1311
Stand Dev	464
Confidence	344

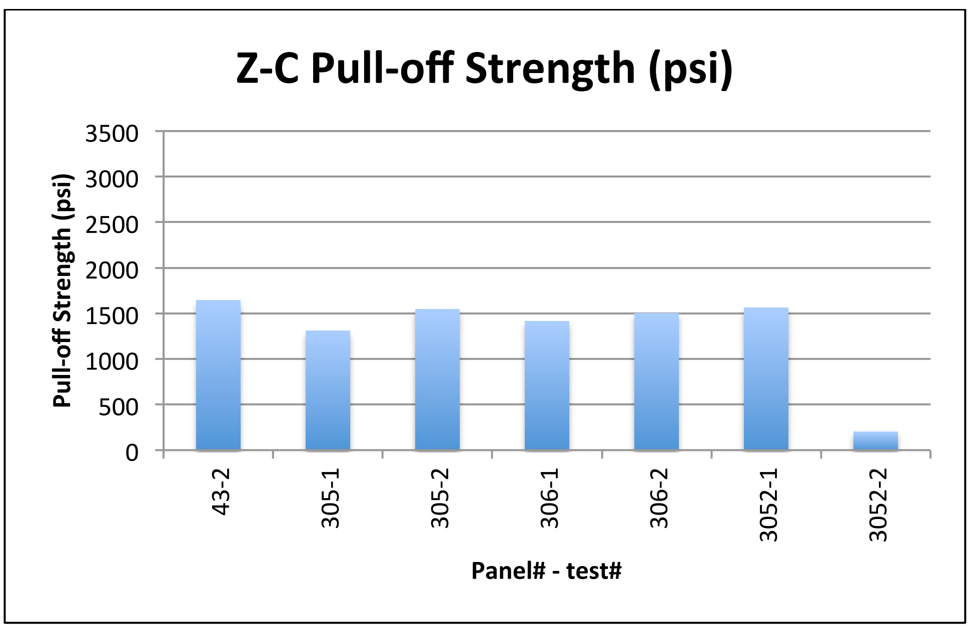


Table 27. Pull off strength (in psi) for samples of organic coating systems on Z-I test panels.

Pull-off Test	Z-I
Panel#-Test#	ZI Pull-off Strength (psi)
307-1	1405
307-2	1360
3072-1	1492
3072-2	2043
308-1	1326
308-2	1738
3082-1	1817
3082-2	1944
Average	1641
Stand Dev	262
Confidence	155

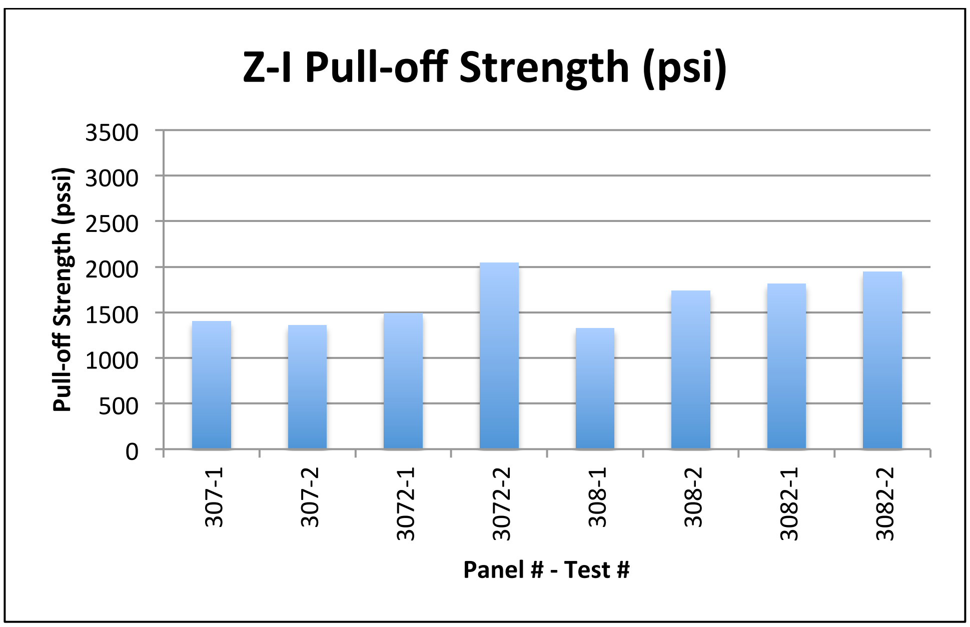


Table 28. Pull off strength (in psi) for samples of organic coating systems on Z-S1 test panels.

Pull-off Test	Z-S1
Panel#-Test#	Z-S1 Pull-off Strength (psi)
309-1	2135
309-2	1894
3092-1	2376
3092-2	1706
310-1	2503
310-2	1972
3102-1	2293
3102-2	1671
Average	2069
Stand Dev	289
Confidence	200

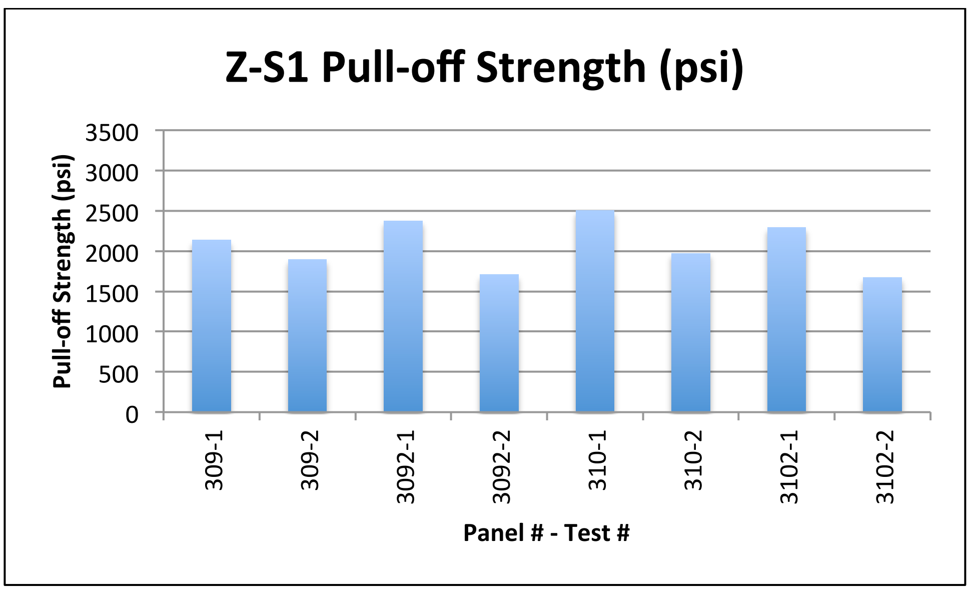
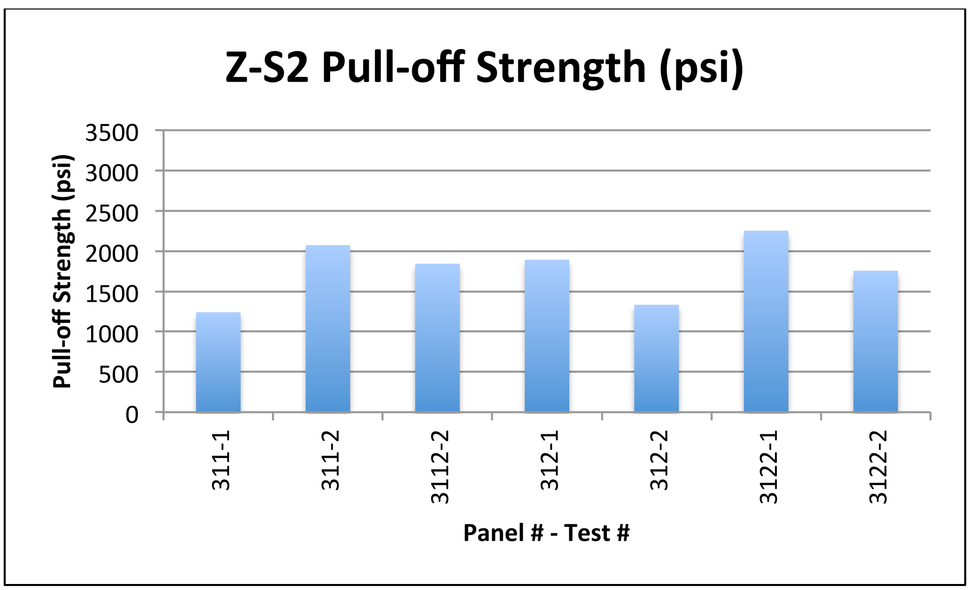


Table 29. Pull off strength (in psi) for samples of organic coating systems on Z-S2 test panels.

Pull-off Test	Z-S2
Panel #-Test #	Z-S2 Pull-off Strength (psi)
311-1	1234
311-2	2067
3112-2	1838
312-1	1892
312-2	1331
3122-1	2250
3122-2	1755
Average	1767
Stand Dev	342
Confidence	253



Z-S3 panels were not fabricated.

This set of panels was not fabricated because we anticipated a very thin dried film thickness of S3 on either the white blasted steel surfaces or on a cured zinc-rich primer.

S3 (Macropoxy 920) is a low viscosity epoxy penetrating sealant. The product data sheet from the paint manufacturer (Sherwin Williams) indicates its use as a sealer (pre-primer) for tight rusted steel surfaces or for porous concrete surfaces. A Sherwin Williams representative recommended use as both a sealant and primer for metallized surfaces but did not recommend its use on either white blasted steel or as an intermediate paint on a zinc-rich primer. Although S3 can spread and penetrate the porous channels within the metallized zinc layer, it is anticipated to be too thin on the white blasted steel surfaces due to its low viscosity.

6.3.2 Average values of the Pull-off Strength for Different Profiling-Paint subgroups

In the previous section we calculated the average value of the pull-off strength for each subgroup of test panel. Although the variation of the pull-off strength values could be dependent on systematic errors that are unknown to us, we performed the statistical analysis with the assumption that the random error is dominant. Based on this assumption we calculated the standard deviation from the mean. From the standard deviation and the size of the sample, we calculated the uncertainty of the average value as defined as the range of 95% confidence limit. In Table 30 we present a comparison of the average values of the pull-off strength for different subgroups of test panels.

Table 30. A List of the average pull-off strengths of different subgroups of test panels.

Paint System	Metal substrate	Subgroup label	Average Pull-off Strength (psi)	Uncertainty of the Average value, (95% confidence)
C	G0m	G0m-C	1372	256
C	G0b	G0b-C	2038	209
C	M0	M0-C	1178	224
C	G2b	G2b-C	2502	101
C	Z	Z-C	1311	344
I	G0m	G0m-I	2525	338
I	G0b	G0b-I	2052	512
I	M0	M0-I	1087	190
I	G2b	G2b-I	2257	121
I	Z	Z-I	1641	182
S1	G0m	G0m-S1	1650	350
S1	G0b	G0b-S1	1815	474
S1	M0	M0-S1	1079	181
S1	G2b	G2b-S1	2389	268
S1	Z	Z-S1	2069	200
S2	G0m	G0m-S2	1988	307
S2	G0b	G0b-S2	1083	392
S2	M0	M0-S2	1103	163
S2	G2b	G2b-S2	1742	197
S2	Z	Z-S2	1767	253
S3	M0	M0-S3	2023	485

6.3.3 Three Tiers of Pull-off Strength Performances

It should be noted that NEPCOAT specification for bare steel used a minimum acceptable Pull-off Strength at 600 psi. By this standard, all the test panels pass the minimum requirement and sometimes by a large margin. Although the Pull-off Strength Tests were mainly used for Pass/Fail tests, we intended to use the Pull-off Strengths in a slightly more quantitative measure so that we could make correlation between the Strength and the Contact Angle.

In Table 31 we arrange the information in Table 30 according to the average pull-off strength. Since the uncertainty of the average values (from 100 to 500) is large enough so that the overlapping values do not justify a ranking by the subgroups of the paints, we group the pull-off strength by three Tiers: Stronger , Medium and Weaker. It should be noted that even the "Weaker" Tier shows pull-off strength higher than 1000 psi. All pull-off strengths are higher than the NEPOCAT specified passing score of 600 psi.

The "Stronger" tier has pull-off strength reaching values above 2000 psi, or at least with the 95% confidence range overlapping the 2000 psi value. The "Medium" tier has values ranging from 1800 psi to 1300 psi. The "Weaker" tier has values between 1000 and 1200 psi.

Table 31. A Three-Tiers Ranking of coating subgroups according to Pull-off Strengths

Ranking by Pull-off Strength	Subgroup label	Average Pull-off Strength (psi)	Uncertainty of the Average value, (95% confidence)
Stronger	G0m-I	2525	338
	G2b-C	2502	101
	G2b-S1	2389	268
	G2b-I	2257	121
	Z-S1	2069	200
	G0b-I	2052	512
	G0b-C	2038	209
	M0-S3	2023	485
	G0m-S2	6.3.3.1.1.1.1.1 1988	307
	G0b-S1	1815	474
	Z-S2	1767	253
Medium	G2b-S2	1742	197
	G0m-S1	1650	350
	Z-I	6.3.3.1.1.1.1.2 1641	182
	G0m-C	1373	256
	Z-C	1311	344
Weaker	M0-C	1178	224
	M0-S2	1103	163
	M0-I	1087	190
	G0b-S2	1083	392
	M0-S1	1079	181

7 Correlation between the Average Pull-off Strength and the Average Contact Angle.

In the preceding section we displayed the pull-off strength data for both the control panels and the 4 different metallic zinc test panels. We found that all control and test panels show good pull-off strengths. There is no significant weakness in the pull-off strength of the test panels when compared with the control panels. This means that the profiled zinc surface in the test panels provide enough "grip" for the intermediate epoxy paint to be competitive with the control panels. This is expected if the surface profiling and the paint process were done properly. We performed the test fabrication process in a real shop environment. The data represents the result of commonly achievable commercial painting process in the coating fabricator's facility.

In this section we discuss the correlation between the Average Contact Angles of Table 6 in Section 5 and the Average Pull-off Strengths in Section 6 for different types of substrate-paint pairs.

7.1 Possible interferences for quantifying the strength-angle correlation

Although the objective of this study is to try to explore the possible use of the paint wetting property and the adhesive strength, we recognized the possibility of not being able to observe any systematic correlation between these two properties before we analyze the correlation. We hope this discussion will illustrate the importance of the experimental methods used for obtaining the correlation.

We can easily appreciate the concept that good wetting of the substrate surface by paint is advantageous for the adhesion of the dried coating. In practice we need to use measurable properties as an approximation to the concept of wetting and the adhesive strength. In this study we chose liquid paint contact angle as a measure for wetting. We have measured the pull-off strength and the X-cut tape test to estimate the adhesive strength. We found that the X-cut tape test score is not suitable for quantifying the adhesive strength. We are mainly relying on the Pull-off strength as a measure for adhesion.

Both the contact angle measurement and the pull-off strengths are prone to variations due to the non-uniformity of the test panels and the necessity for testing the adhesive strength and the contact angle on different panels. We tried to prepare the test panels in a manner that minimize the factors that could produce variations.

The most likely problem comes from the fact that liquid epoxy paint is not a simple fluid, but it is a complex mixture that undergoes polymerization reaction after the paint is mixed according to formulation. For pure liquids (e.g., organic solvent, or water) the contact angle has a relatively simple relation with the wetting of the liquid on a surface. The epoxy paint is different. It is a liquid mixture of two parts (the resin and the hardener) formulated immediately before the painting process. First of all, it is not a single component liquid. The contact angle of a resin suspended in an organic solvent does not necessarily reflect the extent of wetting to the extent that a correlation could exist. This point can be appreciated by considering two limiting cases: (1) resin highly diluted by solvent, and (2) neat resin without solvent. If we add a large amount of solvents (e.g., methyl-ethyl-ketone, or acetone) to the different paint formulations, the contact angles would all be the same as that of the solvent. The dried paints would not have any correlation between the pull-off strength and the contact angle because all contact angles are the same. For the paints with much less solvent then the manufacturer's formulation, the contact angle will be high and varied due to the rheological and reactive property of the two parts of the paint. The lack of solvent would hinder the inter-diffusion between the resin and the hardener, and the adhesion would be highly variable and inconsistent even for the same paint-surface pair.

The last point illustrates that the proper paint formulation is important to the paint adhesion, and the contact angle needs to be measured from the correctly formulated paint and to be tested at the same stage of paint "sweating" or "curing" as that of the spray paint application. We have asked one single skilled paint shop (Boyd Coatings Research) to paint all the test panels and tried to synchronize the timing between contact angle measurement and the paint application.

Because of the complexity of the painting process in contrast to the simplicity of the wetting of by a pure single-component liquid, there is a high possibility that the correlation we seek to quantify would not materialize. There is a high possibility for failing to find experimentally measureable correlation because there could be uncontrolled factors influencing both the contact angle and the pull-off strength. In the next section we examine the experimentally measured correlation with the understanding that it is not necessarily a forgone conclusion that the contact angle and the pull-off strength are correlated.

7.2 Experimentally measured correlation between Pull-off Strength and the liquid paint contact angle.

Table 32 shows the average pull-off strength and the liquid paint contact angle (at t = 5 sec) for different subgroups of coatings. The subgroups are arranged according to the order of the average pull-off strength. It can be seen that for most of the test panels, the coating systems of "Strong" pull-off strength defined in Table 31 show contact angles in the range of 30 to 45 degrees (with an exception for G0b-S2 that has angle of 54 degree). The coating systems with "Medium" strength show contact angles scattered (35, 106 and 82). The coating systems with "Weak" strength show contact angles in the 60 to 100 degrees).

With a few exceptions, the general trend is that the lower contact angles correlate with stronger pull-off strength. This means that despite the high possibility of interfering factors that reduce the correlation, our experimental data do show a certain degree of correlation.

Table 32. Correlation between the Average Pull-off Strengths and the Average Contact Angles.

Subgroup label	Average Pull-off Strength (psi)	Average Contact Angle (degree)
G0m-I	2525	36
G2b-C	2502	36
G2b-S1	2389	46
G2b-I	2257	35
G0b-I	2052	37
G0b-C	2038	37
M0-S3	2023	0
G0m-S2	1988	42
G0b-S1	1815	46
G2b-S2	1742	35
G0m-S1	1650	106
G0m-C	1372	82
M0-C	1178	87
M0-S2	1103	58
M0-I	1087	75
G0b-S2	1083	54
M0-S1	1079	103

Figure 19 shows a scatter plot of Pull-off Strength as a function of the contact angle. The correlation coefficient is -0.70 (Pearson product correlation coefficient) for all the data pairs of Table 32. The general trend is that the smaller the contact angle, the higher the pull-off strength, thus the correlation coefficient has the negative value. The magnitude of 0.66 indicates that although the general trend is observed, there are other factors not accounted for that may due to the differences of the paints or the type of surface profiling. The factors of solvent content, the epoxy curing time and the local variation of the profiled surfaces mentioned in the last section may also contribute to the spread of the data points.

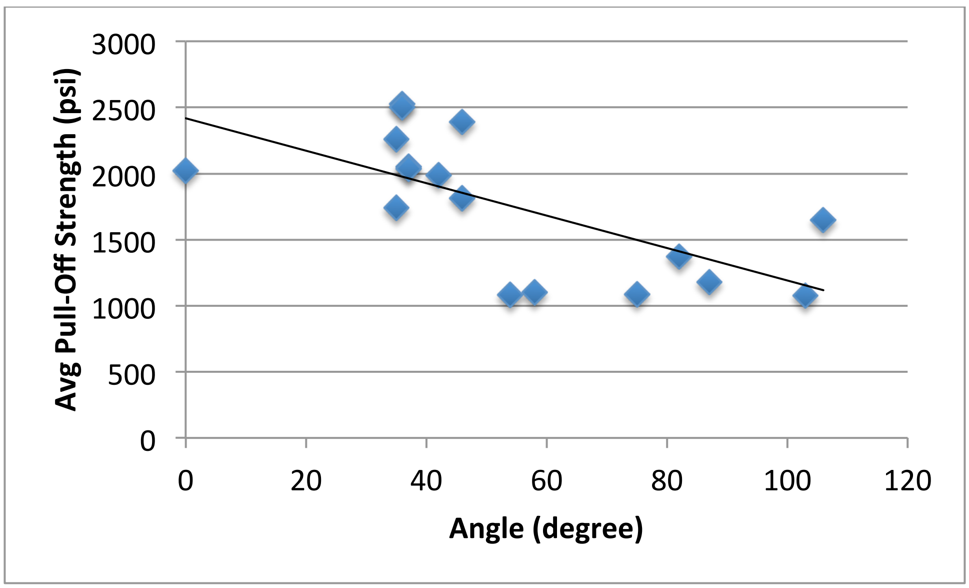


Figure 19. Correlation between the Average Pull-off Strengths and the Average Contact Angles for all types of substrate-paint pairs. The Pearson correlation coefficient is -0.70 for all the data pairs listed in Table 32.

7.3 Strength-angle Correlation for the Same Paint Applied to Different Substrates.

We would like to learn which kind of roughened zinc surface is better for adhesion. In order to be more sharply focused on this question, it is best to compare the Strength-Angle relationship for the same paint system applied to different types of profiled zinc surface.

In section 7.1 we discussed many factors that potentially could reduce the magnitude of correlation. One of the factors is related to the fact that different commercial epoxy intermediate paints are formulated differently. The different resins (part A) may have different molecular weight. The different hardeners (part B) may lead to differences in the curing rate and different hardness of the finished intermediate layer. The adhesive forces at the interfaces may also be different because of the molecular nature of the resin and hardener used for different paints. Furthermore, the solvent content (the thinners) are different for different commercial paints. We mentioned earlier that the contact angle is highly dependent on the solvent content and the rheological properties of the resin at the t = 5 sec after the paint droplet is placed on the zinc metal substrate.

The pull-off strength vs. contact angle plot of Fig. 19 shows a general trend that the wetting (small contact angle) is beneficial to adhesion (the pull-off strength). The magnitude of the Pearson correlation coefficient is moderately high at r = -0.66. Since the data points used in Fig. 19 contain 5 different commercial paint systems, the correlation coefficient would reflect that different paints might have different correlation between their contact angles and the pull-off strength. We anticipate that when the differences among paints are removed, the magnitude of correlation could be higher that of the global plot in Fig. 19

In this section we subdivide the data listed in Table 32 by separating the data according to the type of paint system. We list the contact angles and the pull-off strengths for a given paint system in the following tables. In an attempt to identify the best profiling procedure, we list the data pairs according to an order of descending values of the pull-off strength. The strength vs. angle plots for each paint system are also displayed with the equation of regression line and the correlation coefficients for each plot.

Table 33. Pull-off Strength vs. Contact Angle plot for paint system C on different profiled Zinc-on-Steel surfaces.

Subgroup label	Average Contact Angle	Average Pull-off Strength (psi)
G2b-C	36	2502
G0b-C	37	2038
G0m-C	82	1372
M0-C	87	1178

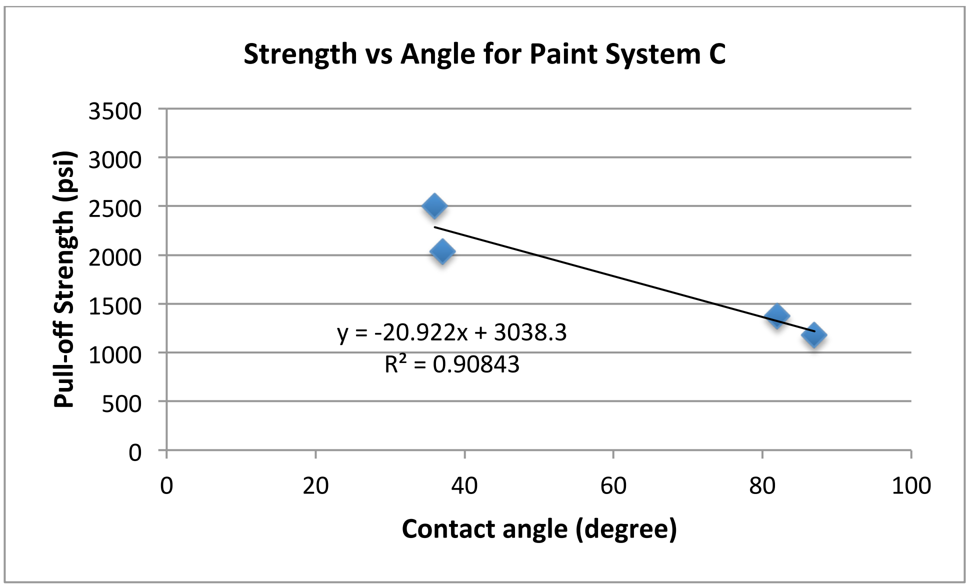


Figure 20. Plot of Pull-off Strength vs. Contact Angle for Paint system C on different profiled Zinc-on-Steel surfaces. The Pearson correlation coefficient r = -0.95.

Note that the magnitude of the correlation coefficient is increased from 0.66 in the global plot to 0.95 for the plot restricted to the same paint system C. This change supports that part of the contribution for the diffused correlation in the global plot is due to the differences in the strength-angle relations among different paint systems.

Table 34. Pull-off Strength vs. Contact Angle for paint system I on different profiled Zinc-on-Steel surfaces.

Subgroup label	Average Contact Angle	Average Pull-off Strength (psi)
G0m-I	36	2525
G2b-I	35	2257
G0b-I	37	2052
M0-I	75	1087

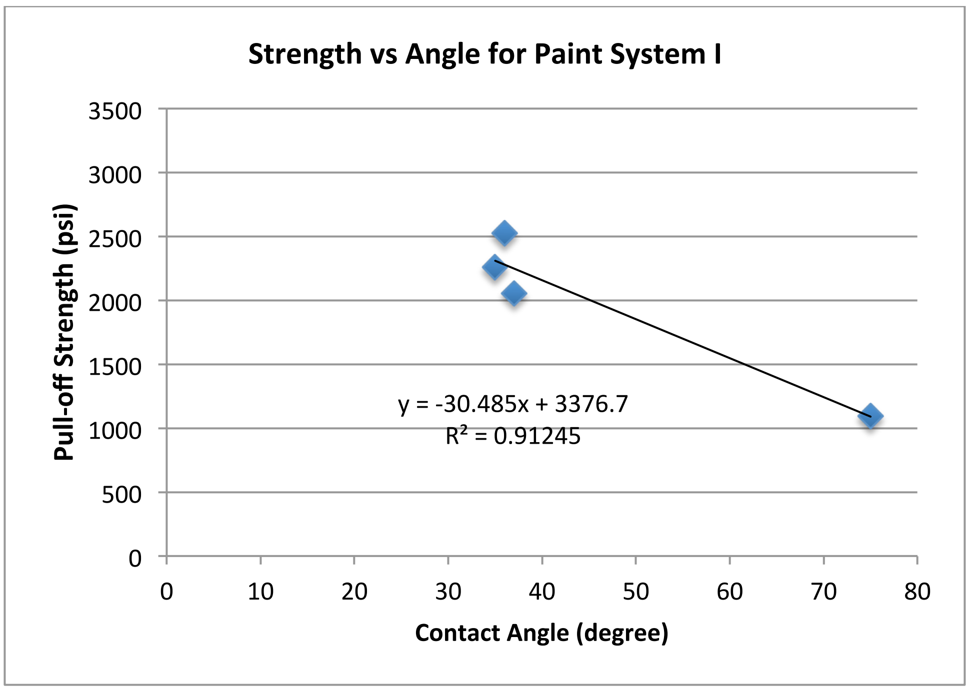


Figure 21. Plot of Pull-off Strength vs. Contact Angle for Paint system I on different profiled Zinc-on-Steel surfaces. The Pearson correlation coefficient r = -0.96.

Note that the magnitude of the correlation coefficient is increased from 0.66 in the global plot to 0.96 for the plot restricted to the same paint system I. Again, we observe a diffused correlation in the global plot in figure 19 changing to a more tightly correlated plot in Figure 21 for a single paint system. The difference in formulations for different commercial paints contributes to a smaller correlation in the global plot of figure 19 for all paint systems.

A Table 35. Pull-off Strength vs. Contact Angle plot for paint system S1 on different profiled Zinc-on-Steel surfaces.

Subgroup label	Average Contact Angle	Average Pull-off Strength (psi)
G2b-S1	46	2389
G0b-S1	46	1815
G0m-S1	106	1650
M0-S1	58	1079

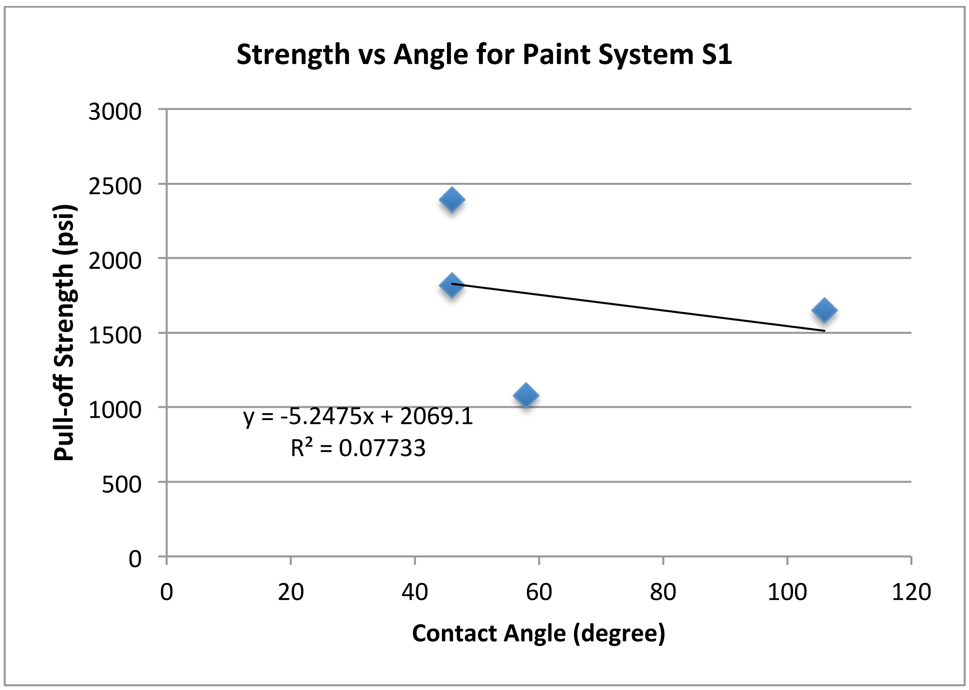


Figure 22. Plot of Pull-off Strength vs. Contact Angle for Paint system S1 on different profiled Zinc-on-Steel surfaces. The Pearson correlation coefficient r = -0.34.

Unlike two previous plots for paint systems C and I, the paint system S1 has a reduced correlation coefficient. The trend of correlation is still in the same direction as the sign of the correlation (r is still negative), but the magnitude of the correlation is reduced. We think that the fast curing property of the resin might make the timing of the contact angle measurements more critical, and thus the contact angles at t =5 second are more varied.

Table 36. Pull-off Strength vs. Contact Angle plot for paint system S2 on different profiled Zinc-on-Steel surfaces.

Subgroup label	Average Contact Angle	Average Pull-off Strength (psi)
G2b-S2	35	1742
G0m-S2	42	1988
G0b-S2	54	1083
M0-S2	58	1103

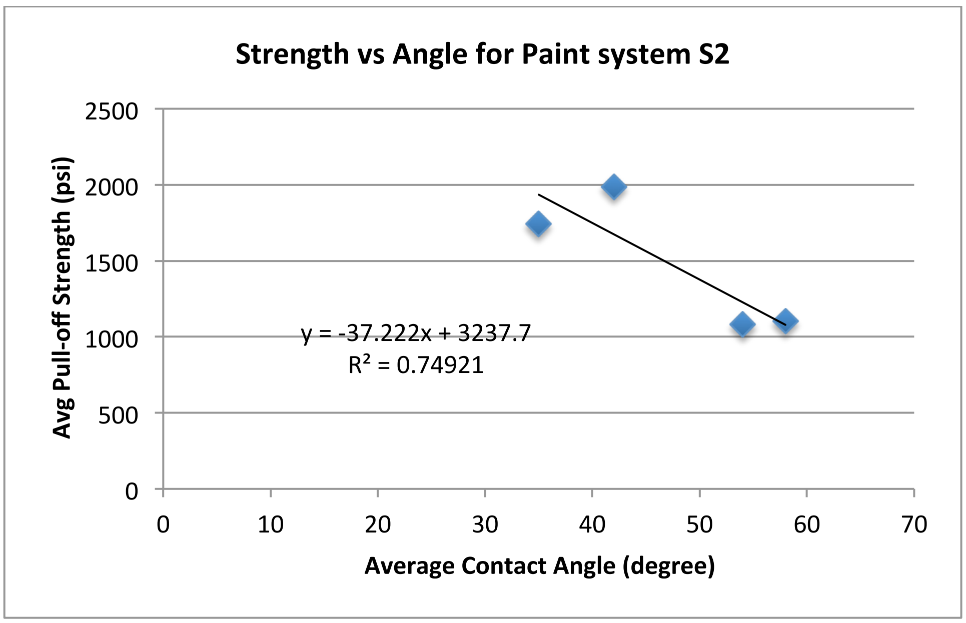


Figure 23. Plot of Pull-off Strength vs. Contact Angle for Paint system S2 on different profiled Zinc-on-Steel surfaces. The Pearson correlation coefficient r = -0.87.

Note that the magnitude of the correlation coefficient is increased from 0.66 in the global plot to 0.87 for the plot restricted to the same paint system S2. Again, we observe a diffused correlation in the global plot in figure 19 changing to a more tightly correlated plot in Figure 23 for a single paint system. This higher correlation indicates that the better wetting leads to the stronger adhesion.

7.4 Strength-angle Correlation between for the same substrate coated with different Paint Systems.

One possible utility of the wetting vs. adhesive strength correlation is to use the contact angle tests to help select a paint system that better matches with a given surface profiled Zinc metallic coating on steel. In this section we analyze the Strength vs. Angle data in a different way to assess this potential utility.

We list the contact angles and the pull-off strengths for different paints applied to a given profiled Zinc coating in a Table and in a Strength-Angle plot. In an attempt to identify the best paint system for a given surface profile, we list the data pairs according to an order of descending values of the pull-off strength. The strength vs. angle plots for different paint systems on a given substrate are displayed with the equation of regression line and the correlation coefficients for each plot.

Table 37. Pull-off Strength vs. Contact Angle for different paints applied to G0m profiled Zinc-on-Steel substrate.

Subgroup label	Average Contact Angle	Average Pull-off Strength (psi)
G0m-I	36	2525
G0m-S2	42	1988
G0m-S1	106	1650
G0m-C	82	1372

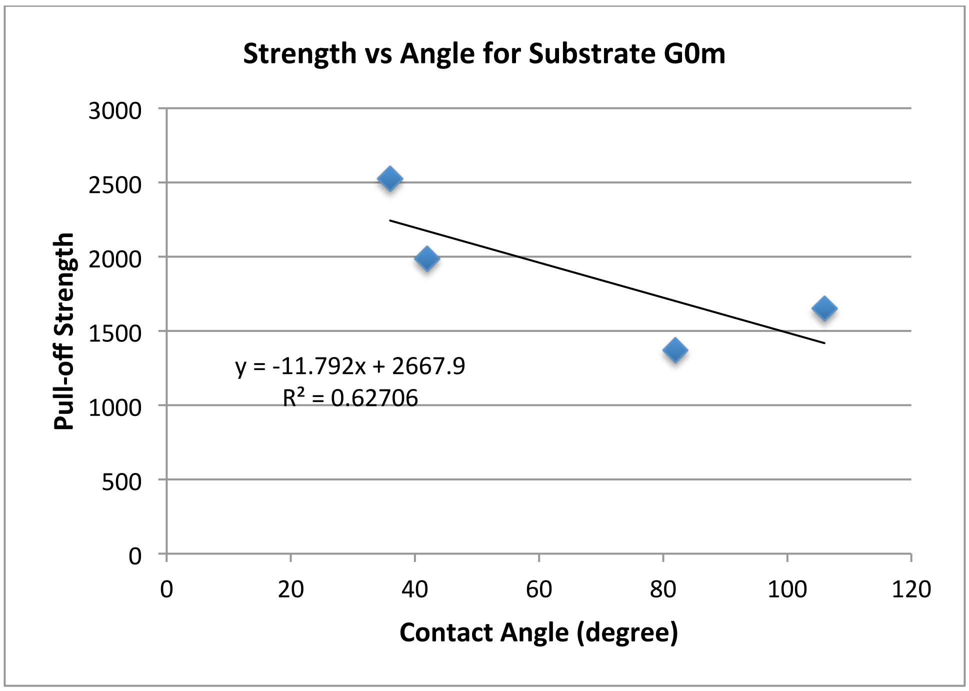


Figure 24. Plot of Pull-off Strength vs. Contact Angle for different paints applied to G0m profiled Zinc-on-Steel substrate. The Pearson correlation coefficient r = -0.79.

Table 38. Pull-off Strength vs. Contact Angle for different paints applied to G0b profiled Zinc-on-Steel substrate.

Subgroup label	Average Contact Angle	Average Pull-off Strength (psi)
G0b-I	37	2052
G0b-C	37	2038
G0b-S1	46	1815
G0b-S2	54	1087

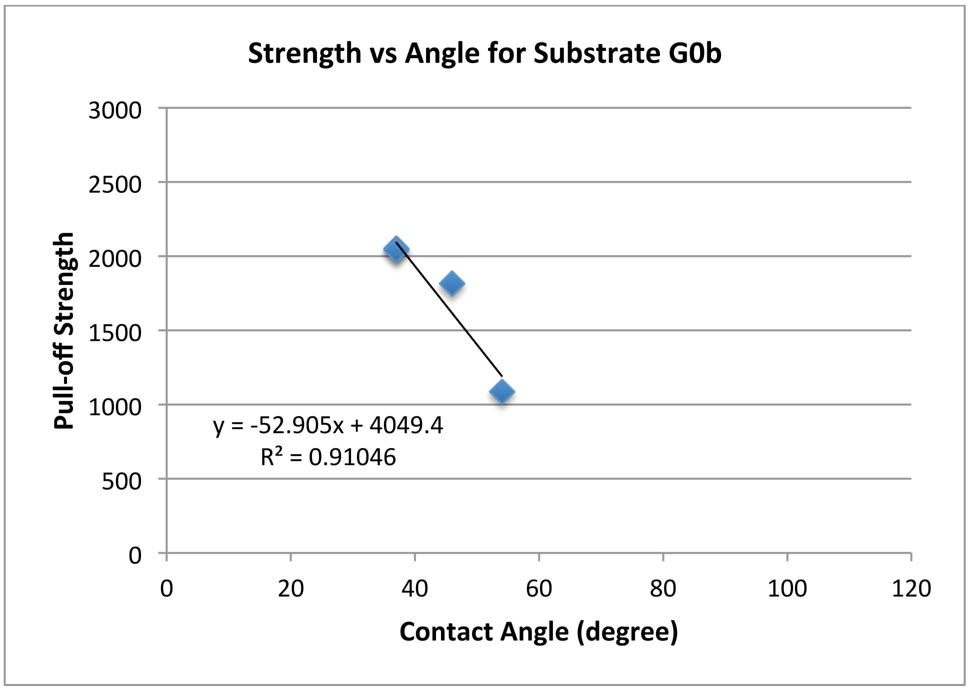


Figure 25. Plot of Pull-off Strength vs. Contact Angle for different paints applied to G0b profiled Zinc-on-Steel substrate. The Pearson correlation coefficient r = -0.95. Note two data points overlap at angle = 37 degree.

Note that there are 4 data points in Figure 25 but two points exactly overlap in the plot. The first two pairs of data in Table 38 have nearly identical pull-off strengths and contact angles. These two data points overlap at the upper left side of f\Figure 25. This set of data again supports that small contact angle correlates with higher pull-off strength.

Table 39. Pull-off Strength vs. Contact Angle for different paints applied to M0 (metallized) Zinc-on-Steel substrate.

Subgroup label	Average Contact Angle	Average Pull-off Strength (psi)
M0-S3	0	2023
M0-S2	58	1103
M0-S1	58	1079
M0-I	75	1087
M0-C	87	1178

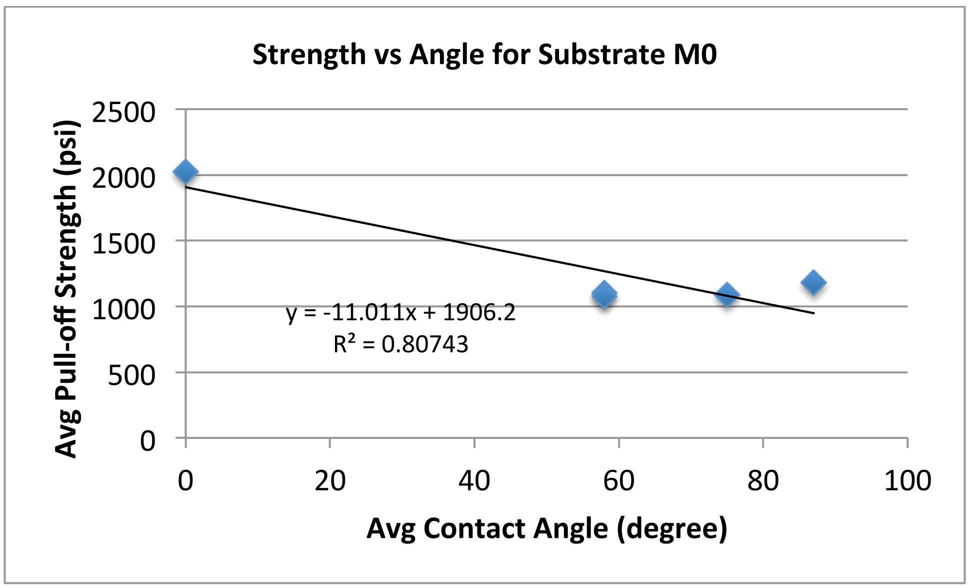


Figure 26. Plot of Pull-off Strength vs. Contact Angle for different paints applied to M0 (metallized) Zinc-on-Steel substrate. The Pearson correlation coefficient r = -0.90.

Note that there are 5 data points in figure 26 but two points (at angle = 58 degree) exactly overlap in the plot. The 3rd and the 5th pairs of data in Table 39 have nearly identical pull-off strengths and contact angles. These two data points overlap at the upper left side of figure 26.

Table 40. Pull-off Strength vs. Contact Angle for different paints applied to G2b profiled Zinc-on-Steel substrate.

Subgroup label	Average Contact Angle	Average Pull-off Strength (psi)
G2b-C	36	2502
G2b-S1	46	2389
G2b-I	35	2257
G2b-S2	35	1742

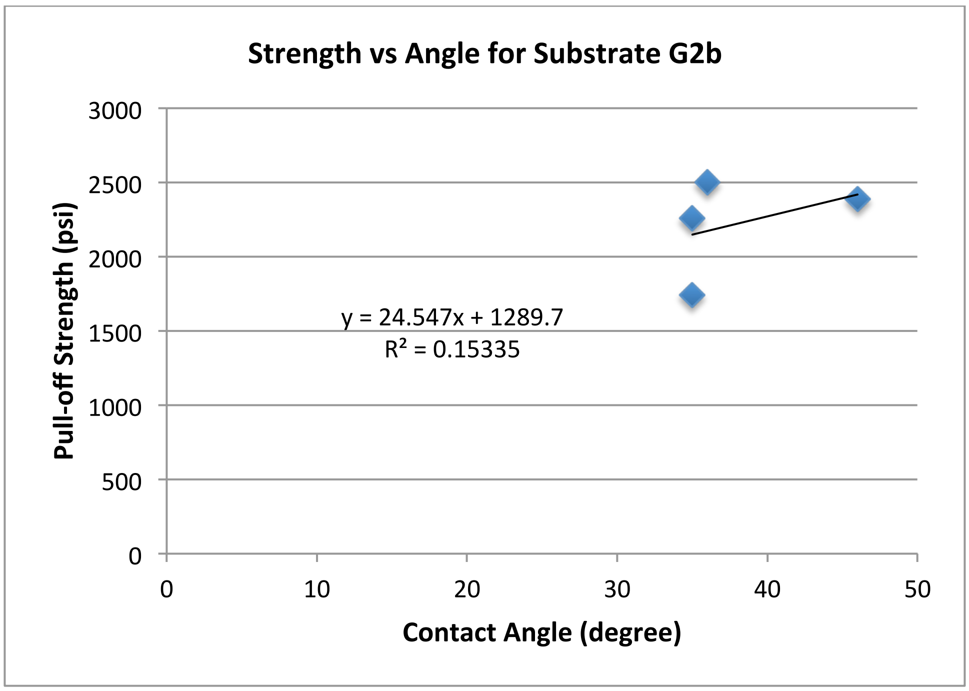


Figure 27. Plot of Pull-off Strength vs. Contact Angle for different paints applied to G2b profiled Zinc-on-Steel substrate. The Pearson correlation coefficient r = + 0.39.

This is the only positive correlation coefficient (r = +0.39) for a Strength-Angle plot. All the other 7 plots show negative correlation coefficients. We do not know the explanation for this reversal of sign. More experimental studies need to be done to ascertain the reproducibility of this exception to the rule. Because of the existence of an example of trend-reversal, we felt that our limited experimental results could not give us a definitive answer to the question of whether the contact angle measurement can be used for selecting a paint system for a given galvanized or metallized steel structure.

8 Discussion and Recommendation:

8.1 NEPCOAT Paint Systems Used as Duplex Paints for Profiled Zinc Surfaces.

The NEPCOAT qualified list of paint systems were originally tested for application of organic or inorganic zinc-rich primers. In our test panels we replaced the zinc-rich primer paint with the galvanized or metallized zinc coating on the steel test panels. One question of interest is whether the duplex paint system using the NEPCOAT intermediate / top paints would have adhesive strength comparable with that of the original NEPCOAT paints on bare steel.

Based on the comparison between the control panels (the Z panels) and the test panels (the G0m, G0b, M0 and G2b panels), we conclude that the initial pull-off strengths of the duplex system are comparable with the performance of NEPCOAT system on bare steel surfaces.

In the literature there is a perception of poor adhesion of paint on the galvanized steel. We think the surface profiling of the zinc metallic surface might have been inadequate for the poorly performing duplex systems.

In view of this comparison between the pull-off strengths of test panels and the control panels we conclude that it is highly likely that more extensive tests would provide data to confirm that the NEPCOAT intermediate and top paints are suitable paints for the Duplex Paint Systems.

8.1.1 There is not a single best paint for all profiled zinc substrates.

At the beginning of this section we had speculated about the potential for using the strength-angle correlation as a tool for selecting the best paint for a given profiled surface. After an inspection of the Tables in section 7.4, we think it is still premature to recommend such use of the data.

All paint systems in the state DOT specified system show “Strong” performance in most of the profiled zinc substrates. For example, the tables in section 7.4 show that paints with range of average pull-off strength in the “Strong” tier of adhesion categories for each profiled surfaces are as the followings:

G0m substrate:	Paints I and S2
G0b substrate:	All paints show “strong” pull off strength. Paints I, C, S2, S1.
M0 substrate:	Paint system S3.
G2b substrate:	Paints C, S1 and I.

There is no single paint system that is a must use for each of the profiled zinc substrates. Only in the metallized substrate (M0) does one paint system (S3) show clear advantage over the paint systems C, I, S1 and S2 (see Table 37). We will discuss more about this point in the next section.

8.1.2 A sealant (S3) for M0 substrate provides significantly better adhesion.

Based on our data for the thermally sprayed zinc test panels (M0, metallized, painted on the same day as metallizing) we suggest that sealant is always used for the Duplex Paint System on zinc metallized surfaces.

The test results displayed in Table 37 and Figure 26 of Section 7.4 strongly support our recommendation. The data show that the average pull-off strength for the S3 paint system (containing a sealant) is 2023 ± 480 psi. The pull-off strengths for the other NEPCOAT epoxy intermediate paints C, I, S1 and S2 are clustered in the range between 1079 to 1178 psi, with estimated error bars at about 200 psi. Although the pull-off strengths of all 5 coating systems exceed the minimum requirement (600 psi) for "Pass" under the NEPCOAT specification, there is a clear difference in the value of the pull-off strengths. The M0-S3 test panels perform in the "Strong Pass" tier while the M0-C, M0-I, M0-S1 and M0-S2 test panels were assigned to the "Weak Pass" tier in our designation discussed in a previous section.

The advantage of using a sealant for metallized steel has been recognized and has been written into state DOT paint specifications (e.g. Rhode Island State DOT metallizing specification). Thus our finding is not surprising but our data showed that the improvement in performance is significant. In this study we also showed the reason for the difference in performance.

The reason for the "Strong Pass" performance for the M0-S3 panels is revealed from both the contact angle measurements and from examining the break surfaces after the pull-off tests.

In our time-dependent contact angle measurement we found the intermediate paint (S3, a sealant) quickly and completely wets and penetrates the porous surface and the channels of the metallized zinc surface. The contact angle of a droplet of S3 paint decreases in a short time (within 3 seconds) to zero. In contrast droplets of the freshly formulated NEPCOAT intermediate paints (C, I, S1, S2) show high contact angles in the range of 80 to 100 degrees and spread very slowly. The sealant spreads and penetrates the M0 surface by wetting and by capillary action. The other intermediate paints (C, I, S1 and S2) exhibit the "lotus effect" and bead up on the rough surface with air pockets trapped within the M0 zinc coatings. A certain type of surface roughness (such as the nano to micro scale fractal topology on a lotus leaf) when in contact with a particular type of liquid with a particular range of surface tension (such as water on the lotus leaf) has been proven to exhibit "super hydrophilic" or "super hydrophobic" effects and leads to beaded up liquid droplets on the surface. We believe that the commercial epoxy intermediate paints specified in the NEPCOAT qualified list exhibit the "lotus effect".

The difference in the wetting property is a consequence of the higher degree of roughness r in the M0 surface due to the nature of the thermal spray process. According to Wenzel's equation for rough surfaces [3], the relation between the measured contact angle θ_{rough} and the theoretical contact angle for perfectly smooth surface θ_{smooth} is

$$Cos\theta_{rough} = r\,Cos\theta_{smooth} \qquad \text{where the roughness } r = \frac{\text{Area of contour surface}}{\text{Area of the envelope surface}}$$

To give an example of how the roughness amplifies the difference in the measured contact angle for slightly different smooth-surface contact angles, we calculate a hypothetical surface with r = 4. Assume the surface contact angle are slightly different, for example θ_{smooth}=76^o and 95^o for two liquid droplets on a smooth surface, the Wenzel's equation gives the expected measured contact angle θ_{rough} = 15^o and 110^o respectively.

The amplification of the contrast in measured contact angle is a phenomenon that has been called the "lotus effect" in the contemporary research literature [5,6]. The reason for the near spherical droplet for the super-high contact angle is that there are microscopic air pockets trapped underneath the paint droplet for the paints containing higher molecular weight epoxy resins (I, C, S1 and S2). The reason for the spreading of the low molecular weight (and low viscosity) S3 paint is because the paint is wicked through the porous surface of the M0 surface by capillary action.

In Appendix D we displayed the images and the analyses of the break surface of both the dolly and the test spot after the pull-off tests. When we compare the break surfaces of the M0-S3 coating with the other M0 surfaces (M0-C, M0-I, M0-S1 and M0-S2) we see a contrast that is consistent with our understanding from the contact angle measurement. The break surfaces in the M0-S3 pull-off tests invariably show the cohesive failure (at high psi range) occurring within either the intermediate (epoxy) paint or the top (polyurethane) layers. There were also adhesive break between the dolly to topcoat interface. In contrast, almost all the other intermediate paints on M0 surface show adhesive failure (at the 1200 psi range) between the intermediate layer and the metallized zinc substrate. In a closer examination of the break surface, we found evidences that the NEPCOAT intermediate paints did not penetrate the porous metallized layer and left air pockets under the paint-M0 interface.

Based on the empirical data (admittedly a small set of data) and the understanding gained from the contact angle measurement, we recommend that sealants be always used for the zinc metallized surface. The NEPCOAT intermediate paint could be replaced by a sealant (which is how our M0-S3 panels were fabricated) or be applied on top of the sealed metallized surface.

An interesting question that we did not address is that of how much sealant should be used. Should the rough surface contour of the metallized zinc to be completely covered to leave a flat surface (intuitively disadvantageous) or left with a degree of roughness comparable to that of the profiled galvanized zinc surface? We recommend a future study on the optimal dosage of the sealant on the metallized zinc surface.

8.2 The effect of 2-week time delay between galvanizing and profiling of the galvanized steel surface.

The fresh galvanized steel has a metallic zinc surface exposed to the ambient environment. Since zinc reacts with oxygen and moisture readily, it is best to minimize the time delays between each of the three stages of duplex paint process: galvanizing, surface profiling and painting. Our test panels in the G0m, G0b, and M0 groups were fabricated with minimum delay between these stages of the process. It simulates the best practice for the fabrication of the duplex system.

In industrial scale manufacturing of duplex painted steel structures, it is sometimes difficult to avoid time delay between these stages of the process. In this situation not only is the delay time is a negative factor but also the ambient environment of the storage facility.

It is well known that outdoor storage of galvanized steel as packed stacks in a moisture-rich environment between galvanizing and painting is to be avoided because the propensity for the formation of white rust (Ref. 1). Thus the next-best practice is to avoid densely packed stacking and provide coverage of the galvanized steel to avoid wetting by rainfall. We simulate this next-best practice for the group of the G2b test panels that are stored indoors for two weeks after galvanizing. After the 2-week delay these panels were then blast profiled and immediately painted with the intermediate epoxy paint.

Although there is no visible white rust formation during the two-week delay time, there is undoubtedly growth of zinc oxide on the zinc surface. The zinc oxide layer formed in this environment could potentially present a problem for the blast profiling process.

The sweep blasting process for galvanized zinc surface is done with soft grit particles and at a lower blasting strength. The blasting for galvanized zinc is gentler than that for steel because zinc is a softer metal. The Mohs hardness scales are 5-7 for steel and 2.5 for metallic zinc. Too strong a blasting process could completely remove the zinc layer.

Zinc oxide (Mohs hardness 4.5) is a harder material than zinc. Could a zinc oxide layer grown on zinc during the 2-week time cause incomplete removal of the zinc oxide surface? Does the extent of incomplete removal of the zinc oxide influence the wetting of the liquid paint on the surface, or the pull-off strength of the cured paint? The wetting property of a paint on the zinc oxide surface is significantly different from that of zinc metal. We therefore expect varied contact angles and uneven wetting of the liquid paint if the soft sweep blasting leaves patches of zinc oxide coverage. An uneven wetting might also result in lower pull-off strength.

We have fabricated two subgroups of test panels with galvanized and blast profiled substrates: G0b and G2b. While the G0b panels are substrates that have minimum delay (within 4 hours) between galvanizing and profiling/painting, the G2b panels are substrates similarly prepared except for 2 weeks of delay between the time of galvanizing and the time for profiling/painting. We stored the galvanized but not blast profiled substrates for two weeks indoors (in a room at the University of Rhode Island). In the industrial scale fabrication of the duplex paint system, it is not always possible to schedule the galvanizing and the profile/paint events on the same day. The set of G2b test panels is to investigate whether there is a difference in the adhesion of cured paint, or the wetting of the liquid paint if we keep it 2 weeks in an environment that does not have moisture accumulaton.

Presumably a layer of zinc oxide is formed during the two-week storage period. Since the zinc oxide has higher hardness than metallic zinc, there is a possibility that the subsequent blast profiling with soft sweep blasting process would leave a non-uniform surface that could cause lower adhesive performance.

From the data collected for the G0b and G2b test panels we conclude that there is no measurable deterioration of adhesive property for a 2-week storage of the G2b substrates in dry indoor environment. It should be noted that the blast profiling should be performed at the end of the 2-week period immediately before the painting process, not at the beginning of the 2-week storage. The contact angle measurements show about the same range of contact angles on both the G0b and the G2b surfaces. This indicates that the oxide grown on the zinc surface is probably removed during the sweep blasting process.

8.3 The correlation between the pull-off strengths and the contact angles.

We found that there is a negative correlation between the contact angle of a liquid paint droplet and the pull-off strength of the cured paint. In general a higher pull-off strength of a test panel is likely to be associated with a smaller contact angle measured for the corresponding intermediate paint droplet on the profiled zinc surface. This observation is in agreement with the conventional wisdom that better liquid paint wetting produces stronger adhesion of the cured paint.

When all the angle-strength data pairs are included in a scatter plot, the Pearson correlation coefficient is $r = -0.74$. Upon closer examination of the data field, we found that there are discernable systematic differences among the paint systems. When we segregate the data according to the paint type and confine the scatter plot for the same paint on different profiled zinc surfaces, we found that the negative correlation is stronger for the segregated groups according to the different paints. The correlation coefficient for these smaller sets of data increases to $r \approx -0.90$. The correlation within each sub group is increased because data for other paint system is not included in the plot. This indicates that although the contact angle is a factor influencing the wetting and therefore the pull-off strength, it is not the only important factor. The difference in other properties of different paint systems may affect both the contact angle and the pull-off strength.

If the rule of thumb of smaller contact angle leads to stronger pull-off strength is generally followed we might be able to use the rule to predict which paint / metal pair is likely to produce paint with higher pull-off strength. Could we use this rule to select a low contact angle paint for higher pull-off strength? Could we perform a contact angle test on a freshly profiled zinc surface and use the contact angle measurement on representative spots to decide which paint system is to be used for the entire painting project?

When we examined the angle-strength data pairs for multiple paints on the same type of profiled surface, we found that the correlation is not definitive enough to be useful for prediction. For our tested panels, two types of surfaces (M0 and G0b) the correlations are strong ($r = -0.84$, and -0.66). For G0m surface the correlation is weak ($r = -0.54$), and there is no correlation for paints on G2b surfaces ($r = 0.3$). We think that in addition to the liquid paint contact angles, other properties of different paints are also a factor that influences the adhesive strength and the contact angle of the paint. It might be worthwhile to revisit this question if we have an opportunity to measure more test panels to increase the statistical significance of the correlations. The number of tests performed in this project is not large enough for us to be confident about the inference of the data.

8.4 Suggestions for the future research

8.4.1 Accelerated corrosion tests on test panels fabricated and tested in this research project.

In this study we tested the adhesion properties within a month of the fabrication of the test panels. It will be highly interesting to monitor the performance of these panels in field conditions or accelerated corrosion tests. With these tests we will be able to answer the following questions:

(1) How does the long-time performance of the Duplex paint correlate with the initial liquid paint wetting and the adhesive test data?

(2) Would the "Strong Pass"test panels continue to perform better than the group of "Weak Pass" test panels?

We have retained all the test panels after the adhesion tests. They are stored and labeled in cardboard boxes. All fabrication conditions and test results are documented in this report. Accelerated tests on these panels could be a good use of the fabricated panels and would yield insights with practical implications.

8.4.2 Factors influencing the correlation between pull-off strength and contact angle.

In this study we found a general correlation (with Pearson correlation coefficient $r = 0.7$) between the pull-off strengths and the contact angles of the liquid paint droplets. Before we engaged in this study, we were not sure that a quantifiable correlation could be measured because of the complexity of the epoxy paints and the potential local inhomogeneity of the profiled zinc surfaces. One significant result of this study is that we realized that a certain extent of quantitative correlation between the pull-off strength and the contact angle is measurable and the basic factors for the relationship are understandable from a relatively fundamental point of view. At this stage, the quantitative correlation is not well defined enough to be useful as a predictor for the paint-to-substrate match. We think that a study to improve the quantitative prediction of the match would have practical significance. For example, when a bridge structure steel has been coated with zinc and profiled, would it be possible to make a contact angle test of several candidates of paint systems to predict which paint will be a good match for a given zinc coated steel? The advantage is that an optimized decision could be made on the spot within a short time after the zinc surface has been profiled, and it is specific to the substrate in question.

In the analysis presented in this report we found that the difference in the commercial paints is a significant factor that causes the diffuseness of the data points around the linear trend line. We think that by studying the rheological differences among the different commercial paints, we could construct a parameter that will merge all the linear regression lines into approximately the same trend line. The idea is to have correlation coefficients for all paint-substrate pairs show a value in the -0.90 range. We notices that most of the trend lines obtained by linear regression have very similar slopes. A paint-related factor when discovered could potentially shift the intercepts of the regression line to result in a merged single predictive relation. We think that it is valuable to experimentally study the rheological properties of the commercial paints to discover the paint-dependent factor that would improve the global correlation for all paint-substrate pairs in the Strength-vs.-Angle plots.

9 Summary

For many highway transportation steel structures, a zinc coating is applied to the surface of the steel for corrosion protection. Zinc is applied to steel in three ways: by zinc-primer paint, by metallizing (where hot zinc is sprayed onto the steel surface), or by hot-dip galvanizing (where the steel part is immersed in a molten zinc bath and a zinc layer metallurgically forms on the steel).

Paints are often applied to the zinc-on-steel surfaces for additional corrosion protection and an aesthetic color finish (the duplex system). The frequent sights of peeled off paints on galvanized posts and other highway structures lead to a general impression that it is harder to achieve a good paint adhesion on metallic zinc-coated steel surface than that on the bare steel surface. One of the objectives of this study is to compare the control paint on bare steel with the duplex system to see if there is any inherent reason for poorer adhesion of the duplex system relative to the standard NEPCOAT qualified paints on bare steel. A second objective is to compare the adhesive strengths of zinc surfaces with different methods of profiling. The third objective is to examine the relationship between the adhesive strengths with the liquid paint wetting of the metal substrates. We hypothesize that the liquid paint wetting property on the profiled zinc surface would be useful information for understanding the adhesive strengths of the cured paints on the surface.

Although the correlation between liquid paint wetting of the surface and the adhesive strength is intuitively appealing it is not clear whether such correlation could be quantitatively demonstrated given the complexity of an epoxy paint formulation that involves complex reacting mixtures. In this study we use the liquid paint contact angles as a measure for the wetting property and use the pull-off strength of the dried paint as a measure for the adhesive strength.

The freshly galvanized steel has a smooth metallic zinc surface. Experiences in the coating industry indicate that paints do not adhere well on smooth metal surfaces. A roughened metal surface provides better paint bonding at the paint/metal interface. Different methods for roughening (also called profiling) zinc surfaces have been used in the duplex paint industry. We prepared metallic zinc coated metal substrates for painting by using 3 different methods for creating the rough surface:

(1) galvanized steel surface roughened by sweep blasting,

(2) galvanized steel surface roughened by mechanical grinding, and

(3) naturally rough zinc surface produced by thermal spray of molten zinc droplets on steel plates (metallizing process).

In this research project we enlisted galvanizing and metallizing companies to produce the surface profiled metal substrates for the test panels. V&S Galvanizing (Taunton, MA) performed the galvanizing and sweep blast profiling of the metal substrates. Duncan Galvanizing (Everett, MA) made galvanized and mechanically profiled metal substrates. Falmer Thermal Spray (Salem, MA) made the metallized metal substrates. In order to have a consistent painting process we enlisted a single painting service for painting all the different batches of the test panels. In addition to the galvanized and metallized test panels a set of control test panels were prepared. The control panels were made from bare steel substrate with 4 different 3-coat NEPCOAT qualified paint systems. For the galvanized and metallized steel test panels we (Boyd Coatings Research) applied the intermediate and top paints of the NEPCOAT system on the metal substrate without the zinc-rich epoxy primer. In our duplex paint the metallic zinc layer is a substitute for the zinc-rich primer paints of the control test panel.

For the metallized steel, the use of sealant has been specified as a requirement (e.g., RIDOT specification). Thus, for the test panels with metallized steel substrate we added to the list of NEPCOAT paints a set of sealant-coated test panels to the interfaces to be tested.

Our test panels consist of 17 different paint/metal pairs and a total of 84 painted test panels. We performed at least 3 pull-off adhesion strength tests (ASTM D4541) and 2 X-cut tape adhesion tests (ASTM D3359) on each painted test panel. In addition to the painted test panels, we also used 34 profiled metal substrates to test the paint wetting properties.

For metallized steel surfaces we added a non-NEPCOAT sealant (recommended by a paint manufacturer) in the pool of test panels to compare with the 4 NEPCOAT intermediate paints on the same surface. We found that the adhesion of paints is much improved by using the sealant as the first layer of contact between the zinc metal and the multi-layered organic paints. When the intermediate paints from the 4 different NEPCOAT qualified list are directly applied to the metallized zinc surface the pull-off strength is good (in the 1100 to 1400 psi range) but not as good as other combinations. The average pull-off strength is increased to 2200 psi when a commercial sealant is used. The reason for the dramatic difference becomes clear when we discuss the liquid-paint wetting measurements.

A freshly galvanized or metallized zinc metal surface undergoes oxidation reactions with oxygen and moisture in the air. Experiences from the coating industry show that a partially oxidized zinc surface frequently leads to poor paint adhesion. The best practice in the industry is to minimize the surface oxidation by profiling and painting the zinc surface on the same day of the galvanizing or metallizing process. Most of our test panels were fabricated with zero delay between the zinc deposition, the profiling and the painting of the intermediate paint. However, in a fabricator shop the delay between galvanizing and painting is sometimes unavoidable in practice. We had included a set of test panels that simulated this situation but avoided the moisture accumulation. We allowed for 2-weeks of delay between galvanizing and blast profiling/painting. We expect partial surface coverage of zinc oxide during the 2-week exposure of the smooth galvanized steel surface. The question of interest is whether the sweep blast process conducted immediately before the painting would remove the accumulated zinc oxide. There is reason to expect the relatively gentle sweep blast used for galvanized surface would not be effective for removing zinc oxide due to the higher hardness of zinc oxide in comparison with the metallic zinc. The force of blast profiling cannot be arbitrarily increased for fear of depleting the entire thin zinc metal coating. We measured the wetting property and the paint pull-off strength of blast profiled galvanized test panels.

Without going into the details of the tests (see the main text and the Appendices) we make several general observations based on the pull-off strength tests:

(1) The pull-off strengths for all the control and test panels are higher than 1100 psi which is substantially higher than the NEPCOAT pull-off strength qualification threshold of 600 psi.

(2) The duplex test panels show competitive or higher average pull-off strengths for the same paints coated on control panels (the 4 NEPCOAT paints on bare steel). The initial adhesive strengths for duplex system are competitive with that of the NEPCOAT on bare steel. We did not find any support to the common perception of inherently poor adhesion for duplex paints. We conclude that high paint adhesion strength in a duplex system is achievable as long as the profiling and the painting of the duplex system are properly performed.

(3) There is a differentiation in the best paint-to-surface match for the pull-off strengths. The pull-off strength values span the range of 1100 psi to 2500 psi. But there are no exclusive winners or losers for either the choice of profiled surfaces or the paint systems. We used a criterion of 2000 psi as a criterion to select interfaces within the field of data for all 17 different paint/substrate interfaces. We found that the high performance interfaces are not restricted to any specific profiled surface, or any specific paint system. All 4 different types of profiled surfaces are represented in one or more of the high-strength paint/substrate pairs. All 5 different paint systems are represented in in one or more of the high-strength interfaces. What is significant is that a particular match between paint and substrate does matter for the pull-off strength performance. We will discuss later how the wetting property measurement provides a correlation between high-strength and low contact angle.

(4) We have compared the wetting and adhesion properties of the G0b and the G2b test panels to try to answer the following question: "Would a 2-week delay between galvanizing and profiling/painting influence the wetting and the adhesion of paint on the zinc surface?" Instead of immediate profiling/painting of the galvanized panels (as done for G0b panels) we stored the galvanized steel panel indoors for 2 weeks before profiling/painting.

We stored the G2b substrates indoors to simulate a good practice in the industry of avoiding moisture and rain on the fresh galvanized surfaces to avoid white rust formation. Although there is no visible white rust formation during the two-week delay time, there is undoubtedly growth of zinc oxide on the zinc surface. The zinc oxide layer formed in this environment could potentially present a problem for the blast profiling process.

The sweep blasting process for galvanized zinc surface is done with soft grit particles and at a lower blasting strength than the blast cleaning of steel because zinc is a softer metal with Mohs hardness scale at 2.5. Too strong a blasting process could completely remove the zinc layer.

At the beginning of this research project we did not know whether the soft sweep blasting process could adequately remove the zinc oxide film. A bulk zinc oxide material (Mohs hardness 4.5) is a harder material than zinc. If the zinc oxide layer is only partially removed by sweep blasting it could leave a surface that is a mosaic of zinc and zinc oxide surface. Since the paint wetting properties of metallic zinc are different from that of the zinc oxide, we might expect an incomplete blast cleaning to cause uneven wetting and poor adhesion.

In this research project we compared the wetting properties and the adhesive strengths of the G2b test panels with the G0b panels. We found that the adhesive strengths of these two groups of test panels are very similar. There was no sign of weakening of the pull-off strength in the G2b test panels in comparison with the G0b panels. We also did not notice significant fluctuation in the measured contact angles in G2b panels. Thus we conclude that 2-week delay between galvanizing and profiling/painting is an acceptable duplex paint process as long as the galvanized steel is stored in an environment that does not cause moisture and water accumulation on the zinc surface. Although we had not performed surface chemical composition analysis of the sweep blasted G2b substrates, we think the zinc oxide layer built up during the 2-week period was adequately removed by the sweep blasting process. A thin layer of zinc oxide on top of a thick layer of metallic zinc might not have a hardness index as high as that of the bulk zinc oxide.

(5) For metallized steel the use of sealant is beneficial. A direct application of the intermediate epoxy paints from the NEPCOAT qualified list gives good pull-off strength (1100 to 1400 psi), but the use of sealant is beneficial for achieving pull-off strengths higher than 2000 psi.

An additional purpose of our research is to examine the potential for using the interfacial tension (surface energy) measurement as a tool for understanding the relation between liquid paint wetting and the cured paint adhesive strength. The conventional wisdom in the paint industry states that "better surface wetting of a liquid paint leads to stronger adhesive strength". Could this conventional wisdom be verified by correlating a liquid paint wetting property with the paint adhesion? In this research project, we propose that the contact angle of a liquid paint on the metal substrate be used as a measure for the wetting property.

The contact angle for a liquid on a perfectly smooth surface is determined by the relative interfacial energy (also known as the surface tension) of the liquid/surface system. The relative interfacial energies are related to the work of adhesion and the contact angle. When the attractive energy between the liquid and the metal surface is stronger than that between the liquid/air interface the liquid paint spreads and wetting of the surface occurs. We experimentally measure the contact angle of liquid droplet as a function of time and extract the paint/surface wetting properties. We are interested in seeing if a low contact angle correlates with high pull-off strength. Does the difference in contact angles help us understand the differences in adhesive strengths for different test panels? Could we use the contact angle data to predict whether a paint/surface combination will result in better pull-off strengths then the other combinations?

A cautionary note should be mentioned before using our liquid paint contact angle data to answer the above-mentioned questions. The liquid paint/metal interface in our system is significantly more complex than the systems investigated in the currently active research field of wetting on rough surfaces. Current research activities are focused on the interfacial interactions between pure liquid (e.g., water) in contact with a well-defined rough surface (e.g., lithographically patterned rough surfaces). Our paint/metal system is far more complex then the typical systems in the research literature in three aspects: (1) The properties of a typical literature system are stable and unchanging. The NEPCOAT two-part epoxy paints contain reactive resin and hardener. The properties (including the contact angle) of the paint change with time. A good paint process involves the right timing for application of the paint on surface after the mixing of the two chemically reactive parts. We need to measure the contact angle at approximately the same time as when the paint is being applied to the surface. (2) The test panel surfaces are rough and are likely to have differences in local roughness. The contact angle can vary due to the local differences in roughness. We cannot be sure that a measured contact angle on a spot of the roughened surface is representative for the test panel. (3) The contact angles are sensitively dependent on the fraction of the polymeric epoxy content (solid content). A change of the percentage of solvents could influence the contact angle. Consistently prepared two-part mixture is important for the reproducibility of experimental data. (4) Although we did observe a high degree of correlation between the contact angle and the pull-off strength in our data, it does not necessarily translate to a prediction of the paint-surface match in a future fabrication process. We do not yet know the influence of a variation of the paint formulation and surface profiling on the contact angle and the adhesive strength. All we know from our study is that for the set of test panels prepared in this research project, the correlation between contact angle and pull-off strength is reasonably high.

In order to reduce the effects of the time-dependent property changes in both the paint and the profiled surface, we measured the contact angles on the same type of zinc metal plates at the same time when the spray painting of the panels took place. We used the same batch of freshly mixed paint for both the painting and the surface contact angle. To reduce the effect of local differences in roughness, we tried as much as possible to measure paint droplets on different locations on the same metal panels and on different profiled zinc test panels in the same batch of zinc surface roughening. To avoid inconsistencies of contact angles due to the variations in the amount of low-viscosity organic solvents (thinners) in the paint, we asked the paint shop to strictly follow the paint manufacturer specified mixing and "sweat-in" procedures.

Our experimental data consist of contact angles and pull-off strengths of 17 different types of paint/surface pairs. The data broadly affirms the conventional wisdom that "better surface wetting of a liquid paint leads to stronger adhesive strength". From a scatter plot of the pull-off strengths vs. the contact angle for all the test panels we found a general correlation between the small contact-angle with higher pull-off strength. This global plot of all the data pairs shows a reasonably good correlation coefficient of $r = -0.75$ (r is the Pearson correlation coefficient).

Our data field contains 4 different NEPCOAT paint systems and one sealant. We included all paint systems in computing the global correlation of our data. When we sub-divide the data according to the type of paints, we found that the correlation coefficient is substantially stronger. For example the correlation coefficient is $r = 0.90$ for angle-strength data of 4 different surfaces G0b, G2b, G0m, and M0 (see the main report for the identity of these surfaces) involving the same paint system S1. The other interface pairs when subdivided according to the NEPCOAT paints (C, I, and S2, see the main text for the identity of the paint systems) show similarly strong correlations ranging from $r = 0.89$ to 0.95. It is interesting to note that different batches of paints of the same types were used in each sub-group of data. Different batches of paints were mixed freshly at Boyd Coatings Research. The consistency of the observed trends is probably an indication that the timing and the paint composition controls by the paint applicators are good enough to provide a consistent trend for different batches of panels fabricated over a period of more than one year.

The increased correlation for dividing the data according to paint system indicates that there are paint-specific properties that influence the pull-off strength. The flip side of the good correlation among test panels with the same paint but different surfaces is that the correlation is expected to be poorer if we sub-divide the data field according to the type of the profiled surfaces. We indeed found that the correlation is weaker. Our data field is not large enough to allow rational interpretation of some of the experimental data. For example, one group of data related to the profiled surface (G2b) coated with 4 different NEPCOAT paints have nearly the same pull-off strengths (about 2000 psi) but with different contact angles (3 small and one large). This set of data shows no correlation between the contact angle and the pull-off strength. The other three types of profiled surfaces show moderate correlation. Here we will discuss one such grouping because it illustrates an example of the contact angle data shedding light on a rationale for the differences in the relative pull-off strengths.

We tested 5 paint systems on the metallized zinc surface. One paint system is a commercial sealant and 4 paint systems are the same NEPCOAT paints used for the galvanized and the control test panels. In an earlier section we described the pull-off strength data that shows pull-off strength is good for the 4 NEPCOAT paints (in the 1100 to 1400 psi range) but could be higher. The average pull-off strength is increased to 2200 psi when a commercial sealant is used. The contact angle data shows a strong correlation ($r = -0.85$) between the contact angle and the pull-off strength. The time-dependent change of contact angle for these 5 paint systems reveals dramatic contrast in the surface wetting of these two types of paints on the metallized zinc surfaces. A liquid droplet of the sealant spreads instantaneously upon contacting with the metallized zinc surface and is absorbed into the void region of the porous zinc surface. In contrast, the 4 NEPCOAT intermediate epoxy paints show droplets with high contact angles. All test panels show one or more sets of images of droplets with contact angles higher than θ=100 degrees. It is evident that the sealant completely wets and penetrates the porous metallized zinc surface, while the other 4 high-solid-epoxy paints wet only the top layer of the zinc coating but leave air pockets in the porous under-layer. The cured sealant paint has a stronger interpenetration between the epoxy and the porous zinc layer. The cured high-solid epoxy paint has surface bonding with zinc but lacks the interlocking bonds provided by the sealant. The aggregate of the contact angle and the pull-off strength data provide support for the DOT specification of the use of sealants for painting metallized zinc surfaces. In the main report we discussed the result in terms of the Wenzle and the Cassie-Baxter equations and the "lotus effect" currently an active area of research on the wetting of liquid on rough surfaces. In this example we found that the difference in pull-off strengths for different paints on metallized steel can be explained from the data of contact angle and the wetting properties of the liquid paint droplets.

What we learned from this research project is that it is possible to obtain very good adhesion strength in duplex system provided the following good practices are used. (1) Perform surface profiling and painting according to the specifications. (2) Use a proper match between paint and the substrate pair using tests of contact angle of paint on the profiled substrate. High contact angle paints should not be used. (3) For metallized steel the use of sealant is recommended. A test of paint wetting on the metallized surface can be very useful for determining if the paint/substrate match is optimal.

Our study showed that there is recognizable correlation between contact angle and pull-off strength. The correlation is strong if we specify a paint system and change the type of profiled surface. In principle this correlation can be used to decide which profiled surface is the best match for a specific paint. However this predictive power is not useful in practical situations. The choice of surface profiling is predetermined in a construction project. It is not practical to choose the type of surface profiling according to the paint system to be used.

A more practical application would be choosing the matching paint based on the contact angles measured on the freshly profiled metal base. Unfortunately, the angle-strength correlation is considerably weaker for a given surface with different paints.

In our analysis we observed linear regression trends between the contact angle and strengths for each paint system. The regression lines are nearly parallel with nearly the same slope but with different intercept. The data suggests that there could be empirical scaling factors for the contact angles that would collapse the different parallel regression lines into a single trend. We recommend that it is worthwhile to conduct a study for finding the empirical scaling factor and an understanding of the origin of the paint-dependent scaling factor. When these empirical factors are found, there is a good chance that it will become practical to use the contact angle measurement to chose the best paint for a given profiled zinc surface.

There is a good chance that the ranking of the pull-off strength could be changed in a long-term accelerated weathering and corrosion test. The pull-off strength for the dry coatings may be different in a coating exposed to salt-fog tests. Although the test panels include welded U-channels to emulate welding joints in a real structure, we could not sample the coated paint immediately next to the joint because the pull-off strength tester could not be fit into an area next to the welded joint. We recommend that a study of the salt-fog spray test to be done on the test panels we have already fabricated and tested. The study may yield useful additional information on the question of profiling and paint adhesion.

10. References

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11. Appendices

Four appendices are attached at the end of this document.

11.1 Appendix A. Work Plan

11.2 Appendix B. Data related to the fabrication of test panels.

11.3 Appendix C. Data related to the measurement of wetting of paint on zinc coated surfaces.

11.4 Appendix D. Pull-off Strength Data and Photographic Images of test panels after the adhesion tests.

11. Appendix

11.1. Appendix A. Work Plan

Acknowledgment:

The PI's of this research project wish to acknowledge the NETC05-5 technical committee members for furnishing the attached Work Plan. The PI's especially grateful for the time and expertise donated by Mr. Jerry Zoller (NHDOT) in formulating this Work Plan.

Implementation of the Work Plan:

The content of the original Work Plan (6/2009) is attached in this Appendix. The research work was carried out according to the Work Plan with the following deviations from the original plan.

1. PI did not use a NACE-trained person for conducting paint application and evaluation (see part 3, 1.5.1). Boyd Coatings Research Co was reluctant to allow observers into the paint application area because of an on-going proprietary coating process of Boyd's client in the same work area.
2. Metalic abrasives were used (i.e., alum oxide, see part 2, 2.3.A.3)
3. Coating thickness sometimes exceeded maximum value specified in Part 2, 2.4.2. (e.g. Carboline intermediate paint, Appendix B, page B-18).
4. PI did not perform a literature or industry survey of industry practice related to duplex coating (Part 1, Task 1). A Technical Committee member (Jerry Zoller) organized a discussion session with participants including a Massachusetts Highway Department expert, one galvanizer and technical representatives from 4 paint manufacturers.
5. Metallizing thickness was 6-10 mil which is thinner than the 8 mil (min) specified in Part 2, 4.3.4)
6. The paint applied over metallized zinc and sealer was only the topcoat (vs. Part 2, 4.5.1 specified "apply intermediate and topcoat over sealer). The representatives of the paint manufacturer, Sherwin Williams, recommended direct coating of topcoat on the sealed metallized surface.
7. The paints for panels G2b were prepared and tested two years after the other tests. The paints used were from different lots from the manufacturers.

NETC 05-5

MEASUREMENT OF ADHESION PROPERTIES BETWEEN TOPCOAT PAINT AND METALLIZED OR GALVANIZED STEEL WITH "SURFACE ENERGY" MEASUREMENT EQUIPMENT.

WORK PLAN

The work plan for the NETC 05-5 research project consists of the following:

Part 1 - Scope of Work (dated March 27, 2006)

Part 2 - Specifications

Part 3 - Work Procedures

Part 4 - Test Matrix

The NETC 05-5 research project will not provide pass/fail acceptance criteria nor will evaluation reports indicate pass/fail.

NEW ENGLAND TRANSPORTATION CONSORTIUM

PART 1 - SCOPE OF WORK

PROJECT NUMBER: NETC 05-5

PROJECT TITLE: Measurement of adhesion properties between topcoat paint and metallized/galvanized steel with "surface energy" measurement equipment.

RESEARCH PROBLEM STATEMENT: For many highway transportation products, a zinc coating is added to the structural steel to act as a sacrificial layer for corrosion protection. Zinc is applied to steel in three ways – by a zinc-primer paint, by metallizing (where hot zinc is sprayed onto the steel surface), or by galvanizing (where the steel part is immersed in a molten zinc bath and a zinc layer metallurgically forms on the steel). Paint topcoats are often applied to zinc-coated steel surfaces to provide additional protection and an aesthetic color finish. The adhesion performance of these topcoats appear to vary considerably for coatings applied over galvanizing versus metallizing. The effectiveness of different zinc coatings with topcoat paint applications can be quantified by measuring adhesion properties between the topcoat paint and zinc-coated steel. Measurement of these adhesion properties is the primary objective of this research.

OBJECTIVES:

1: Compare the adhesion properties of NEPCOAT-approved topcoat paint over metallizing to topcoat paint over galvanizing using specialized "surface-energy" measuring lab methods. As a control the adhesion properties of topcoat paint over zinc primer painted steel substrates will also be measured.

2: Investigate various factors affecting the adhesion of topcoat paint over galvanizing.

3: Report and recommend practices which produce the best adhesion of NEPCOAT-approved topcoat paints over metallized and particularly galvanized steel surfaces.

PRINCIPAL TASKS:

Observe and measure adhesion properties between topcoat paints and zinc-coated (i.e. primer painted, metallized and galvanized) steel test panels with various surface conditions. The tasks to complete the project will be thoroughly documented and include the following:

Task 1. Literature survey and industry contacts

A comprehensive literature survey will be completed to review adhesion properties and testing methods, results, and recommended practices concerning the adhesion of topcoat paints over zinc-treated steel surfaces for highway transportation products. Best industry practice and the recommendations of galvanizers and paint suppliers are to be included in this survey.

Task 2. Complete assembly of lab equipment and testing

The specialized "surface energy" measurement lab apparatus will be assembled and tested to verify it is in working order by repeating adhesion property measurements on control samples or duplicating prior work by others.

Task 3. Acquisition and preparation of samples

All test samples and materials required for lab testing, including topcoat paints and zinc-coated steel panels will be acquired from an approved commercial painting or paint testing facility using uniform procedures conforming to manufacturers recommendations. Galvanized test panels will be prepared per ASTM A123. Metallizing will be performed per SSPC-CS23.00/AWS C2.23M/NACE No. 12.

Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc and Their Alloys and Composites for the Corrosion Protection of Steel. (SSPC/AWS/NACE)

3a) Zinc-coated test samples will be prepared using various methods of surface cleaning or preparation, including solvent cleaning, alkaline cleaning, zinc phosphate treatment, imparting profile by sweep blasting, imparting a dense profile by sand blasting, roughening the surface by grinding and power wire brush . Each of the samples will be documented as how they were prepared. The use of other manufacturer recommendations (e.g. wash primer or tie coat) will also be recorded.

3b) The zinc-coated test panels will be lab tested for adhesion properties by the specialized lab methods. The probe area for test samples is 3”×1”. The zinc-coated samples will be in the form of a coated layer on a flat substrate. These surfaces will be prepared for contact angle measurements. If the metallizing and galvanized surfaces are „rough‟, as expected, the contact angle will display a range. This range will be considered in the analysis.

3c) After the zinc-coated test panels are lab tested, the panels will be topcoated with three NEPCOAT-approved paint systems by the commercial painting facility. The investigator will forward the selected paint systems to the technical committee for approval prior to their use. The prime coat from each system shall not be applied to the panels. Each panel will be tested for adhesion properties by the specialized lab methods after the intermediate coat and again after the final topcoat. The data collected will be used in the overall adhesion analysis.

<u>Task 4.</u> <u>Measurement and data analysis</u>

Contact angle measurements will be conducted on test samples using probe liquids. The data will be analyzed to compare the adhesion properties between the topcoat paints and various zinc-coated steel surfaces over various time periods.

4a) Galvanizing - The adhesion properties shall be measured on the galvanized surface with the time-dependent development of zinc oxides (e.g. after 8 hours, two weeks). Each of the prepared samples will be tested. The time interval after galvanizing is an important variable corresponding to the formation of zinc oxides. The addition of any chemical additive to manufacturer-recommended treatments to the zinc-coat to make a stronger bond will also be investigated. Include weathered (over 12 month‟s exposure) galvanized steel samples if reasonably available from one of the participating Owners.

4b) Metallizing - Metallized surfaces shall be coated with sealer. Adhesion properties shall be measured on metallized surfaces under varying conditions of oxidation. The metallizing shall be identified by chemical composition (e.g. 85% zinc, 15% aluminum), and the initial porosity of the metallizing surface observed as well. The effect of the metallizing profile on adhesion will also be documented.

MEETINGS WITH PROJECT TECHNICAL COMMITTEE: The proposal should provide for a minimum of three (3) meetings with the Technical Committee that has been established to monitor the progress of the project. A meeting between the committee and the PI during the lab testing during Phases 3 and 4 is encouraged.

REPORTS: The Principal Investigator will be required to prepare and distribute the following reports:
Quarterly Progress Reports: One (1) copy prepared and e-mailed, on a calendar quarter basis, to the NETC Coordinator. The Coordinator will forward copies to the Project Technical Committee.
Draft Final Report: Seven (7) copies of the Draft Final Report will be prepared and distributed to the members of the Project Technical Committee for review prior to printing of the Final Report
Final Report: Upon receipt of approval from the Chairman of the Project Technical Committee to complete the Final Report, the PI will provide the following to the NETC Coordinator: 70 paper copies

bound with NETC covers and backs, and a copy in ADOBE™ Portable Document Format. Included in the submittal will be sample specifications for facility owners" use.

TECHNOLOGY TRANSFER STRATEGY: NETC recognizes that research results are not automatically put into practice upon completion of the research and publication of the final report. Effective implementation is more likely when researchers and user agencies collaborate to plan for implementation. Therefore, NETC requires that all research proposals, for NETC funded research, include a technology transfer and implementation plan for incorporating the research results/products into practice. The plan should indicate the type of technology transfer activity (workshops, demonstrations, etc.) that would be considered the most effective means for disseminating the results of the study to potential users.

TIME TO COMPLETE: 15 months (12 months for research and 3 months for draft report preparation, review and final report).

DEVIATION FROM THE SCOPE OF WORK: In the event that the Proposer deems it necessary to deviate from the Scope of Work (Cost, Principal Tasks, Time to Complete, etc.) in order to accomplish the objectives of the research project, such deviation should be noted and the reasons clearly stated in the proposal.

NEW ENGLAND TRANSPORTATION CONSORTIUM

PART 2 - SPECIFICATIONS

SECTION 1 - DESCRIPTION

1.1 General. This section specifies duplex systems for steel test panels:

1. Shop-applied paint over galvanizing (see Section 3);
2. Shop-applied paint over metallizing (see Section 4);
3. Provide all materials, apparatus, and labor necessary to perform the scope of work whether or not the material or apparatus is specifically identified.
4. Conduct all galvanizing, metallizing, surface preparation, and painting operations in a workmanlike manner in compliance with the governing specifications, and to the satisfaction of the NETC PI.
5. The work shall comply with applicable OSHA safety regulations.

1.2 Scope of work.

1. The original Scope of Work is outlined in NETC 05-5 Work Plan- Part 1, and described in detail in the Work Plan- Parts 2, 3, and 4.

1.3 NETC Principle Investigator (PI)

1. The PI will perform "surface energy" measurements on the test panel after galvanizing and surface preparation (or metallizing), and before topcoating. Pre-arranged coordination with the Facility is required.
2. The PI work area should be adjacent to the shop painting area;
3. The PI requires a small sample of intermediate paint from the same mixed batch used by the facility at the same time and under the same atmospheric conditions;
4. The PI "surface energy" measurements take about one hour per test. See Part 3- Work Procedures.

1.4 Facilities furnishing duplex coatings.

1. The facility shall have experience successfully furnishing duplex coatings.
2. The facility shall have a QC Program with personnel having coatings training (e.g. NACE).
3. The facility shall provide a clean room adjacent to the work area for use by the NETC PI furnished with a sturdy lab bench, appropriate ventilation, lighting, and power, and free of building shaking and vibrations.
4. The facility will furnish test panels in the manner described in the Work Plan, ID tages, product data and MSD sheets, coordinate with the NETC PI, and conduct QC functions.
5. The facility will use a QC form to record equipment (e.g. spray tip size, pressures, etc.), procedures, measurements (e.g. profile, DFT, etc.), environmental conditions (e.g. RH, temperatures, dew point, etc.) and furnish a paper and electronic copy (e.g. .pdf format) of the data to the NETC PI.

1.5 Essential Variables in the Test Matrix.

1. The NETC 05-5 project intends to study essential variables in the processes involved. See Part 4- Test Matrix.
2. Essential variables for painting over galvanizing are (a) the nature of the surface preparation of the galvanized surface, (b) the time frame between galvanizing and surface profiling, (c) the time frame between surface profiling and painting.
3. Essential variables for painting over metallizing are (a) the nature of the surface preparation of the steel surface, (b) the time frame between metallizing and painting, (c) selected paint systems, (d) the use of a penetrating sealer.
4. All surface preparation and paint application procedures should be documented and reported.

1.6 Paint manufacturer.

1. Paint application shall conform to the paint manufacturer's product data sheet
2. Paint suppliers may witness the preparation and application of their coating to the test panels.

1.7 Reference standards. The latest edition of the following standards and regulations apply.

1. ASTM A123, *Standard Specification for Zinc (Hot Dip Galvanized) Coatings on Iron and Steel Products*
2. ASTM A385, *Standard Practice for Providing High-Quality Zinc Coatings (Hot Dip)*
3. ASTM D3359, *Standard Test Methods for Measuring Adhesion by Tape Test*
4. ASTM D4285, *Standard Test Method for Indicating Oil or Water in Compressed Air*
5. ASTM D4541, *Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*
6. ASTM D4940, *Test Method for Conductimetric Analysis of Water Soluble Ionic Contamination of Blasting Abrasives*
7. ASTM D6386, *Standard Practice for Preparation of Zinc (Hot Dip Galvanized) Coated Iron and Steel Product and Hardware Surfaces for Painting*
8. ASTM D6677 *Standard Test for Evaluating Adhesion by Knife*
9. SSPC-CS 23.00 *Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc and Their Alloys and Composites for the Corrosion Protection of Steel.*
10. SSPC-SP 1, *Solvent Cleaning*
11. SSPC-SP 5, *White Metal Blast Cleaning*
12. SSPC-SP 7, *Brush Off Blast Cleaning*
13. SSPC-SP 10, *Near-White Metal Blast Cleaning*
14. SSPC- AB 1, *Mineral and Slag Abrasives*
15. SSPC-PA 1, *Shop, Field, and Maintenance Painting*
16. SSPC-PA 2, *Measurement of Dry Film Thickness with Magnetic Gages*
17. SSPC SP-COM, *Surface Preparation and Abrasives Commentary for Steel Substrates*, SSPC Painting Manual, Vol. 2, “Systems and Specifications”

SECTION 2 - MATERIALS

2.1 Test panels.

1. Use commercially available test panels made of A36 material, such as listed below (or equal);
2. Use the KTA "Composite Test Panel Mill Scale" (3/16" x 4" x 6" unblasted) having a 1" channel section welded to the front face. Add a hole for handling during galvanizing. Use three composite test panels for each test option. See www.ktagage.com.
3. For each test option, the NETC PI requires one additional panel (without the channel section) with the same galvanizing (or metallizing) and surface preparation. Use the KTA "Flat Panel Mill Scale (3/16" x 4" x 6") with a hole added.
4. For each test option, after the four test panels are prepared in the same manner, three will be painted by the facility and one given at the same time to the NETC PI for "surface energy" measurements (this PI panel will not be painted).
5. Test panels shall not be preblasted before galvanizing. Test panels for metallizing shall be blasted by the facility prior to metallizing as specified herein.
6. The duplex system shall cover the top surface and four edges of the test.
7. Furnish stamped metal tags and wire for attachment to and identification of test panels.
8. The test panels shall remain the property of the NETC PI at the conclusion of the project.

2.2 Galvanizing.

1. Hot-dip galvanizing shall conform to ASTM A123 and utilize the dry kettle process.
2. The galvanizing process shall not include water quenching or a chromate conversion coating.
3. The NETC 05-5 project is researching only newly galvanized surfaces, not partially-weathered or fully-weathered galvanized surfaces.
4. The minimum dry film thickness of galvanizing shall meet ASTM A123 (anticipated to be 3.0 mils DFT for material < 1/4 inch).

2.3 Abrasives.

A. Abrasives used on galvanizing for painting.

1. Provide abrasives that are dry and free of oil, grease, and corrosion producing, or other deleterious contaminants.
2. Provide a abrasives that are sized to produce a dense, consistent, sharp, angular, uniform anchor pattern on the galvanized surface with a profile height of 1.0-3.0 mils.
3. Steel or metallic abrasives are not permitted.
4. Use abrasives and sizes as recommended in SSPC-COM or by industry to achieve the desired profile, such as coal slag (Black Beauty), Dupont StarBlast®, aluminum oxide, or garnet.
5. Inspect the profiled surface with a Surface Profile Comparator and measure with Testex tape.

B. Abrasives used on bare steel for metallizing

1. Provide abrasives that are dry and free of oil, grease, and corrosion producing, or other deleterious contaminants.
2. Provide an abrasive that is sized to produce an angular, uniform anchor pattern on the steel surface with a profile height of > 2.5 mils.

2.4 Duplex Paint Systems.

1. All paint coatings shall be applied according to SSPC-PA1 and the paint manufacturer's recommendations for use over galvanizing or metallizing.
2. The duplex system (i.e. galvanize-paint and metallize-paint) shall consist of the zinc coating (e.g. galvanizing or metallizing) and the intermediate (4-6 mils min. DFT) and finish (3-4 mils min. DFT) coats of an approved paint system.
3. The maximum VOC of coatings is 2.8 lb/gal at the time of application, including thinners.
4. Approved paint systems are those on the current NEPCOAT QPL List A, B, or C, or as recommended by coating manufacturers for the NETC 05-5 research project (see Table 1).

TABLE 1 - Approved Paint Systems

a. Carboline Company (www.carboline.com)

Primer:	(galvanizing or metallizing)
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

b. International Protective Coatings (www.international-pc.com)

Primer:	(galvanizing or metallizing)
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

c. Sherwin Williams Company (www.sherwin-williams.com)

Primer:	(galvanizing) or (metallizing w/ and w/o Macropoxy 920 sealer)
Intermediate:	Macropoxy 646 Fast Cure Epoxy
Finish:	Acrolon 218 HS Acrylic Polyurethane

d. Sherwin Williams Company (www.sherwin-williams.com)

Primer:	(galvanizing or metallizing)
Intermediate:	Recoatable Epoxy Primer Series B67
Finish:	High Solids Polyurethane Series B58

2.5 Color

1. The final color of the painted panels is Dark Green (semi-gloss) Federal Standard 595 color number #24109, unless agreed otherwise.

2.6 Metallizing

1. Metallizing shall conform to SSPC-CS 23.00.
2. Use zinc (99.99%) metallizing wire.

2.7 Equipment

1. Verify compressed air cleanliness with a white blotter test, per ASTM D 4285;
2. Provide any necessary personal protective equipment (PPE) for two NETC representatives to assure protection from hazards during work activities. Repair or replace PPE as necessary.
3. Provide all of the coatings inspection equipment needed to verify the quality of the galvanizing, metallizing, surface preparation, and painting, including a Positector 6000 dry film thickness gage, Surface Profile Comparator and reference disks, Testex Press O-Film replica tape, spring micrometer, flashlight, and make the equipment available for use by the NETC PI.

2.8 Dry Film Thickness

1. Measure the thickness of each coat (galvanizing, metallizing, paint) using nondestructive magnetic dry film thickness gages per SSPC-PA2.

2.9 Protective measures

1. Coated parts shall be carefully wrapped or padded with appropriate materials to protect the coating from any scraping, marring, or other damage to the surface finish.

SECTION 3 - DUPLEX COATING (GALVANIZING AND PAINT)

3.1 General

1. Perform work to conform to the Work Plan, reference standards (1.7), and coating manufacturer's recommendations, respectively.
2. The Facility shall conduct and document quality control inspection of the galvanizing, surface preparation, cleaning, and painting operations, including measurements of environmental conditions, surface profile, dry film coating thickness, and visual inspection for coating defects.
3. Prepare panels per ASTM A 385 (for material composition, cleanliness, drainage vents, etc.)

3.2 Surface Preparation of Galvanizing

1. Prepare galvanized surfaces for painting in conformance to ASTM D6386, and as specified herein.
2. All visually evident detrimental surface imperfections (e.g. flux inclusions, dross inclusions, oil) that are present on galvanized surfaces shall be cleaned, and any high spots, rough areas and edges, spikes, and sharp protrusions shall be removed by grinding to produce a smooth surface. Peeling of galvanizing is not acceptable and the piece shall be regalvanized.
3. Prior to painting, clean galvanized surfaces with SSPC-SP1, Solvent Cleaning as needed;
4. Provide surface preparation conforming to SSPC-SP7, Brush-Off Blast Cleaning, with non-metallic abrasives at a low nozzle pressure needed to achieve the required profile, or abraded by approved mechanical means using sanding disks with 36-grit abrasive, to thoroughly roughen the entire surface and produce a dense, consistent, sharp, angular, uniform anchor pattern with a profile height of 1.0-3.0 mils, exhibiting a uniform gray color free of any bright, shiny spangles and to an appearance and feel similar to sandpaper. The required

thickness of the zinc coating shall be maintained and checked prior to painting. Surface preparation shall be acceptable to the paint manufacturer's requirements (see 1.6).

5. Profile the surface prior to the formation of "white rust" (as defined in the *Inspection of Products Hot Dip Galvanized After Fabrication*, Table IV, by the AGA) on the galvanized surface. If any "white rust" is detected by visual means, the piece shall be regalvanized.
6. Prior to painting galvanized products shall not be nested, stacked or stored with adjacent surfaces touching but shall be kept separated to permit the circulation of air between products. Galvanized products shall be sloped to drain and kept as dry as possible.
7. Inspect the profile prior to painting with a Surface Profile Comparator.

3.3 Paint Application

1. Verify that the galvanized surface exhibits the specified degree of cleaning immediately prior to painting. Apply the first coat before degradation of the surface occurs, but in no case allow the prepared surface to stand for more than 12 hours prior to painting.
2. The timeframe essential variable also requires paint application after a minimum of 14 days after galvanizing with appropriate surface cleaning. See Test Matrix.
3. Apply paint in a controlled environment meeting applicable atmospheric requirements as recommended by the coating manufacturer.
4. The intermediate and finish paint coats shall each be maintained in a protected environment within a temperature range recommended by the product data sheet for the duration of the cure time.
5. Apply paint under the following conditions unless the requirements of the paint manufacturer are more restrictive. Do not apply paint under less restrictive conditions.
   a) Surface and air temperatures between 40°F and 100°F.
   b) Relative humidity – Less than 85%.
   c) Dew Point – Surface temperature 5°F min. above the dew point.
   d) Frost/Rain - Do not apply paint to surfaces containing frost or damp, or during rain, fog, or similar detrimental weather conditions, but only to surfaces that are thoroughly dry.
6. Apply all coats by spray, unless other methods are necessary.
7. Apply each coat of paint only after the previous coat has been allowed to dry as required by the manufacturer's written instructions, but as soon as possible to minimize the length of time that the coating is exposed to dust and contamination. Do not allow any coat to remain exposed for longer than 14 days prior to overcoating.
8. Apply each coat in a workmanlike manner to assure thorough wetting of the substrate or underlying coat, and to achieve a smooth, streamline surface free of dryspray, overspray, and orange peel. Shadow-through, pinholes, bubbles, skips, misses, lap marks between applications, or other visible discontinuities in any coat are unacceptable.
9. Remove dryspray and overspray (e.g. by sanding) prior to the application of the next coat. When present on the finish, remove as directed by the Department and apply another coat of finish to the area. Remove all other defective coating to sound material and reapply.
10. Thoroughly coat all surfaces with special attention to hard-to-reach areas and irregular surfaces.

3.4 Paint Adhesion.

1. Apply all coats in such a manner to assure that they are well adhered to each other and to the substrate. If the application of any coat causes lifting of an underlying coat, or there is poor adhesion between coats or to the substrate, remove the coating in the affected area to adjacent sound, adherent coating, and reapply the material. Document and report conditions and activities.

SECTION 4 - DUPLEX COATING (METALLIZING AND PAINT)

4.1 General

1. Perform work as described in Section 3 with appropriate modifications for metallizing.
2. This procedure is for the application of metallic thermal spray coatings (TSC) of zinc (i.e. metallizing) and subsequent topcoating with paint.
3. The essential variables will topcoats metallized surfaces with and without a sealer.
4. Record thermal spray variables (e.g. spray offset distance, amperage, voltage, air pressure).

4.2 Surface preparation

1. Prepare the steel substrate to an SSPC-SP5 white metal finish.
2. The steel substrate shall have at a minimum, an angular profile depth $\geq$ 2.5 mils with a sharp angular shape. Measure the profile with replica tape, x-coarse (ASTM D4417).
3. Use clean dry angular blasting media. Confirm the absence of oil contamination with the water sheen test per ASTM D4940.

4.3 Applying Metallizing

1. The thermal spray equipment shall be operated per manufacturer's instructions. Gas or arc type are acceptable.
2. Apply spray by hand rather than by automatic processes.
3. The time between final steel surface preparation and completion of thermal spraying should be no greater than 6 hours, except 4 hours in environments of high humidity. If rust bloom or a degraded coating appears at any time while spraying, stop spraying. Document and record conditions and activities.
4. The minimum metallizing thickness shall be 8 mils.
5. The coating thickness shall be applied in several crossing passes. The coating strength is greater when the spray passes are kept thin.

4.4 Applying sealer

1. The thermal sprayed steel should be sealed with a seal coat thin enough to penetrate into the body of the TSC and seal the porosity. Typically the seal coat is applied at a spreading rate resulting in a theoretical 1.5 mils DFT.
2. The sealer should be applied within 8 hours after thermal spraying.

4.5 Applying Paint

1. The paint intermediate and topcoats should be chemically compatible with the sealer and applied according to the paint manufacturer's instructions.

NEW ENGLAND TRANSPORTATION CONSORTIUM
PART 3 - WORK PROCEDURES

1.1 General. This section describes work procedures by the NETC Principal Investigator (PI):

1. The work of the NETC PI to measure surface energy requires close coordination in the timing and sequencing with the Facility furnishing the zinc-coated test panels during surface preparation and topcoating operations;

1.2 Test Panels

1. See sketch;
2. Metal tags should be attached to the test panels for identification
3. The identification nomenclature should be concise and accurate for tracking all panels;

1.3 QC Inspection

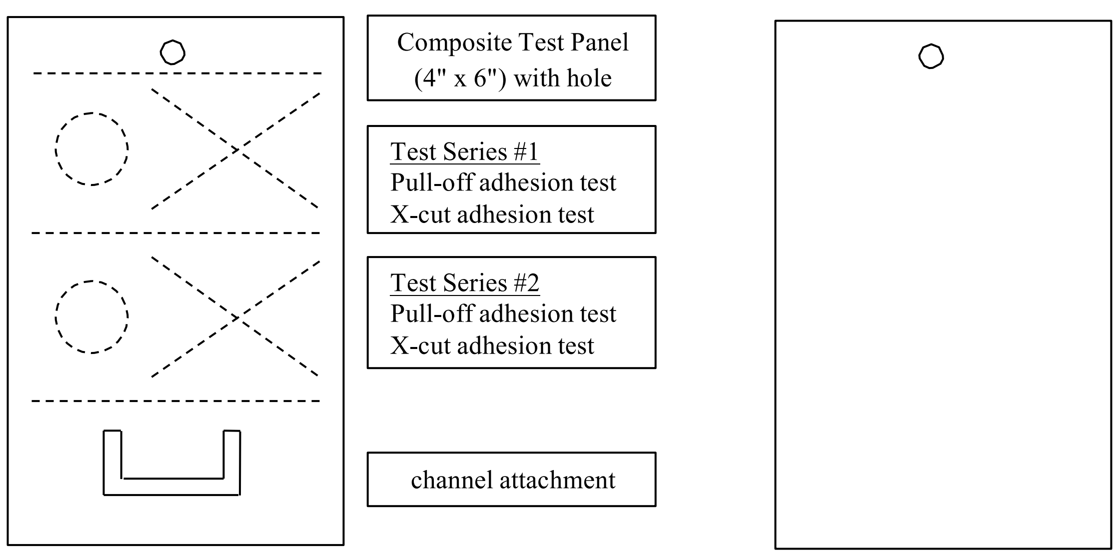
1. All test panel surface preparation and coating should be subject to the oversight and inspection of qualified and experienced facility QC personnel.
2. Test panels should be inspected at each stage and the conditions recorded using QC forms.
3. Inspect the angularity of the profile with a Surface Profile Comparator and document results.

1.4 NETC PI "Surface energy" optical measurements

1. The NETC PI measures "surface energy" by placing a drop of paint on the prepared surface and measuring the droplet with optical instruments for a period of time (approximately 30 minutes).
2. It is important that the PI test panel have the same surface preparation as the panels to be painted, that the paint droplet comes from the same batch of paint, and that the environmental conditions are the same. That is why the PI must do optical measurements at the facility in an area adjacent to the facility's painting area.

1.5 NETC PI Adhesion testing and panel evaluation

1. All adhesion testing and evaluation should be subject to the oversight and inspection of qualified NACE-trained personnel provided by the NETC PI / DOT Owners.
2. The same operator should conduct adhesion testing and panel evaluation for consistency of reporting;
3. Adhesion testing should be performed after a minimum of two weeks following the final application of the color coating;
4. The adhesion pull-off test should use a self-alignment adhesion tester (e.g. Patti).
5. The coatings should be visually examined at the channel surfaces, welds, crevices, and edges and results documented.
6. Additional adhesion testing may be performed with the ASTM D 3359 (Method A, X-cut tape test, or Method B, Cross-cut tape test), and the ASTM D6677.
7. If possible, the NETC PI may perform additional testing after additional lab testing and time.



Type A Test Panel Configuration for Facility to paint

Type B Test Panel Configuration for NETC PI "surface energy" measurements

Table 2. Test Matrix showing the tested panels and the subgroup names.

TEST MATRIX (Revised) NETC 05-05 Revised to reflect the actual tested panels. Process Variables (essential)	**1** Duplex Galv steel - Paint	1	2	3	Con-trol	**2** Duplex TS Metallize-Paint		
Test panel group name		**G0b**	**G2b**	**G0m**	**Z**		**M0**	**M0-S3**
Test piece, surface prep	none				paint	SP5	x	
Zinc over steel	Galv					Metallize		
Galvanizing (ASTM A123)		x	x	x				
Kettle process, dry or wet	dry							
Test piece, thickness (in.)	<1/4					<1/4		
Thickness of coating, mils (min)	3.0 (min)					8.0 avg	x	
Profilling steel					x	(6-10)	(6-10)	
Cleaning (ASTM D6386)								
5.2 Surface smoothing	as needed							
Profiling Zn (ASTM D6386, 5.4.1)								
Temperature of galv part	ambient					ambient		
Abrasive sized to produce profile		x	x		x			
Abrasive hardness (Mohr)	record				Al Ox			
Low Nozzle pressure (psi)	record							
Profile (mils) - angular	1.0 - 3.0	x	x		x	>2.5	x	
Mechanical abrasion-grinding	record			x				
						Metal wire Zn 99.99%	x	
Time-coat steel after surf prep (max)	na					4 hrs		
Time-coat zinc after surf prep (max)	12 hrs	x		x		8 hrs	x	
ditto - max **DAYS**	14 days		x					
Facility - same galv & paint		no	no	no	yes		no	
Paint Selection Thickness (min)						Sealer		x
primer/intermediate/top 2-5 / 4-6 / 3-4 (mils)								
1. Carboline 859/888 / 133 LH	1 IT*	1 IT	1 IT	1 IT	1 PIT✚	Interm-Top	1	
2. International 52/345 /870 UHS	1 IT	1 IT	1 IT	1 IT	1 PIT	Interm-Top	1	
3. Sh Wm Zn Clad III / Recoat epoxy primer B67 / HS PU B58	1 IT	1 IT	1 IT	1 IT	1 PIT	Interm-Top	1	
4. Sh Wm Zn Clad III/646 /218HS	1 IT	1 IT	1 IT	1 IT	1 PIT	Interm-Top	1	
5. Sh Wm 920 /218HS						Interm-Top		1
(panels per test)	**4**	4	4	4	4	**4**	4	4
number of panels		16	16	16	16		16	4
number of test pieces	**64**					**20**		

Notes: * IT means Intermediate/Topcoat, ✚ PIT means Primer/Intermediate/Topcoat

11.2 Appendix B

Data on Test Panel Fabrication recorded by galvanizer, thermal spray service and painting service providers.

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1. Galvanizing event on 7/22/2009 for preparing mechanically abraded zinc surface at Duncan Galvanizing. 16 the type A panels* and 8 type B panels* were galvanized and mechanically abraded. The 16 type A panels becomes the Group G0m test panels when they are painted with intermediate and top coats. The type B panels were used for contact angle analysis with the liquid epoxy intermediate paints.

   Zinc coating thickness report by Duncan Group, Everett, MA. See Page B-3

2. Thermal spray event on 7/22/2009 at Falmer Thermal Spray, Salem, MA
   20 type A panels* and 10 type B panels* were zinc metallized by the thermal spray process. The 20 type A panels becomes the Group M0 test panels when they are painted with intermediate and top coats. The type B panels were used for contact angle analysis with the liquid epoxy intermediate paints.

   Thermal spray coating parameters reported by Falmer Thermal Spray. See Page B-4

3. Paint coating event started on 7/22/2009 at Boyd Coatings Research, Hudson MA.
   A total of 36 type A test panels were spray painted with the intermediate paints. These painted panels are designated as the Group G0m and M0 test panels after the intermediate and top paints were applied and cured. The type B panels* were not painted but were used for contact angle analysis on site at Boyd Coatings Research on the same day using the freshly formulated epoxy intermediate liquid paint.

   Paint coating conditions and thickness data report by Boyd Coatings Research. See Page B-6

4. Galvanizing event on 8/19/2009 at V&S Galvanizing, Taunton, MA
   16 the type A panels* and 8 type B panels* were galvanized and blast profiled. The 16 type A panels becomes the Group G0b test panels when they are painted with intermediate and top coats. The type B panels were used for contact angle analysis with the liquid epoxy intermediate paints.

   A transcript of V&S verbal statement on coating parameters. See Page B-13

5. Paint coating event started on 8/19/2009 at Boyd Coatings Research, Hudson MA. A total of 16 type A test panels* were spray painted with the epoxy intermediate paints. These painted panels are designated as the Group G0b test panels after the intermediate and top paints were applied and cured. The type B panels* were not painted but were used for contact angle analysis on site at Boyd Coatings Research on the same day using the freshly formulated epoxy intermediate liquid paint.

   Paint coating conditions and thickness data report by Boyd Coatings Research.
   See Page B-14

6. Galvanizing event on 1/05/2011 at V&S Galvanizing, Taunton, MA
   16 the type A panels* and 8 type B panels* were galvanized but were not blast profiled. These galvanized test panels were stored for 2 weeks indoor and exposed to open air in a room (a room for instrument and office desks) with ambient environment similar to a clean storage area of a galvanizing facility.
   A transcript of V&S verbal statement on coating parameters. See Page B-21

7. Blast profiling event on 1/20/2011 at V&S Galvanizing, Taunton MA
   16 the type A panels* and 8 type B panels* galvanized on 1/05/2011 were blast profiled during the morning and were transported to Boyd Coatings Research, Hudson, MA for painting of epoxy intermediate coating in the afternoon.

   A transcript of V&S verbal statement on coating parameters. See Page B-22

8. Paint coating event started on 1/20/2011 at Boyd Coatings Research, Hudson MA. A total of 16 type A test panels* were spray painted with the epoxy intermediate paints. These painted panels are designated as the Group G2b test panels after the intermediate and top paints were applied and cured. The type B panels* were not painted but were used for contact angle analysis on site at Boyd Coatings Research on the same day using the freshly formulated epoxy intermediate liquid paint.

   Paint coating conditions and thickness data report by Boyd Coatings Research.
   See Page B-22

9. Paint coating event for group Z test panels (Zinc Rich Primer Paint) started on 6/20/2011 at Boyd Coatings Research.
   A total of 16 type A bare steel test panels* were blasted (SP10 near white blasting) and painted with zinc rich primers. These painted panels are designated as the Group Z test panels after the intermediate and top paints were applied and cured.

   Paint coating conditions and thickness data report by Boyd Coatings Research.
   See Page B30

***Note: See Appendix A for the descriptions of the Type A and the Type B test panels.**

The following pages contain the reports of test panel fabrication conditions and thickness from the galvanizers (Duncan and V&S), the zinc thermal spray service (Falmar), and the Painting Service provider (Boyd Coatings Research). The reports are assembled according to the chronological order listed on page B-1.

1. Galvanizing event on 7/22/2009 for preparing mechanically abraded zinc surface at Duncan Galvanizing. 16 the type A panels* and 8 type B panels* were galvanized and mechanically abraded. The 16 type A panels becomes the Group G0m test panels when they are painted with intermediate and top coats. The type B panels were used for contact angle analysis with the liquid epoxy intermediate paints.

Page B-3 shows the Zinc coating thickness data report by Duncan Group, Everett, MA

DUNCAN GALVANIZING
69 Norman Street, Everett, MA 02149

GALVANIZING THICKNESS TEST LOG

DATE	JOB #	DESCRIPTION	READING #1	READING #2	READING #3	TESTED BY
7-22-09	21		3.4	3.3	3.3	
	41		4.0	3.5	3.8	
	11		2.8	3.1	3.2	
	31		3.2	3.2	3.0	
	265		3.5	4.0	4.0	
	254		3.0	4.0	3.6	
	264		3.7	2.6	4.0	
	263		3.4	3.5	3.3	
	268		3.5	4.2	3.4	
	255		4.0	3.6	3.5	
	258		4.0	4.2	3.3	
	257		4.1	4.0	3.5	
	259		3.7	4.0	3.6	
	253		2.8	3.0	3.2	
	261		3.2	3.5	4.0	
	266		3.5	3.0	3.7	
	256		3.0	3.5	3.5	
	260		4.0	3.6	3.5	

2. Thermal spray event on 7/22/2009 at Falmer Thermal Spray, Salem, MA

   20 type A panels* and 10 type B panels* were zinc metallized by the thermal spray process. The

   20 type A panels becomes the Group M0 test panels when they are painted with intermediate and top coats. The type B panels were used for contact angle analysis with the liquid epoxy intermediate paints.

   Thermal spray coating parameters reported by Falmer Thermal Spray

Table 1 - Thermal Spray Process and Spray Parameters for Arc Wire Spraying for Corrosion Protection **TSOQT # AS-1**

Substrate material:	STEEL
Feedstock	
Wire type & ID#:	99.997 ZINC LOT# 2.068
Wire diameter, in. [mm]:	1/16
Masking	
Material:	NA
Area(s) to be masked:	
Surface preparation	
Grit type & size	#24 Al2 O3
Anchor-tooth profile depth, 0.001 in. [micron]	Testex 2.0
Pressure-pot blasting pressure, psi [kPa]	40 PSI
Blasting nozzle type	NORBIDE
Blasting nozzle to work distance, in. [mm]	6"
Blasting nozzle to work angle, degrees	90°
Blasting rate, sqft/hr [sqm/hr]	NA
Spray equipment	
Type & model	MILLER BP400
Gun nozzle type & size	HV SPRAY TIP
Air cap type	HV AIRCAP
Power supply	38 V / 450 AMP
Arc control unit Serial #	KG-400160
Spray parameters	
Amperage, A	110
Voltage, V	26
Atomizing ~~gas~~ AIR	100 PSI
Atomizing gas pressure, psi [kPa]	"
Gun to substrate distance, in. [mm]	6"
Gun to substrate angle, degrees	90°
Starting area preheat temperature, deg. F [deg. C]	77
Maximum substrate temperature, deg. F [deg. C]	125
Gun traverse rate, in./min [mm/min]	1 FT / SEC.
Minimum coating thickness/pass, 0.001 in. [micron]	.001
Maximum coating thickness/pass, 0.001 in. [micron]	.003
Final coating thickness	
Minimum, 0.001 in. [micron]	..006
Maximum, 0.001 in. [micron]	.010
Sealer type:	
Finishing method & parameters: NA	
Other/Remarks:	

Abbreviations: sqft - square foot; sqm - square meter; cfh - cubic feet per hour; cmh - cubic meter per hour.

Thermal sprayer (print name): Bal Chwmmers [signature] Date: 7-22-09

Reviewed & accepted by Test Supervisor: [signature] Date: 7-22-09

3. Paint coating event started on 7/22/2009 at Boyd Coatings Research, Hudson MA.
   A total of 36 type A test panels were spray painted with the intermediate paints. These painted panels are designated as the Group G0m and M0 test panels after the intermediate and top paints were applied and cured. The type B panels* were not painted but were used for contact angle analysis on site at Boyd Coatings Research on the same day using the freshly formulated epoxy intermediate liquid paint.

   Paint coating conditions and thickness data report by Boyd Coatings Research.

   The attached report from Boyd Coating Research contains several editorial modifications of the text to make the description of the paints consistent with the main text. In the original report by Boyd Coatings, the "intermediate" paint of the NEPCOAT qualified list was referred as "primer". We modified the text in the Boyd report so that the designation of "intermediate" paint in the following pages agrees with the main text. All other texts and numbers are the same as the original report.

   See report by Boyd Coatings Research on pages B7 –B12.

University of Rhode Island
Steel Panel Coating Project

For the

New England Transportation Consortium
NETC 05-5 Research Project

Report on activities performed by

Boyd Coatings Research Co., Inc.
Hudson MA 01749

EVENT # 1

Starting date: 7/22/2009

PROJECT NUMBER: NETC 05-5

PROJECT TITLE:
Measurement of adhesion properties between topcoat paint and metallized or galvanized steel with “surface energy” measurement equipment.

COATING APPLICATION:

Multiple duplex coating systems to be applied to previously primed (galvanized or metallized) steel test panels as delivered to Boyd Coatings Research by the University of Rhode Island.

TEST PANEL DESCRIPTION:

4” x 6” steel panels, 0.250” thick, with a 1” u channel welded perpendicularly to the lower front face of the panel.
Each panel has a ¼ “ mounting hole located near the top end of the panel.
Panels are identified on an attached metal tag via a three-digit number.
That number is also inscribed on the top front face of each panel.
All panels were pre-treated by the customer (galvanized or metallized) prior to receipt at Boyd Coatings Research.

SCHEDULE:

Work to be performed by Boyd Coatings Research Co., Inc. is scheduled to take place in three separate events. Event #1 started on July 22, 2009. Event #2 is scheduled for August 19, 2009. Event #3 is slated for October of 2009.

EVENT # 1

SCOPE OF WORK TO BE PERFORMED:

A total of thirty-six (36) test panels, either galvanized or matallized, are to be coated, one side only and on all four edges, using a total of five (5) different duplex coating systems. Each duplex coating system consists of an intermediate coat and a topcoat.

	INTERMEDIATE COAT	TOPCOAT
System # 1	Carboline 888 Epoxy	Carboline 133 LH Aliphatic Polyurethane
System # 2	Intergard 345 Epoxy	Interthane 870 UHS
System # 3	Macropoxy 646 Fast Cure Epoxy	Acrolon 218 HS Acrylic Polyurethane
System # 4	Recoatable Epoxy Primer Series B67	High Solids Polyurethane Series B58
System # 5	Macropoxy 920 Pre-Primer	Acrolon 218 HS Acrylic Polyurethane

Intermediate coat DFTs are to be 4-6 mils. Topcoats are 3-4 mils.

All five systems are air cure with full curing times ranging from 2.5 hours up to ten (10) days.

Boyd Coatings Research Co., Inc. internal document number is Job # 3371288

Intermediate paint Application

Spray Technician: Steve Bachand		Start Date: 07-22-2009

Spray Equipment Used

Gun	DeVilbiss HVLP Compact w/siphon cup feed
Fluid Tip	SP-200S-14
Needle Air Cap	HVLP 22 PSI max COM-507
Atomizing Pres.	20 PSI
Air Hose	3/8”

Primer Applied:
Applied specific primers as indicated by customer’s labeling on each box of parts (4 panels per box).

Environmental Conditions:
Date: 07-22-2009
Time: 3:15 PM
Temperature: 80 degrees F
Humidity: 65 %

Surface preparations:
Panels blown off, wiped with IPA soaked cloth, and blown off again

Thinners:
Per mfg.’s specification on Data Sheets (all materials supplied by the customer)

Curing:
Air curing per manufacturer’s specification on Data Sheets

Dry Film Thickness:
Desired thickness of all primers is 4-6 mils.

Topcoat Application

Spray Technician: Steve Bachand Start Date: 08-03-2009

Spray Equipment Used

Gun	DeVilbiss Siphon Gun w/siphon cup feed
Fluid Tip	SP-200S-1.8
Needle Air Cap	510+
Atomizing Pres.	40 PSI
Air Hose	3/8”

Topcoat Applied:
Applied specific topcoats as indicated by customer’s labeling on each box of parts (4 panels per box).

Environmental Conditions:
Date: 08-03-2009
Time: 8:00 AM
Temperature: 79 degrees F
Humidity: 72 %

Surface preparations:
Panels blown off

Thinners:
Per mfg.’s specification on Data Sheets (all materials supplied by the customer)

Curing:
Air curing per manufacturer’s specification on Data Sheets

Dry Film Thickness:
Desired thickness of all topcoats is 3-4 mils.

DFT Test Results

Panel # Substrate	Zinc on steel Pretreatment	Intermediate Paint material	Intermediate DFT	Topcoat material	Topcoat DFT	Total DFT
253-256	GALV	888	4.19	133	3.63	7.82
269-272	METL	888	4.50	133	4.12	8.62
257-260	GALV	345	4.19	870	3.69	7.88
273-276	METL	345	4.25	870	3.09	7.34
265-268	GALV	B67	5.81	B58	3.75	9.56
277-280	METL	B67	5.69	B58	3.08	8.77
261-264	GALV	646	4.00	218	3.11	7.11
281-284	METL	646	4.25	218	3.76	8.01
285-288	GALV	920	4.13	218	3.03	7.16

GALV = Galvanized
METL = Metallize

888 = Carboline 888 Epoxy
133 = Caboline 133 LH Aliphatic Polyurethane
345 = Intergard 345 Epoxy
870 = Interthane 870 UHS
B67 = Recoatable Epoxy primer Series B67
B58 = High Solids Polyurethane Series B58
646 = Macropoxy 646 Fast Cure Epoxy
218 = Acrolon HS Acrylic Polyurethane
920 = Macropoxy 920 Pre-Prime

Compressed air checked in accordance with ASTM D 4285

Solvent Cleaning performed per SSPC- SP 1.

DFT (Dry Film Thickness) measurements were made according to SSPC-PA 2, using a Fischer Dualscope MP20, Number 102-20369A, with a Certification Date of 09/2008

4. Galvanizing event on 8/19/2009 at V&S Galvanizing, Taunton, MA

   16 the type A panels* and 8 type B panels* were galvanized and blast profiled. The 16 type A panels becomes the Group G0b test panels when they are painted with intermediate and top coats. The type B panels were used for contact angle analysis with the liquid epoxy intermediate paints.

   V&S Galvanizing did not provide recorded data on the galvanizing, blast profiling conditions, and the thickness the coating.

   The general manager of V&S Taunton facility verbally communicated to the PI that the operators followed the best practice and the conditions for galvanizing and blasting are in conformity of the Work Plan (with relevant sections highlighted) delivered to V&S for each of the coating event. In general, the Galvanized layer thickness has an average around 3 mils DFT. The abrasive material is aluminum oxide grits (the abrasive material was different from that specified in the original plan) of proper size. The blasted surface profile is in the range of 1 to 2 mils.

5. Paint coating event started on 8/19/2009 at Boyd Coatings Research, Hudson MA. A total of 16 type A test panels* were spray painted with the epoxy intermediate paints. These painted panels are designated as the Group G0b test panels after the intermediate and top paints were applied and cured. The type B panels* were not painted but were used for contact angle analysis on site at Boyd Coatings Research on the same day using the freshly formulated epoxy intermediate liquid paint.

Paint coating conditions and thickness data report by Boyd Coatings Research.

The attached report from Boyd Coating Research contains several editorial modifications of the text to make the description of the paints consistent with the main text. In the original report by Boyd Coatings, the “intermediate” paint of the NEPCOAT qualified list was referred as “primer”. We modified the text in the Boyd report so that the designation of “intermediate” paint in the following pages agrees with the main text. All other texts and numbers are the same as the original report.

See pages B15 – B20 for the modified report.

University of Rhode Island
Steel Panel Coating Project

For the

New England Transportation Consortium
NETC 05-5 Research Project

Report on activities performed by

Boyd Coatings Research Co., Inc.
Hudson MA 01749

EVENT # 2

Starting date: 8/19/2009

PROJECT NUMBER: NETC 05-5

PROJECT TITLE:
Measurement of adhesion properties between topcoat paint and metallized or galvanized steel with "surface energy" measurement equipment.

COATING APPLICATION:

Multiple duplex coating systems to be applied to previously primed (galvanized) steel test panels as delivered to Boyd Coatings Research by the University of Rhode Island.

TEST PANEL DESCRIPTION:

4" x 6" steel panels, 0.250" thick, with a 1" u channel welded perpendicularly to the lower front face of the panel.
Each panel has a ¼ " mounting hole located near the top end of the panel.
Panels are identified on an attached metal tag via a three-digit number.
That number is also inscribed on the top front face of each panel.
All panels were pre-treated by the customer (galvanized) prior to receipt at Boyd Coatings Research.

SCHEDULE:

Work to be performed by Boyd Coatings Research Co., Inc. is scheduled to take place in three separate events. Event #1 started July 22, 2009. Event #2 started on August 19, 2009. Event #3 is slated for October of 2009.

EVENT # 2

SCOPE OF WORK TO BE PERFORMED:

A total of sixteen (16) test panels, galvanized, are to be coated, one side only and on all four edges, using a total of four (4) different duplex coating systems. Each duplex coating system consists of an intermediate coat and a topcoat.

	INTERMEDIATE COAT	TOPCOAT
System # 1	Carboline 888 Epoxy	Carboline 133 LH Aliphatic Polyurethane
System # 2	Intergard 345 Epoxy	Interthane 870 UHS
System # 3	Macropoxy 646 Fast Cure Epoxy	Acrolon 218 HS Acrylic Polyurethane
System # 4	Recoatable Epoxy Primer Series B67	High Solids Polyurethane Series B58

Desired minimum Intermediate coat DFTs are 4-6 mils. Topcoats are 3-4 mils.

All four systems are air cure with full curing times ranging from 2.5 hours up to ten (10) days.

Boyd Coatings Research Co., Inc. internal document number is Job # 3371439

Intermediate coat Application

Spray Technician: Steve Bachand Start Date: 08-19-2009

Spray Equipment Used

Gun	DeVilbiss HVLP Compact w/siphon cup feed
Fluid Tip	SP-200S-14
Needle Air Cap	HVLP 22 PSI max COM-507
Atomizing Pres.	20 PSI
Air Hose	1/4"

Intermediate Paint Applied:
Applied specific primers as indicated by customer's labeling on each box of parts (4 panels per box).

Environmental Conditions:
Date: 08-19-2009
Time: 1:45 PM
Temperature: 97 degrees F
Humidity: 23 %

Surface preparations:
Panels blown off, wiped with IPA soaked cloth, and blown off again

Thinners:
Per mfg.'s specification on Data Sheets (all materials supplied by the customer)

Curing:
Air curing per manufacturer's specification on Data Sheets

Dry Film Thickness:
Desired thickness of all primers is 4-6 mils.

Topcoat application

Spray Technician: Steve Bachand   Start Date: 08-27-2009

Spray Equipment Used

Gun	DeVilbiss Siphon Gun w/siphon cup feed
Fluid Tip	SP-200S-1.8
Needle Air Cap	510+
Atomizing Pres.	40 PSI
Air Hose	¼”

Topcoat Applied:
Applied specific topcoats as indicated by customer’s labeling on each box of parts (4 panels per box).

Environmental Conditions:
Date: 08-27-2009
Time: 8:00 AM
Temperature: 79 degrees F
Humidity: 31 %

Surface preparations:
Panels blown off

Thinners:
Per mfg.’s specification on Data Sheets (all materials supplied by the customer)

Curing:
Air curing per manufacturer’s specification on Data Sheets

Dry Film Thickness:
Desired minimum thickness of all topcoats is 3-4 mils.

DFT Test Results

Panel #	Substrate Pretreatment	Intermediate Material	Intermediate DFT	Topcoat Material	Topcoat DFT	Total DFT
289-292	GALV	888	10.95[1]	133	6.50[2]	17.45
293-296	GALV	345	5.59	870	3.08	8.67
297-300	GALV	646	5.80	218	4.32	10.12
301-304	GALV	B67	8.33[1]	B58	3.36	11.69

GALV = Galvanized

888 = Carboline 888 Epoxy
133 = Caboline 133 LH Aliphatic Polyurethane
345 = Intergard 345 Epoxy
870 = Interthane 870 UHS
646 = Macropoxy 646 Fast Cure Epoxy
218 = Acrolon HS Acrylic Polyurethane
B67 = Recoatable Epoxy primer Series B67
B58 = High Solids Polyurethane Series B58

Compressed air checked in accordance with ASTM D 4285

Solvent Cleaning performed per SSPC- SP 1.

DFT measurements were made according to SSPC-PA 2, using a Fischer Dualscope MP20, Number
102-20369A, with a Certification Date of 09/2008

Notes on DFT test results added after the Boyd Coatings Research Co. Report:

1. Two sets of intermediate paints (Carboline 888, and Epoxy B67) were thicker than the 4-6 mils specified in the Work Plan.

2. The top coat Caboline 133LH paint was thicker than the 3-4 mils specified in the Work Plan.

6. Galvanizing event on 1/05/2011 at V&S Galvanizing, Taunton, MA
   16 the type A panels* and 8 type B panels* were galvanized but were not blast profiled. These galvanized test panels were stored for 2 weeks indoor and exposed to open air in a room (a room for instrument and office desks) with ambient environment similar to a clean storage area of a galvanizing facility.

   V&S Galvanizing did not provide recorded data on the galvanizing, blast profiling conditions, and the thickness the coating.

The general manager of V&S Taunton facility verbally communicated to the PI that the operators followed the best practice and the conditions for galvanizing and blasting are in conformity of the Work Plan (with relevant sections highlighted) delivered to V&S for each of the coating event. In general, the Galvanized layer thickness has an average around 3 mils DFT. The abrasive material is aluminum oxide grits (the abrasive material was different from that specified in the original plan) of proper size. The blasted surface profile is in the range of 1 to 2 mils.

7. Blast profiling event on 1/20/2011 at V&S Galvanizing, Taunton MA

   16 the type A panels* and 8 type B panels* galvanized on 1/05/2011 were blast profiled during the morning and were transported to Boyd Coatings Research, Hudson, MA for painting of epoxy intermediate coating in the afternoon.

   V&S Galvanizing did not provide recorded data on the galvanizing, blast profiling conditions, and the thickness the coating.

   The general manager of V&S Taunton facility verbally communicated to the PI that the operators followed the best practice and the conditions for blast profiling are in conformity of the Work Plan (with relevant sections highlighted) delivered to V&S for each of the coating event. The abrasive material is aluminum oxide grits of proper size. The blasted surface profile is in the range of 1 to 2 mils.

8. Paint coating event started on 1/20/2011 at Boyd Coatings Research, Hudson MA. A total of 16 type A test panels* were spray painted with the epoxy intermediate paints. These painted panels are designated as the Group G2b test panels after the intermediate and top paints were applied and cured. The type B panels* were not painted but were used for contact angle analysis on site at Boyd Coatings Research on the same day using the freshly formulated epoxy intermediate liquid paint.

   The attached report from Boyd Coating Research contains several editorial modifications of the text to make the description of the paints consistent with the main text. In the original report by Boyd Coatings, the "intermediate" paint of the NEPCOAT qualified list was referred as "primer". We modified the text in the Boyd report so that the designation of "intermediate" paint in the following pages agrees with the main text. All other texts and numbers are the same as the original report.

   See pages B23 – B29 for the modified report.

   Paint coating conditions and thickness data report by Boyd Coatings Research are displayed on pages B22 – B-25.

BOYD COATINGS RESEARCH CO., INC.
51 Parmenter Road
Hudson, MA 01749-3213
Tel: 978-592-7561
800-258-0110
Fax: 978-562-9622
Email: info@boydcoatings.com
Web: www.boydcoatings.com

University of Rhode Island
Steel Panel Coating Project

For the

New England Transportation Consortium
NETC 05-5 Research Project

Report on activities performed by

Boyd Coatings Research Co., Inc.
Hudson MA 01749

Starting date:
February 15, 2011

PROJECT NUMBER: NETC 05-5

PROJECT TITLE:
Measurement of adhesion properties between topcoat paint and galvanized steel with “surface energy” measurement equipment.

COATING APPLICATION:

Multiple duplex coating systems to be applied to previously primed (galvanized) steel test panels as delivered to Boyd Coatings Research by the University of Rhode Island.

TEST PANEL DESCRIPTION:

4” x 6” steel panels, 0.250” thick, with a 1” u channel welded perpendicularly to the lower front face of the panel.
Each panel has a ¼ “ mounting hole located near the top end of the panel.
Panels identified via three-digit number inscribed in the panel, top front face.
All panels were pre-treated by the customer (galvanized) prior to receipt at Boyd Coatings Research.

SCHEDULE:

Work to be performed by Boyd Coatings Research Co., Inc. is scheduled to start on 01-20-2011. On that date the intermediate coatings will be applied. After all panels have air cured per the manufacturers’ specifications, the topcoats will be applied and allowed to air cure.

SCOPE OF WORK TO BE PERFORMED:

A total of sixteen (16) test panels, galvanized, are to be coated, one side only and on all four edges, using a total of four (4) different duplex coating systems. Each duplex coating system consists of an intermediate coat and a topcoat.

	INTERMEDIATE COAT	TOPCOAT
System # 1	Carboline 888 Epoxy	Carboline 133 LH Aliphatic Polyurethane
System # 2	Intergard 345 Epoxy	Interthane 870 UHS
System # 3	Macropoxy 646 Fast Cure Epoxy	Acrolon 218 HS Acrylic Polyurethane
System # 4	Recoatable Epoxy Primer Series B67	High Solids Polyurethane Series B58

Desired minimum Intermediate coat DFTs are 4-6 mils. Topcoats are 3-4 mils.

All four systems are air cure with full curing times ranging from 2.5 hours up to ten (10) days.

Boyd Coatings Research Co., Inc. internal document numbers are
Job # 3385277, 3385278, 3385279, and 3385208

Intermediate Paint Application

Spray Technician: Steve Bachand Start Date: 01-20-2011

Spray Equipment Used

Gun	DeVilbiss Siphon Gun w/siphon cup feed
Fluid Tip	SP-200S-1.8
Needle Air Cap	COM-507
Atomizing Pres.	32 PSI
Air Hose	3/8”

Intermediate Paint Applied:
Applied specific primers as indicated by customer’s labeling on each box of parts (4 panels per box).

Environmental Conditions:
Date: 01-20-2011
Time: 3:15 PM
Temperature: 71 degrees F
Humidity: 18 %

Surface preparations:
Panels blown off, wiped with IPA soaked cloth, and blown off again

Thinners:
Per mfg.’s specification on Data Sheets (all materials supplied by the customer)

Curing:
Air curing per manufacturer’s specification on Data Sheets

Dry Film Thickness:
Desired thickness of all primers is 4-6 mils.

Topcoat Application

Spray Technician: Steve Bachand   Start Date: 02-01-2011

Spray Equipment Used

Gun	DeVilbiss Siphon Gun w/siphon cup feed
Fluid Tip	SP-200S-1.8
Needle Air Cap	COM-507
Atomizing Pres.	32 PSI
Air Hose	3/8”

Topcoat Applied:
Applied specific topcoats as indicated by customer’s labeling on each box of parts (4 panels per box).

Environmental Conditions:
Date: 02-01-2011
Time: 9:45 AM
Temperature: 71 degrees F
Humidity: 18.5%

Surface preparations:
Panels blown off

Thinners:
Per mfg.’s specification on Data Sheets (all materials supplied by the customer)

Curing:
Air curing per manufacturer’s specification on Data Sheets

Dry Film Thickness:
Desired minimum thickness of all topcoats is 3-4 mils.

DFT Test Results

Panel #	Zinc coating	Intermediate Material	Intermediate DFT	Topcoat Material	Topcoat DFT	Total DFT
636-639	GALV	888	5.55	133	4.70	10.25
640-643	GALV	345	6.50	870	3.50	10.00
644-647	GALV	646	5.50	218	2.15	7.65
648-651	GALV	B67	7.00	B58	1.95	8.95

GALV = Galvanized

888 = Carboline 888 Epoxy
133 = Caboline 133 LH Aliphatic Polyurethane
345 = Intergard 345 Epoxy
870 = Interthane 870 UHS
646 = Macropoxy 646 Fast Cure Epoxy
218 = Acrolon HS Acrylic Polyurethane
B67 = Recoatable Epoxy primer Series B67
B58 = High Solids Polyurethane Series B58

Compressed air checked in accordance with ASTM D 4285

Solvent Cleaning performed per SSPC- SP 1.

DFT measurements were made according to SSPC-PA 2, using a Fischer Dualscope MP20, Number
105-22136A, with a Certification Date of 03/17/2010

9. Paint coating event for group Z test panels (Zinc Rich Primer Paint) started on 6/20/2011 at Boyd Coatings Research.
   A total of 16 type A bare steel test panels* were blasted (SP10 near white blasting) and painted with zinc rich primers. These painted panels are designated as the Group Z test panels after the intermediate and top paints were applied and cured.

   Paint coating conditions and thickness data report by Boyd Coatings Research are shown on pages B-31 to B-37.

University of Rhode Island
Steel Panel Coating Project

For the

New England Transportation Consortium
NETC 05-5 Research Project

Report on activities performed by

Boyd Coatings Research Co., Inc.
Hudson MA 01749

June/July 2011

PROJECT NUMBER: NETC 05-5

COATING APPLICATION:

Four different triplex coating systems to be applied to steel test panels delivered to Boyd Coatings Research by the University of Rhode Island.

TEST PANEL DESCRIPTION:

Sixteen 4" x 6" steel panels, 0.250" thick, half with and half without a 1" u channel welded perpendicularly to the lower front face of the panel. One set of four additional panels, to be used for testing without being coated, do not have the 1" u channels.
Each panel has a 0.250 inch diameter mounting hole located near the top of the panel through which a color coded ring is attached.
Panels are identified by one or more of three methods; 1) number inscribed in the panel (top front face), 2) number inscribed on a metal disc attached to a ring through the 0.250 inch hole, or 3) by a colored ring through the 0.250 inch hole.

SCHEDULE:

Work to be performed by Boyd Coatings Research Co., Inc. is scheduled to start on 06-20-2011. On that date the steel panels will be sandblasted and the zinc primer coatings will be applied. After all panels have air cured per the manufacturers' specifications, the intermediate and topcoat materials will be applied and allowed to air cure per manufacturer's data sheets.

SCOPE OF WORK TO BE PERFORMED:

A total of twenty (20) test panels will be delivered to Boyd. All twenty will be sandblasted. Four (4) panels each, for a total of sixteen (16), are to be coated, one side only and on all four edges, using a total of four (4) different triplex coating systems. Each triplex coating system consists of a zinc primer, an intermediate coat and a topcoat. The remaining four (4) panels will be given back to the URI representative(s) on the day the panels are sandblasted, along with a small sample of each of the mixed primer materials.

SYSTEM A	Carboline Company
Primer:	Cabozinc 859 Organic Zinc Rich Epoxy Primer:
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

SYSTEM B	International Protective Coatings
Primer:	Interzinc 52 Epoxy Zinc Rich
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

SYSTEM C	Sherwin Williams Company
Primer:	Zinc Clad III HS Organic Zinc Rich Epoxy Primer
Intermediate:	Macropoxy 646 Fast Cure Epoxy
Finish:	Acrolon 218 HS Acrylic Polyurethane

SYSTEM D	Sherwin Williams Company
Primer:	Zinc Clad III HS Organic Zinc Rich Epoxy Primer
Intermediate:	Recoatable Epoxy Primer Series B67
Finish:	High Solids Polyurethane Series B58

All coating systems are air cures with cure times for the topcoat materials ranging from five (5) hours to ten (10) days per coating.

Panels are to be sandblasted at 60 PSI, using 80 grit aluminum oxide media.

Boyd Coatings Research Co., Inc. internal documents: #3391570AD, #3391570BD, #3391570CD, and #3391570DD.

Primer Application

Spray Technician: Steve Bachand Start Date: 06-20-2011

Spray Equipment Used

Gun	DeVilbiss Siphon Gun w/siphon cup feed
Fluid Tip	SP-200S-1.8
Needle Air Cap	COM-507
Atomizing Pres.	18 PSI
Air Hose	3/8”

Primer Applied:
Applied the primer indicated by customer’s label on each box of parts (4 panels per box).

Environmental Conditions:
Date: 06-20-2011
Start Time: 1:00 PM
Temperature: 85 degrees F
Humidity: 58 %

Surface preparations:
Panels were sandblasted using aluminum oxide media (80 grit), at 60 PSI, blown off with compressed air, wiped with an IPA soaked cloth, and blown off again.

Thinners/Cleaners:
As indicated on manufacturer’s Data Sheets. All materials supplied by the customer.

Curing:
Air curing per manufacturer’s specification on Data Sheets

Dry Film Thickness:
Desired thickness of all primer coatings is 2-5 mils.

Intermediate Application

Spray Technician: Steve Bachand   Start Date: 06-24-2011

Spray Equipment Used

Gun	DeVilbiss Siphon Gun w/siphon cup feed
Fluid Tip	SP-200S-1.8
Needle Air Cap	COM-507
Atomizing Pres.	18 PSI
Air Hose	3/8"

Intermediate Coat Applied:
Applied intermediate coats as indicated by customer's labeling on each box of parts (4 panels per box).

Environmental Conditions:
Date: 06-24-2011
Time: 10:50 AM
Temperature: 74 degrees F
Humidity: 59 %

Surface preparations:
Panels blown off with compressed air.

Thinners/Cleaners:
Per manufacturer's specification on Data Sheets (all materials supplied by the customer)

Curing:
Air curing per manufacturer's specification on Data Sheets

Dry Film Thickness:
Desired thickness of all intermediate coatings is 4-6 mils.

Topcoat Application

Spray Technician: Steve Bachand   Start Date: 06-27-2011

Spray Equipment Used

Gun	DeVilbiss Siphon Gun w/siphon cup feed
Fluid Tip	SP-200S-1.8
Needle Air Cap	COM-507
Atomizing Pres.	18 PSI
Air Hose	3/8”

Topcoat Applied:
Applied topcoats indicated by customer’s labeling on each box of parts (4 panels per box).

Environmental Conditions:
Date: 06-27-2011
Time: 10:55 AM
Temperature: 81 degrees F
Humidity: 41 %

Surface preparations:
Panels blown off with compressed air.

Thinners/Cleaners:
Per manufacturer’s specification on Data Sheets (all materials supplied by the customer)

Curing:
Air curing per manufacturer’s specification on Data Sheets

Dry Film Thickness:
Desired minimum thickness of all topcoat coatings is 3-6 mils.

DFT Test Results (in mils)

System	Primer Avg. DFT	Intermediate Avg. DFT	Topcoat Avg. DFT	Total Avg. DFT
A	8.80 [1]	3.15	6.55 [3]	18.50
B	3.50	2.90 [2]	3.10	9.50
C	7.35 [1]	2.90 [2]	3.75	14.00
D	5.50	5.75	5.00	16.25

Sandblasting performed to SSPC-SP10/NACE 2, Near White Metal Blast or better

Compressed air checked in accordance with ASTM D 4285

Solvent Cleaning performed per SSPC- SP 1.

DFT measurements were made according to SSPC-PA 2, using a Fischer Dualscope MP20, Number 092-20338A, with a Certification Date of 06/20/2011

Notes added after Boyd reporting:
1. Primers for systems A and B are thicker than specification of 2-5.
2. Intermediate coat DFT's for paint system B and C are lower than the recommended range of 3-10.
3. Topcoat for paint system A is slightly higher than the specified range of 3-6.

11.3 Appendix C: Paint wetting and contact angle measurements on Type B panels

Appendix C.1 G0m substrate

Paint wetting and contact angle measurements on Type B panels with G0m zinc surface.

The G0m panels are 4”x6’ flat steel panels Galvanized (G in “G0m” stands for galvanizing), profiled and painted on the same day (0 in “G0m” stands for zero delay between galvanizing and profiling/painting), and the zinc coated surface was mechanically roughened by abrasive grinding disk (m in “G0m” stands for mechanical surface profiling).

Both the type A and the type B panels were galvanized and mechanically roughened in the same process by Duncan Galvanizing in Everett, MA. The galvanizing and mechanical profiling processes were completed early in the morning on a workday at Duncan Galvanizing. We then took the mechanically profiled test panels to Boyd Research Co at Hudson MA to perform the contact angle tests on the Type B panels and at the same time spray-paint the Type A panels.

At Boyd Coatings Research, 4 different epoxy paint systems (NEPCOAT list) were mixed and sweat-in according to the paint manufacturer’s specification. After the sweat-in time (from 0 to 30 minutes depending on the paint) samples of the mixed paint liquid were taken for contact angle measurements. The same batch of the mixed paint was spray painted on the Type B panels with the same G0m surfaces. The painting and the contact angle measurements were performed at about the same time (within 30 minutes) under approximately the same indoor condition.

The images of the droplets of the paints on the panel surface were recorded as a function of time and were analyzed with “DROP” analysis software using a Ramé-Hart Model 200 goniometer (made by Ramé-Hart Instrument Co., Succasunna, NJ). The contact angle θ, the height h of the droplet, and the width d (or the diameter) of the droplet-to-surface of the contacting interface were recorded as a function of time t after the initial drop-to-surface contact. For some samples, the images were stored as a function of time.

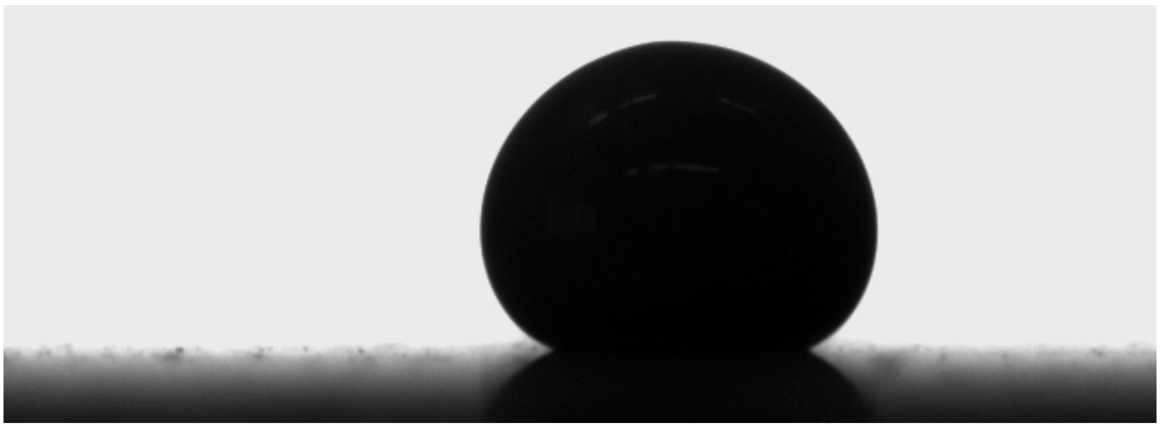
In the following charts we display the contact angle θ vs. t curve with the value of the angle (in degree) marked on the left vertical axis. The other droplet shape parameters are displayed with the values marked on the right vertical axis. The parameters include the height of the droplet h (in millimeter, mm), the width d (in mm) and the computed volume V (in micro liter, μL).

Some selected images of the droplets on the G0m surface were included to give a visual impression of the changes of droplet shape.

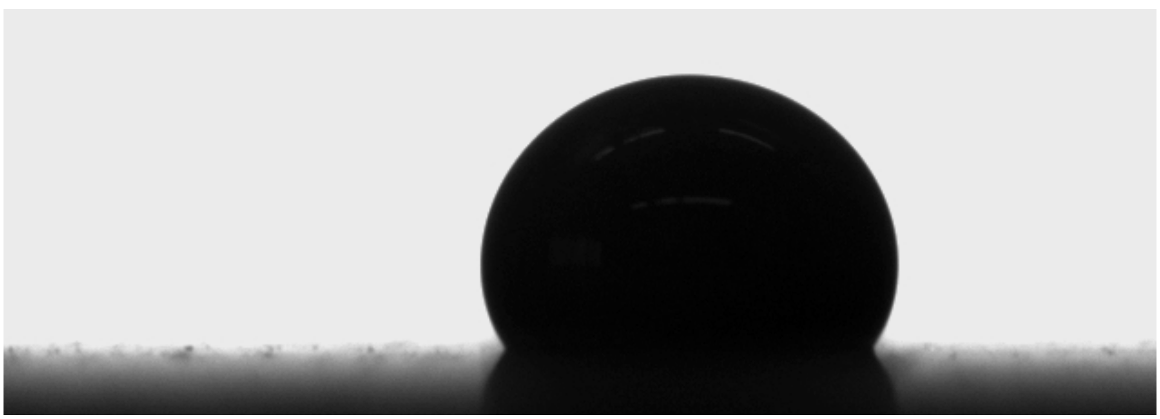
a. Test panel subgroup G0m-C

Panel surface: galvanizing followed by mechanical profiling
Paint formulation: Carboline 888 Epoxy

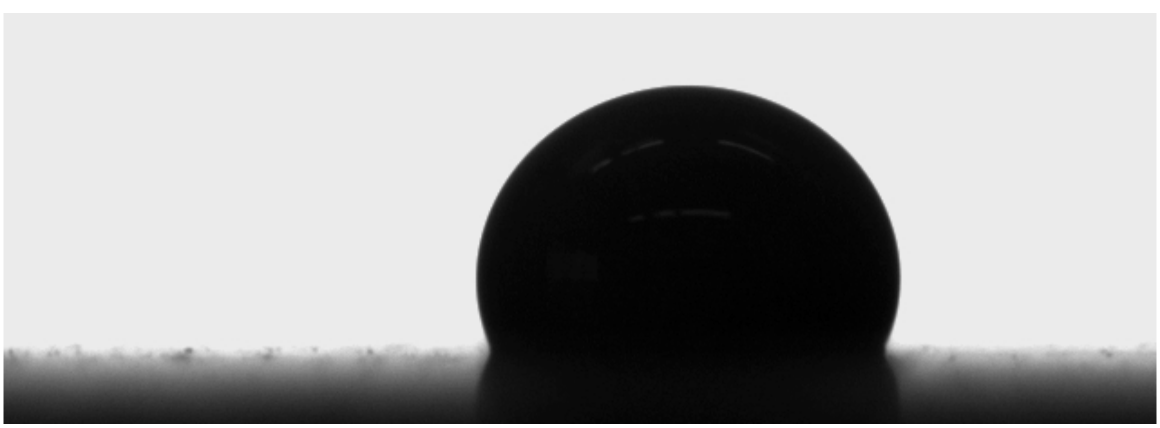
The following figures show the image of trial 1 droplet of paint C as a function of time after contact with the G0m surface. The paint droplet C did not wet G0m surface initially and was spreading slowly.



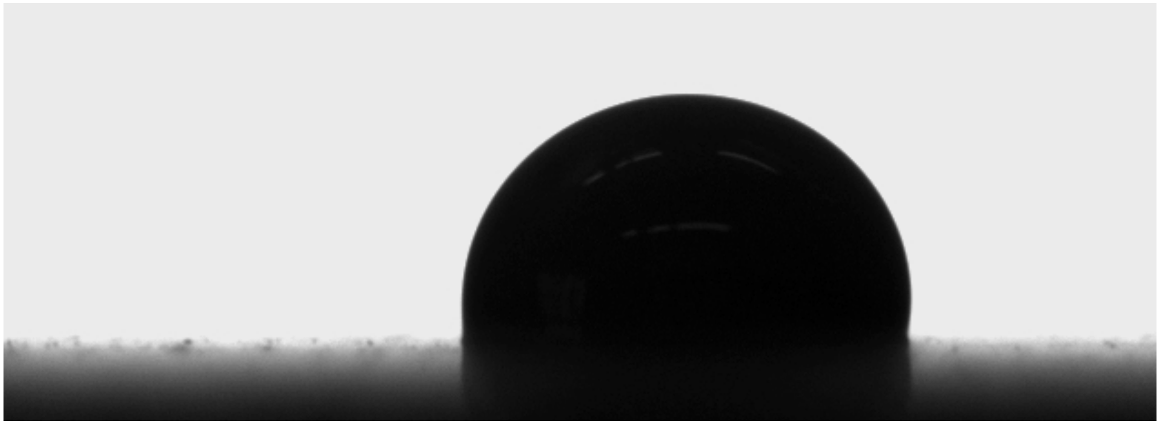
Paint C droplet on G0m surface, Trial 1, t=0 sec., contact angle = 151°.



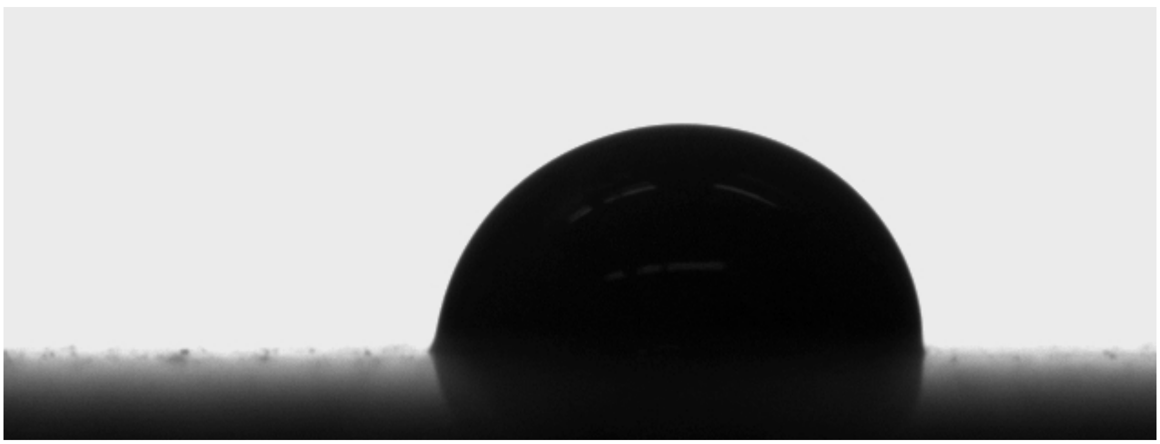
Paint C droplet on G0m surface, Trial 1, t=3 sec, contact angle = 121°



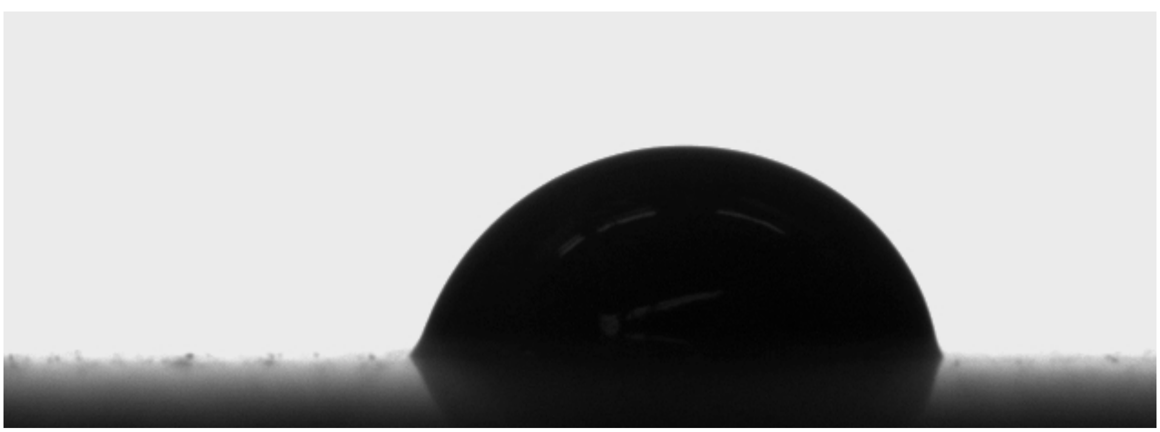
Paint C droplet on G0m surface, Trial 1, t=6 sec, contact angle = 114°.



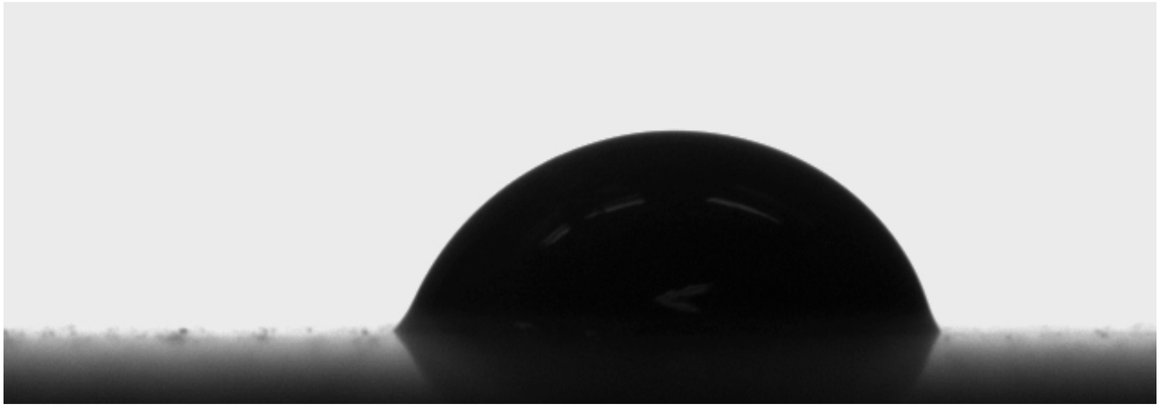
Paint C droplet on G0m surface, Trial 1, t=9 sec, Contact angle = 107°.



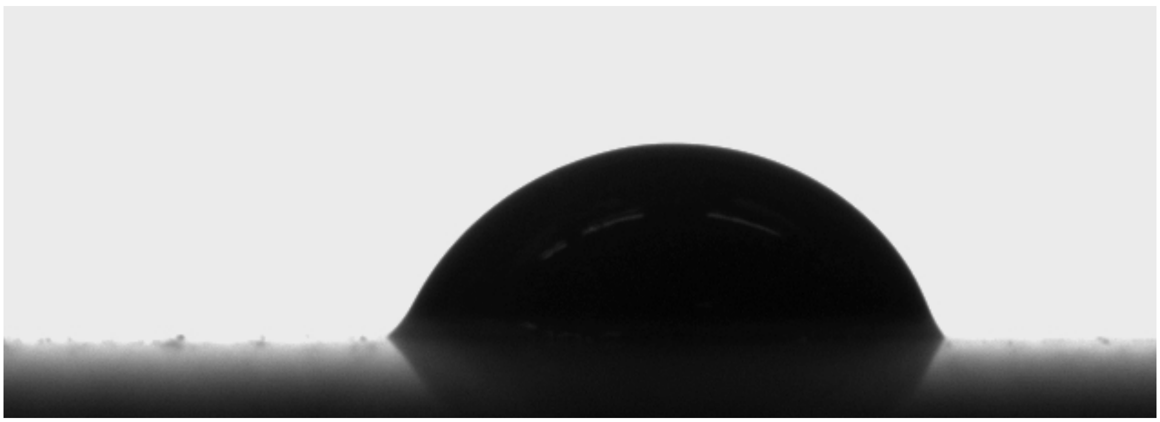
Paint C droplet on G0m surface, Trial 1, t=30 sec, contact angle = 88°.



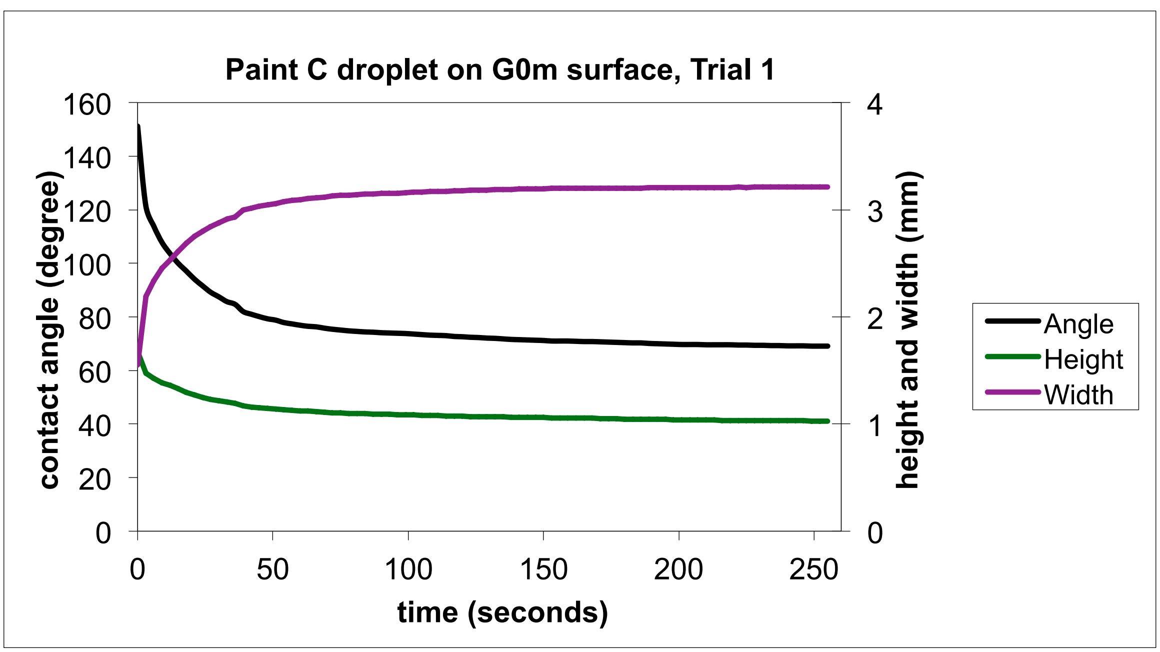
Paint C droplet on G0m surface, Trial 1, t=60 sec, contact angle = 77°



Paint C droplet on G0m surface, Trial 1, t=120 sec, contact angle = 73°

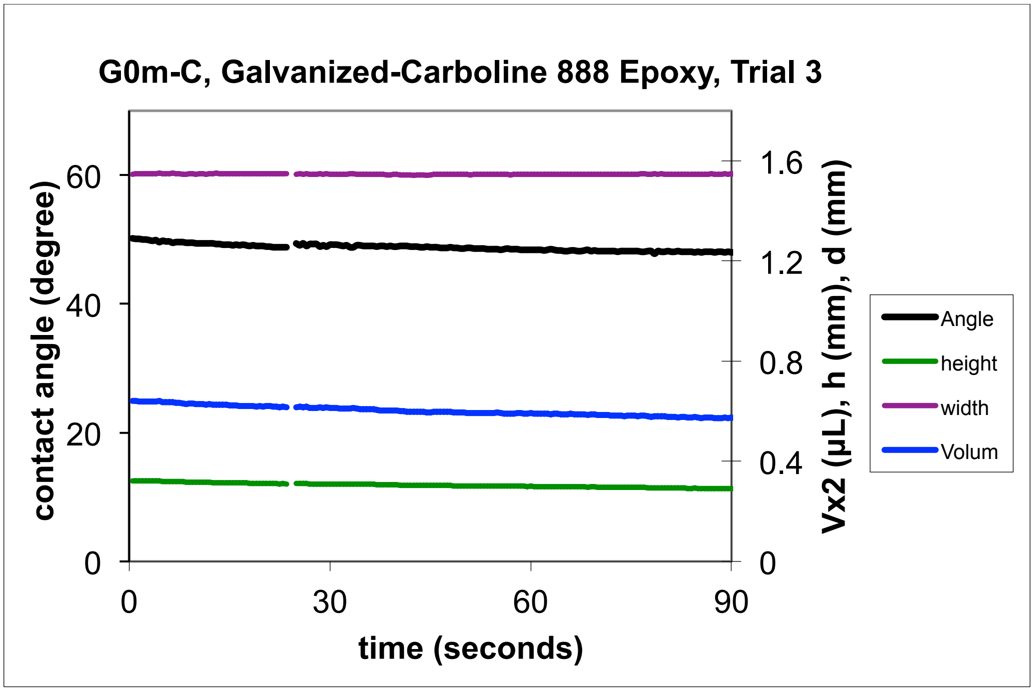


Paint C droplet on G0m surface, Trial 1, t=240 sec, contact angle = 69°



Paint C droplet on G0m surface, Trial 1, Contact angle, height and width of the droplet is plotted as a function of time. The contact angle at t = 6 sec is 114° .

Trial 2 was a calibration test. It is not relevant to this appendix.



Paint C droplet on G0m surface, Trial 3, Contact angle, height and width of the droplet is plotted as a function of time. The contact angle at t = 6 sec is 50°.

Average contact angle for G0m-C interface is $\theta_{Avg} = 82^0$

From Appendix E, the average value of the G0m-C pull-off strength is 1372 $\pm$ 256 psi.

b. Test panel subgroup G0m-I

Panel Surface: Thermal sprayed zinc metallizing coating
Paint : Intergard 345 Epoxy

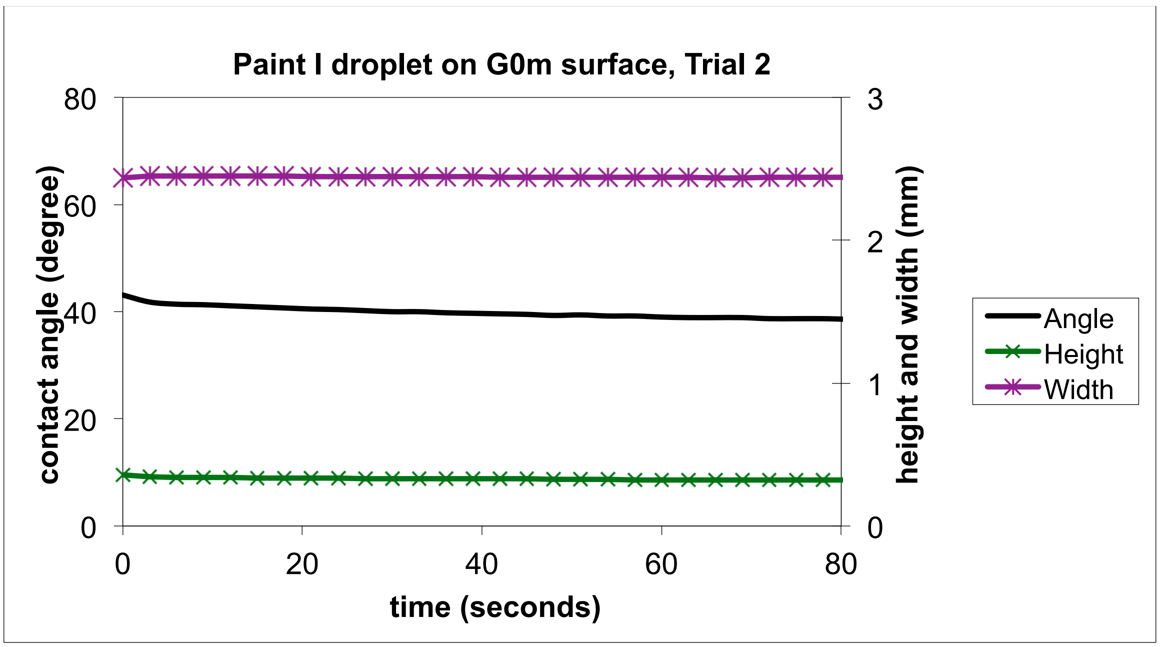
Image of paint I droplets on the G0m surface, trial 2.

Paint I droplet on G0m surface trial 2 at t = 0 second, contact angle = 43°

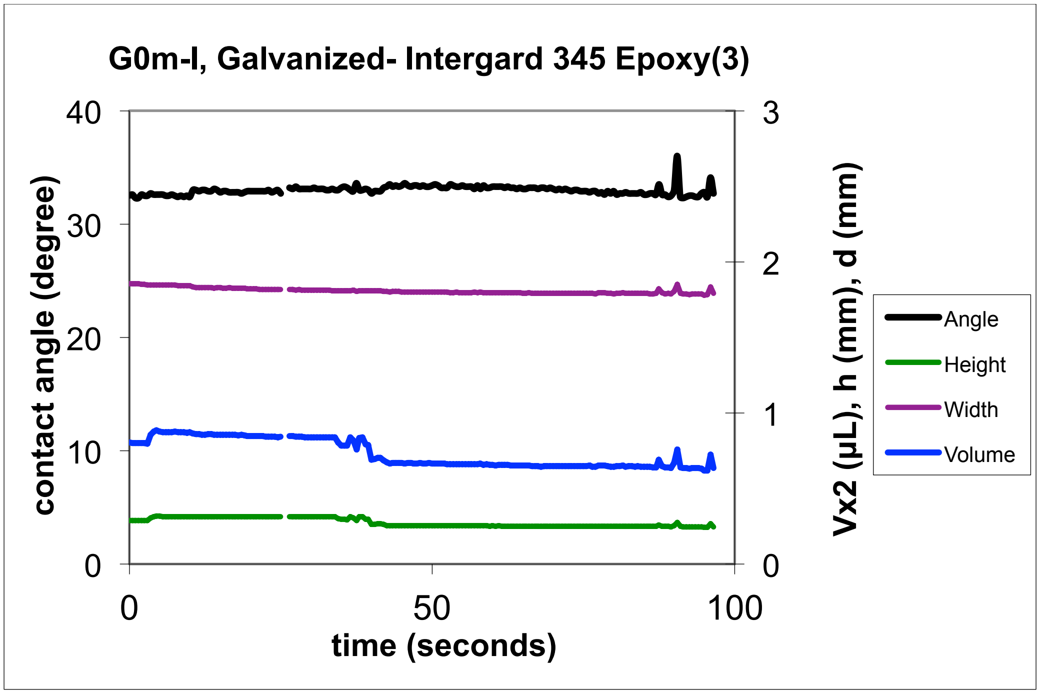
Paint I droplet on G0m surface trial 2 at t = 3 second, contact angle = 42°

Paint I droplet on G0m surface trial 2 at t = 6 sec, contact angle = 40°

Paint I droplet on G0m surface trial 2 at t = 30 sec, contact angle = 40° Contact angle at t = 5 sec is 41° ,



Paint I liquid droplet on G0m surface, contact angle, height and width of the droplet as a function of time after initial contact.



Paint I droplet on G0m-I surface, contact angle at t = 5 sec is 32°,

Average contact angle for G0m-I interfaces: θ_{Avg} = 36°
From Appendix E, the pull-off strength of G0m-I test panels is 2525 ± 338 psi.

c. Test panel subgroup G0m-S1

Panel Surface: Thermal sprayed zinc metallizing coating

Paint: Macropoxy 646 Fast Cure Epoxy

The following figures show the time sequence of the images of a droplet of paint S1 on the G0m surface.

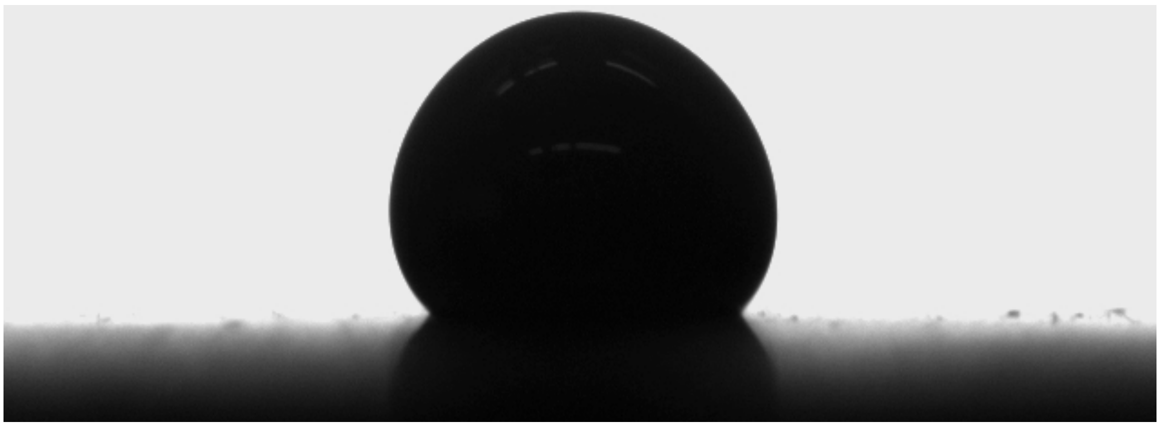


Image of a droplet of liquid paint S1 at the initial contact (t =0) with the G0m surface, trial 1. Contact angle θ = 133°.

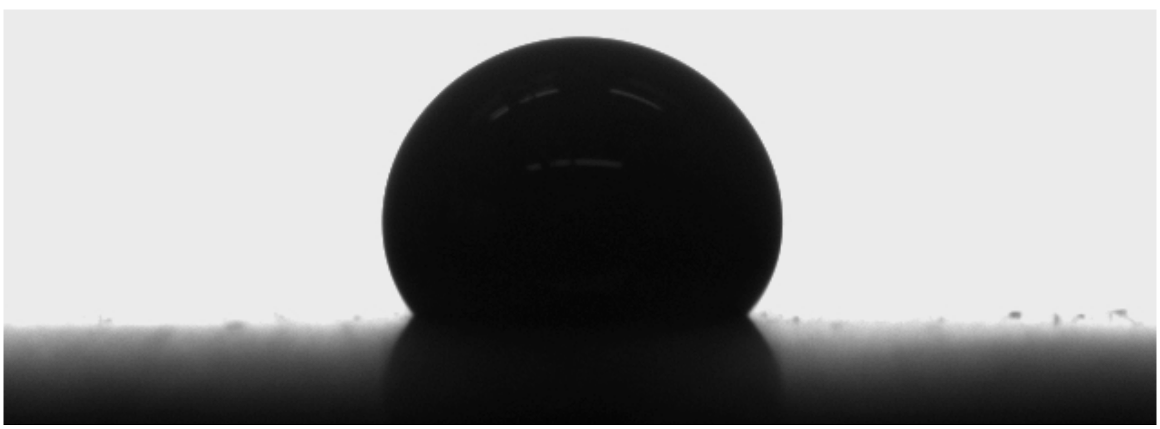


Image of a droplet of liquid paint S1 on the G0m surface, trial 1 t = 3 sec. Contact angle θ = 129°.

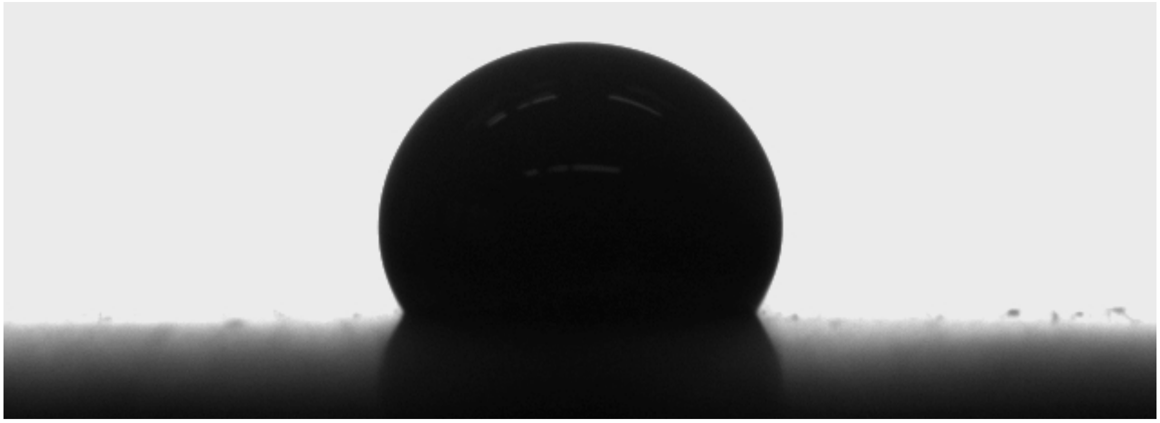


Image of a droplet of liquid paint S1 on the G0m surface, trial 1 t = 6 sec. Contact angle θ = 123°.

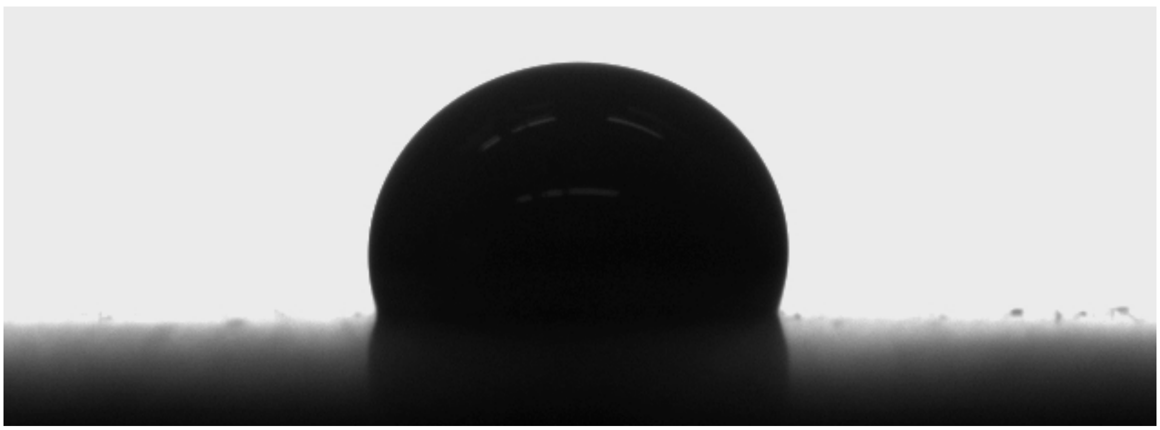


Image of a droplet of liquid paint S1 on the G0m surface, trial 1 t = 6 sec. Contact angle θ = 109°.

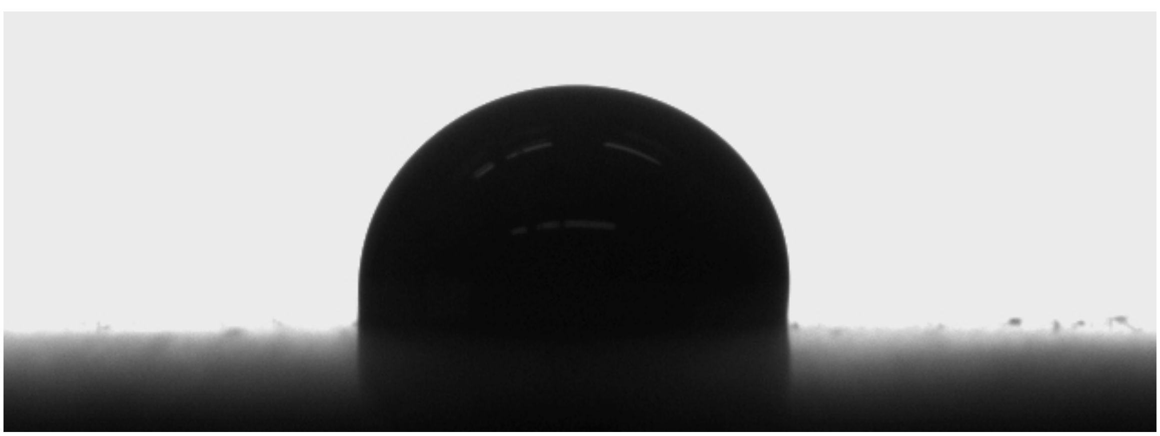
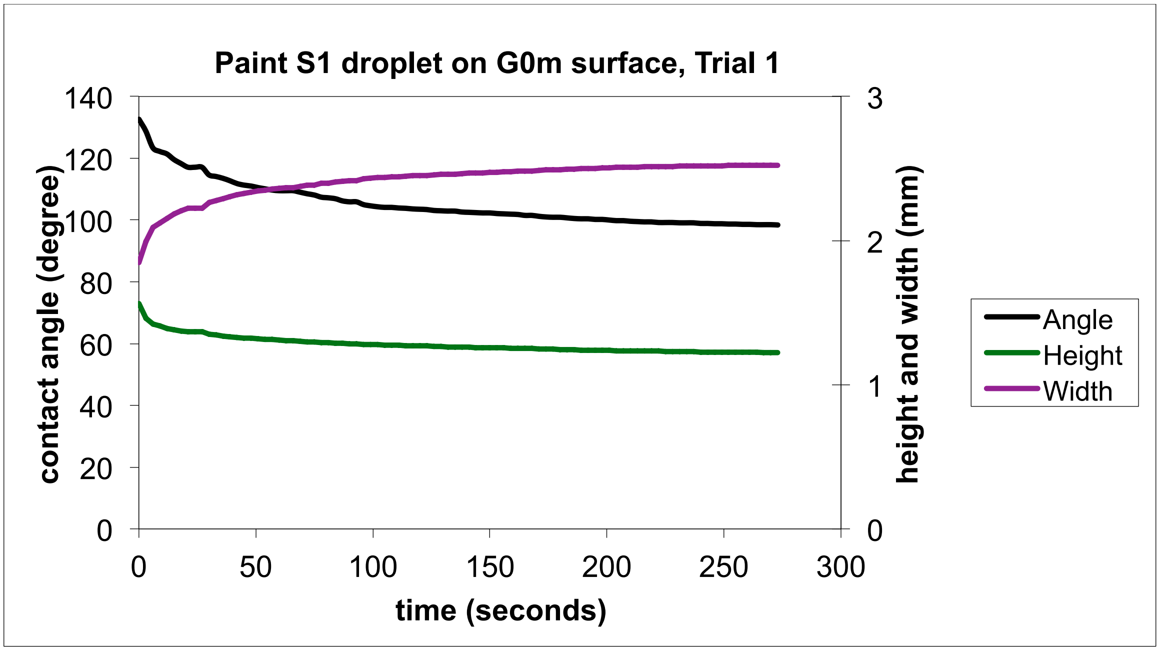
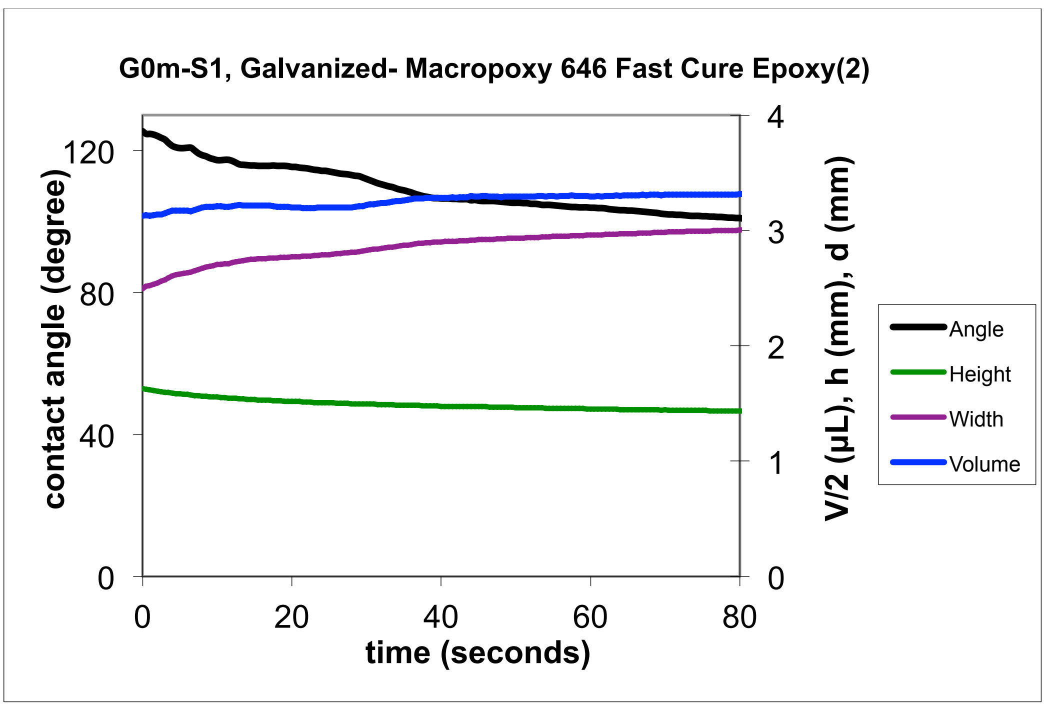


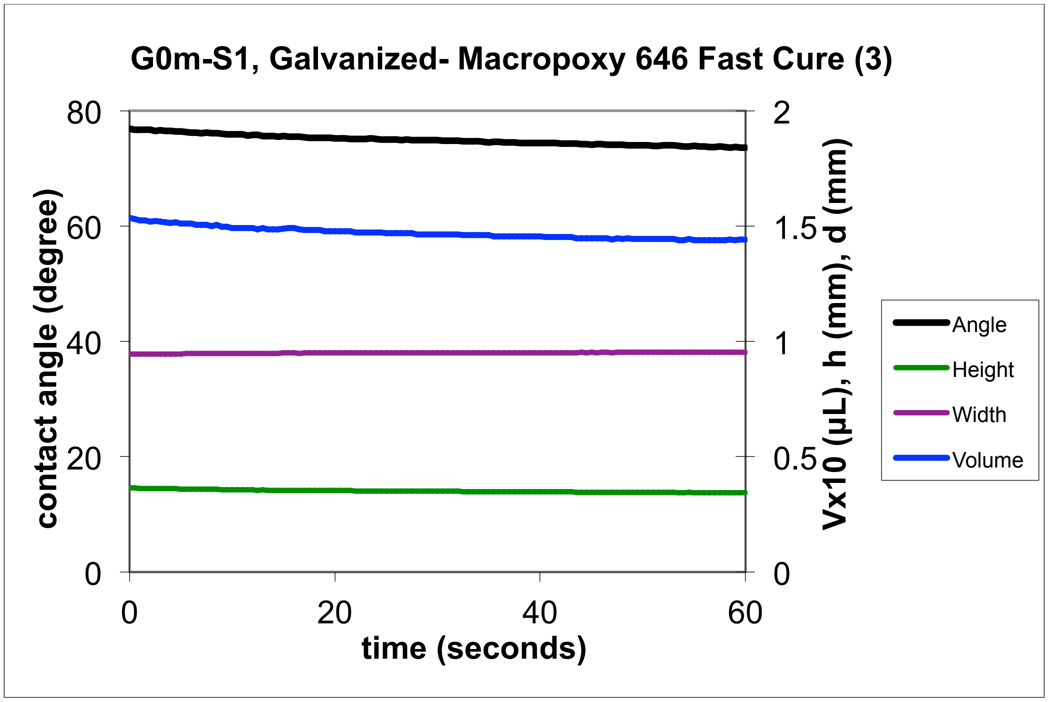
Image of a droplet of liquid paint S1 on the G0m surface, trial 1 t = 240 sec. Contact angle θ = 99°



Paint S1 liquid droplet on G0m surface, trial 1, contact angle, height and width of the droplet as a function of time after initial contact. At t = 6 second, the contact angle θ = 123°.



Paint S1 liquid droplet on G0m surface, trial 2, contact angle, height and width of the droplet as a function of time after initial contact. At t = 6 second, the contact angle θ = 121°.



Paint S1 liquid droplet on G0m surface, trial 3, contact angle, height and width of the droplet as a function of time after initial contact. At t = 6 second, the contact angle θ = 76°.

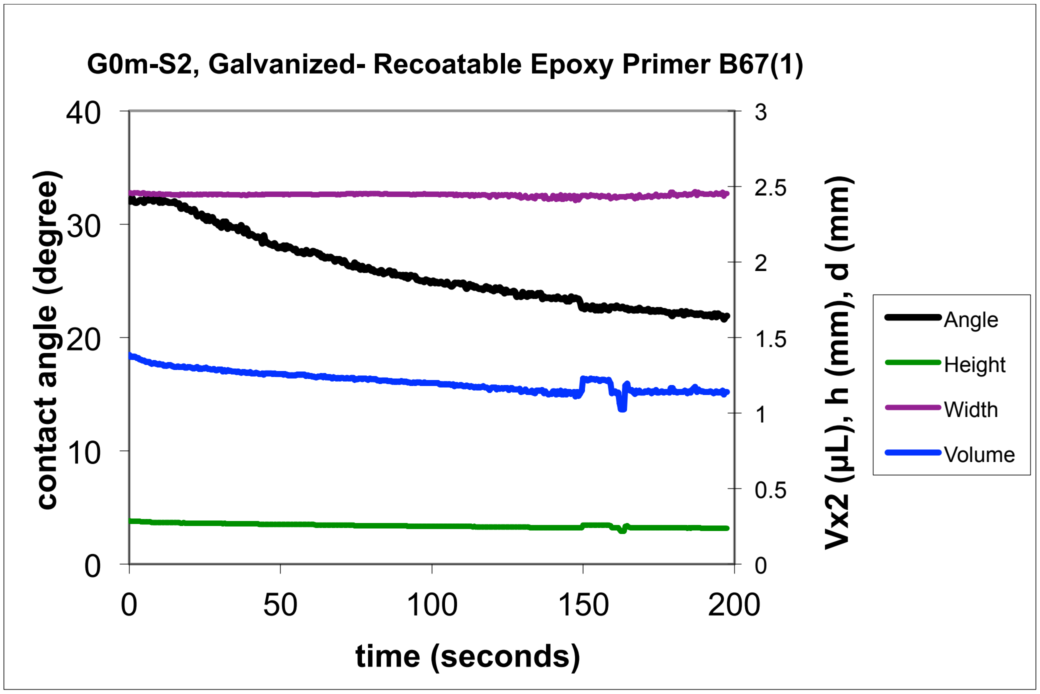
Average contact angle for G0m-S1 surface: θ =106°

From Appendix E, the pull-off strength of G0m-S1 is 1650 ± 350 psi.

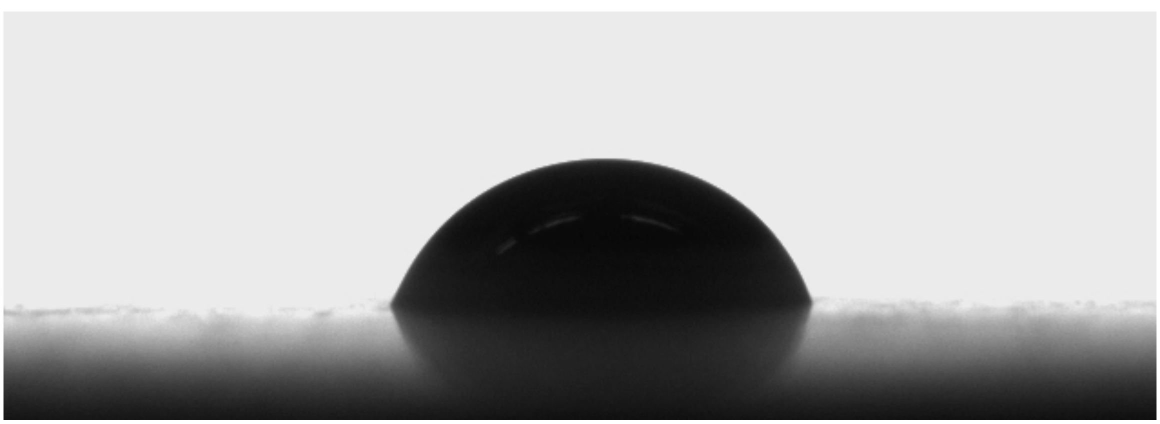
d. Test panel subgroup G0m-S2

Panel Surface: Thermal sprayed zinc metallizing coating

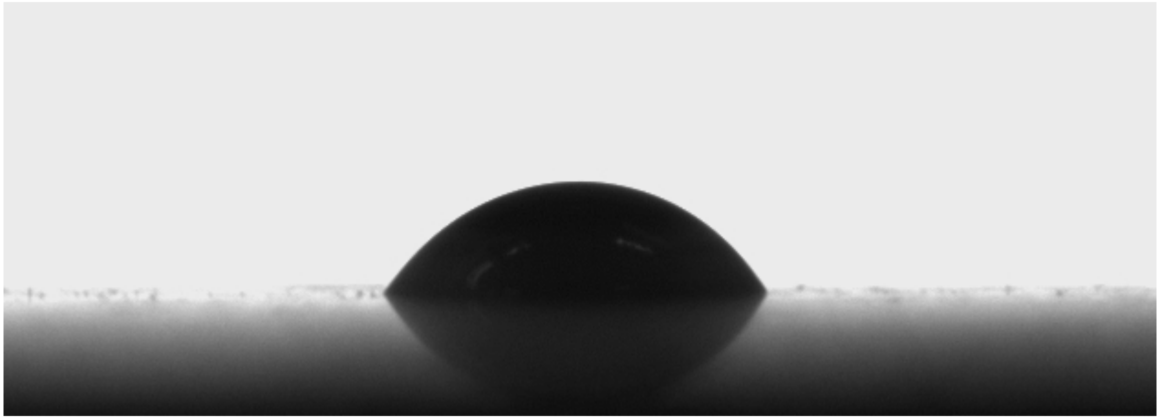
Paint: Recoatable Epoxy Primer Series B67



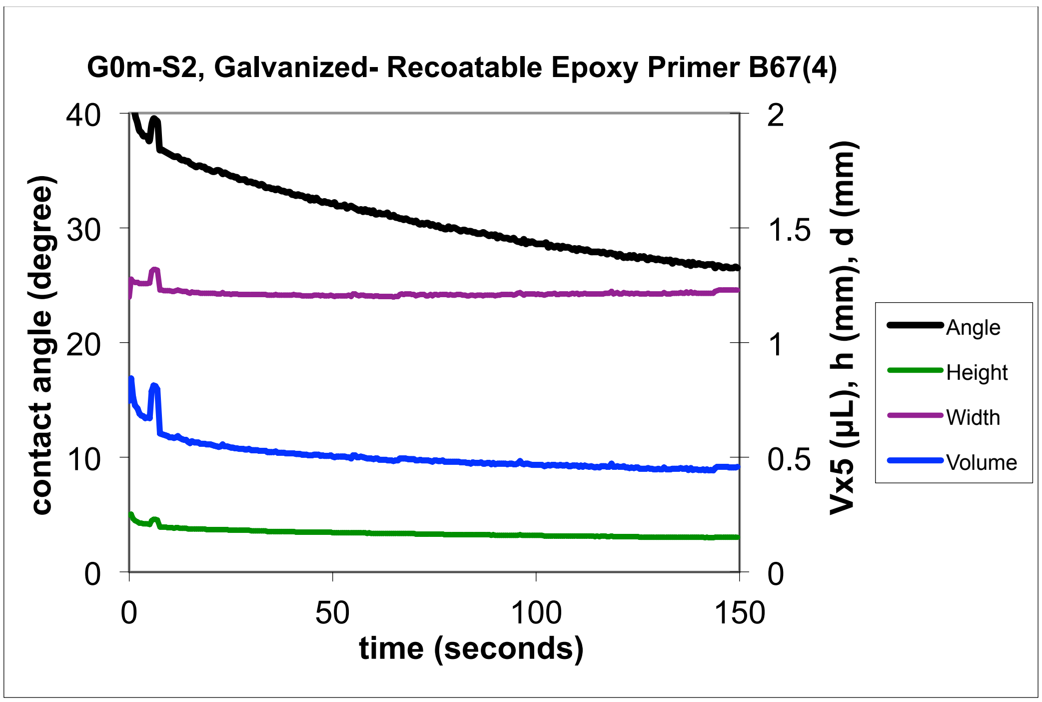
Paint S2 liquid droplet on G0m surface, trial 1, contact angle, height and width of the droplet as a function of time after initial contact. At t = 5 second, the contact angle θ = 32º.



Paint S2 liquid droplet on G0m surface, trial 2, contact angle, height and width of the droplet as a function of time after initial contact. At t = 5 second, the contact angle θ = 52º



Paint S2 liquid droplet on G0m surface, trial 3, contact angle, height and width of the droplet as a function of time after initial contact. At t = 5 second, the contact angle θ = 46°



Paint S2 liquid droplet on G0m surface, trial 1, contact angle, height and width of the droplet as a function of time after initial contact. At t = 5 second, the contact angle θ = 38°.

Average contact angle for G0m-S2 interfaces: θ = 42°
The pull-off strength for the cured G0m-S2 is 1860 ± 250 psi.

Appendix C

Appendix C.2

Paint wetting and contact angle measurement on Type B panels coated with G0b zinc surface.

The G0b panels are 4”x6’ flat steel panels Galvanized (G in “G0b” stands for galvanizing), profiled and painted on the same day (0 in “G0b” stands for zero delay between galvanizing and profiling/painting), and blast profiled (b in “G0b” stands for blast profiling).

Both the type A and the type B panels were galvanized and blast profiled the zinc surface in the same batch process by V&S Galvanizing in Taunton, MA. The blast profiling work was completed early in the morning on a workday at V&S. We then took the blast profiled test panels to Boyd Research Co at Hudson MA to perform the contact angle tests on the Type B panels and at the same time spray-paint the Type A panels.

At Boyd Coatings Research, 4 different epoxy paint systems (NEPCOAT list) were mixed and sweat-in according to the paint manufacturer’s specification. After the sweat-in time (from 0 to 30 minutes depending on the paint) samples of the mixed paint liquid were taken for contact angle measurements. The same batch of the mixed paint was spray painted on the Type B panels with the same Gob surfaces. The painting and the contact angle measurements were performed at about the same time (within 30 minutes) under approximately the same indoor condition.

The images of the droplets of the paints on the panel surface were recorded as a function of time and were analyzed with “DROP” analysis software using a Ramé-Hart Model 200 goniometer (made by Ramé-Hart Instrument Co., Succasunna, NJ). The contact angle θ, the height h of the droplet, and the width d (or the diameter) of the droplet-to-surface of the contacting interface were recorded as a function of time t after the initial drop-to-surface contact. For some samples, the images were stored as a function of time.

In the following charts we display the contact angle θ vs. t curve with the value of the angle (in degree) marked on the left vertical axis. The other droplet shape parameters are displayed with the values marked on the right vertical axis. The parameters include the height of the droplet h (in millimeter, mm), the width d (in mm) and the computed volume V (in micro liter, μL).

Some selected images of the droplets on the G0b surface were included to give a visual impression of the changes of droplet shape.

a. Test panel subgroup G0b-C

Panel surface: galvanizing followed by blast surface profiling
Paint: Carboline 888 Epoxy

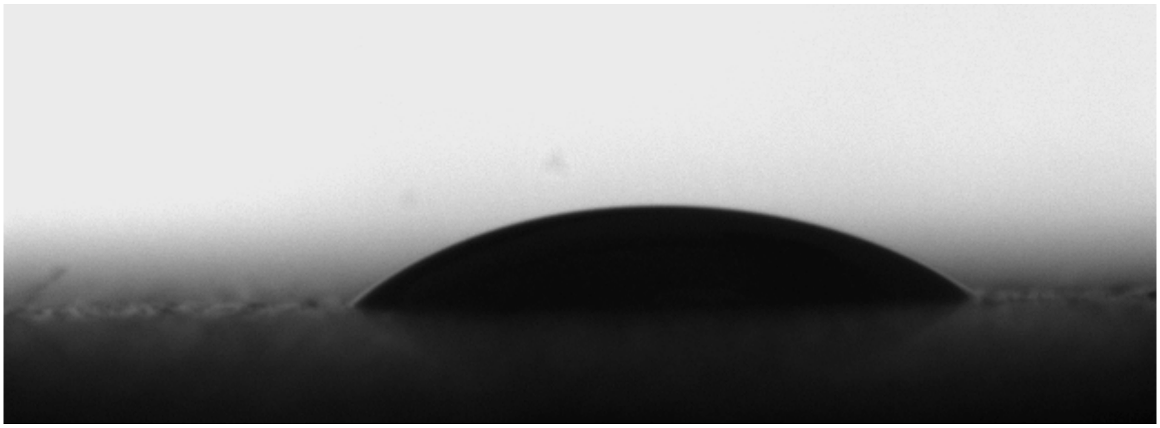
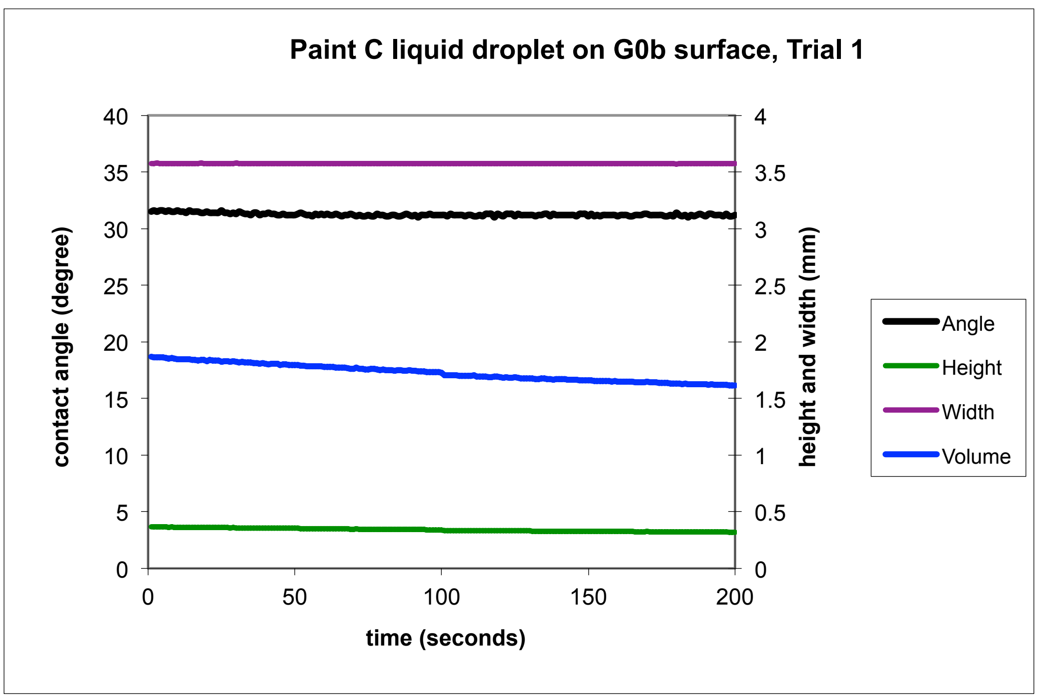
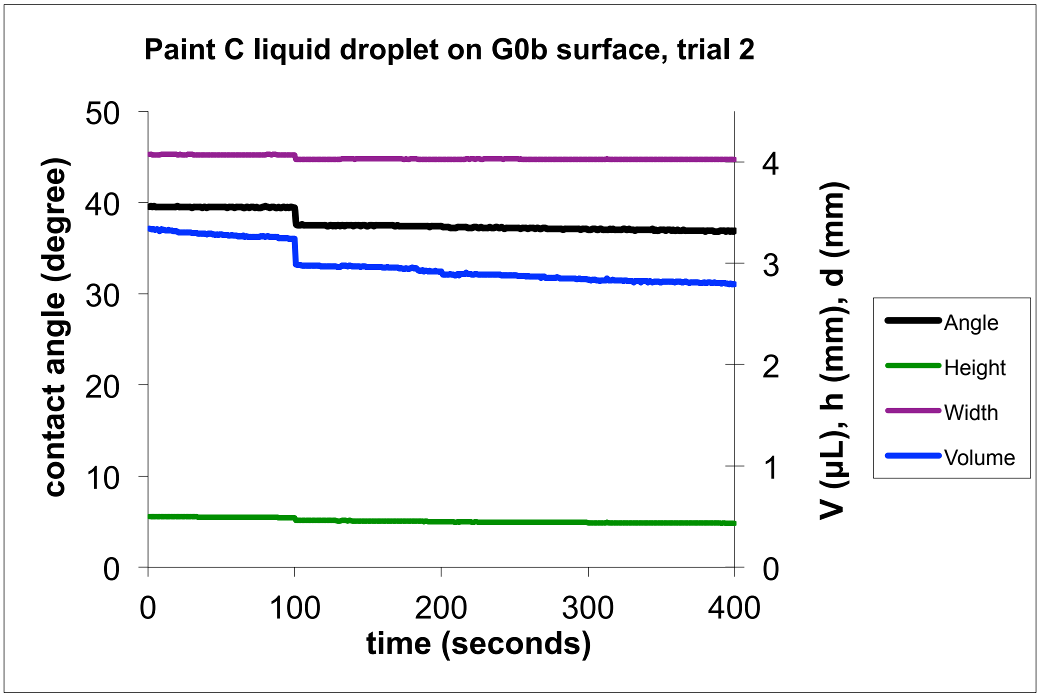


Image of liquid paint C droplet on G0b surface, trial 1 at t = 6 sec, contact angle = 32°



Paint C liquid droplet on G0b surface, trial 1, contact angle, height, width and volume of the droplet as a function of time. The contact angle at t = 6 sec is 32°



Paint C liquid droplet on G0b surface, trial 2, contact angle, height, width and volume of the droplet as a function of time. The contact angle at t = 5 sec is 40°.

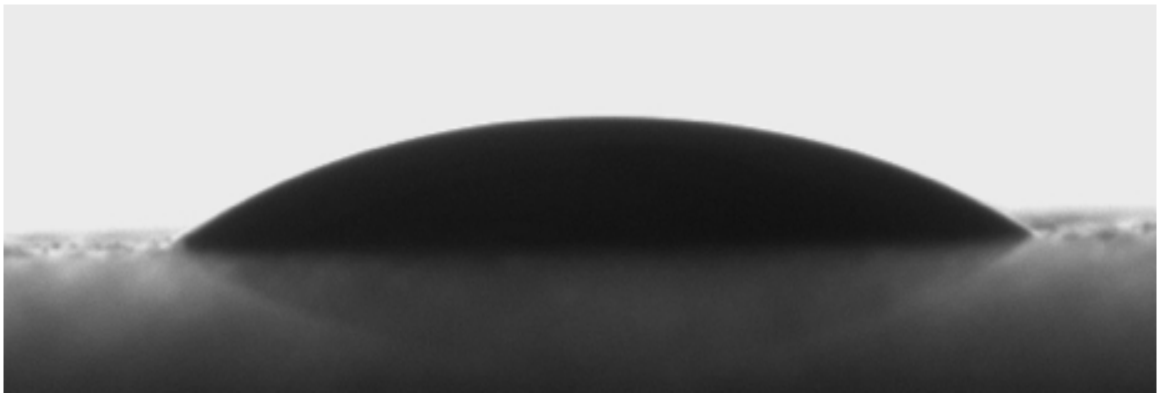
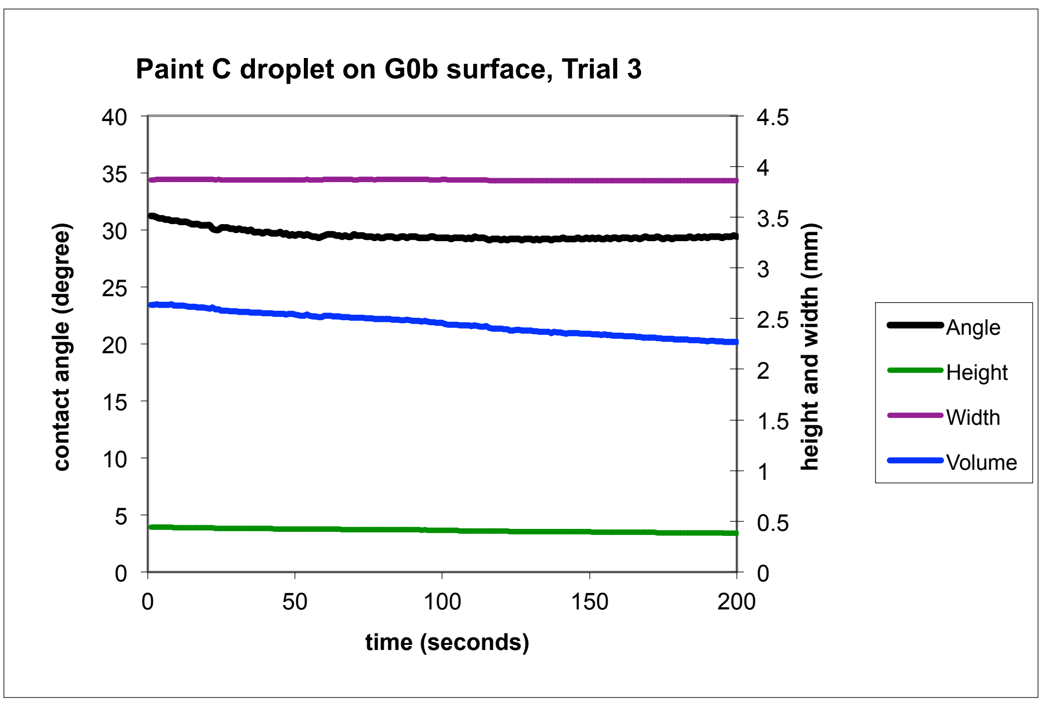


Image of a droplet of paint C on Galvanized and blast profiled zinc surface, Trial 3, at t = 5 sec., contact angle = 31°.



Paint C liquid droplet on G0b surface, trial 3, contact angle, height, width and volume of the droplet as a function of time. The contact angle at t = 5 sec is 31°.

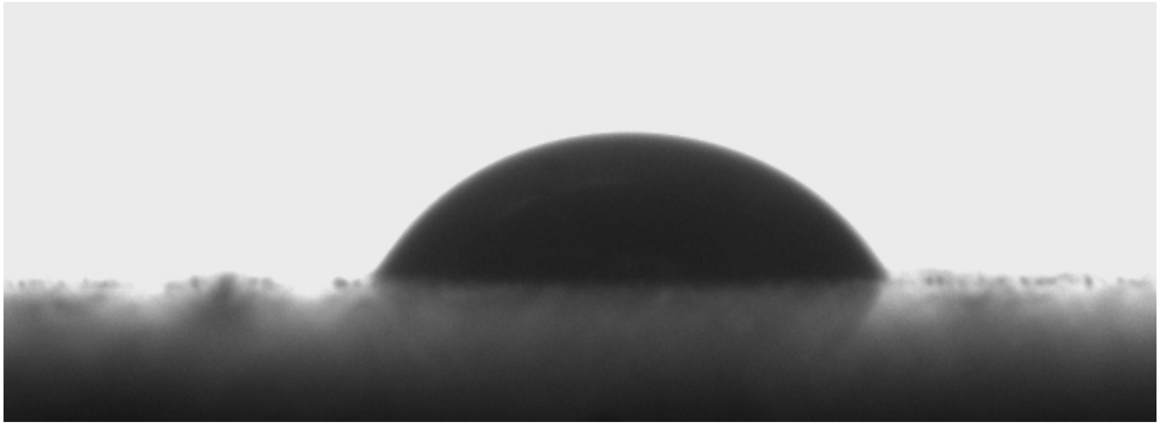
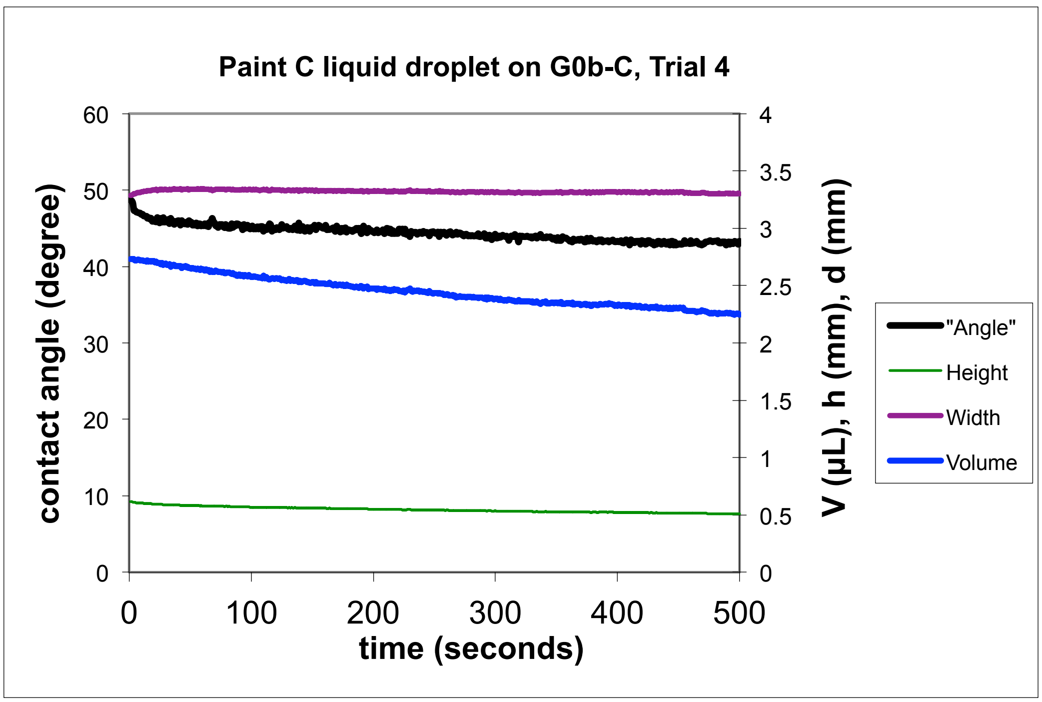


Image of a droplet of paint C on Galvanized and blast profiled zinc surface, Trial 4, at t = 5 sec, contact angle = 47^o



Paint C liquid droplet on G0b surface, trial 3, contact angle, height, width and volume of the droplet as a function of time. The contact angle at t = 5 sec is 47^o.

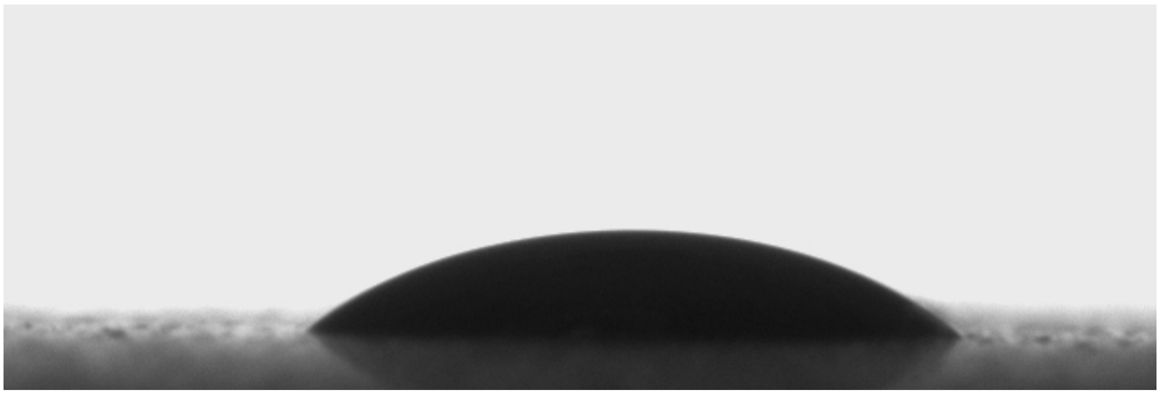
Summary of the contact angle measurements for G0b-C interface:

Average contact angle for the G0b-C surface, θ_{Avg} = 37^o
Average (of 8 samples) pull-off strength for G0b-C is 2040 ± 250 psi.

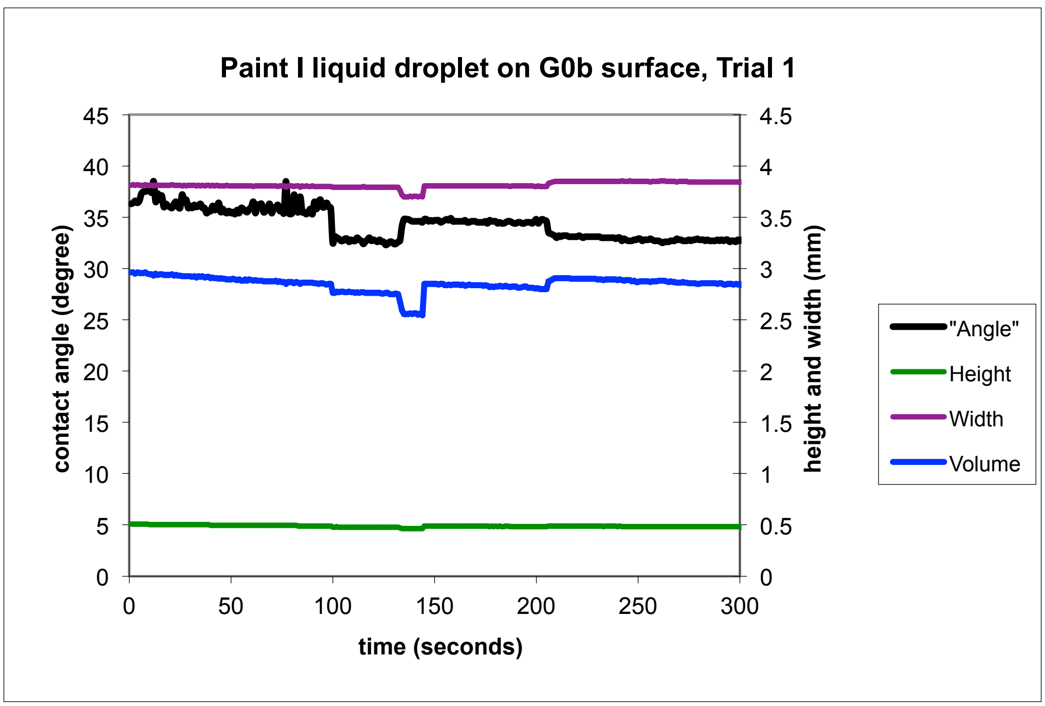
b. Test panel subgroup G0b-I

Panel surface: galvanizing followed by blast surface profiling

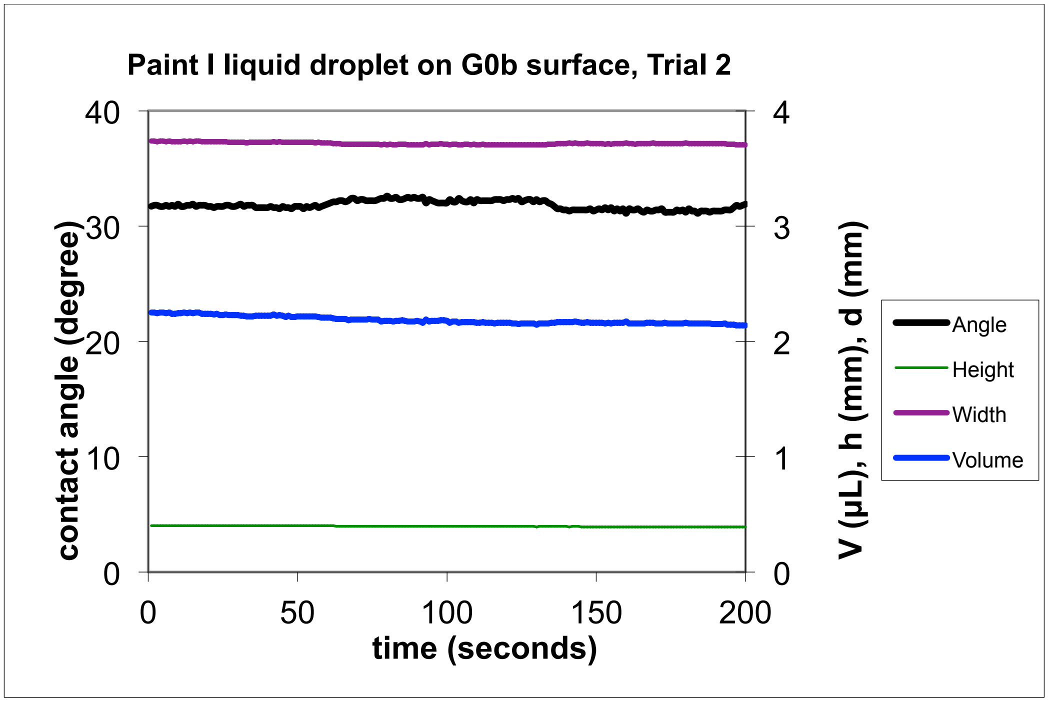
Paint: Intergard 345 Epoxy



Paint I liquid droplet on G0b surface, trial 1 image at t = 6 sec, contact angle = 37º.



Paint I liquid droplet on G0b surface, trial 1. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=37º at t =5 sec.



Paint I liquid droplet on G0b surface, trial 2. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=32° at t =5 sec.

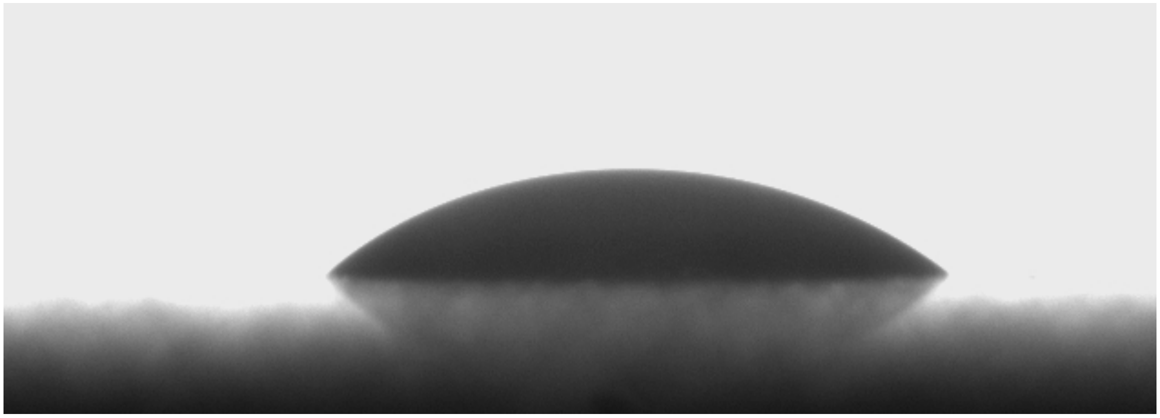
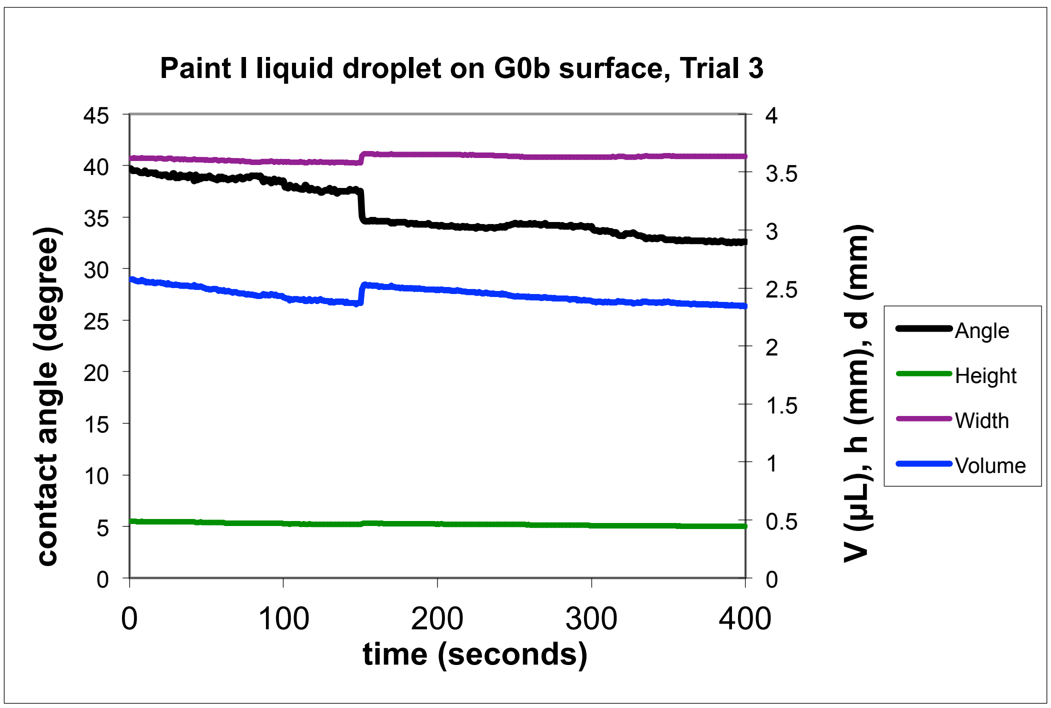


Image of Paint I liquid droplet on G0b surface, trial 3, contact angle θ=40º at t =5 sec.



Paint I liquid droplet on G0b surface, trial 3. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=40º at t =5 sec.

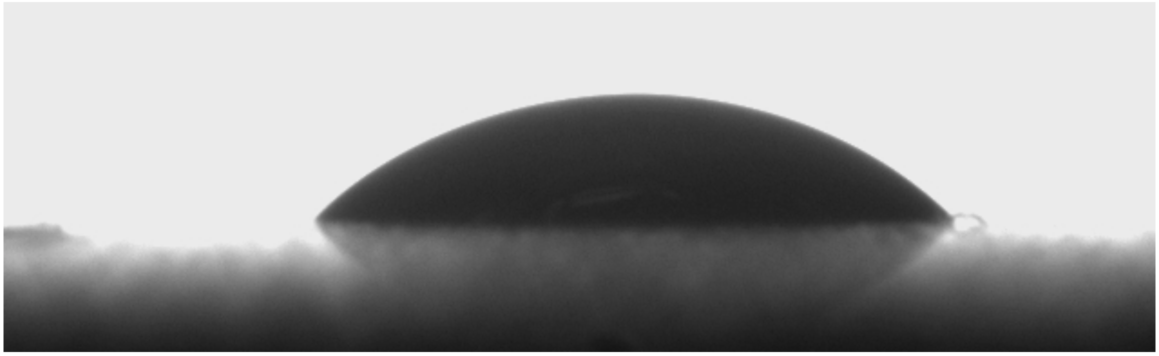
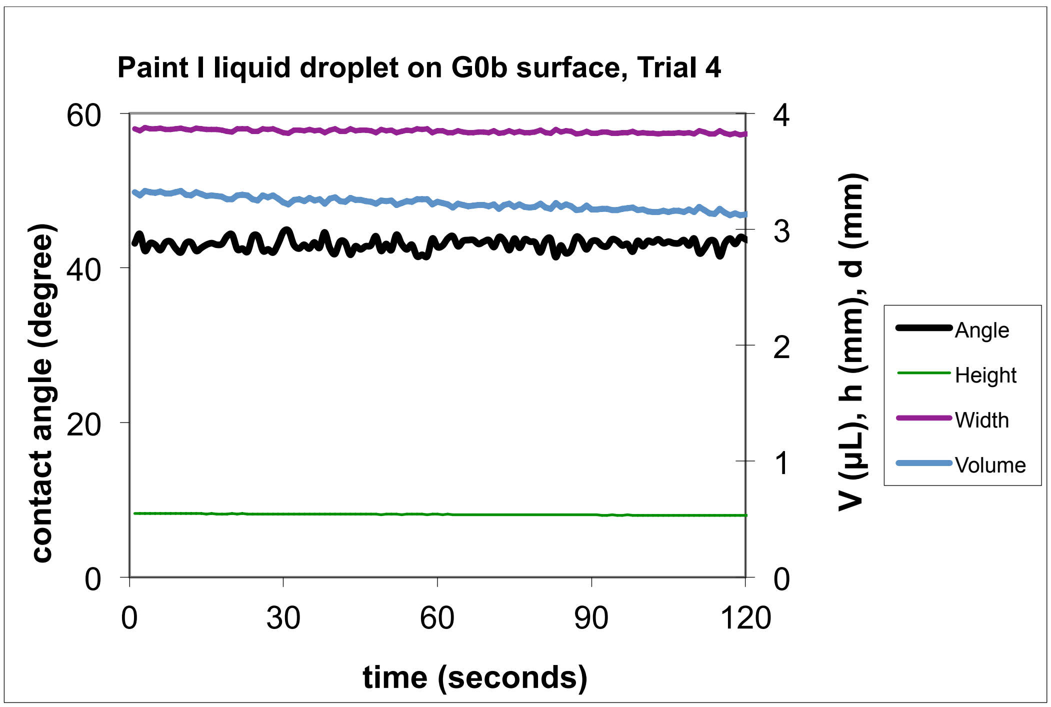


Image of Paint I liquid droplet on G0b surface, trial 4, contact angle θ=43° at t =5 sec.



Paint I liquid droplet on G0b surface, trial 4. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=43° at t =5 sec.

Summary of contact angles for G0b-I interface:
Average contact angle θ_{Avg} = 37°
From Appendix E: Average pull-off strength = 1940 ± 580 psi

c. **Test panel subgroup G0b-S1**

Metal surface: galvanizing followed by (with no delay) blast surface profiling
Paint: Macropoxy 646 Fast Cure Epoxy

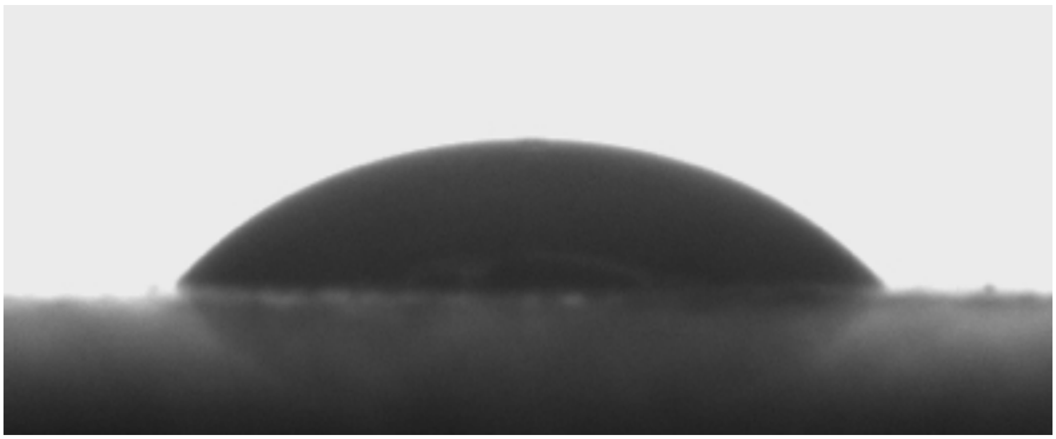
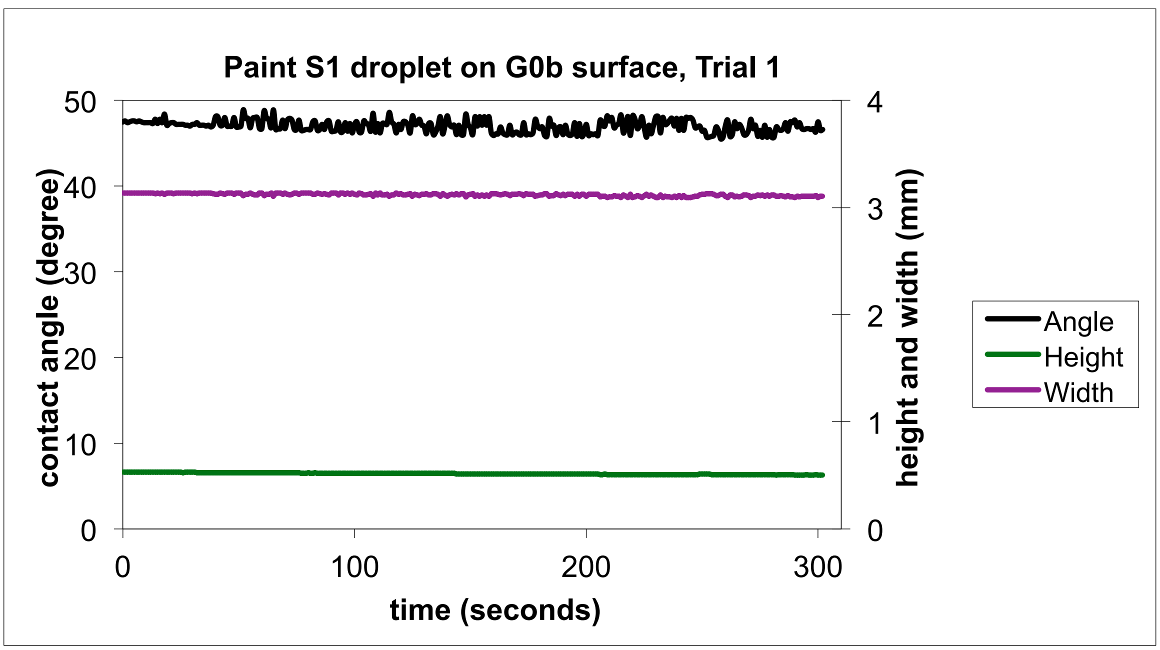
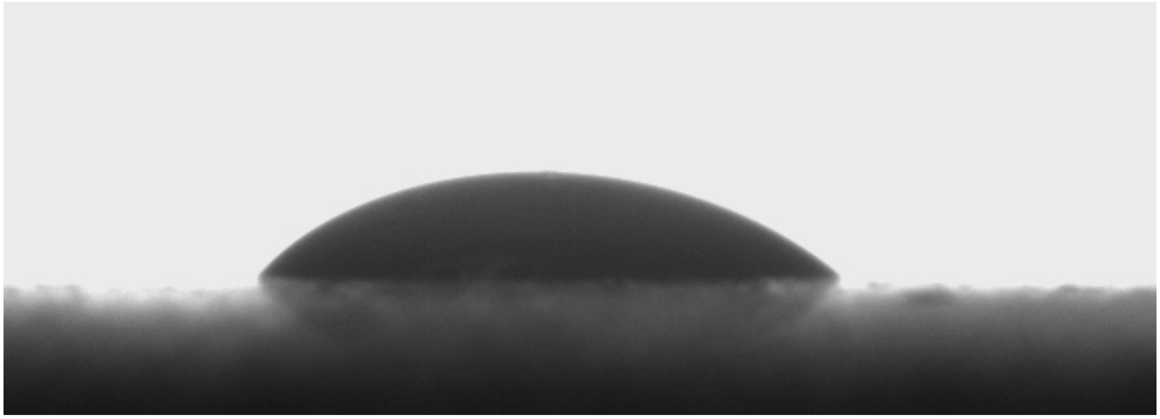


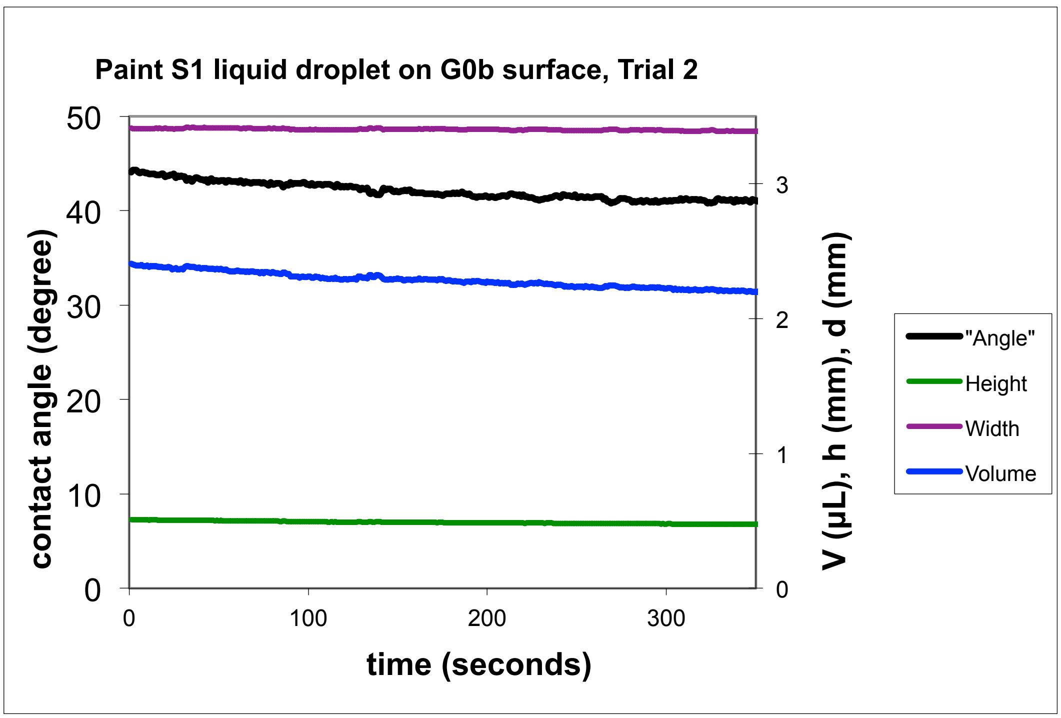
Image of a droplet of S1 paint on Galvanized and blast profiled zinc Trial 1 surface at t = 5 sec, contact angle = 48^o.



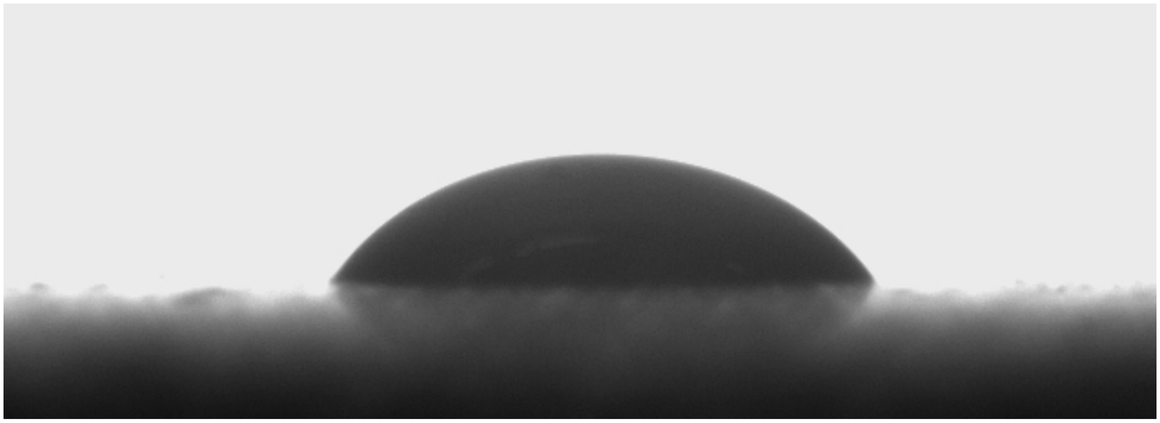
Paint S1 liquid droplet on G0b surface, trial 1. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=48^o at t =5 sec.



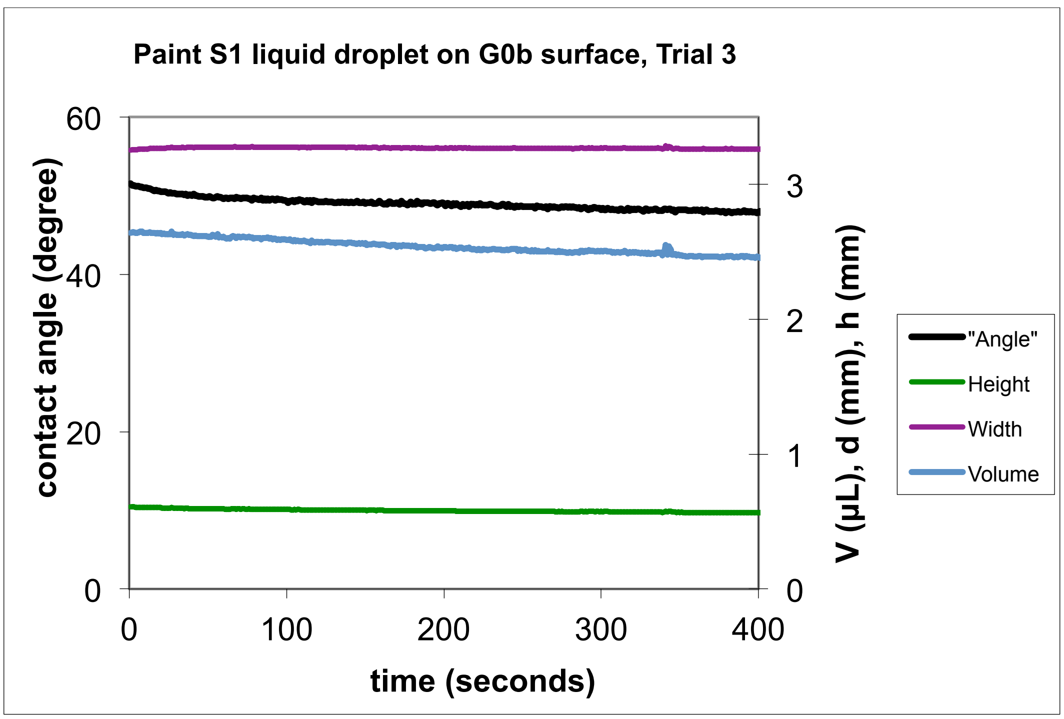
Paint S1 liquid droplet on G0b surface at t = 5 sec, trial 2, contact angle = 44°.



Paint S1 liquid droplet on G0b surface, trial 2. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=44° at t =5 sec.



Paint S1 droplet on G0b surface, trial 3, contact angle (at t = 5 sec) = 51º.



Paint S1 liquid droplet on G0b surface, trial 3. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=51º at t =5 sec.

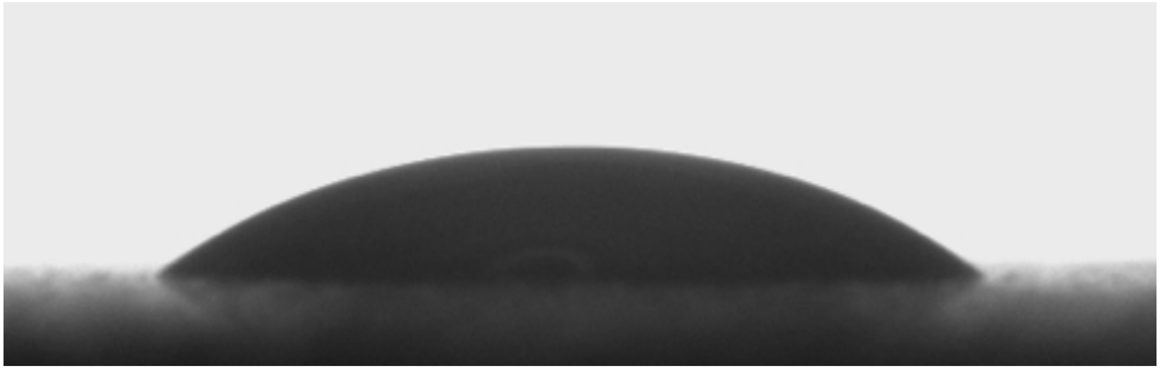
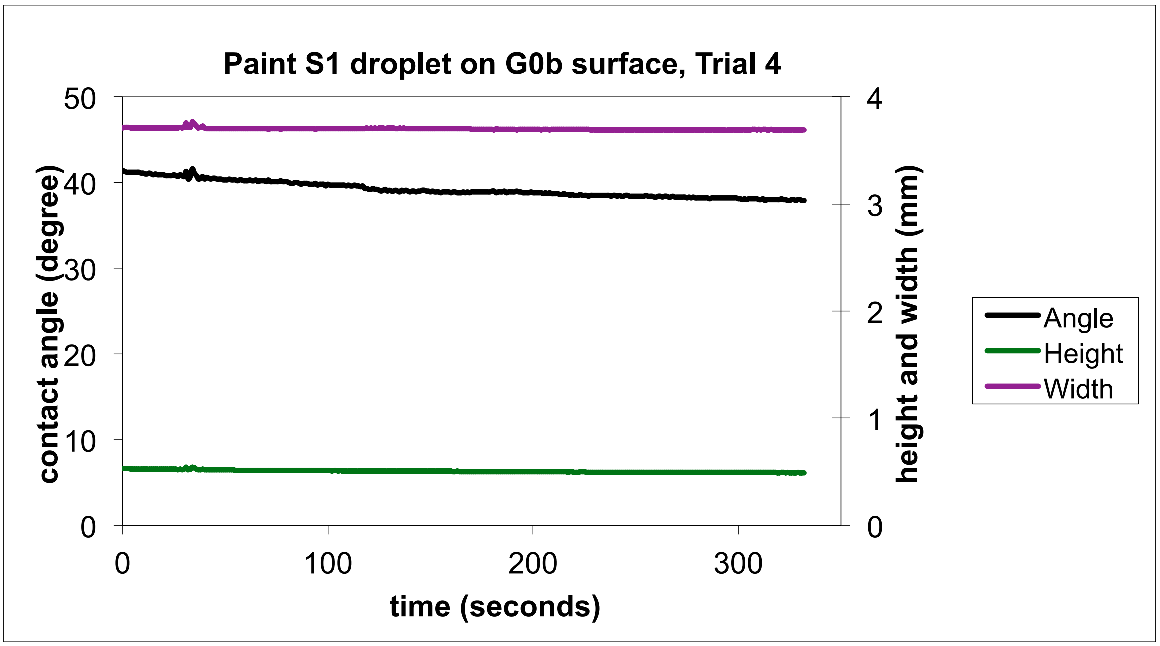


Image of a droplet of S1 paint on Galvanized and blast profiled zinc Trial 4 surface at t = 5 sec. Contact angle = 41°.



Paint I liquid droplet on G0b surface, trial 4. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=41° at t =5 sec.

Average contact angle for G0b-S1 = 46°

From Appendix E: Average pull-off strength = 2170 ± 640 psi.

d. Test panel subgroup G0b-S2

Metal Surface: galvanizing followed immediately by blast surface profiling
Paint: Recoatable Epoxy Primer Series B67

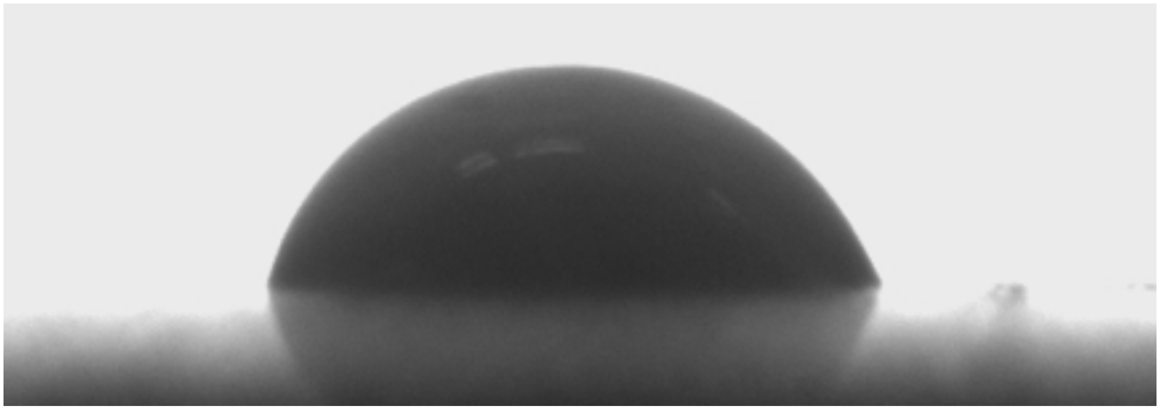
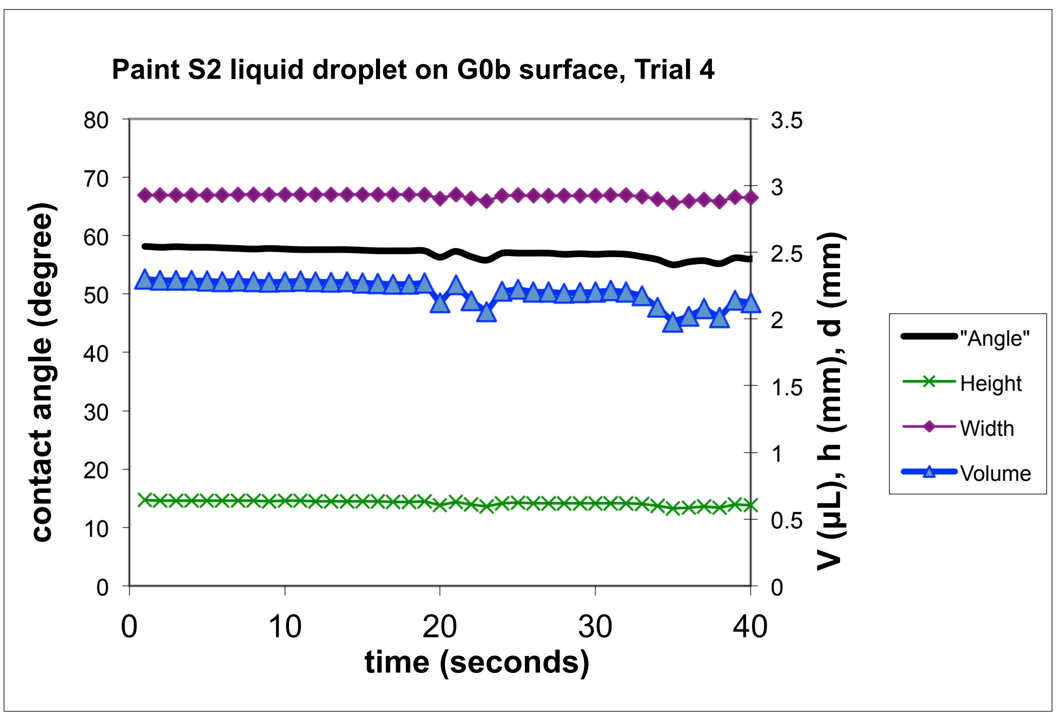
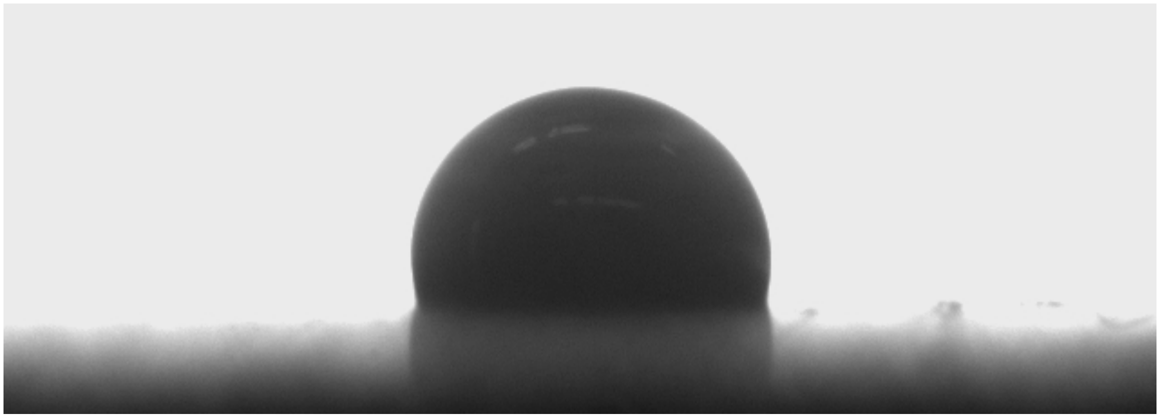
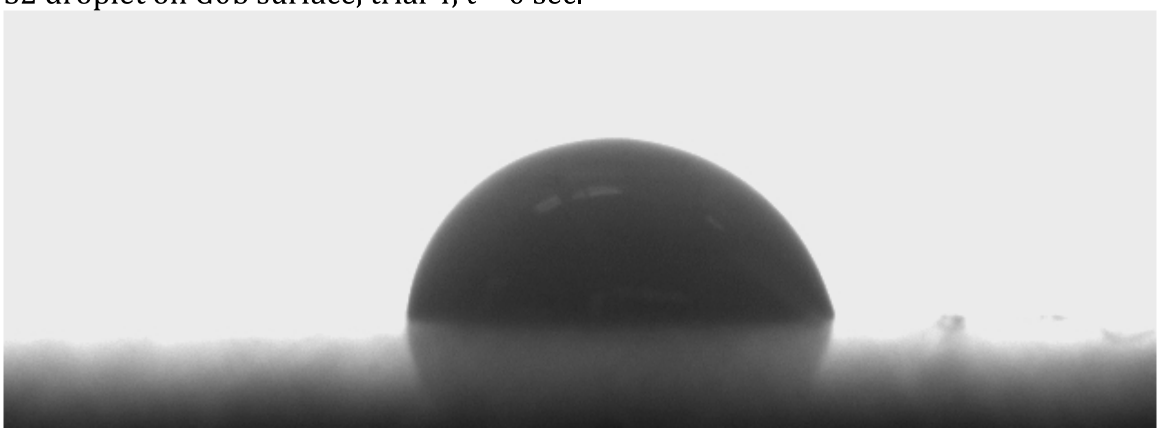


Image of a droplet of liquid paint S2 on G0b surface, Trial 4 at t = 5 sec, contact angle = 58°

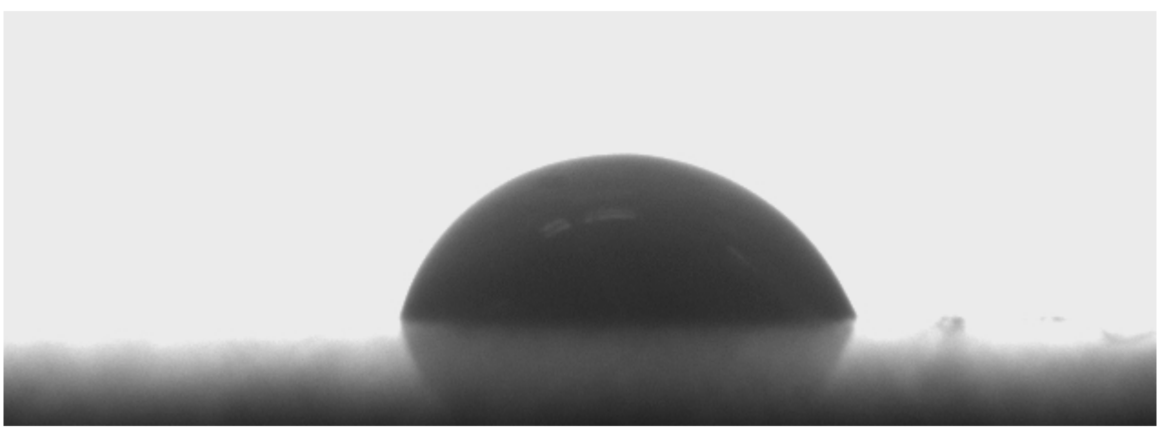


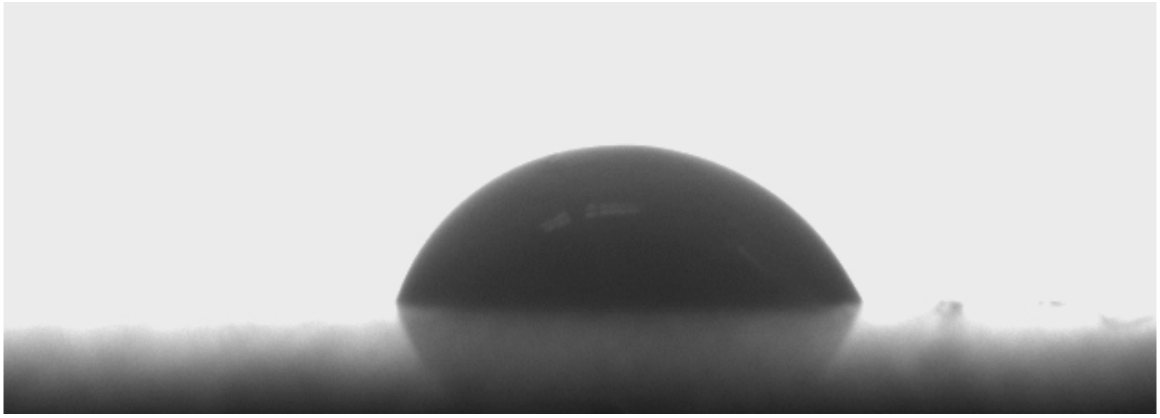
Paint S2 liquid droplet on G0b surface, trial 2. Contact angle, height, width and diameter as a function of time after initial liquid/surface contact. The contact angle θ=58° at t =5 sec.


S2 droplet on G0b surface, trial 4, t = 0 sec.



S2 droplet on G0b surface, trial 4, t = 3 sec.


S2 droplet on G0b surface, trial 4, t = 6 sec, contact angle θ = 58^o


S2 droplet on G0b surface, trial 4, t = 9 sec.

Average contact angle for G0b-S2 interface = 58^{o}
From Appendix E: Average pull-off strength = 1310 ± 280 psi.

Appendix C.3

Paint wetting and contact angle measurement on Type B panels of M0 surface.

The Type B M0 panels are 4”x6’ flat steel panels metallized (M, thermal sprayed). These panels were thermal sprayed in the same batch process for fabricating the Type B M0 panels (4’x6” panel with welded U channel) so that the surfaces are considered as the same. The thermal spray of zinc on steel were performed at Falmer Thermal Spray, Salem MA. No surface roughening process was needed because the surface is sufficiently rough due to the nature of the granular deposition of zinc due to the thermal spray process.

The zinc-coated panels were transported on the same day (the “0” designation in “M0” stands for zero time delay before painting) to Boyd Coatings Research, Hudson, MA and were painted within 4 hours of thermal spray coating process.

At Boyd Coatings Research, 4 different epoxy paint systems (NEPCOAT list) were mixed and sweat-in according to the paint manufacturer’s specification. After the sweat-in time (from 0 to 30 minutes depending on the paint) samples of the mixed paint liquid were taken for contact angle measurements. The same batch of the mixed paint was spray painted on the Type B panels with the same M0 surfaces. The painting and the contact angle measurements were performed at about the same time (within 30 minutes) under approximately the same indoor condition.

The images of a droplet of the paint on the panel surface were taken as a function of time and were analyzed with “DROP” analysis software using a Ramé-Hart Model 200 goniometer (made by Ramé-Hart Instrument Co., Succasunna, NJ). The contact angle θ, the height h of the droplet, and the width d (or the diameter) of the droplet-to-surface of the contacting interface were recorded as a function of time t after the initial drop-to-surface contact. For some samples, the images were stored as a function of time.

In the following charts we display the contact angle θ vs. t curve with the value of the angle (in degree) marked on the left vertical axis. The other droplet shape parameters are displayed with the values marked on the right vertical axis. The parameters include the height of the droplet h (in millimeter, mm), the width d (in mm) and the computed volume V (in micro liter, μL).

Some selected images of the droplets on the M0 surface were included to give a visual impression of the changes of droplet shape.

a. Test panel subgroup M0-C

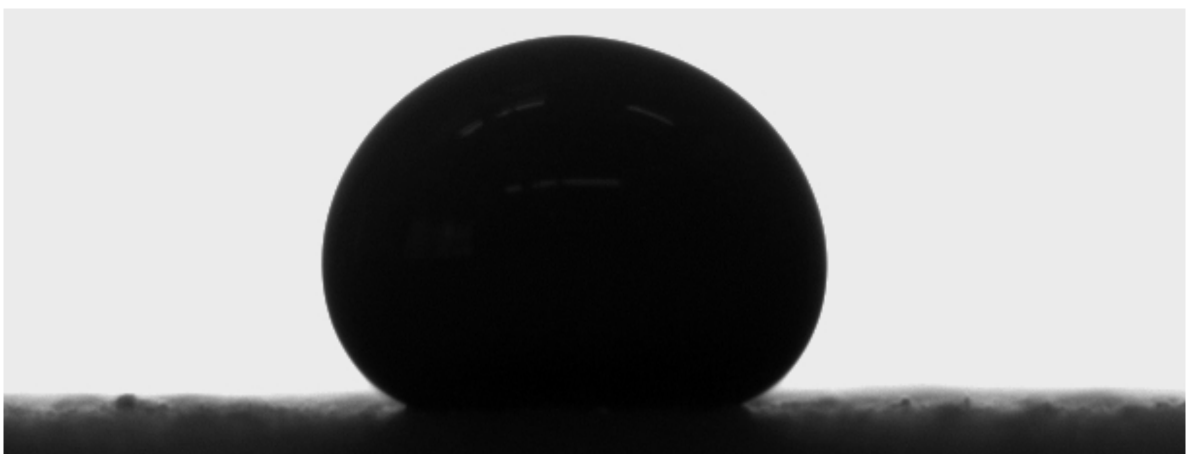
Panel surface: Thermal sprayed zinc metallizing coating

Paint: Carboline 888 Epoxy

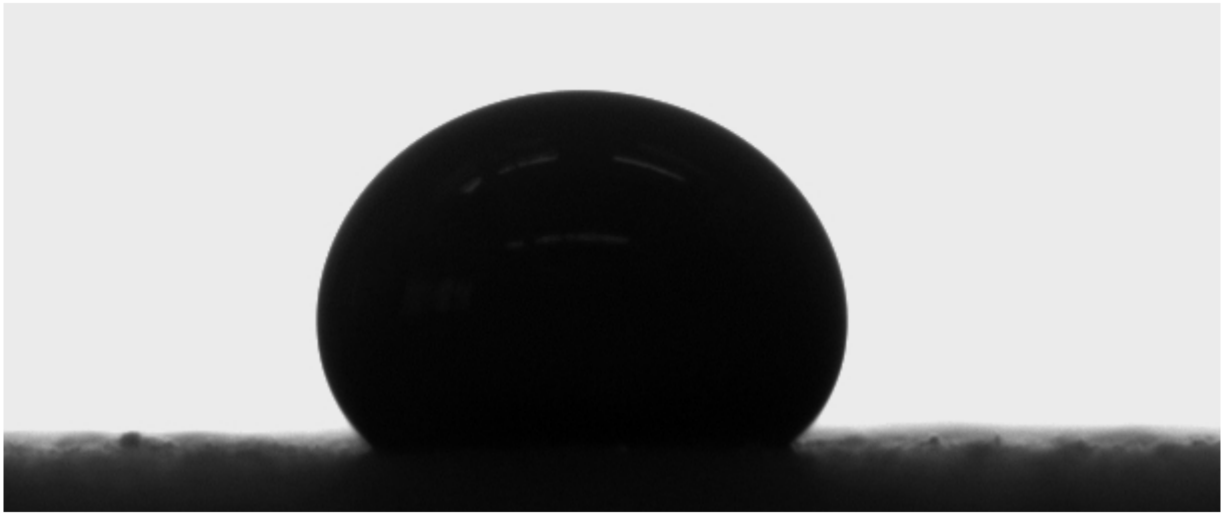
For these wetting tests, the test panel surfaces were fresh metallized surface without the application of sealant.

M0-C Trial 1: Images of Paint C droplet on M0 surface as a function of time.
This set of test showed an example of a non-wetting contact between a liquid paint and a metallized surface without sealant.

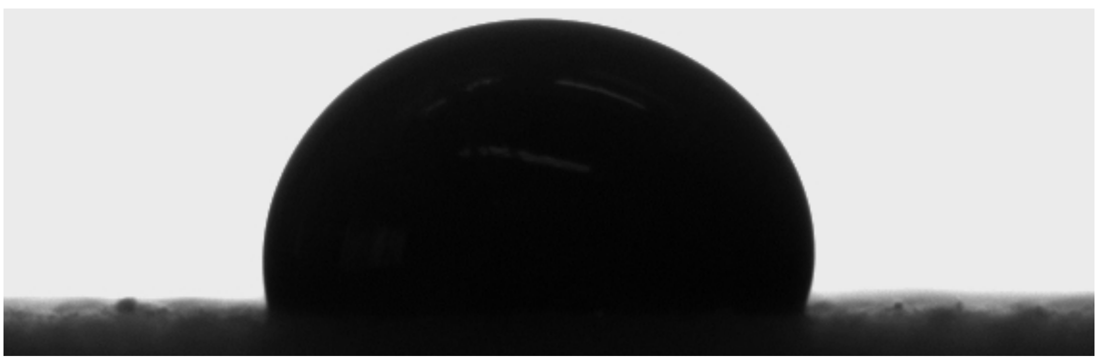
Contact angle data for M0-C interface.
Paint C droplet on metallized surface freshly thermal sprayed on the same day of paint application.
Contact angle at t= 5 sec: 136°
Average pull-off strength = 1290 psi.



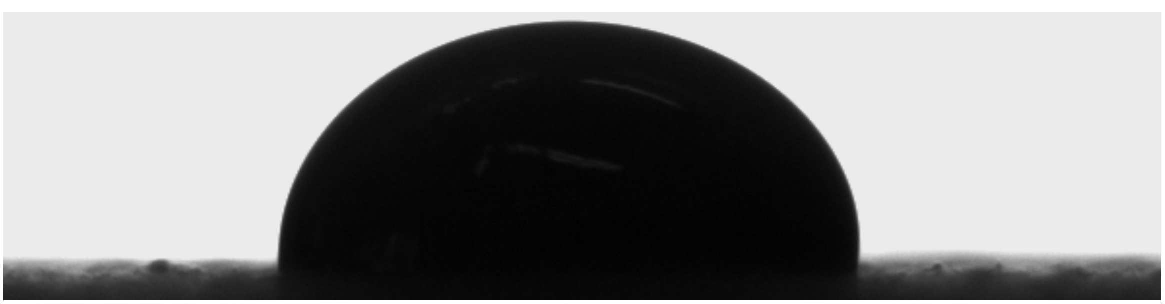
Paint droplet C on M0 surface, Trial 1, t=3 sec., contact angle = 150°



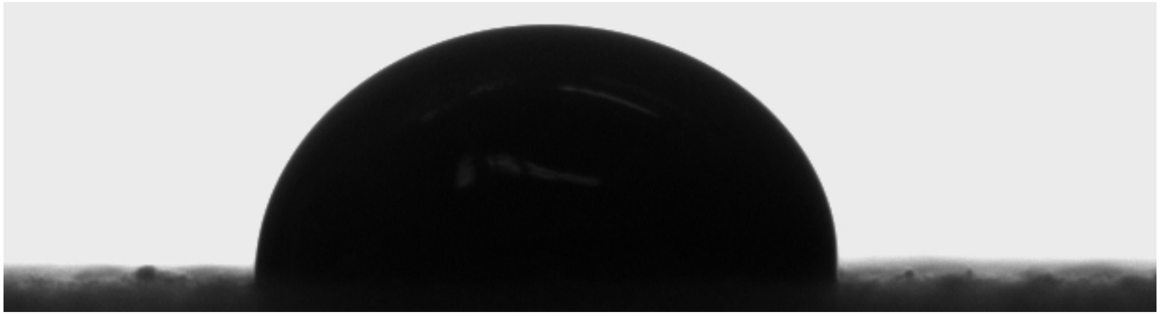
Paint droplet C on M0 surface, Trial 1, t=6 sec, Contact angle: 135.6 degrees



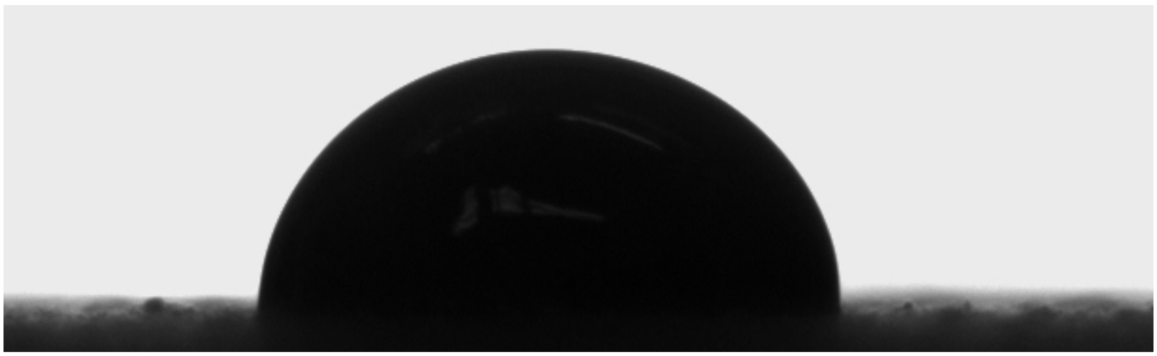
Paint droplet C on M0 surface, Trial 1, t=30 sec. Contact angle = 105°



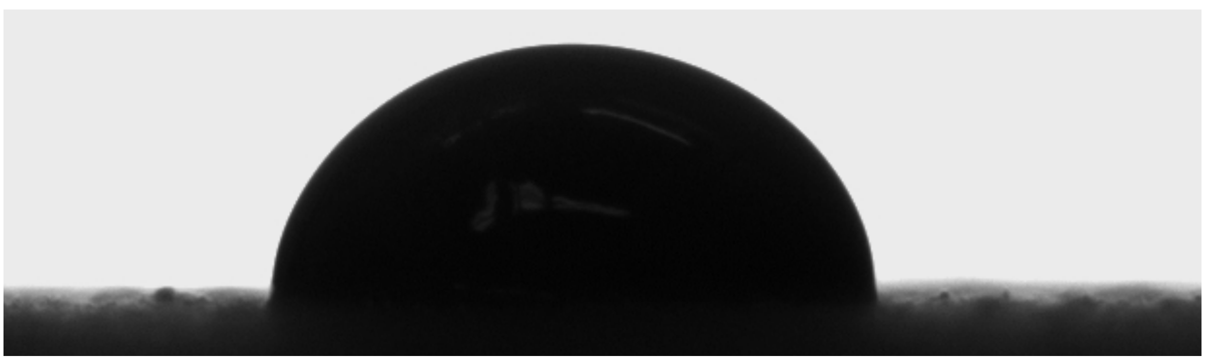
Paint droplet C on M0 surface, Trial 1, t=60 sec., contact angle = 95°



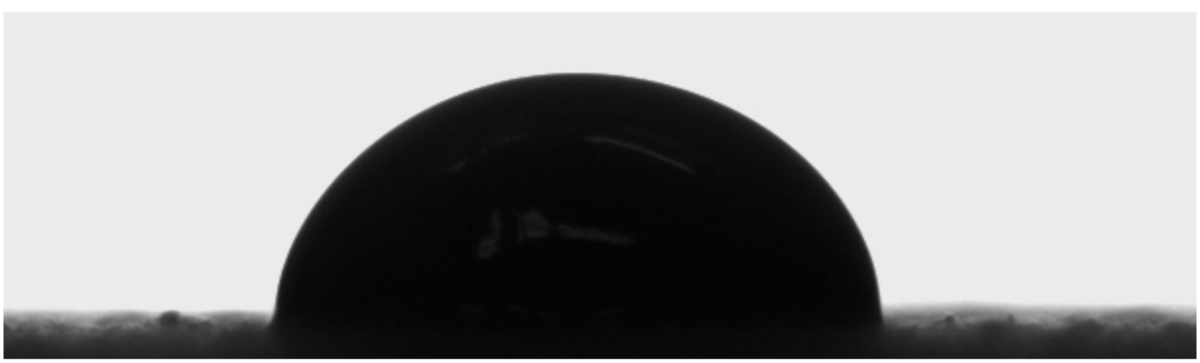
Paint droplet C on M0 surface, Trial 1, t=90 sec., contact angle = 92^{o}



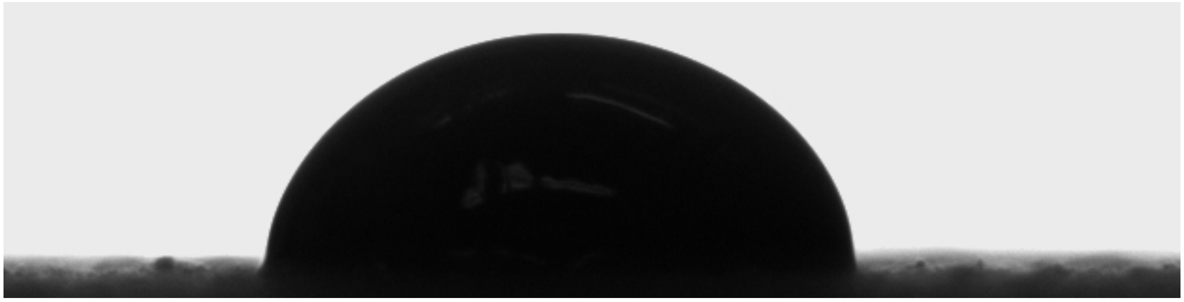
Paint droplet C on M0 surface, Trial 1, t=120 sec., contact angle = 90^{o}



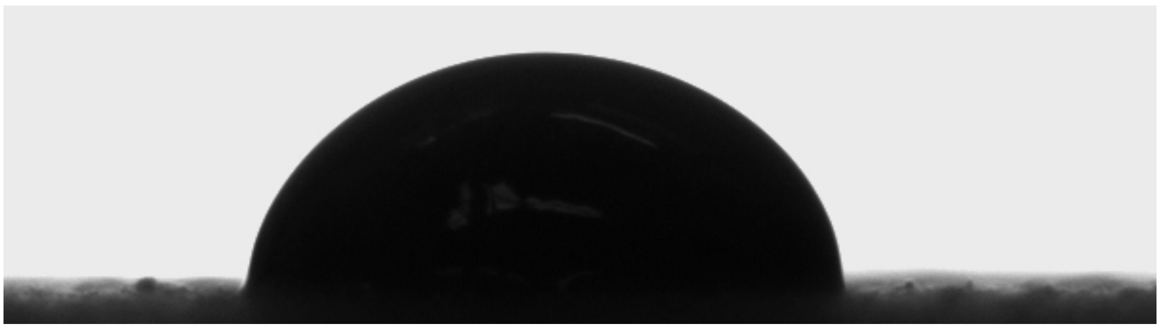
Paint droplet C on M0 surface, Trial 1, t=150 sec., contact angle = 89^{o}



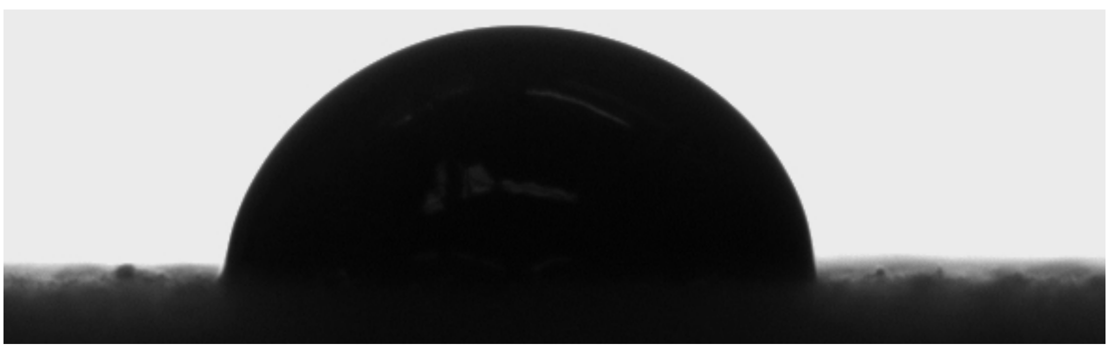
Paint droplet C on M0 surface, Trial 1, t=180 sec., contact angle = 88^{o}



Paint droplet C on M0 surface, Trial 1, t=210 sec., contact angle = 88°

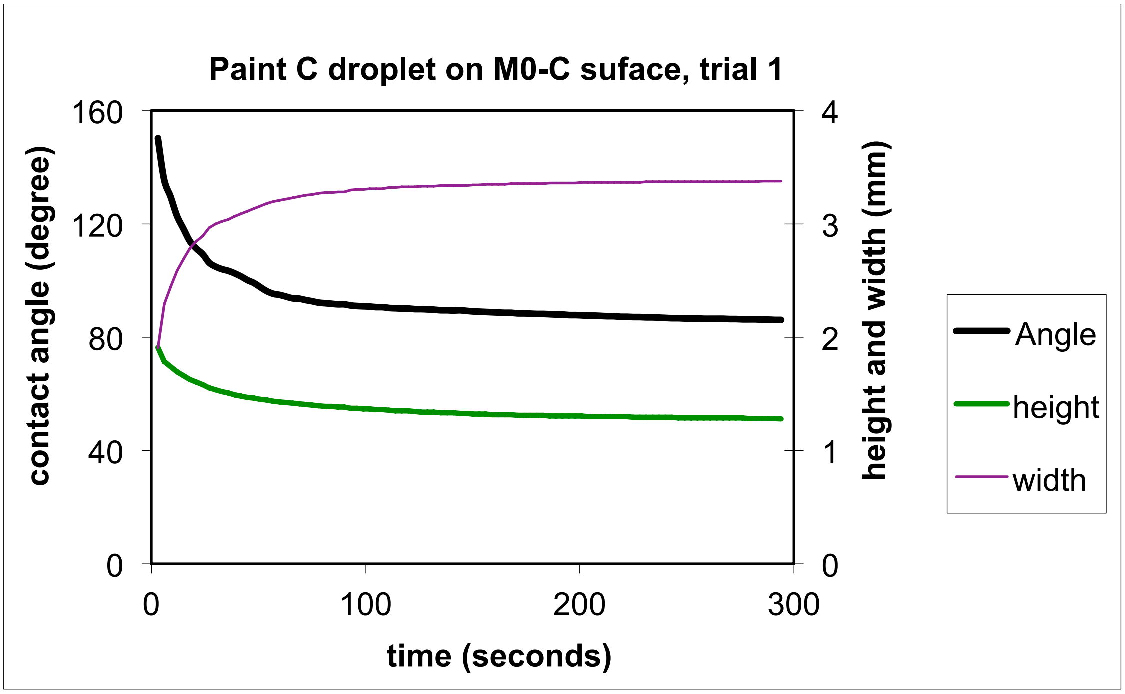


Paint droplet C on M0 surface, Trial 1, t=240 sec., contact angle = 87°



Paint droplet C on M0 surface, Trial 1, t=270 sec., contact angle = 86°

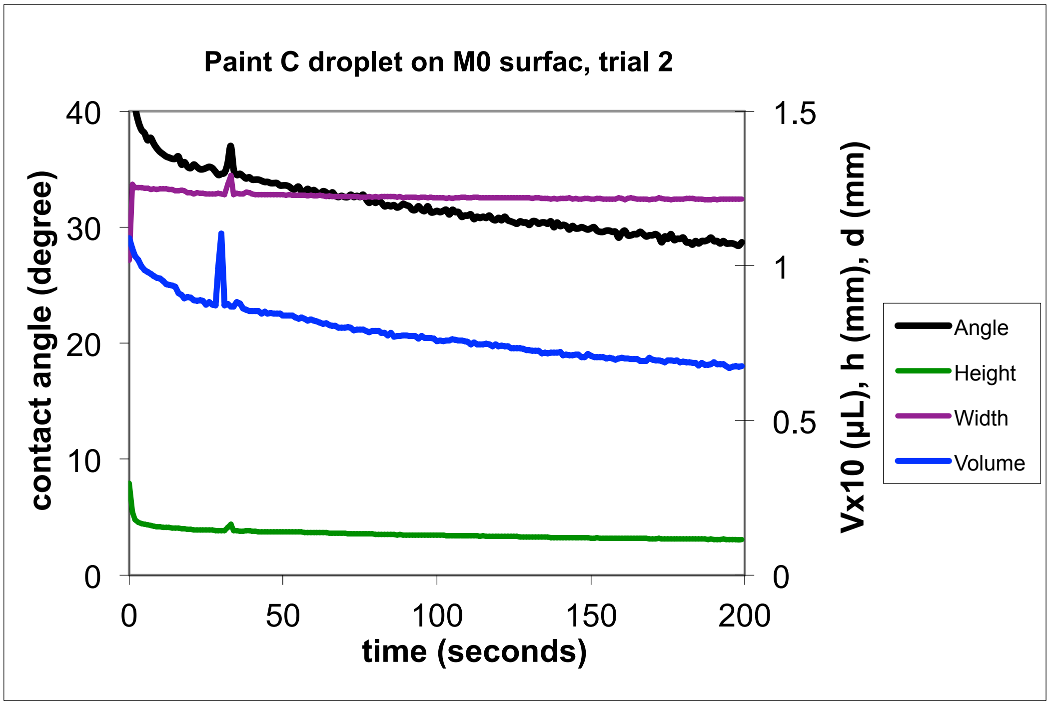
The contact angle, the height and the diameter of the liquid paint C droplet on M0 surface are recorded as a function of time. The plot is shown in the following figure.



From this figure we can see that the initial contact angle is very high, 136 degree at t = 5 second. The paint C droplet does not wet the rough zinc surface produced by thermal spray. The paint does not penetrate into the channels and the cavities of the metallized surface. There are air pockets beneath the paint droplet. The interfacial interaction at the interface between paint C and the metallized zinc surface exhibit the "lotus effect". The interaction is similar to that of a water droplet sitting on top of a lotus leave. The water droplet beads up on a microscopically rough surface of the lotus leaf to achieve minimization of the Gibbs free energy for the interfacial interactions.

There is a slow spreading of the droplet evidenced by the decrease in the contact angle and the height of the droplet, and with concomitant increase of the droplet-to-surface contact area. The spreading of the paint droplet is slow. It took 2 minutes for the contact angle to decrease from 150^o to 90^o. This indicates that paint C does not penetrate into the microscopic capillary and voids in the zinc surface.

Not all droplets lead to high contact angles for the M0-C surface-paint pair. There are droplets that has modest contact angle ($\theta \approx 40^o$). Trial 2 is an example for the smaller than 90^o samples. A contact-angle vs. time plot is shown here.



Contact angle for trial 2 at t = 5 second is 38^o.

This figure shows that for this point of paint C droplet to M0 surface contact the initial contact angle is small enough to wet the cavity and capillary of the metallized zinc surface. The initial contact angle is small (38^o) indicating wetting. We use the measured liquid cap height and width to calculate the change of droplet volume as a function of time. Both the contact angle and the volume of the droplet decrease by about 30% during the course of the measurement (200 sec). This indicates that the paint C liquid spreads and is being absorbed at a slow rate. This absorption rate is much slower that that of the sealant S3 droplet on the same M0 surface to be discussed in the last section of this Appendix C.3. While paint C is only 30% absorbed in 200 second, paint S3 is completely absorbed within 1 second.

Contrasting the above two measurements, we see that the M0 surface texture is not uniform. There is certain area of the zinc surface that is wetted by the paint but certain other area shows the “lotus effect”. Lacking extensive statistical study of the relative importance of these two types of surface wetting on the same test panel, we take the simple average of these two measurements of contact angle at t = 5 sec. The average contact angle is taken as $\theta_{avg}= 87^o$.
It will be presented in Appendix E that the average pull-off strength for the corresponding dried paint system C is 1290 psi. The test panels were prepared with the same batch of

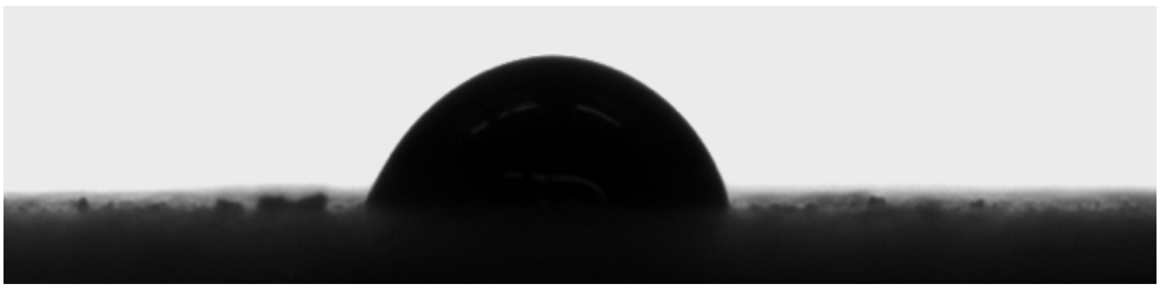
paint C coated on the same batch of M0 panels at about the same time as the contact angle measurements were performed.

Summary for the M0-C interface:
Average M0-C contact angle, θ = 87°
From Appendix E, average pull-off strength of M0-C coating system is 1742 ± 197 psi

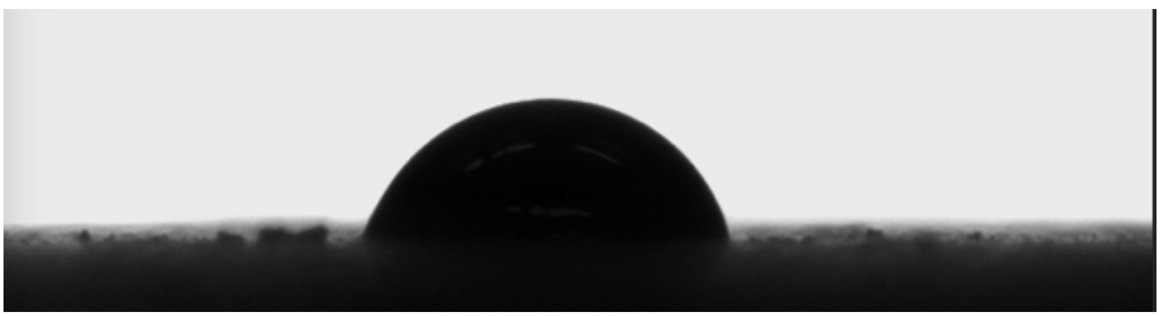
b. Test panel subgroup M0-I

Metal surface: Thermal sprayed zinc metallizing coating, Fresh
Paint: Intergard 345 Epoxy

M0-I Trial 2: Images of Paint I droplet on M0 surface as a function of time.
This set of test showed an example of a non-wetting contact between a liquid paint and a metallized surface without sealant.



M0-I Trial 2, t = 0 sec.



M0-I Trial 2, t = 5 sec., contact angle = 75 °.

M0-I Trial 2, t = 25 sec.

The paint I does not have high affinity to the M0 surface as evidenced by the relatively high contact angle of 75 ° and the slow process of spreading. There are two other trials obtained with automatic recording of the contact angles without images being taken at the same time. We suspected that the DROP software program was not properly analyzing the contact angles because we neglected in performing a calibration of the image analysis with a standard sphere before running the auto-analysis. Because of the possible defect of these data, we use trial 2 images to report a contact angle at t = 5 second at 75°.

There were two other trials for measuring the contact angles of M0-I but the data were not analyzed because images were not taken to verify the reliability of the auto-recording program used for these experiments. We think that the data for those two trials are unreliable because we forgot to calibrate the droplet shape measurement before the data acquisition, and we did not record the images of the droplets. Since we had visually observed beading up of the droplets in all experimental trials, we will take the value of $\theta = 75$ from the valid data for trial 2 as the representative contact angle for the M0-I coatings.

It will be presented in Appendix E that the average pull-off strength for the corresponding dried paint system I is 1170 psi. The test panels were prepared with the same batch of paint I coated on the same batch of M0 panels at about the same time as the contact angle measurements were performed.

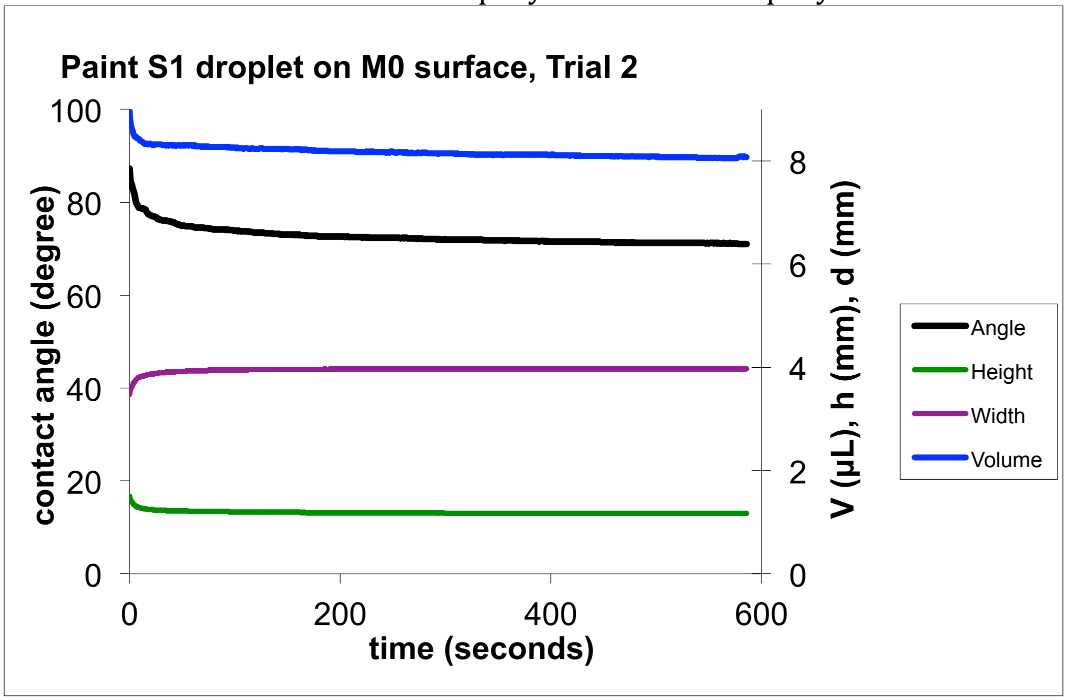
Contact angle for M0-I coated panels is 75^o. This is based on the result of trial 2.

From Appendix E, average pull-off strength for M0-I coated panels: 1094 $\pm$ 186 psi.

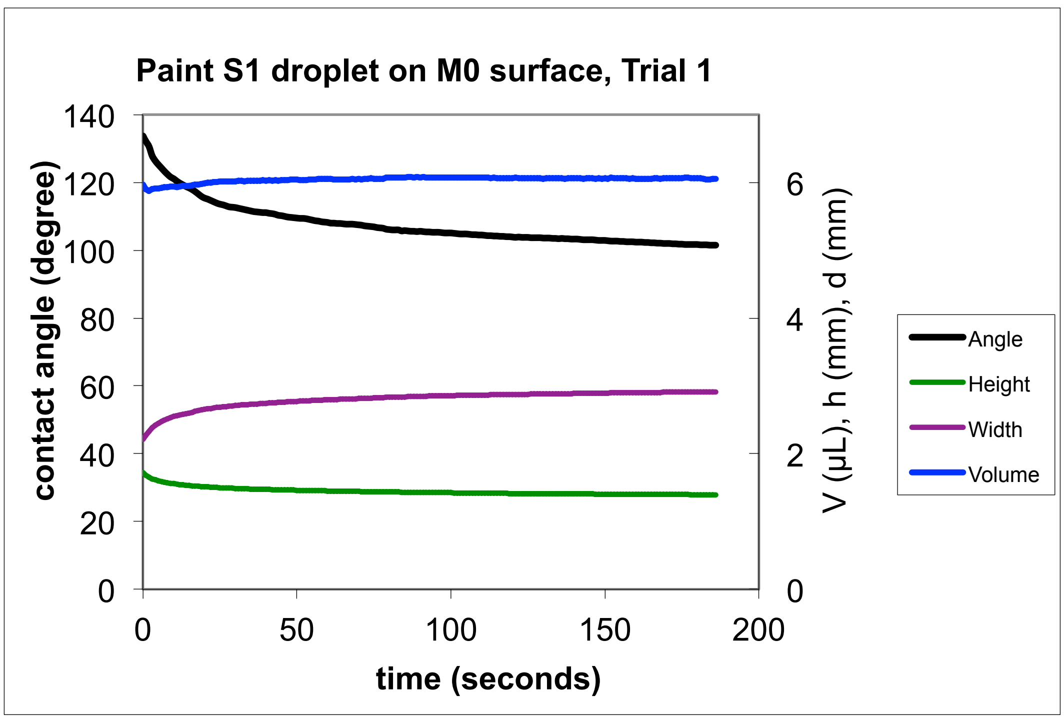
c. **Test panel subgroup M0-S1**

Metal surface: galvanizing followed by blast surface profiling, Fresh

Paint: S1: Macropoxy 646 Fast Cure Epoxy



Paint S1 liquid droplet on M0 surface, trial 2. The contact angle at t = 5 sec is 81°.



Paint S1 liquid droplet on M0 surface, trial 1. The contact angle at t = 5 sec is 125°.

Trial 3 droplet was too small to be measured accurately. We have not included the data for trial 3 for analysis.

The average contact angle for M0-S1 coated panels (at t = 5 sec) is 103^{o}.
It is shown in Appendix E that the average pull-off strength is 1079 ± 103 psi for the corresponding M0-S1 cured paint system.

d. **Test panel subgroup M0-S2**

Metal surface: Thermal sprayed zinc metallizing coating, Fresh
Paint: Recoatable Epoxy Primer Series B67

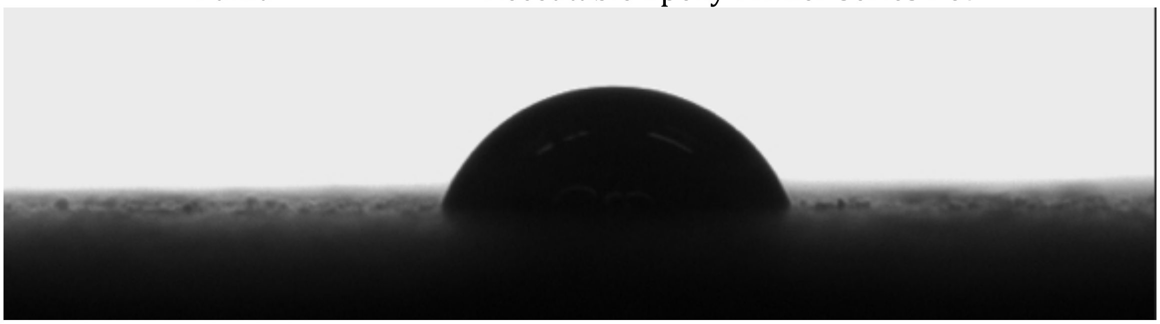


Image of paint S2 liquid droplet on M0 surface, trial 2, t = 3 sec, contact angle = 60^{o}

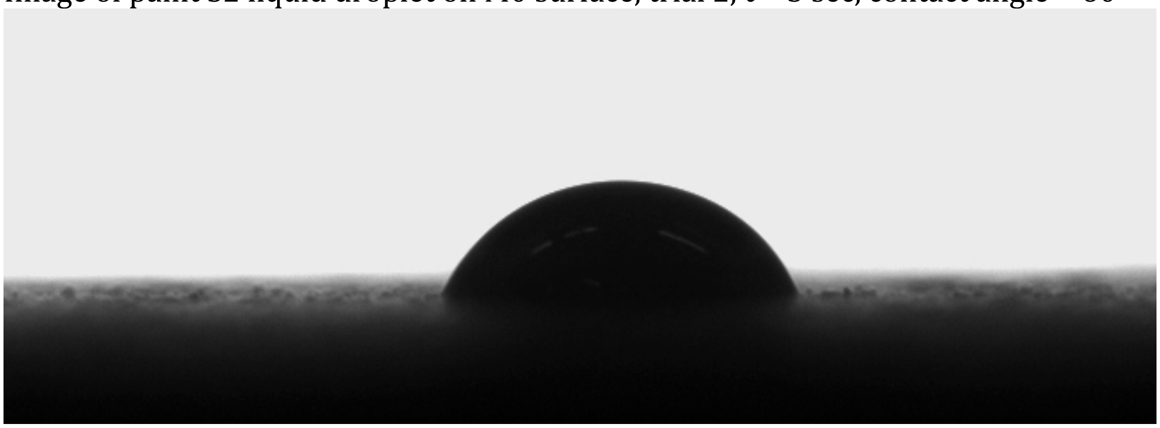
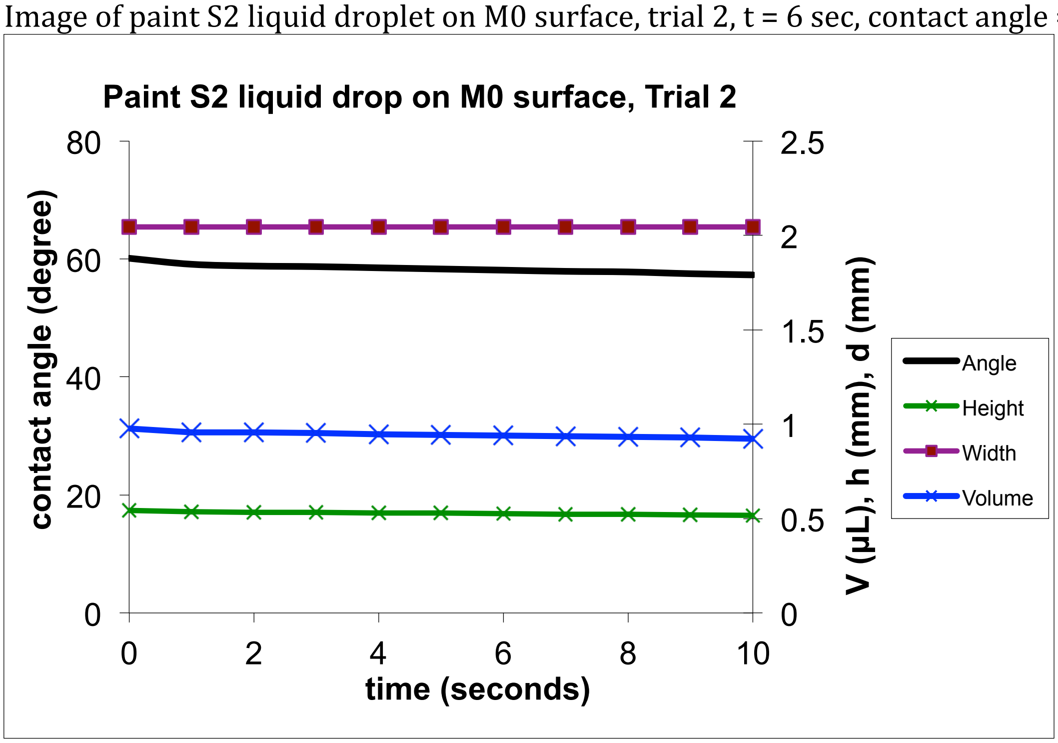
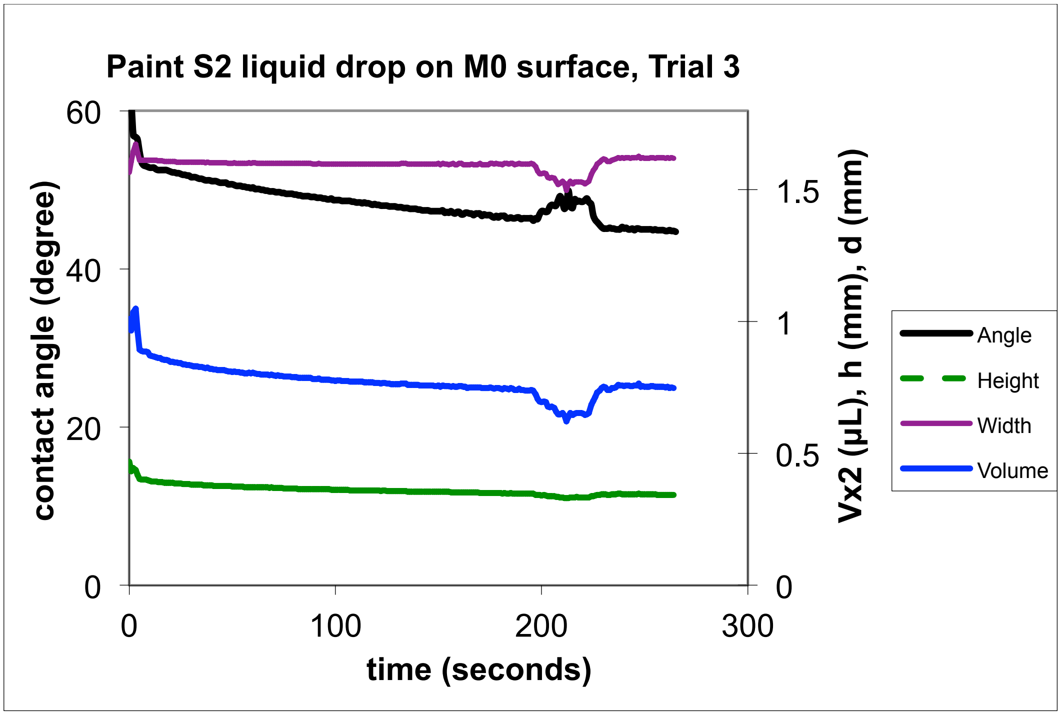


Image of paint S2 liquid droplet on M0 surface, trial 2, t = 6 sec, contact angle = 58^{o}.



Paint S2 liquid drop on M0 surface, Trial 2, contact angle at t = 5 sec is 58^{o}.



Paint S2 liquid drop on M0 surface, Trial 3, contact angle at t = 5 sec is 58°.

M0-S2 Trial 2: Images of Paint S2 droplet on M0 surface as a function of time.
This set of test showed an example of a non-wetting contact between a liquid paint and a metallized surface without sealant.

Trial 1 data was not used because the auto-recording was not pre-calibrated for angle measurement.

Average contact angle for M0-S2 coated panels is $\theta_{Avg} = 58^o$

It will be presented in Appendix E that the average pull-off strength for the corresponding dried paint system C is 1103 ± 163 psi. The test panels were prepared with the same batch of paint S2 coated on the same batch of M0 panels at about the same time as the contact angle measurements were performed.

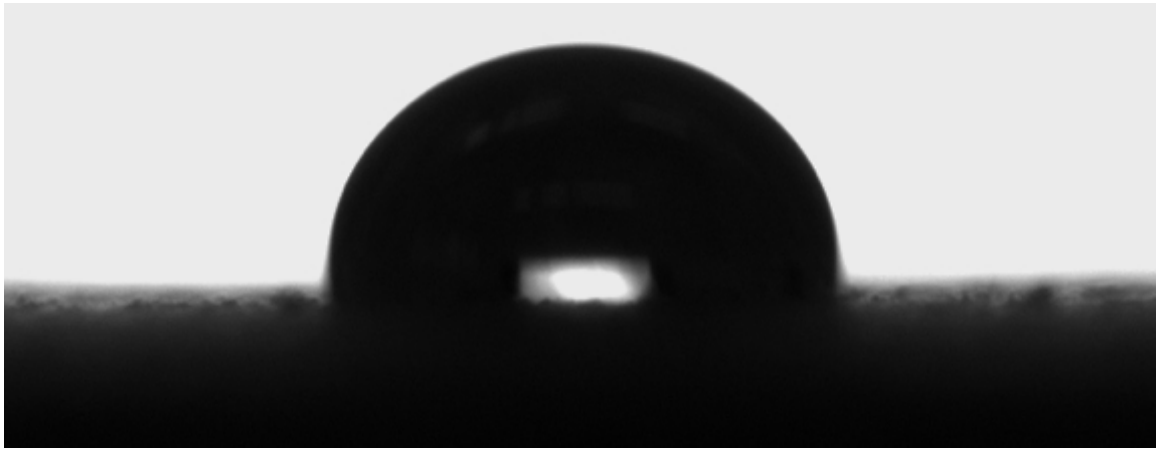
e. Test panel subgroup M0-S3

Primer: Thermal sprayed zinc metallizing coating
Intermediate: Macropoxy 920 penetrating pre-primer

The graphs were taken with rapid data acquisition starting from 1 second before the droplet comes in contact with the metallized surface, and the data acquisition ends after the droplet is completely absorbed by the metallized zinc surface. We assigned the time t =0 by identifying the time when the fluctuating angles in the data stream stopped fluctuating and the values of all three droplet shape parameters (Angle, width and height) becomes well defined. In the rapid data acquisition mode, the computer program automatically assigns the contact angle, height and width of the presumed droplet within the field of the captured images (which was analyzed but not stored). When there is lack of actual droplets the assigned contact angle fluctuates between 0^o and 180^o, the height stays near zero, but the width wildly varies. We assign t=0 to the data when the fluctuation in the contact angle stops and the height changes from zero to a finite value. When the droplet is completely spread out to form a thin film with thickness too small for the goniometer to measure, the contact angle and the width data again begin to fluctuate, and the reported value of the height again return to zero. We took this as a signal for the complete spreading of the paint droplet, and the liquid paint has penetrated into the voids underneath the metallized surface.

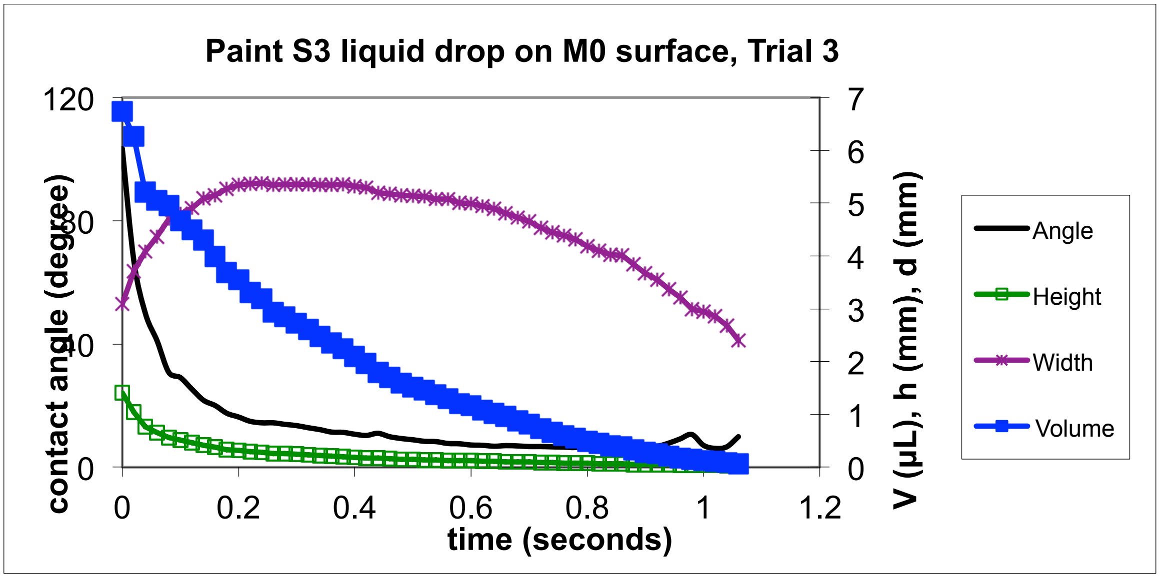
The following sequence of the droplet images show that the S3 sealant spreads rapidly on the M0 surface and is readily absorbed by the pores in the metallized zinc surface. The t=0 droplet shape is shown in part (a) of the following figure. The liquid droplet spreads to a very thin and wide liquid pool within 1 second as shown in the second frame of image for t= 1 sec. The liquid droplet is completely undetectable by the time of t = 5 sec as shown in the third frame of the image. This indicates that the liquid drop is absorbed in the voids of the metallized zinc coating.

M0-S3 Trial 2: Images of Paint S3 droplet on M0 surface as a function of time.
This set of test showed an example of a fast spreading and absorption of paint S3 (which is a low viscosity sealant) on the M0 surface.


M0-S3 Trial 2, a droplet of sealant S3 on the surface of M0 at t = 0 sec.

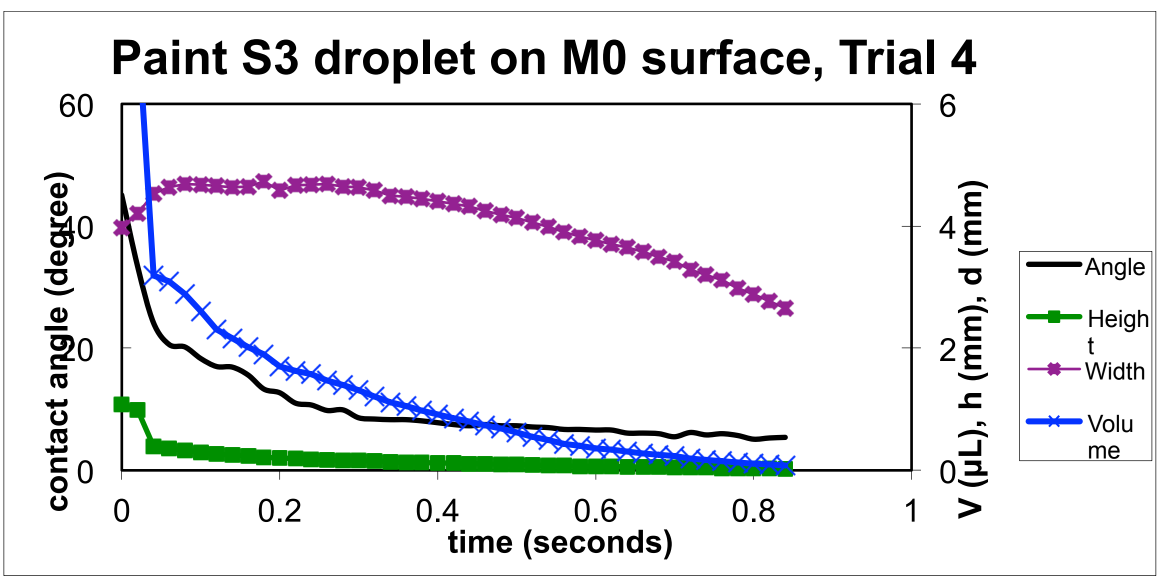

M0-S3 Trial 2, a droplet of sealant S3 on the surface of M0 at t = 1 sec, contact angle 5^o.


M0-S3 Trial 2, a droplet of sealant S3 on the surface of M0 at t = 5 sec, contact angle 0^o

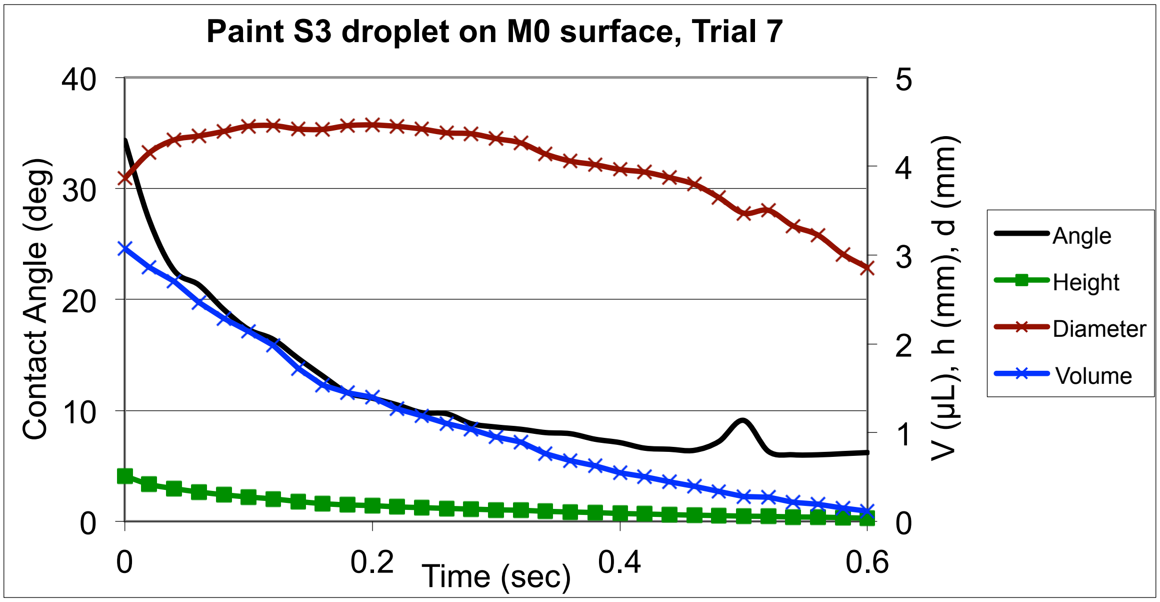


Paint S3 liquid droplet on M0 surface, trial 3, contact angle, height, width, and volume of the liquid droplet as a function of the time after initial paint-to-surface contact. Note that the contact angle, the height and the volume of the droplet decrease rapidly and reached near zero value within 1 second. This indicates that the droplet was absorbed into the microscopic voids and channels within the textured surface of zinc created by the thermal spray process.

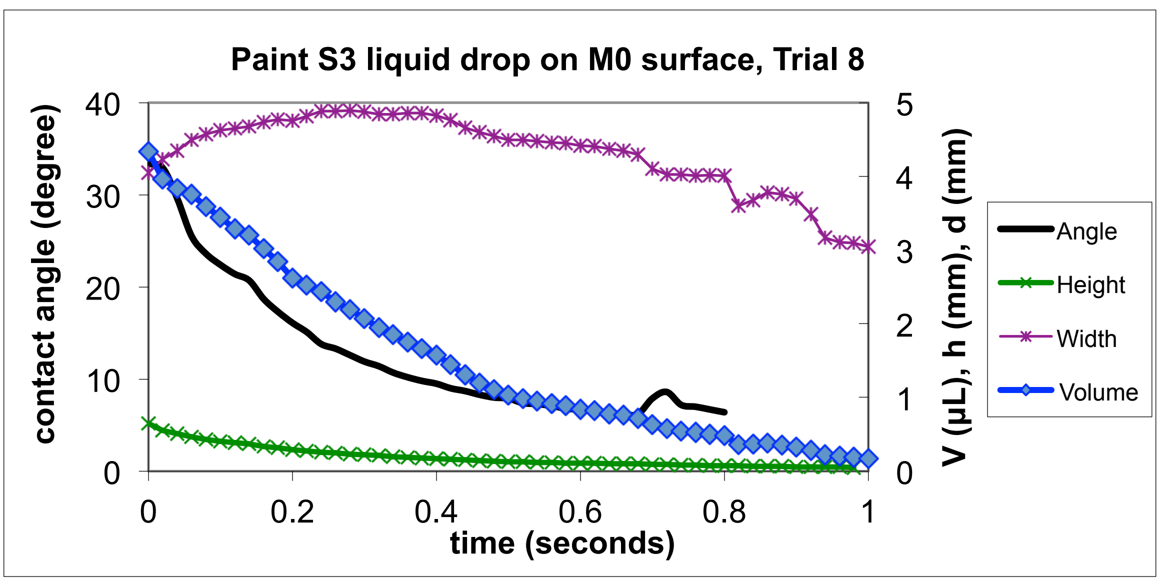
The width of the droplet (the diameter of the liquid-surface contact area) initially increase during the first 0.2 second, then begin to decrease at t = 0.5 second until the droplet disappears at t = 1 second. The initial (t <0.2 second) increase of the droplet width signals the spreading of the liquid droplet. The flattening out and eventual decrease of the width is consistent with the absorption of the liquid paint by the metallized zinc surface.



Paint S3 liquid droplet on M0 surface, trial 4, contact angle, height, width, and volume of the liquid droplet as a function of the time after initial paint-to-surface contact.



Paint S3 liquid droplet on M0 surface, trial 7, contact angle, height, width, and volume of the liquid droplet as a function of the time after initial paint-to-surface contact.



Paint S3 liquid droplet on M0 surface, trial 8, contact angle, height, width, and volume of the liquid droplet as a function of the time after initial paint-to-surface contact.

The contact angle decreases to zero before t= 5 second for all trials. We assign the average angle $\theta_{Avg} = 0^o$.

It will be presented in Appendix D that the average pull-off strength for the corresponding dried paint system S3 is 2023 ± 485 psi. The test panels were prepared with the same batch of paint S3 coated on the same batch of M0 panels at about the same time as the contact angle measurements were performed.

Appendix C.4

Paint wetting and contact angle measurement on Type B panels of G2b surface.

The G2b panels are 4"x6' flat steel panels Galvanized (G in "G2b" stands for galvanizing), stored for 2 weeks (2 in "G2b" stands for 2-week indoor storage), and blast profiled (b in "G2b" stands for blast profiling). Both the type A panels for spray painting, and the type B panels for contact angle measurement were galvanized in the same batch process by V&S Galvanizing of Taunton, MA. The test panels were then stored in a room at the University of Rhode Island (Room 335 Pastore Hall, not exposed to outdoor environment, not exposed to volatile chemicals) for 2 weeks. After 2-weeks of aging, the test panels were again taken to V&S, Taunton. for the second time to blast profile. The blast profiling work was completed early in the morning on a work day at V&S. We then took the blast profiled test panels to Boyd Research Co at Hudson MA to perform the contact angle tests on the Type B panels and at the same time spray-paint the Type A panels. At Boyd Coatings Research, 4 different epoxy paint systems (NEPCOAT list) were mixed and sweat-in according to the paint manufacturer's specification. After the sweat-in time (from 0 to 30 minutes depending on the paint) samples of the mixed paint liquid were taken for contact angle measurements. The same batch of the mixed paint was spray painted on the Type B panels with the same M0 surfaces. The painting and the contact angle measurements were performed at about the same time (within 30 minutes) under approximately the same indoor condition.

The images of the droplets of the paints on the panel surface were recorded as a function of time and were analyzed with "DROP" analysis software using a Ramé-Hart Model 200 goniometer (made by Ramé-Hart Instrument Co., Succasunna, NJ). The contact angle θ, the height h of the droplet, and the width d (or the diameter) of the droplet-to-surface of the contacting interface were recorded as a function of time t after the initial drop-to-surface contact. For some samples, the images were stored as a function of time.

In the following charts we display the contact angle θ vs. t curve with the value of the angle (in degree) marked on the left vertical axis. The other droplet shape parameters are displayed with the values marked on the right vertical axis. The parameters include the height of the droplet h (in millimeter, mm), the width d (in mm) and the computed volume V (in micro liter, μL). Some selected images of the droplets on the G2b surface were included to give a visual impression of the changes of droplet shape.

a. Test panel subgroup G2b-C

Metal surface: (galvanized steel, stored in door for 2 weeks before blast profiling)

Paint droplet: Carboline 888 Epoxy

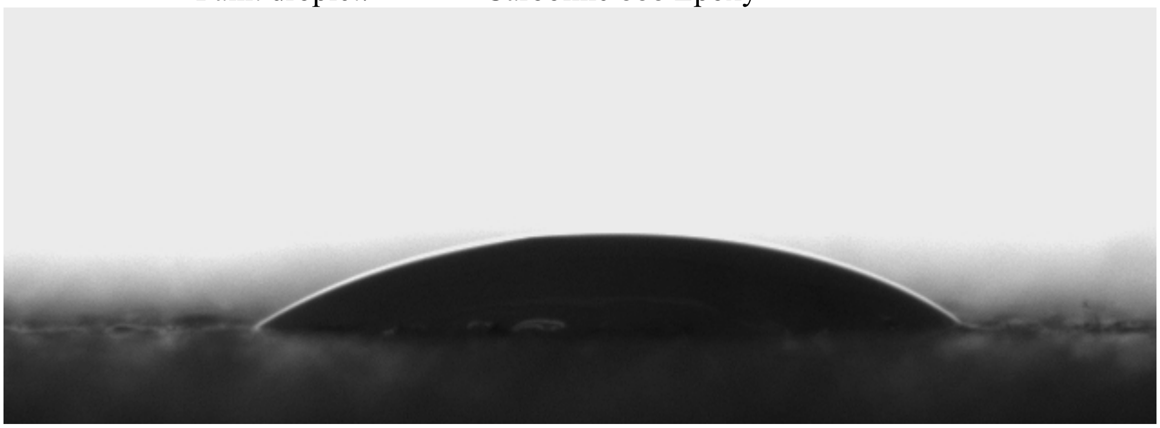
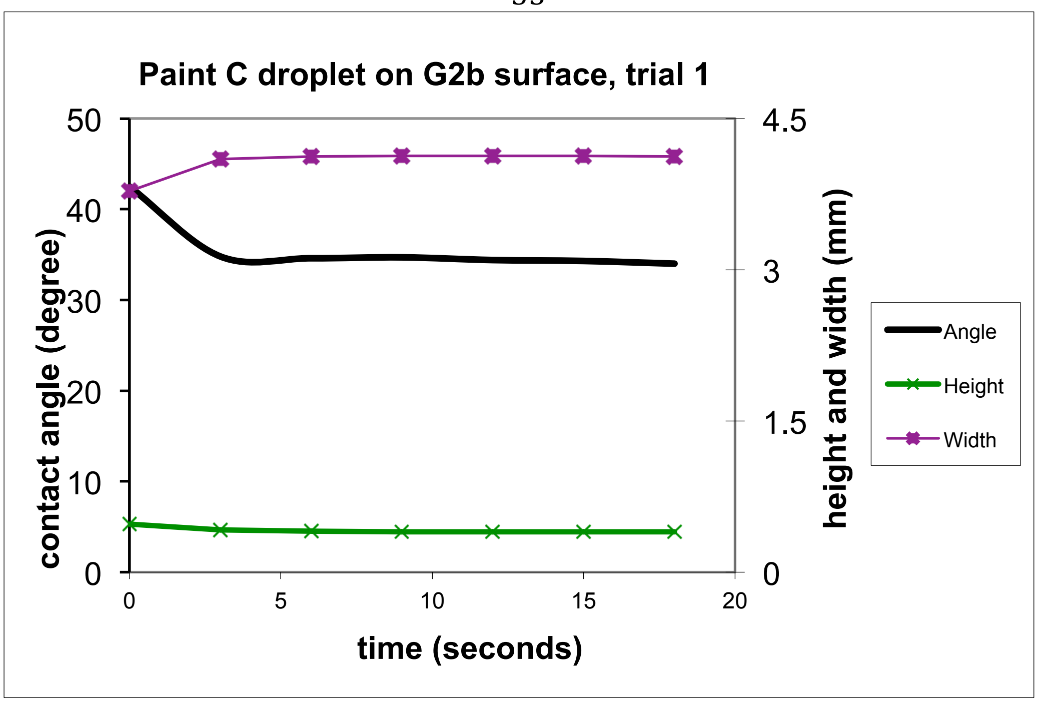
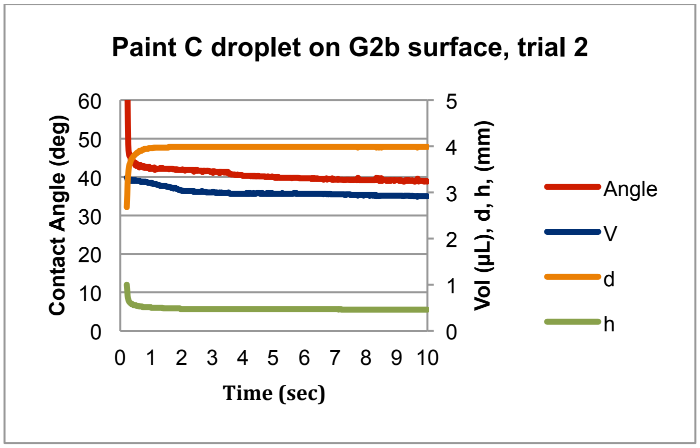


Image of a droplet of liquid paint C on G2b surface, Trial 1, at t = 6 sec, contact angle = 35º



Paint C liquid droplet on G2b surface, trial 1, contact angle, height and width of the droplet as a function of tim



Paint C liquid droplet on G2b surface, trial 2, contact angle, height, width and the volume of the droplet as a function of time. Contact angle θ = 41º at t = 5 sec.

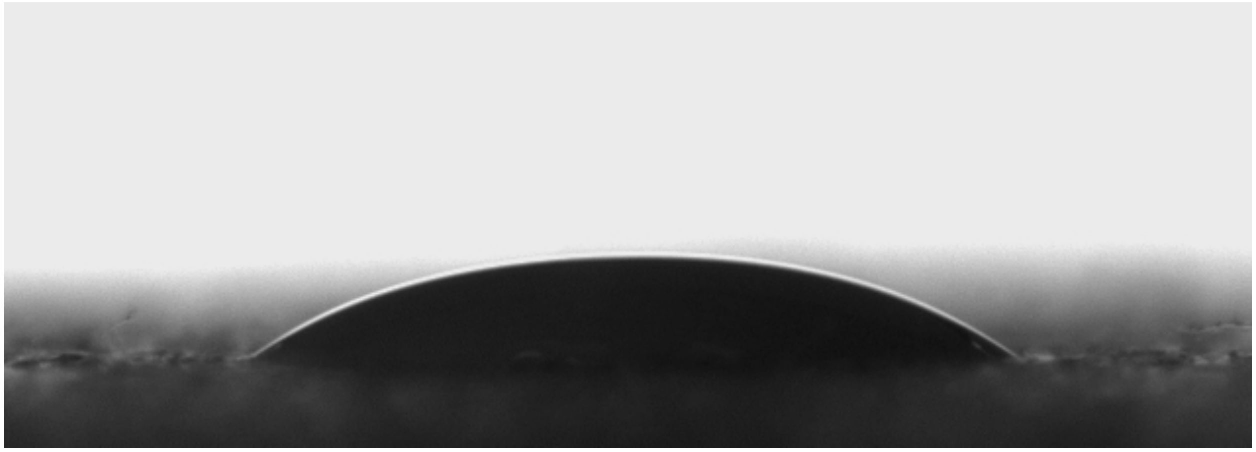
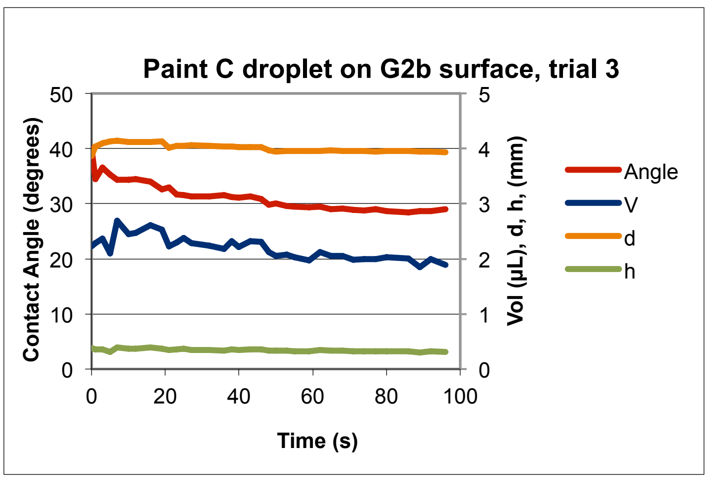
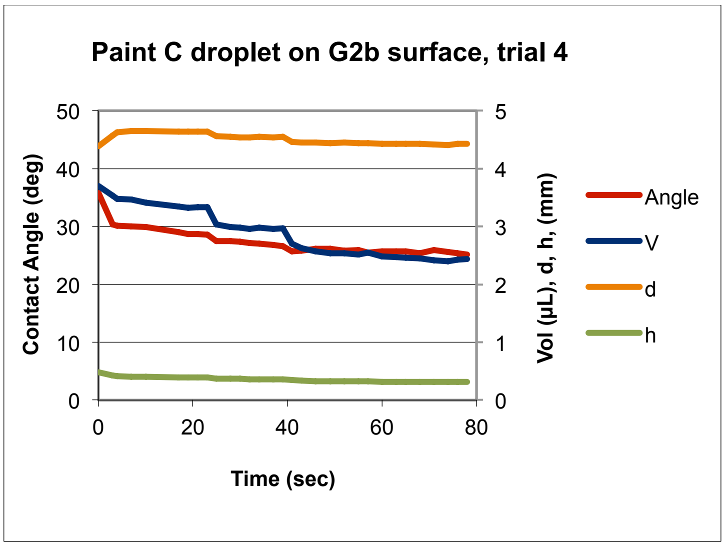


Image of a droplet of liquid paint C on G2b surface, Trial 3, at t = 6 sec, contact angle = 33º



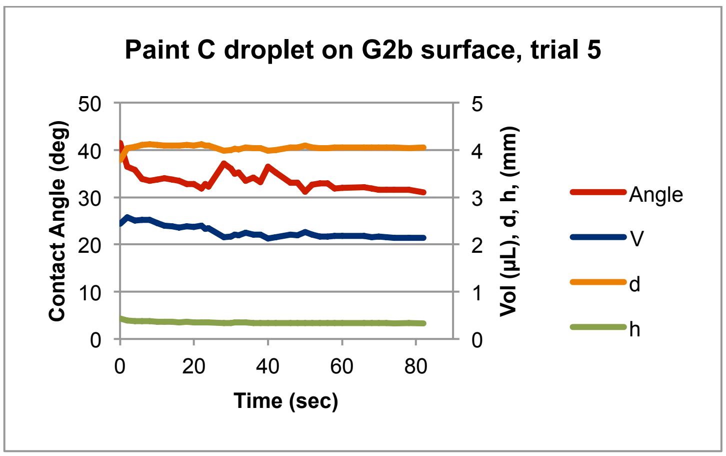
Paint C liquid droplet on G2b surface, trial 3, contact angle, height, width and the volume of the droplet as a function of time. Contact angle θ = 33º at t = 5 sec.

Image of a droplet of liquid paint C on G2b surface, Trial 4, at t = 6 sec, contact angle = 30º



Paint C liquid droplet on G2b surface, trial 4, contact angle, height, width and the volume of the droplet as a function of time.

Image of a droplet of liquid paint C on G2b surface, Trial 5, at t = 6 sec, contact angle = 35^{o}



Paint C liquid droplet on G2b surface, trial 5, contact angle, height, width and the volume of the droplet as a function of time.

Summary for G2b-C contact angle measurements: Average contact angle θ = 36^{o}

From Appendix E, the average pull-off strength of G2b-C paint system is 2502 ± 101 psi.

b. **Test panel subgroup G2b-I**

Metal surface: (galvanized steel, stored in door for 2 weeks before blast profiling)

Paint droplet: Intergard 345 Epoxy

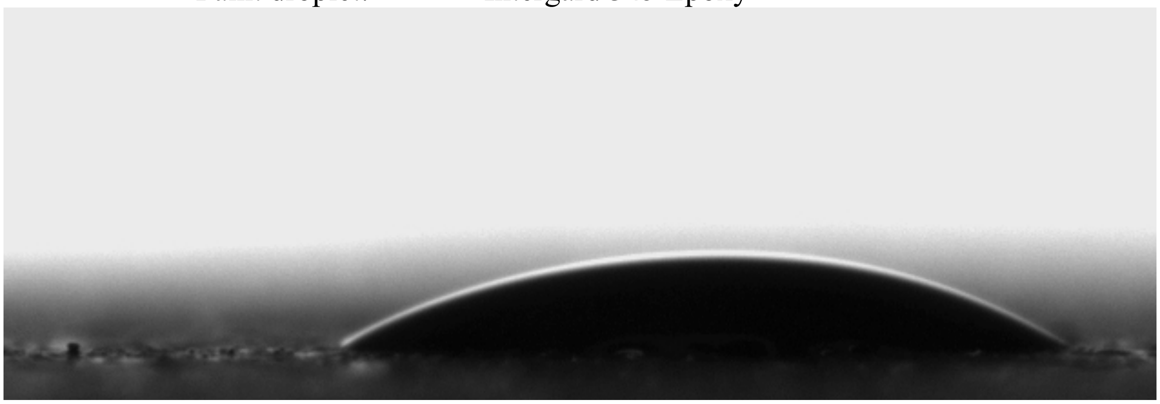


Image of paint I liquid droplet on G2b surface, trial 1, t = 6 sec, contact angle θ = 38°.

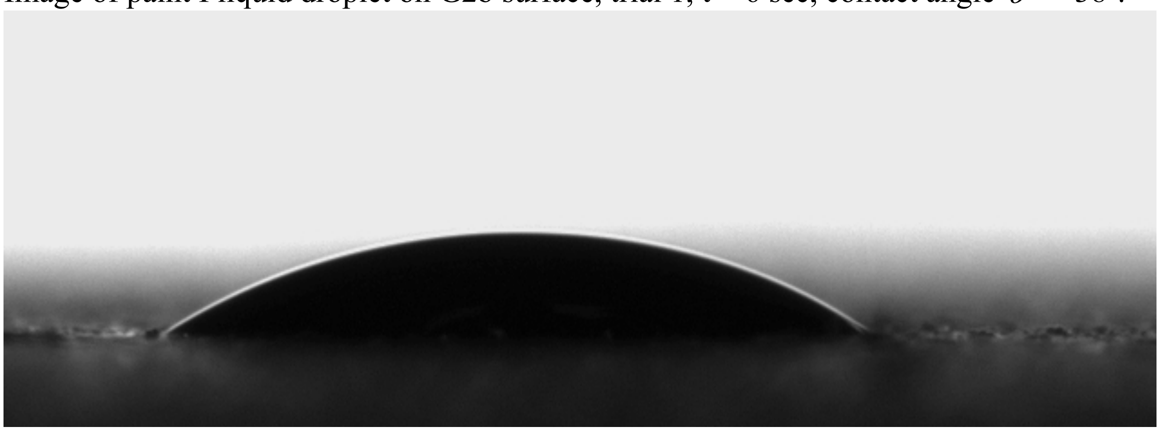
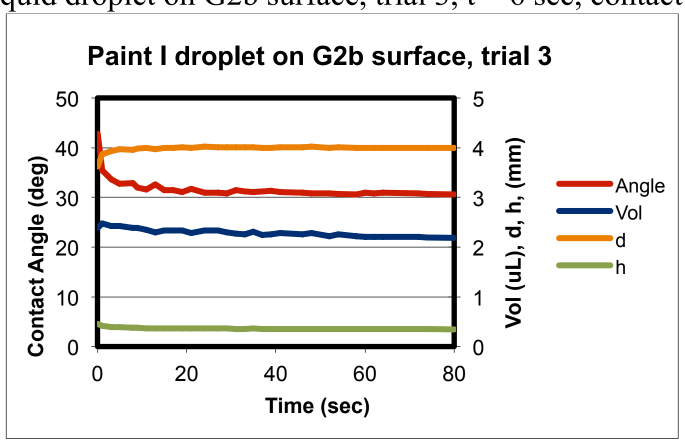
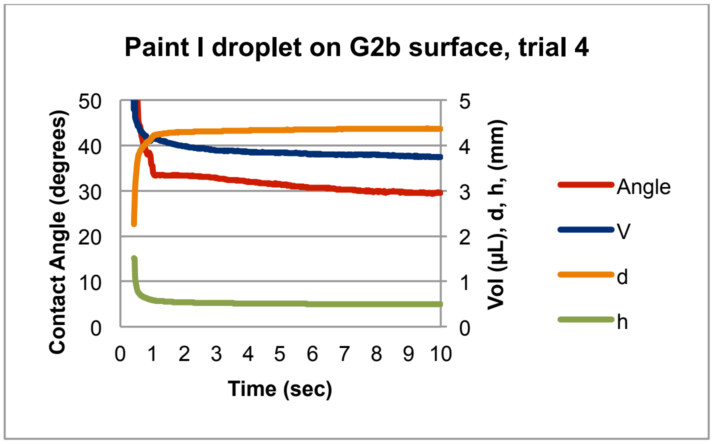


Image of paint I liquid droplet on G2b surface, trial 3, t = 6 sec, contact angle θ = 35°



Paint I liquid droplet on G2b surface, trial 5, contact angle, height, width and volume of the droplet as a function of time.



Paint I liquid droplet on G2b surface, trial 4, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 31°

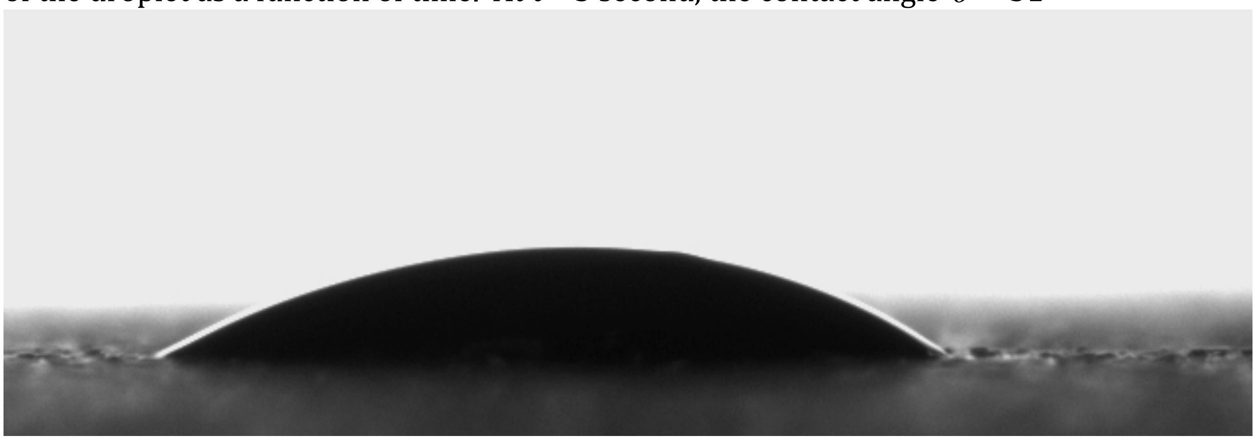
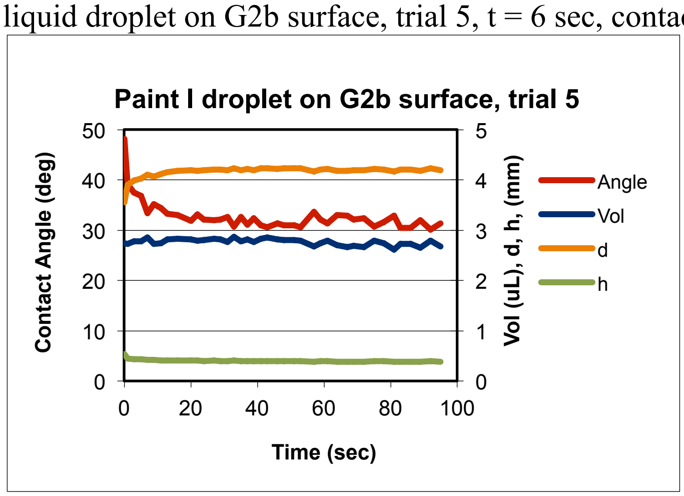


Image of paint I liquid droplet on G2b surface, trial 5, t = 6 sec, contact angle θ = 35°



Paint I liquid droplet on G2b surface, trial 5, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 35°

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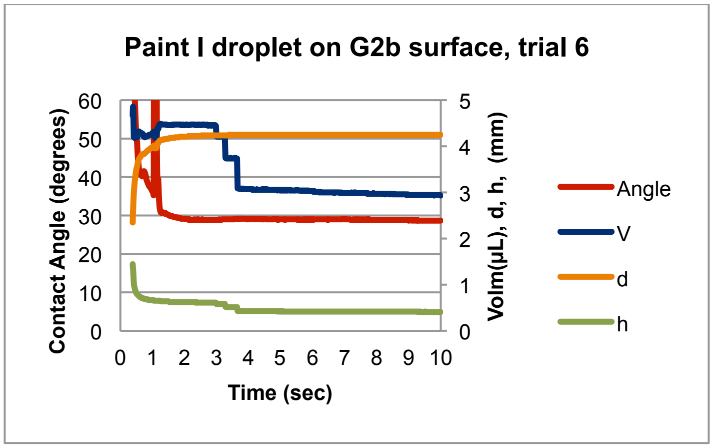
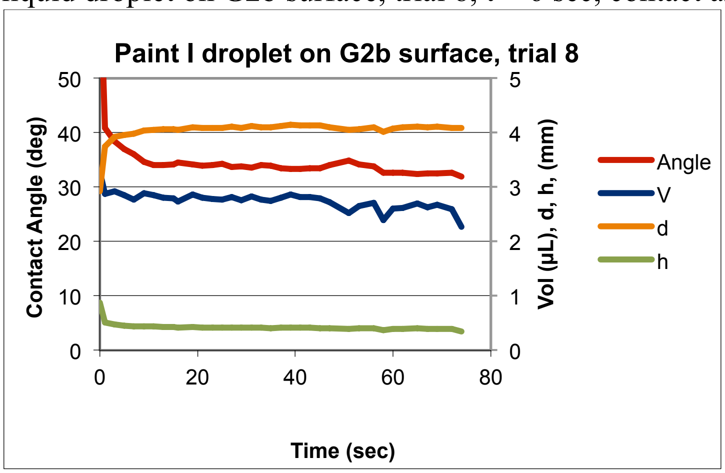
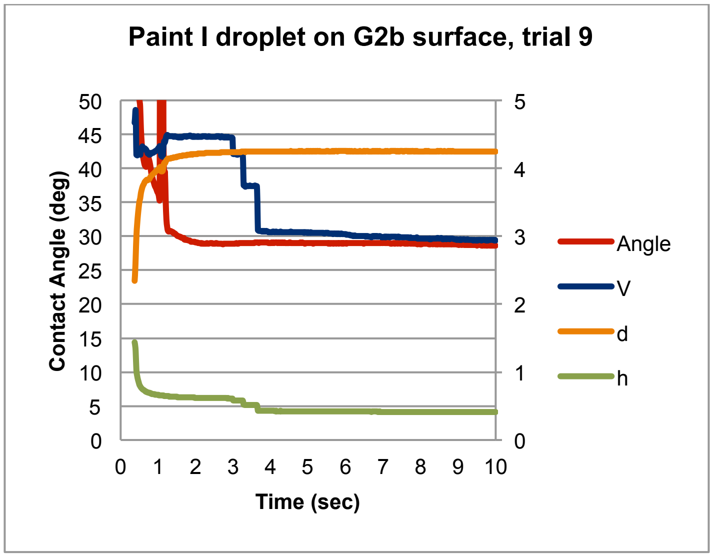


Paint I liquid droplet on G2b surface, trial 6, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 30°
Trial 7 is not analyzed because of the presence of an air bubble near the top of the paint droplet.

Image of paint I liquid droplet on G2b surface, trial 8, t = 6 sec, contact angle θ = 38°.



Paint I liquid droplet on G2b surface, trial 8, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 38°



Paint I liquid droplet on G2b surface, trial 9, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 29°

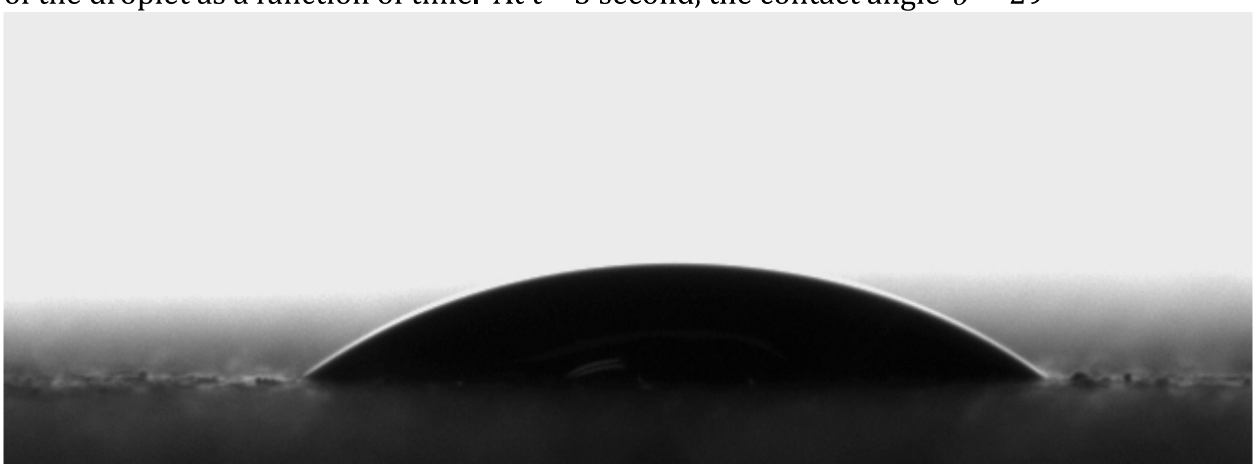
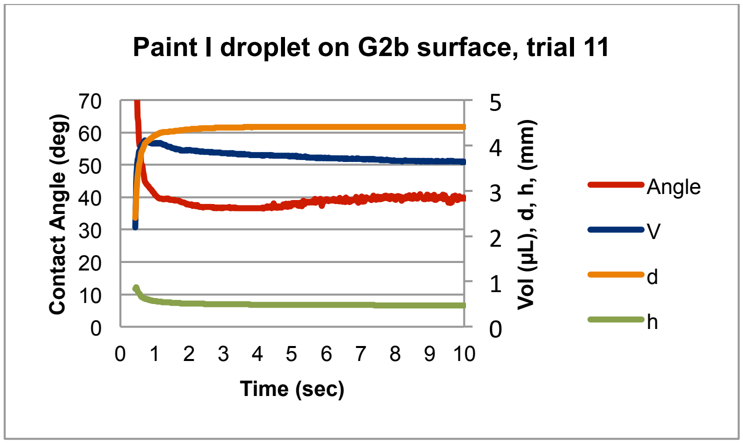


Image of paint I liquid droplet on G2b surface, trial 10, t = 6 sec, contact angle θ = 38°



Paint I liquid droplet on G2b surface, trial 11, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 38°

Average contact angle for G2b-I interfaces: $\theta_{Avg} = 35^o$.

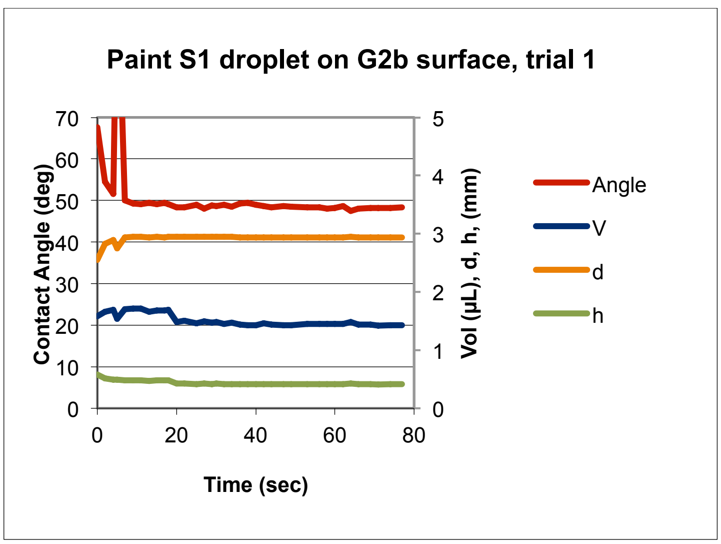
From Appendix E: Average pull off strength for G2b-I (12 test samples): 2257 ± 121 psi

c. **Test panel subgroup G2b-S1**

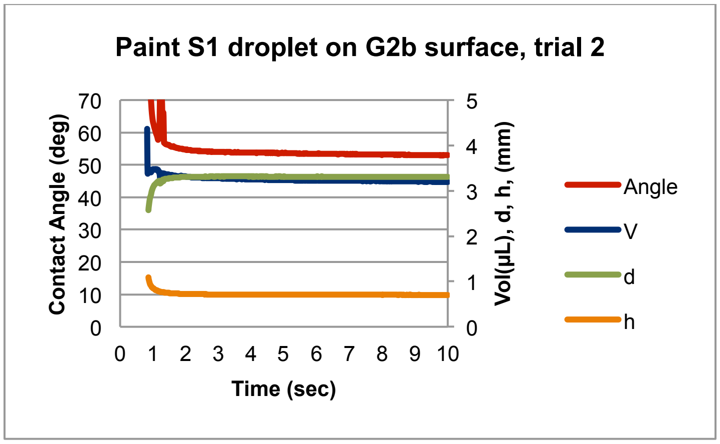
Metal surface: (galvanized steel, stored in door for 2 weeks before blast profiling)

Paint droplet: Macropoxy 646 Fast Cure Epoxy

Image of a droplet of liquid paint S1 on G2b surface, trial 1 t = 6 sec, contact angle θ = 45^{o}



Paint S1 liquid droplet on G2b surface, trial 1, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 45^{o}



Paint S1 liquid droplet on G2b surface, trial 2, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 55º

Trial 3 data is not analyzed because the droplet image shows trapping of air bubble.

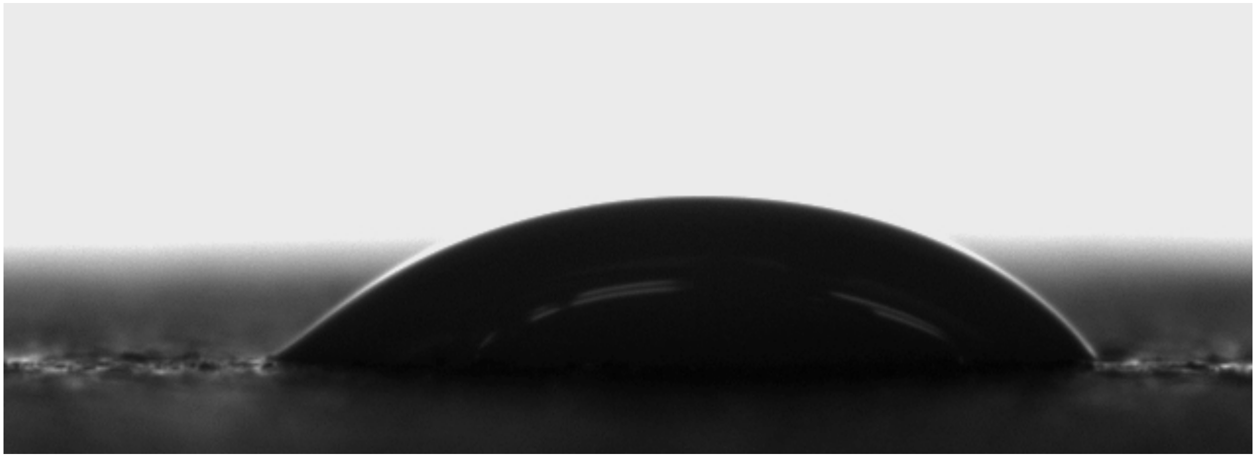
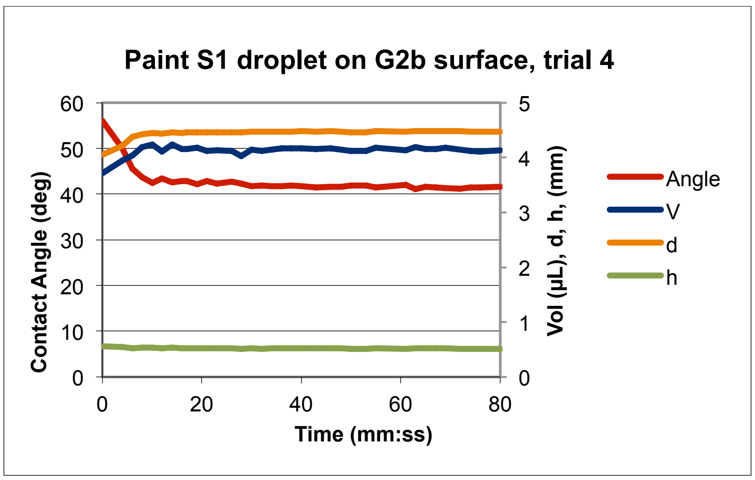
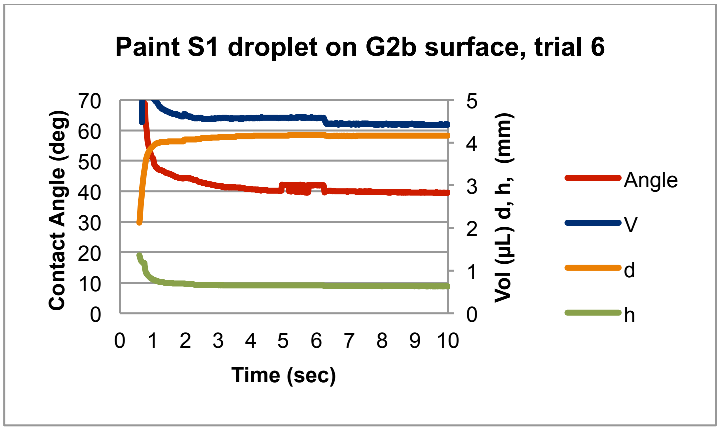


Image of a droplet of liquid paint S1 on G2b surface, trial 4 t = 6 sec, contact angle θ = 45º



Paint S1 liquid droplet on G2b surface, trial 4, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 45º.

Trial 5 data is not analyzed because trapped air bubble in the paint droplet is evident in the images.



Paint S1 liquid droplet on G2b surface, trial 6, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 40°.

Average value of the G2b-S1 contact angle is 46°.

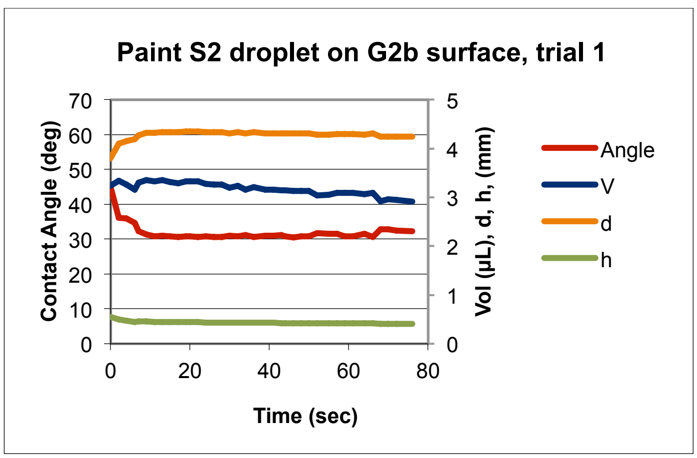
From Appendix E, the average pull-off strength of G2b-S1 coating system is 2389 ± 268 psi.

d. Test panel subgroup G2b-S2

Metal surface: (galvanized steel, stored in door for 2 weeks before blast profiling)

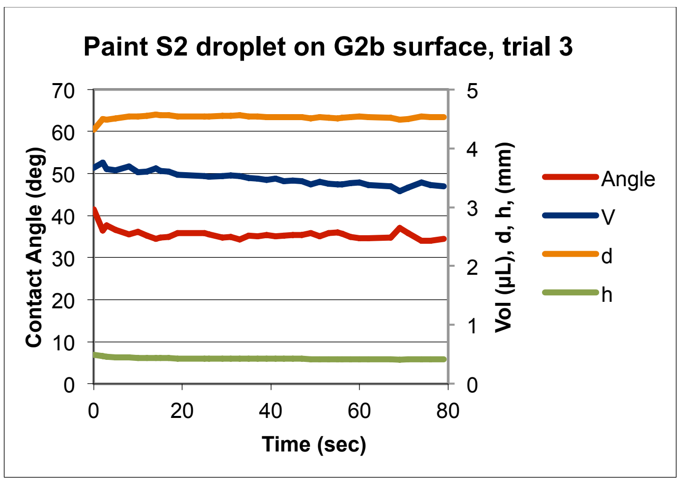
Paint droplet: Recoatable Epoxy Primer Series B67

G2b-S2, Trial 1. A droplet of paint S2 on Galvanized, stored for 2 weeks before blast profiling and painting. At t=5 sec, θ = 36 °



Paint S2 droplet on G2b surface, trial 3, contact angle, volume, width and height of the droplet as a function of time.

Image of a droplet of liquid paint S2 on G2b surface, trial 3, contact angle θ = 38º at t = 5 sec.



Paint S2 droplet on G2b surface, trial 3, contact angle, volume, width and height of the droplet as a function of time.

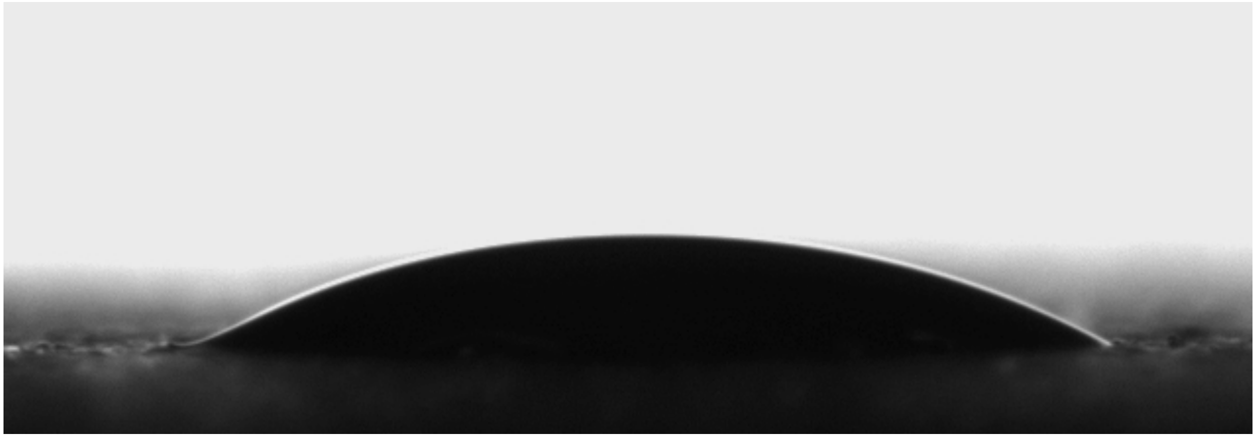
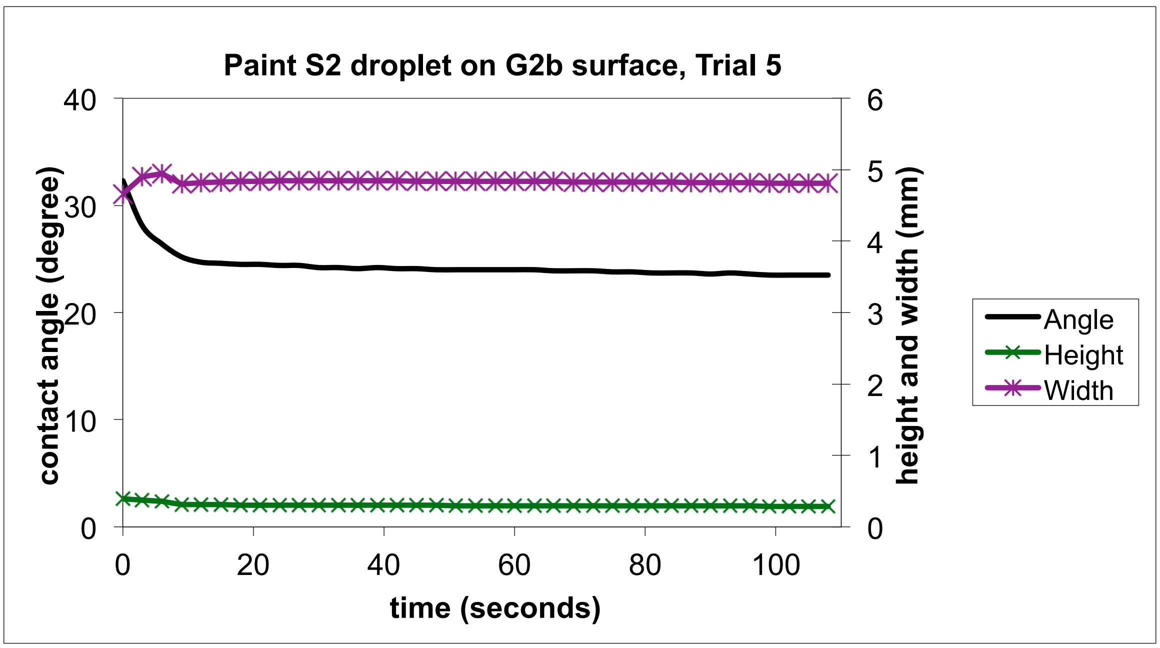


Image of a droplet of liquid paint S2 on G2b surface, trial 5, contact angle θ = 26° at t = 5 sec



Paint S2 droplet on G2b surface, trial 5, contact angle, width and height of the droplet as a function of time.

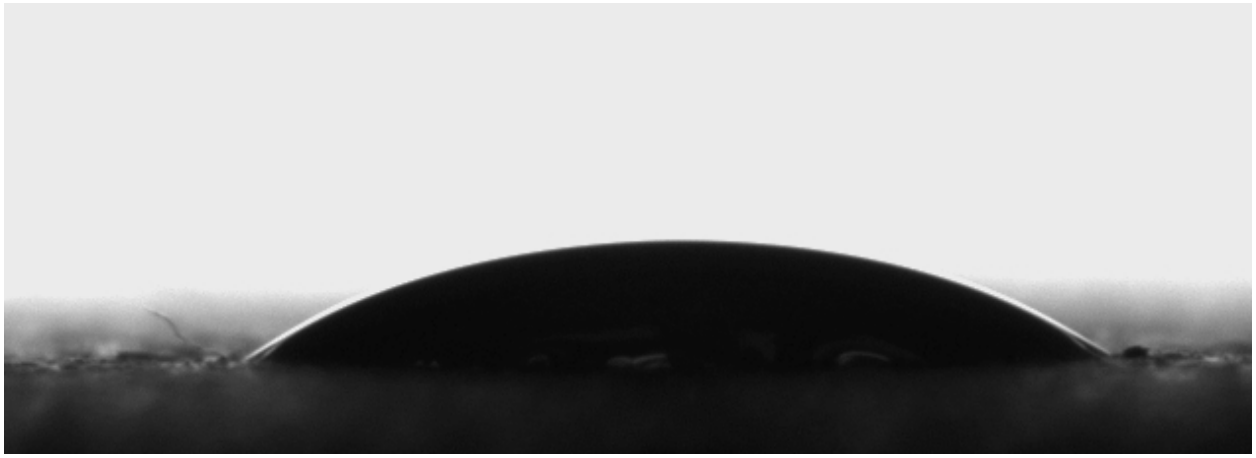
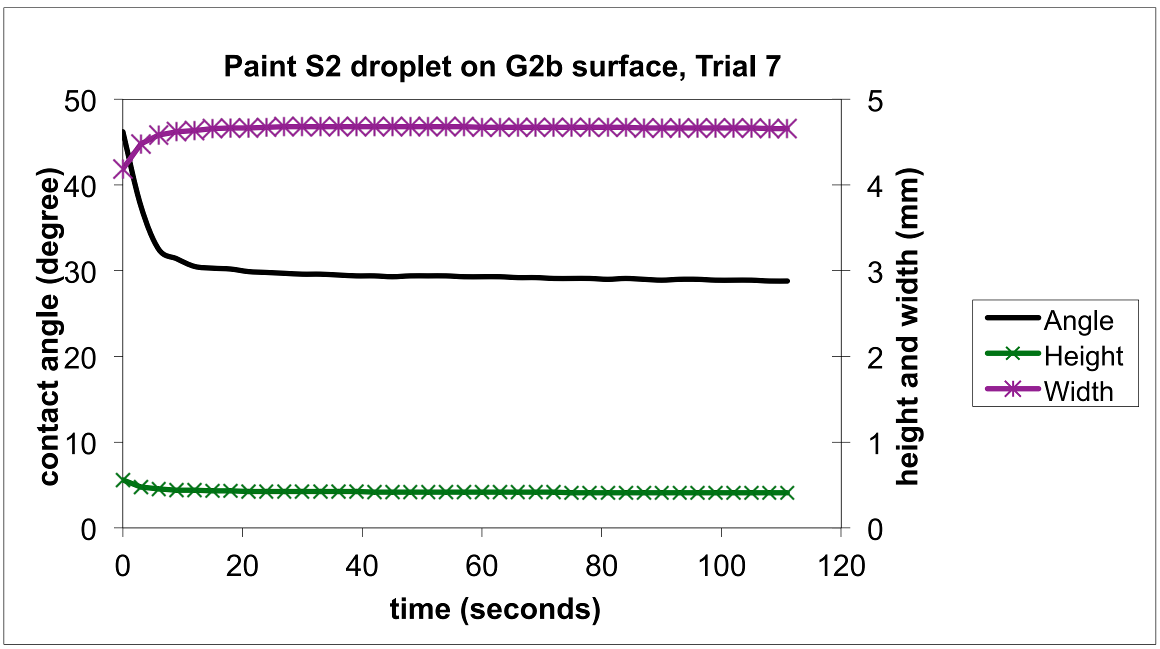
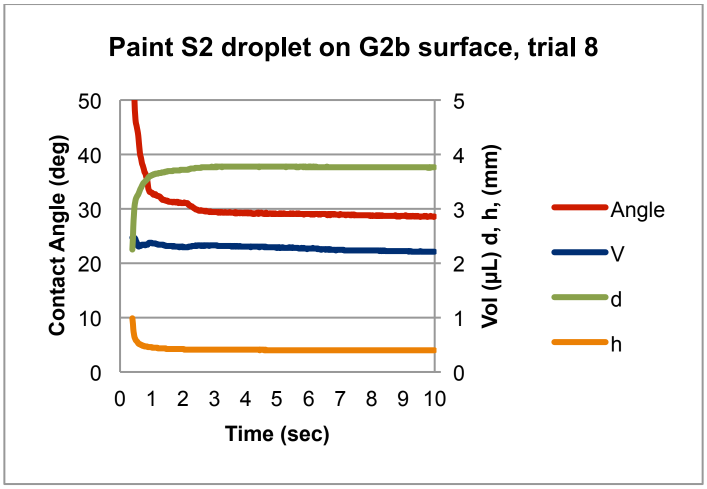


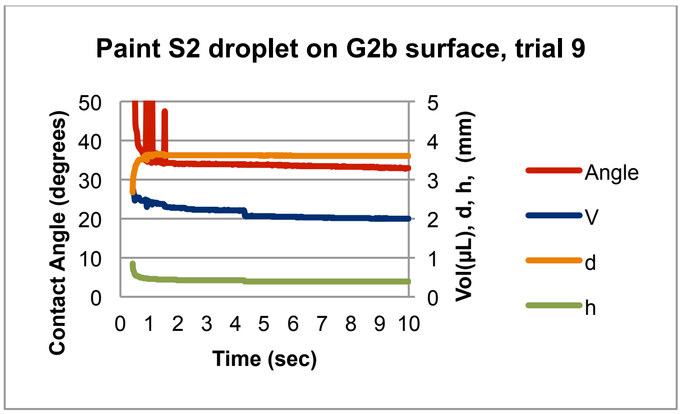
Image of a droplet of liquid paint S2 on G2b surface, trial 7, contact angle θ = 35° at t = 5 sec.



Paint S2 droplet on G2b surface, trial 7, contact angle, width and height of the droplet as a function of time.



Paint S2 liquid droplet on G2b surface, trial 8, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 29^{o} .



Paint S2 liquid droplet on G2b surface, trial 9, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 35^{o}.

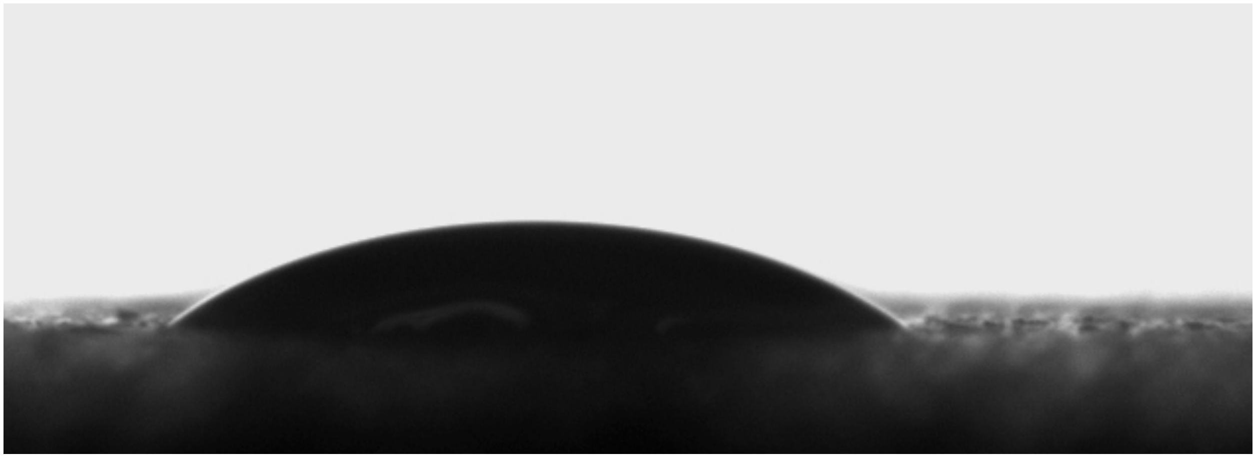
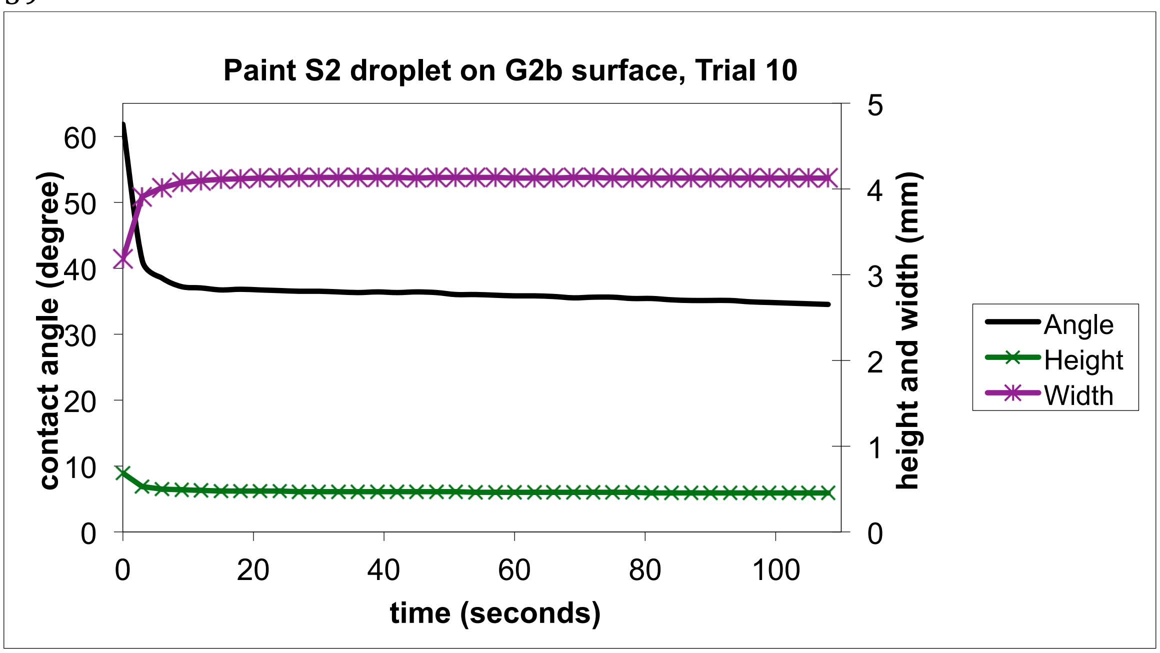
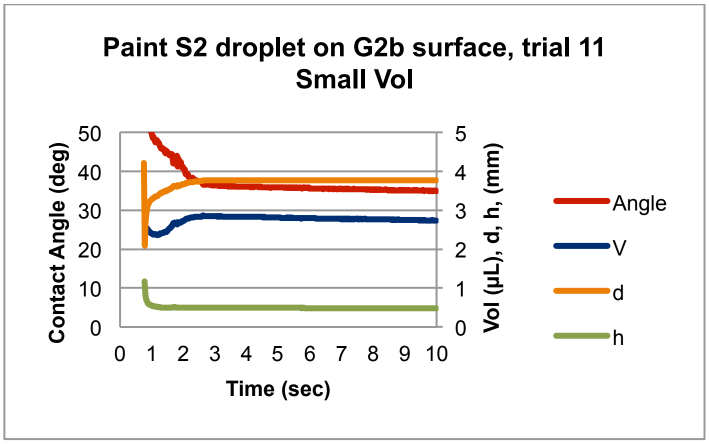


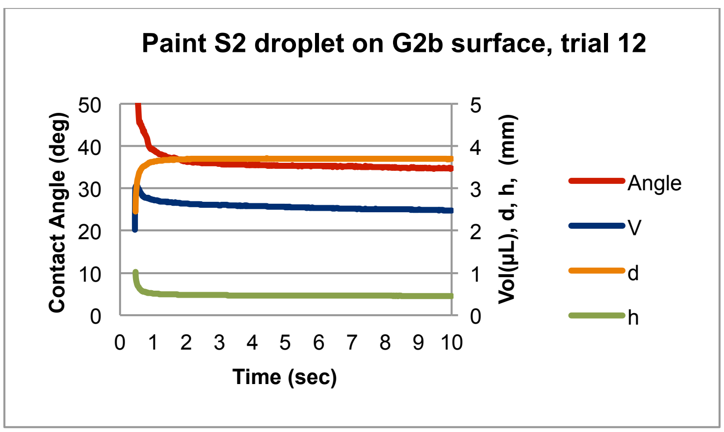
Image of paint S2 liquid droplet on G2b surface, trial 10 at t = 6 sec, contact angle θ = 39º



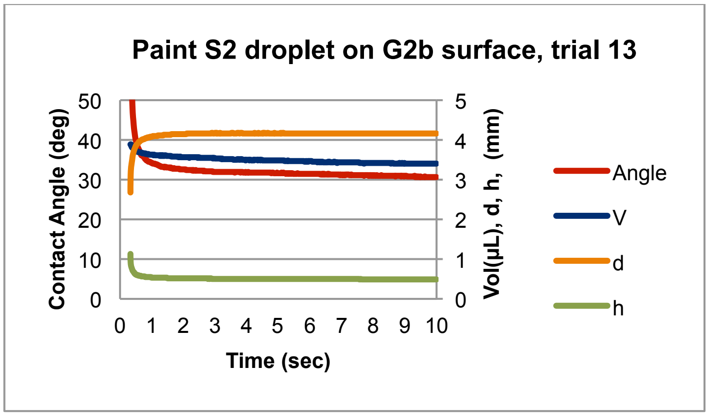
Paint S2 liquid droplet on G2b surface, trial 10, contact angle, height, and width of the droplet as a function of time, at t = 6 sec, contact angle θ = 39º



Paint S2 liquid droplet on G2b surface, trial 11, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 37º.



Paint S2 liquid droplet on G2b surface, trial 12, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 36º.



Paint S2 liquid droplet on G2b surface, trial 13, contact angle, height, width and volume of the droplet as a function of time. At t = 5 second, the contact angle θ = 31°.

Average value of G2b-S2 contact angle is θ = 35°

From Appendix E, the average pull off strength of G2b-S2 test panels: 1742 ± 197 psi

11.4 Appendix D

Photographic Images of test panels and the adhesive test results

The photos of the test panels are shown in this appendix. The images of the panels are grouped according to the substrate-paint interfaces. The pull-off strength test results (ASTM D4541) and the X-cut Tape test results (ASTM D3359) are summarized in a table. The pull-off strength is reported in the unit of lb per square inch (psi) followed with a description of the break surfaces after the dolly was pulled off. A system of abbreviation is used to describe the exposed surface. The following table shows the abbreviations used.

Abbreviation for a layer	Description of the layer
St	Steel substrate
Zn-G	Galvanized zinc coating
Zn-M	Metallized zinc coating
Zn-P	Painted zinc rich organic primer
Int	Intermediate coat
Top	Top coat
Glue	Adhesive used to attach the dolly to the topcoat.

We also try to describe the break as a "cohesive" or "adhesive" failure. A cohesive break is within the coating layer. An adhesive break is between two layers. In most cases the break surface is composed of more than one type of material. We estimate the percentage of coverage of each type of surface and report the estimated percentage coverage.

Several examples of the description of the pull-off surface break are shown here:

1. If the break was between the dolly and topcoat and the break surface is within the glue layer, the notation is "100% Glue."
2. If the pulled off dolly shows 100% surface area of the top coat while 100% of the area in the test spot of the panel shows the intermediate paint, showing an adhesive failure between the top and the intermediate paints, the notation is "100% adhesive between Top & Int".
3. If the surface of both the dolly and the panel test spot showed 100% coverage by the Topcoat, signifying a cohesive failure of the Topcoat, the notation would be "100% cohesive within Top".
4. If the dolly surface were covered 100% by the Intermediate paint and the panel test spot were covered 25% by the Intermediate paint with the remaining surface area showed bare galvanized zinc surface, the notation would be "75% adhesive between Int & Zn-G, 25% cohesive within Int."
5. If the break was completely in the Zn layer the notation would be "100% cohesive within Zn-G."

The X-cut tape test scores are also listed in the table of results. The scores were determined by the visual inspection of the cut. The 5-point scale specified by ASTM D3359 Type A corresponds to the following observations at the X-cut:

Score	Observation at the X-cut region after removal of tapes
5	No peeling or removal
4	Trace peeling or removal along incisions or at their intersection
3	Jagged removal along incisions up to 1/16 in. (1.6 mm) on either side
2	Jagged removal along most of incisions up to 1/8 in. (3.2 mm) on either side
1	Removal from most of the area of the X under the tape
0	Removal beyond the area of the X.

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	Test panel type		**Page number**
1.	Group G0m	Galvanized Coating / no delay / mechanical prep	D-04
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b.	Subgroup G0m-I		D-21
c.	Subgroup G0m-S1		D-37
d.	Subgroup G0m-S2		D-50
2.	Group G0b	Galvanized Coating / no delay / blast prep	D-63
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b.	Subgroup G0b-I		D-78
c.	Subgroup G0b-S1		D-90
d.	Subgroup G0b-S2		D-101
3.	Group M0	Metallized /no delay /no prep	D-112
a.	Subgroup M0-C		D-113
b.	Subgroup M0-I		D-126
c.	Subgroup M0-S1		D-139
d.	Subgroup M0-S2		D-152
e.	Subgroup M0-S3		D-164
4.	Group G2b	Galvanized Coating / 2 wk delay / blast prep	D-176
a.	Subgroup G2b-C		D-177
b.	Subgroup G2b-I		D-194
c.	Subgroup G2b-S1		D-211
d.	Subgroup G2b-S2		D-228
5.	Group Z Control system / blast /no delay/zinc rich primer/paint		D-245
a.	Subgroup Z-C		D-246
b.	Subgroup Z-I		D-258
c.	Subgroup Z-S1		D-270
d.	Subgroup Z-S2		D-282
e.	Subgroup Z-S3		D-294

(Z-S3 Panels not fabricated, S3 sealant not designed for coating on primers)

1. Group G0m: List and photographic image of the tested panels.

This group of test panels was made from galvanized steel with mechanical grinding profiling of the zinc surface. The galvanizing, surface profiling and the application of the epoxy paint were performed on the same day.
This group of test panels is labeled as group "G0m". In this group label "G" signifies the galvanizing process, "0" signifies zero delay time (same day) between galvanizing and blast profiling. The finish paint was done after the epoxy layer was cured. Four different paint systems were used for the subgroups with the following designations for the subgroups and the test panels.

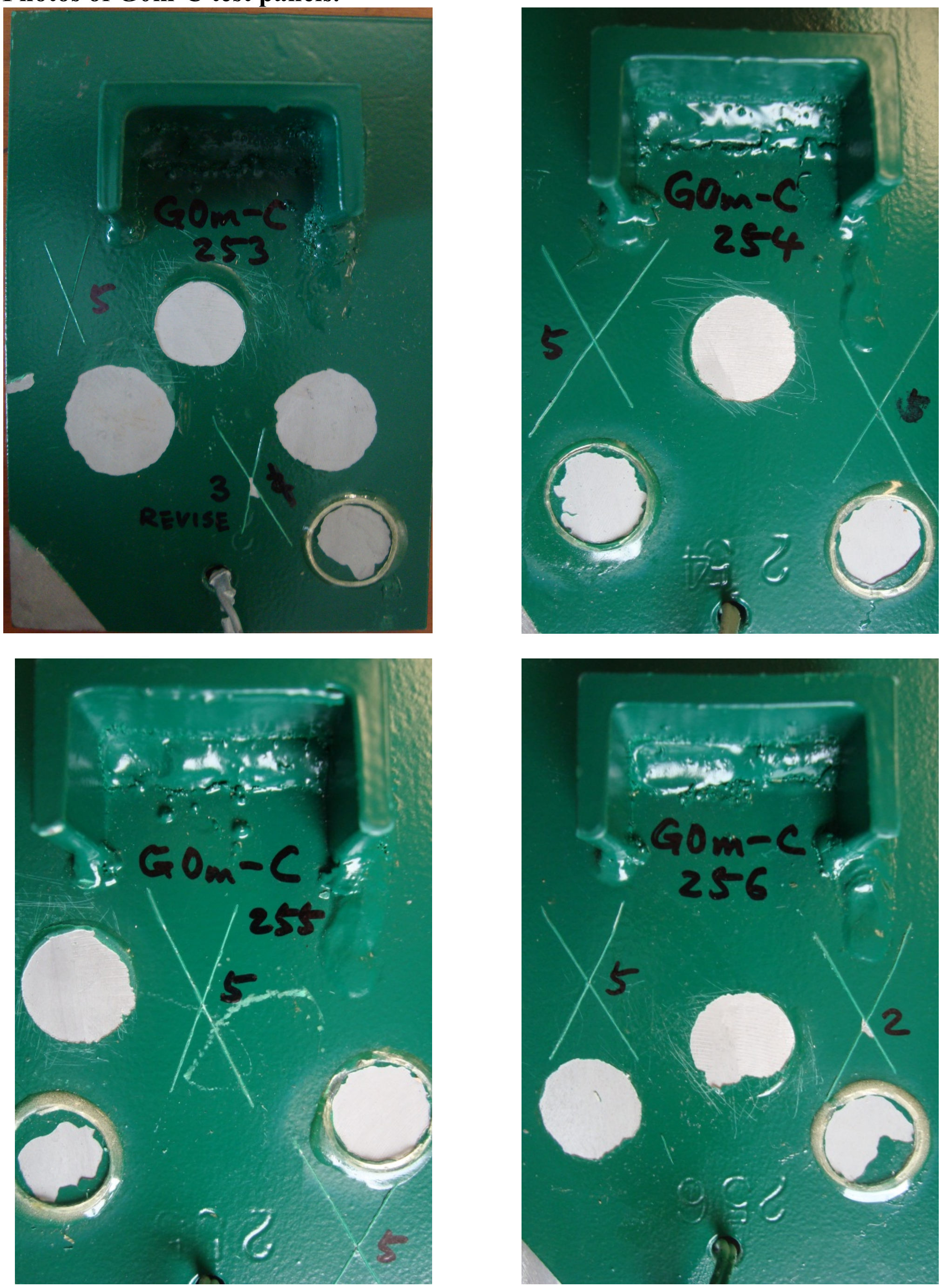
Each pull-off test spot on a test panel is given an identification number according to the following convention: We assign the uppermost test spot in the images of the panels as test sample #1. Pretending that sample #1 is at the 12-oclock position of a clock, the remaining test spots are ordered according to its position in the clockwise rotation order. Occasionally, a pull-off test is omitted from the list because of technical problems observed during the test. For example the dolly was not property glued to the paint surface, or the surface near the test spot is too close to a welding burr so that the tester cannot be seated correctly. A replacement test is listed (using a different test spot identification number) is listed in the table in place of the omitted test.

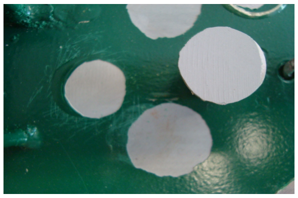
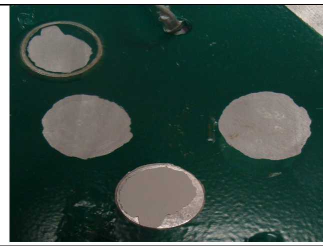
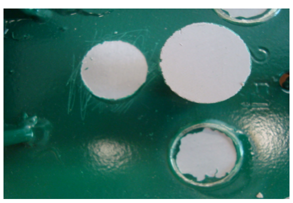
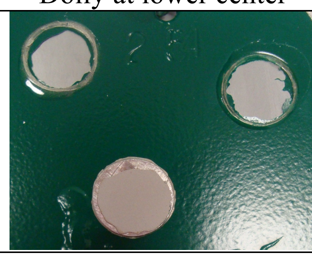
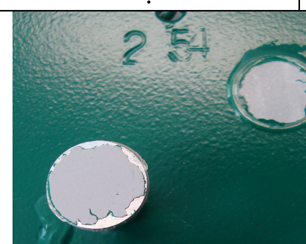
1.a. Test panel subgroup G0m-C

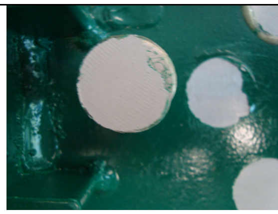
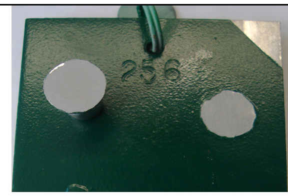
Primer:	galvanizing followed by mechanical profiling
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

Test panel numbers 253, 254, 255, 256 stored in box 1

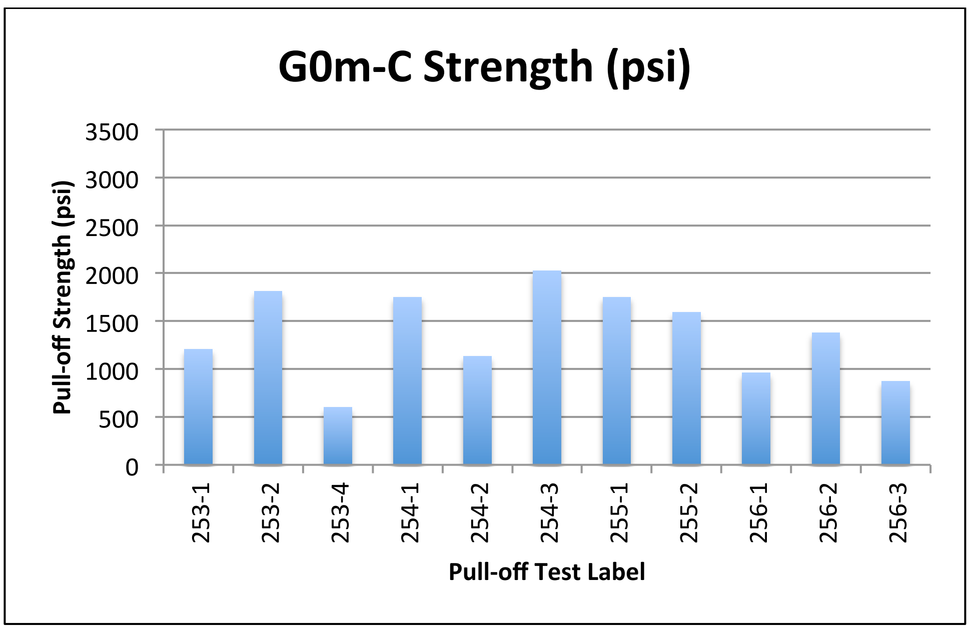
1.a.1 Photos of G0m-C test panels.



1.a.2 Adhesive strengh test results for G0m-C test panels					
Test Panel	Pull Test 1	Pull Test 2 (or Test 3 if Test 2 is not shown)	Pull Test 3 (or Test 4 if Test 3 is not shown)	X-cut 1 Score	X-cut 2 Score
253				5	4
	Strength: 1208 psi	Strength: 1811 psi (Test 3)	Strength: 600 psi (Test 4)		
	Break: 95% adhesion between Int & Zn-G/ 5% adhesion btwn Glue and Top	Break: 85% cohesion within Int; 15% Adhesion between Int and Zn-G.	Break: 100% adhesion between Int and Zn-G		
	Test spot center left Dolly at center right	Test spot at upper left Dolly at lower center	Dolly at upper right .		
254				5	5
	Strength: 1766 psi	Strength: 1134 psi	Strength: 2028 psi		
	Break: 100% cohesion within Int.	Break: 85% cohesion within Int; 15% adhesion between Glue and Top.	Break: 90% adhesion between Int and Zn-G; 10% adhesion between glue and Top.		
	Test spot at upper left. Dolly at upper right.	Test spot at upper left. Dolly at lower center.	Test spot at upper right. Dolly at lower left		
255				5	5
	Strength: 1752 psi	Strength: 1594 psi	Pull-off Strength: Not valid (119 psi)		
	Break: 100% adhesion between Int and Zn-G.	Break: 100% adhesion between Int and Zn-G.	Tilted tester		
	Dolly at left	Dolly at right	Dolly at lower right		

1.a.2 Adhesive strength test results for G0m-C test panels (continued)					
Test Panel	Pull Test 1	Pull Test 2	Pull Test 3	X-cut 1 Score	X-cut 2 Score
256				5	4
	Strength: 961 psi	Strength: 1379 psi	Strength: 872 psi		
	Break: 85% adhesion between Int and Zn-G; 15% adhesion between Glue and Top	Break: 70% cohesion within Int; 30% adhesion between Glue and Top	Break: 100% adhesion between Int and Zn-G.		
	Test spot center right Dolly at left.	Test spot at lower center. Dolly at Upper left.	Dolly at left		

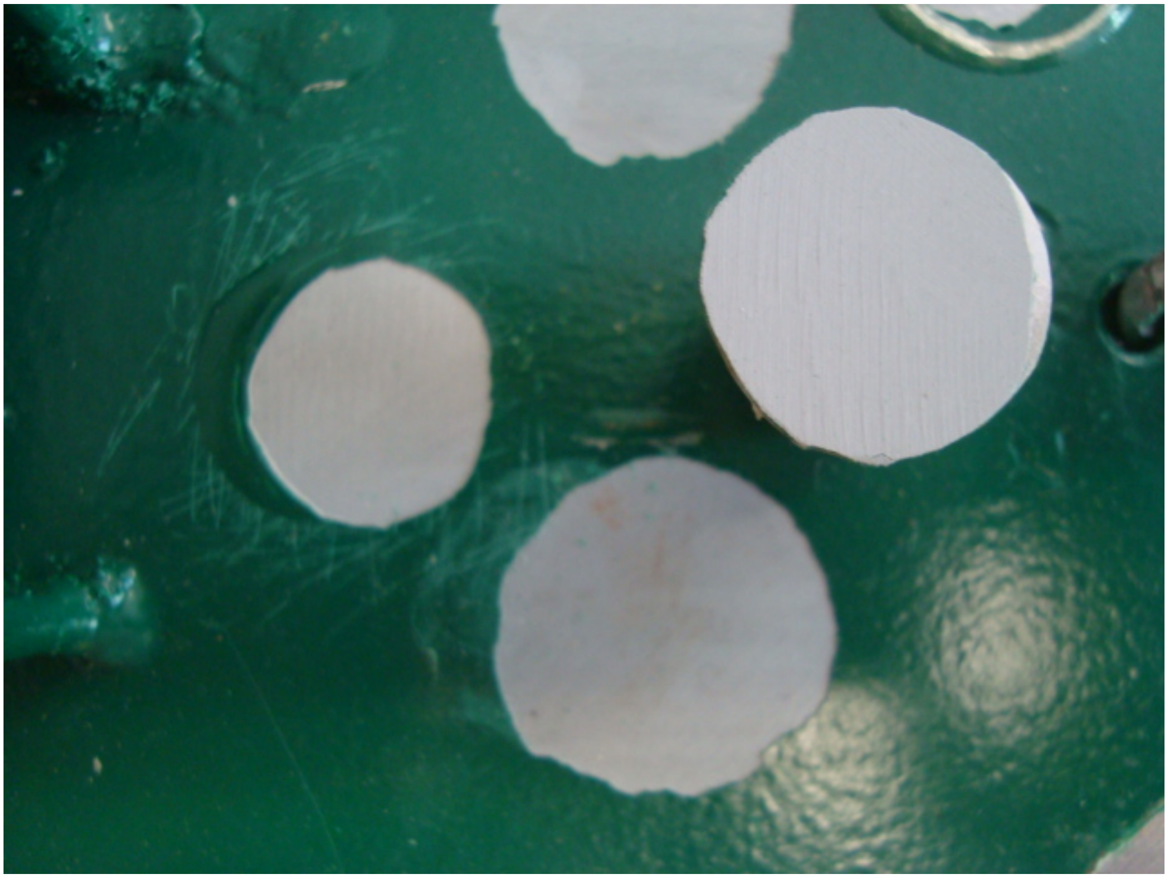
Pull-off Test	G0m-C
Panel#-Test#	Strength (psi)
253-1	1208
253-2	1811
253-4	600
254-1	1752
254-2	1134
254-3	2028
255-1	1752
255-2	1594
256-1	961
256-2	1379
256-3	872
Average	1372
Standard Dev	433
Confidence	256



1.a.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

1.a.3.1 Panel #253, G0m-C

1.a.3.1.1 Panel 253 test 1. G0m-C



Pull-off strength 1208 psi, Test spot at center left.

Break: 95% adhesion between Int and Zn-G; 5% Adhesion between Glue and Top.

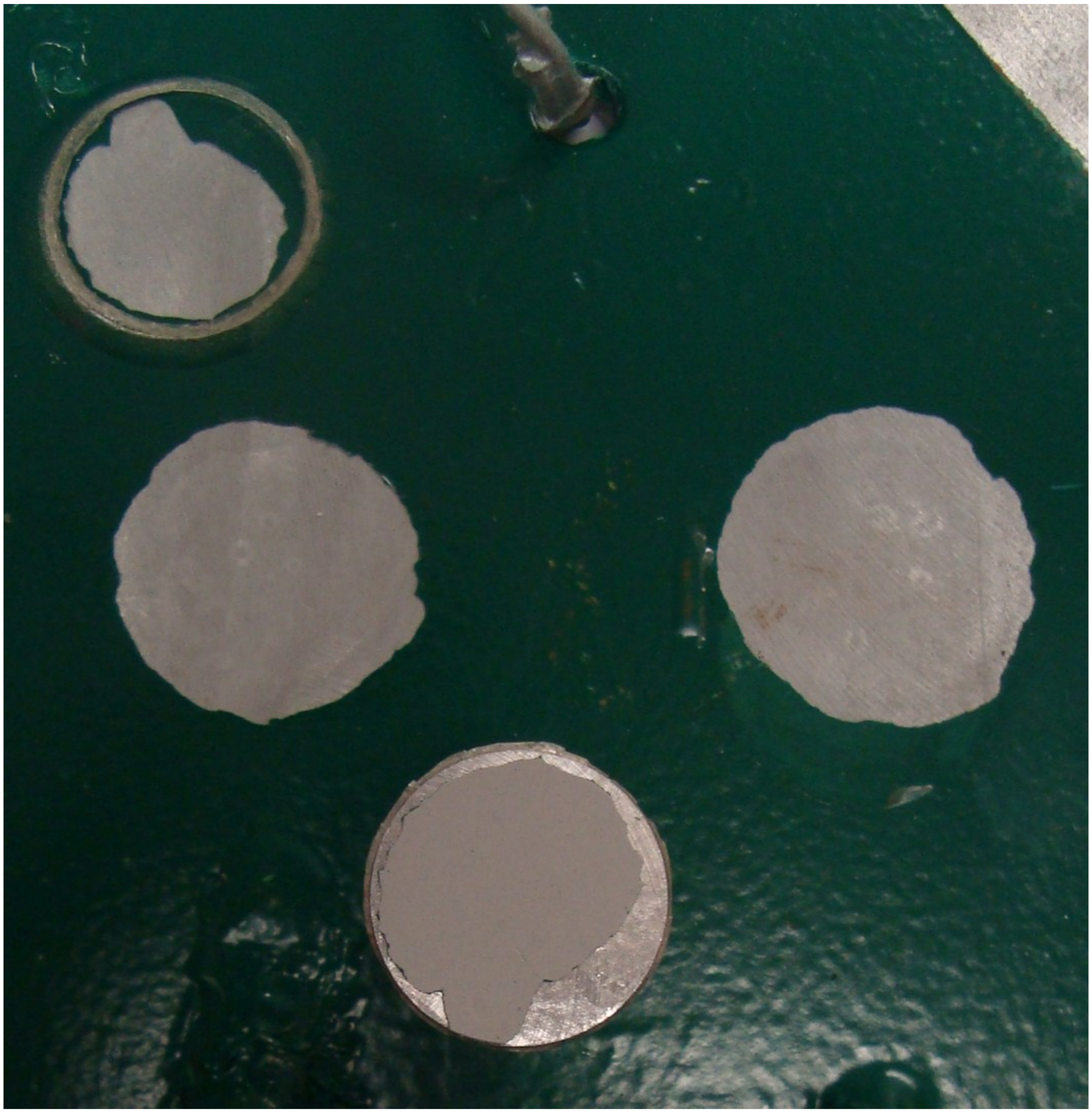
(Notice the matching tracks on dolly. They are replicas of the mechanically roughened track on substrate)

Dolly at center right (pull-off spot at middle left.)

1.a.3.1.2 Panel 253 Test 2, Paint G0m-C

Panel 253 test 2 was not recorded. The base of the pull-off tester was tilted when pulling thus the data was invalidated. The test spot was too close to an uneven surface resulting from the welding residue for the U-channel.

1.a.3.1.3 Panel 253 Test 3, G0m-C



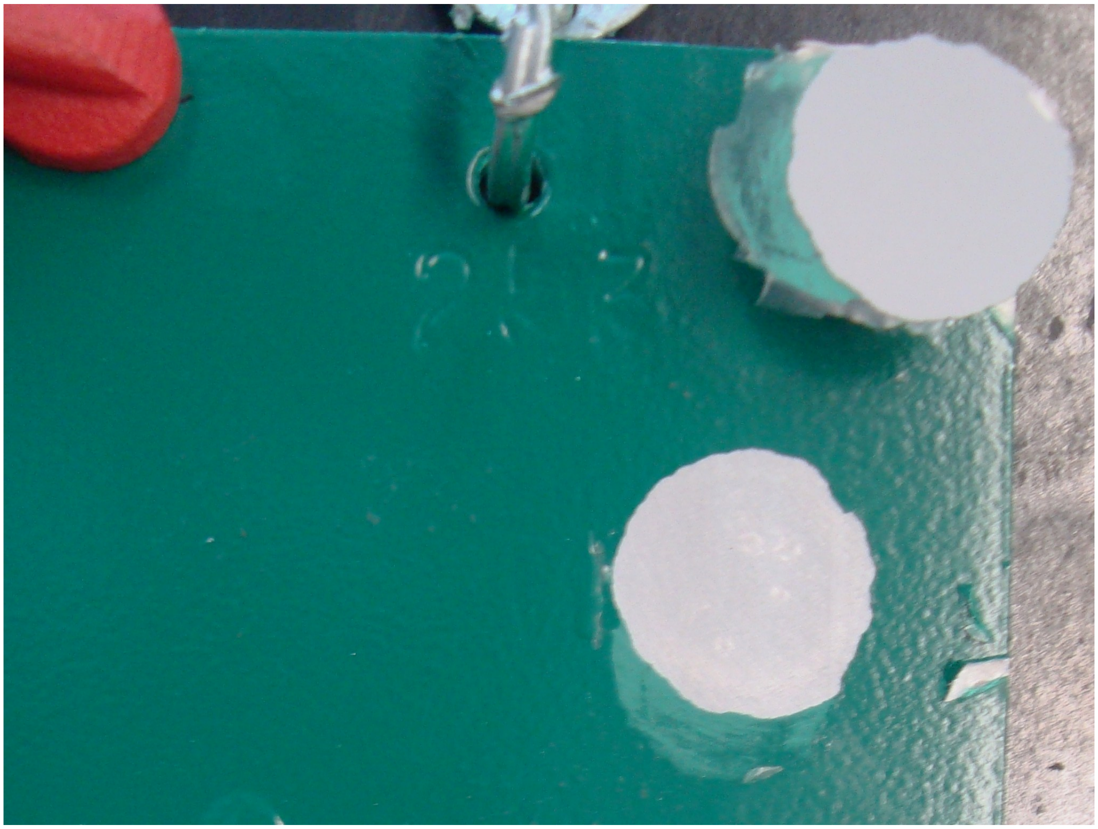
Panel 253 Test 3. G0m-C

Pull-off strength 1811 psi,

Break: 85% cohesion within Int; 15% Adhesion between Int and Zn-G.

Dolly at Lower Center

1.a.3.1.4 Panel 253 Test 4, G0m-C



Panel 253 Test 4. G0m-C

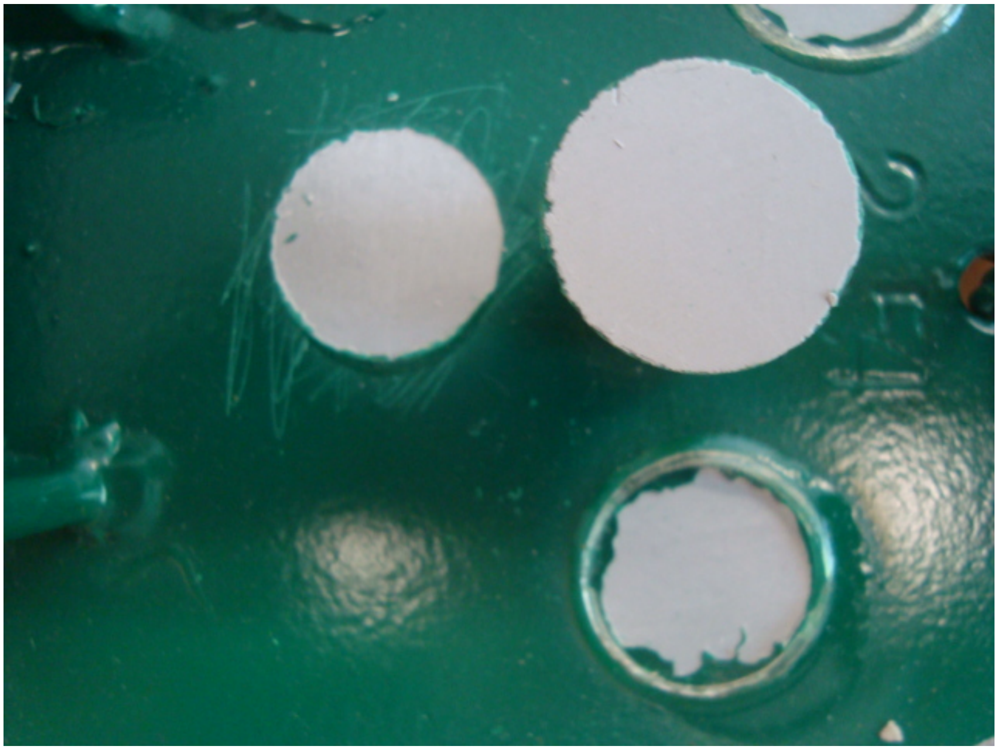
Pull-off Strength 600 psi,

Break: 100% adhesion between Int and Zn-G

Dolly at upper right, test spot at lower right

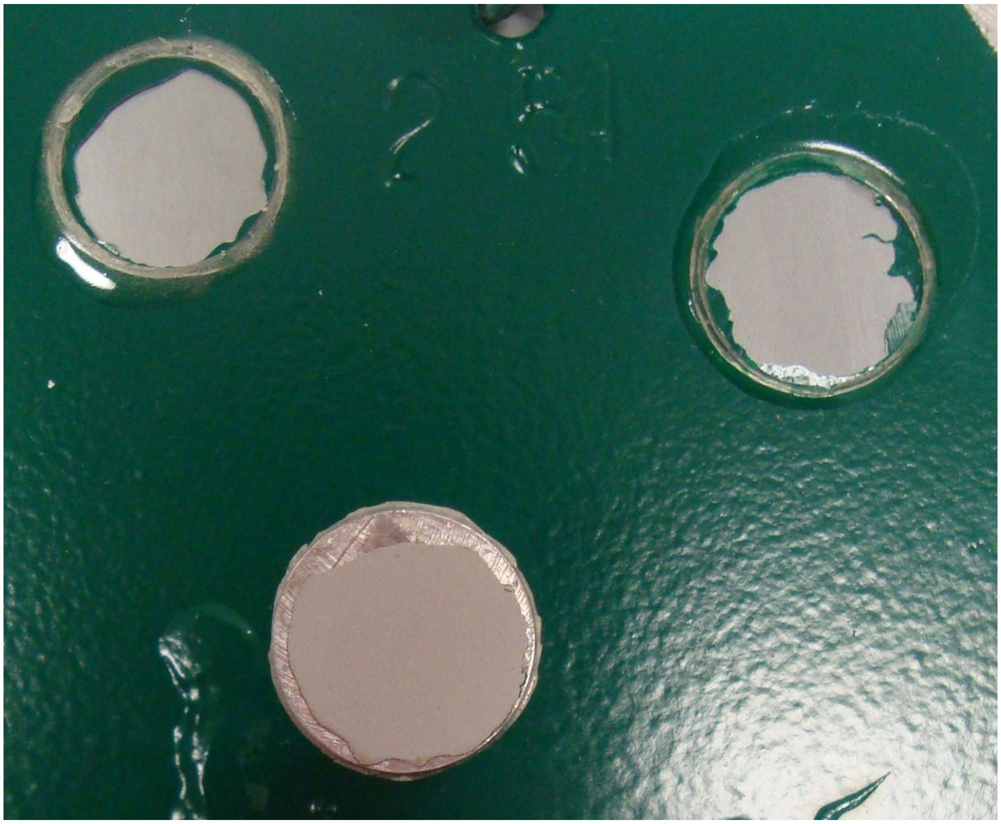
1.a.3.2 Panel #254, G0m-C

1.a.3.2.1 Panel 254 Test 1, G0m-C



Panel 254 Test 1. G0m-C
Pull-off strength 1766 psi,
Break: 100% cohesion within Int.
Dolly at upper right, Test spot at upper left.

1.a.3.2.2 Panel 254 Test 2, G0m-C



Panel 254 Test 2. G0m-C

Pull-off strength 1134 psi,

Break: 85% cohesion within Int ; 15% adhesion between Glue and Top.

Dolly at lower center, Test spot at upper left.

1.a.3.2.3 Panel 254 Test 3, G0m-C

Panel 254 Test 3. G0m-C

Pull-off strength: 2028 psi. Test sample image at upper right

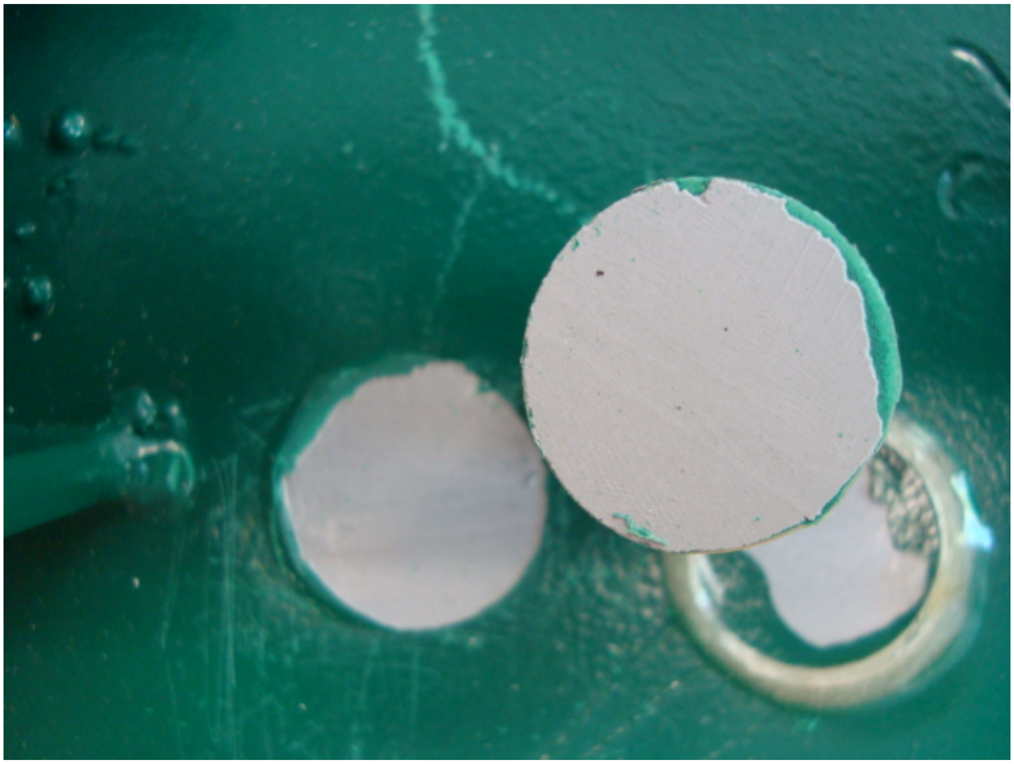
Break: 90% adhesion between Int and Zn-G; 10% adhesion between glue and Top.

Dolly at lower left.

(Notice the track mark on the Int surface of dolly. They match the mechanically grinded track on the substrate).

1.a.3.3 Panel #255 G0m-C

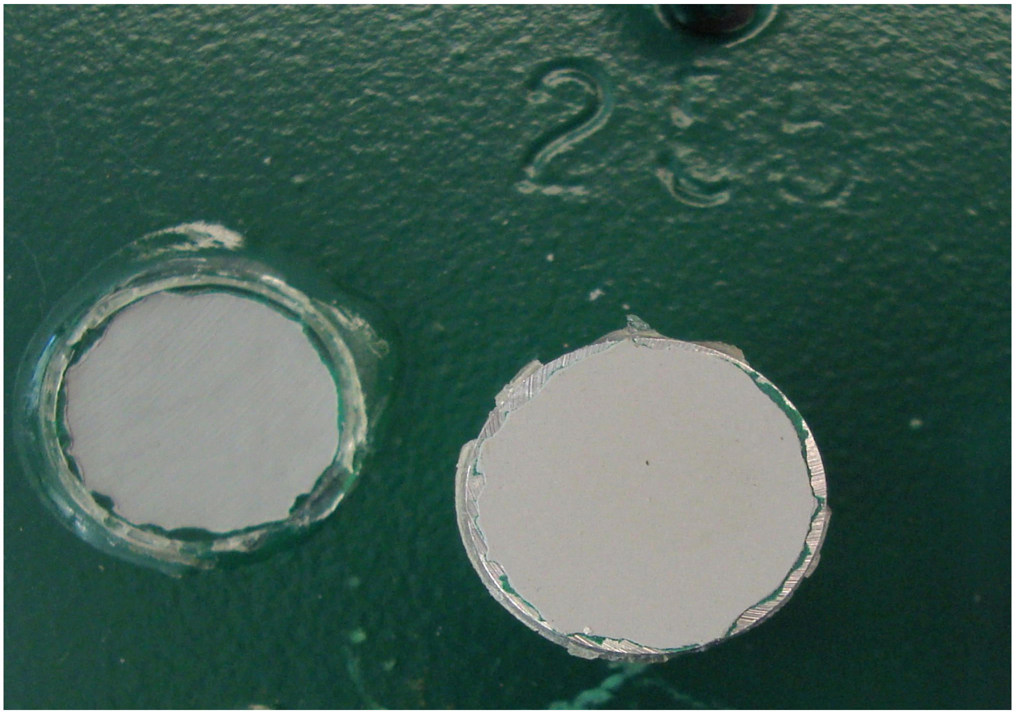
1.a.3.3.1 Panel #255 G0m-C, Test 1



Panel 255 Test 1. G0m-C

Pull-off strength: 1752 psi, test spot at lower center, dolly at center right.
Break: 100% adhesion between Int and Zn-G. (Notice the parallel ridgelines on the intermediate paint on the dolly. The ridgelines match with the grooves on the G0m substrate.)
Dolly at center right.

1.a.3.3.2 Panel #255 G0m-C, Test 2

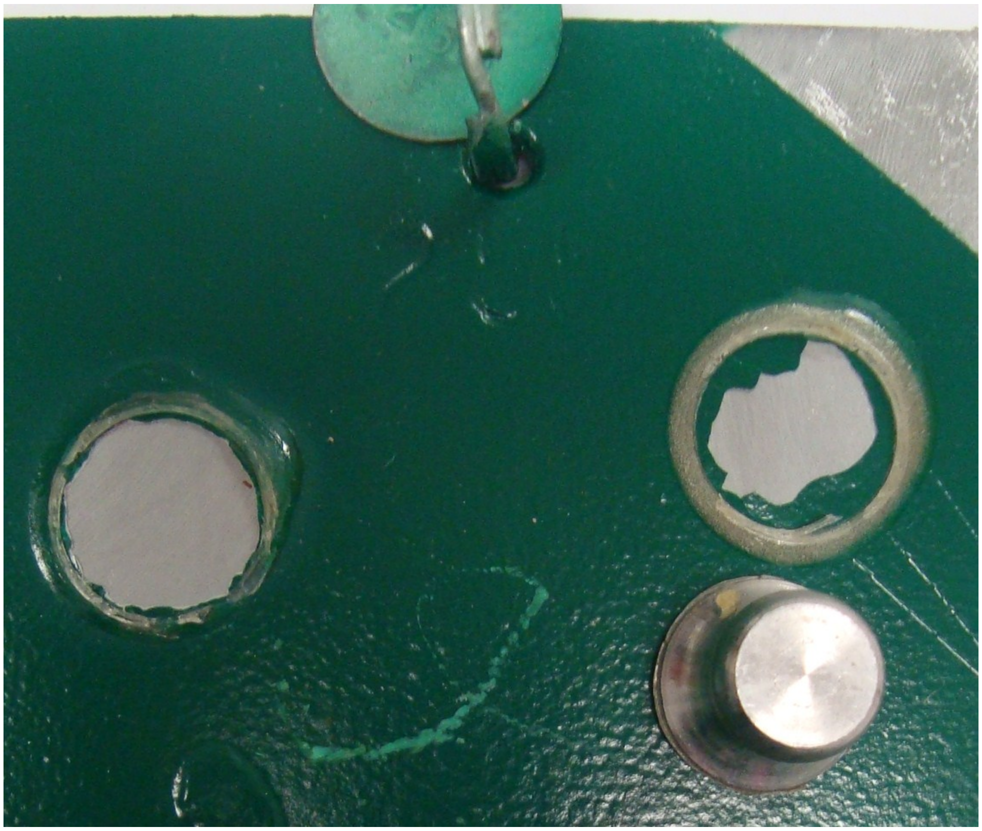


Panel 255 Test 2. G0m-C

Pull-off Strength: 1594 psi, Test spot at left

Break: 100% adhesion between Int and Zn-G. (Notice the track of the mechanically roughened Zn-G surface on the test spot. There is a thin layer of Int left on the substrate.) Dolly at right.

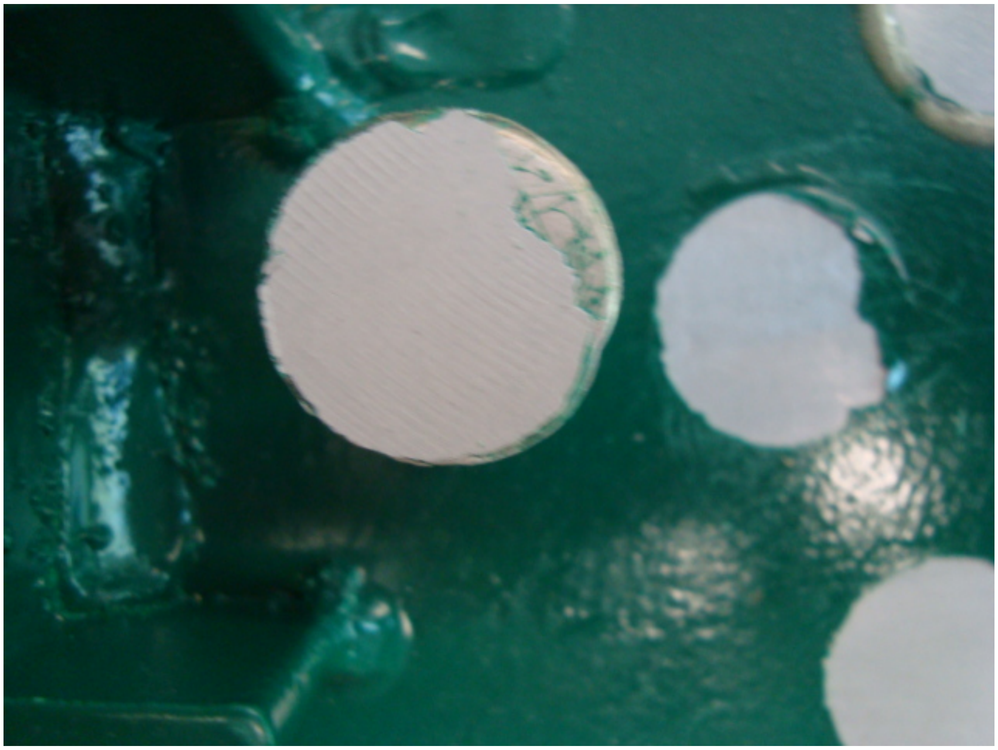
1.a.3.3.3 Panel #255 G0m-C, Test 3



Panel 255 Test 3. Invalid data, dolly was tilted, pulled off at reading of 119 psi. Test spot at central right. Dolly (adhesive surface not shown) at lower right.

1.a.3.4 Panel #256, G0m-C

1.a.3.4.1 Panel #256, G0m-C, Test 1



Panel 256 Test 1.

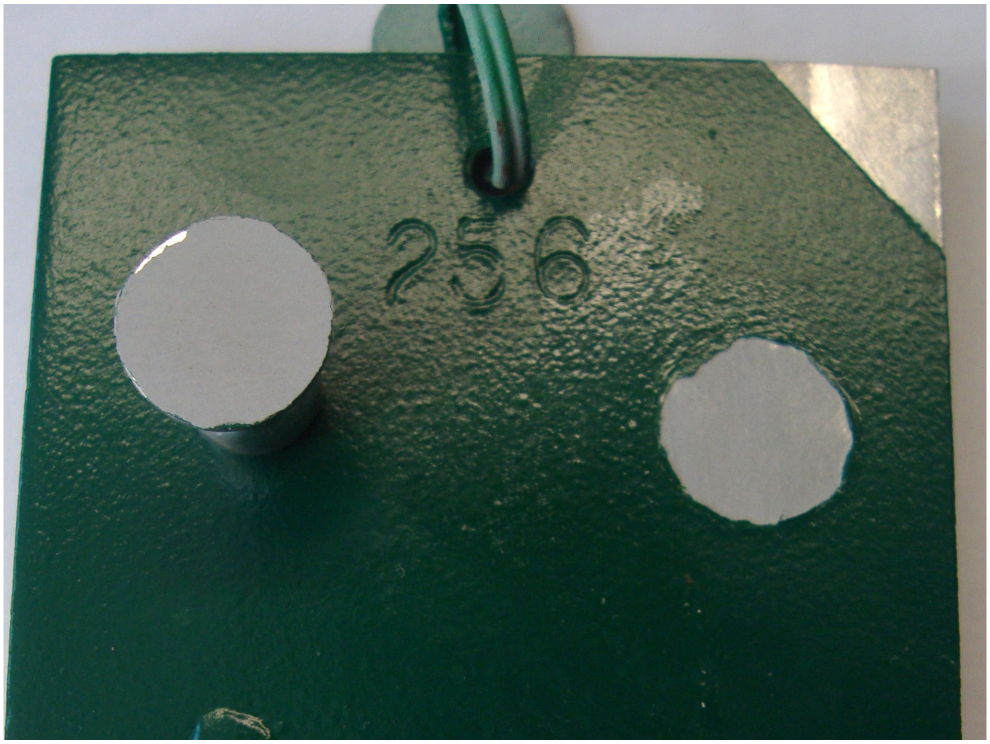
Pull-off strength: 961 psi, Test spot at center right, Dolly at left.
Break: 85% adhesion between Int and Zn-G; 15% adhesion between Glue and Top.
(Note that the line tracks on the surface of the intermediate paint on the dolly matches with the mechanically grinding tracks on the G0m substrate surface.)
Dolly at left.

1.a.3.4.2 Panel #256, G0m-C, Test 2

Panel 256 Test 2.

Pull-off strength: 1379 psi, Test spot at upper left, Dolly at lower center,
Break: 70% cohesion within Int; 30% adhesion between Glue and Top.
Dolly at lower center.

1.a.3.4.3 Panel #256, G0m-C, Test 3



Panel 256 Test 3.

Pull-off strength: 872 psi, test spot at right, dolly at left,

Break: 100% adhesion between Int and Zn-G. (Note that the metallic shine of the Zn-G surface is partially visible through the nearly transparent Int paint remaining on Zn-G substrate.)

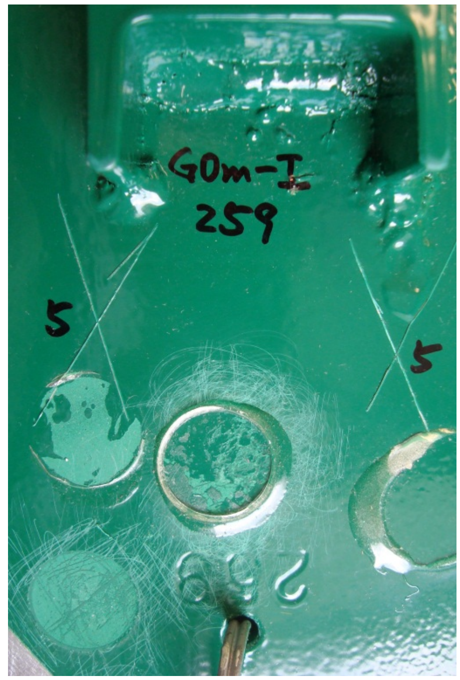
Dolly at left.

1.b Test panel subgroup G0m-I

Primer:	Galvanizing, mechanical profiling and painted on the same day
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

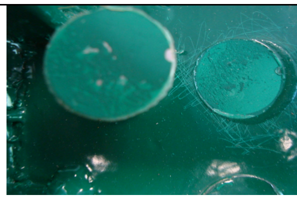
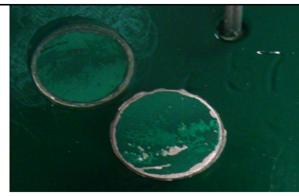
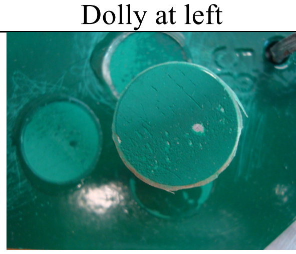
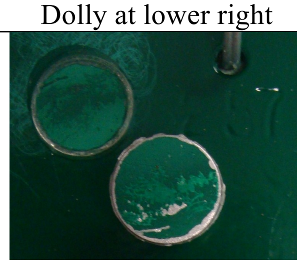
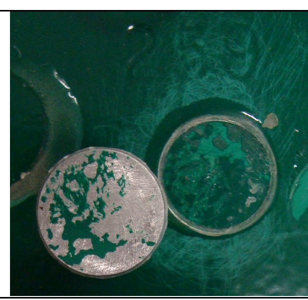
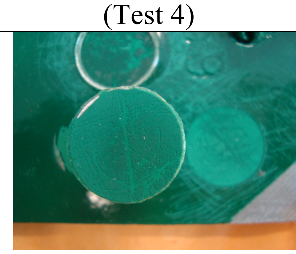
Panel numbers 257, 258, 259, 260, stored in box 2

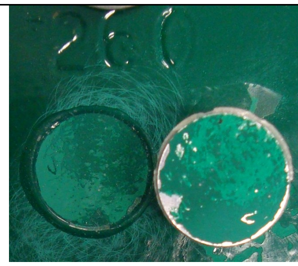
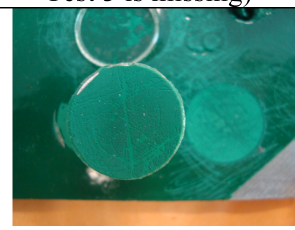
1.b.1 Photos of G0m-I test panels.



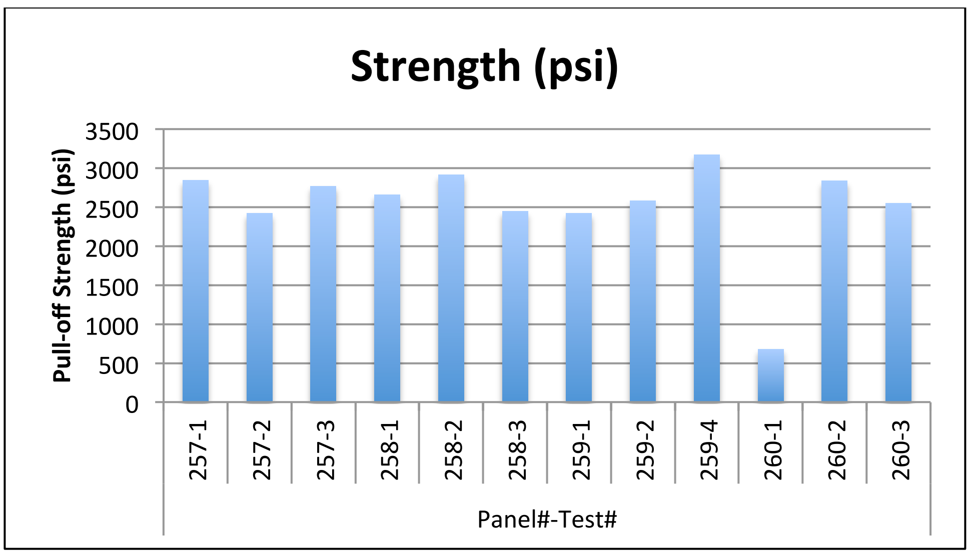
1.b.2 Adhesive strength test results for G0m-I test panels

1.b.2 Adhesive strength test results for G0m-I test panels

Test Panel	Pull Test 1	Pull Test 2	Pull Test 3 (or Test 4 if Test 3 is missing)	X-cut 1 Score	X-cut 2 Score
257				5	5
	Strength: 2844 psi	Strength: 2421 psi	Strength: 2770 psi		
	Break: 95% cohesive within Top; 5% adhesive between Glue and Top	Break: 90% cohesive within Top; 10% Glue, Dolly at lower right.	Break: 70% adhesion between Glue and Top; 30% cohesion within Top.		
	Dolly at left	Dolly at lower right	Dolly at left.		
258			 Test 4 shown (no Test 3)	5	5
	Strength: 2660 psi	Strength: 2912 psi	Strength: 2448 psi		
	Break: 97% cohesive within Top; 3% adhesive between Glue and Top.	Break: 80% cohesive within Top; 20% adhesive between Glue and Top.	Break: 80% adhesive between Glue and Top; 20% cohesive within Top		
	Dolly at right.	Dolly at lower right	Dolly at left. (Test 4)		
259			 Test 4 Shown (no Test 3)	5	5
	Strength: 2423 psi	Strength: 2582 psi	Strength: 3170 psi		
	Break: 70% cohesive within Top; 30% adhesive between Glue and Top.	Break: 85% adhesive between Glue and Top; 15% cohesive within Top.	Break: 100% cohesive within Top.		
	Dolly at left.	Dolly at lower left.	Dolly at left, test spot at right. Note: Test 4		

1.b.2 Adhesive strength test results for G0m-I test panel 260					
Test Panel	Pull Test 1	Pull Test 2	Pull Test 3 (or Test 4 or Test 5 if Test 3 is missing)	X-cut 1 Score	X-cut 2 Score
260				5	5
	Strength: 680 psi	Strength: 2835 psi	Strength: 2551 psi		
	Break: 50% adhesive between Glue and Top; 50% cohesive within Top	Break: 85% adhesive between Glue and Top; 15% cohesive within Top.	Break: 97% cohesive within Top; 3% adhesive between Glue and Top.		
	Dolly at lower center, test spot at right.	Dolly at lower left.	Dolly at right. Note: Test 5 shown		

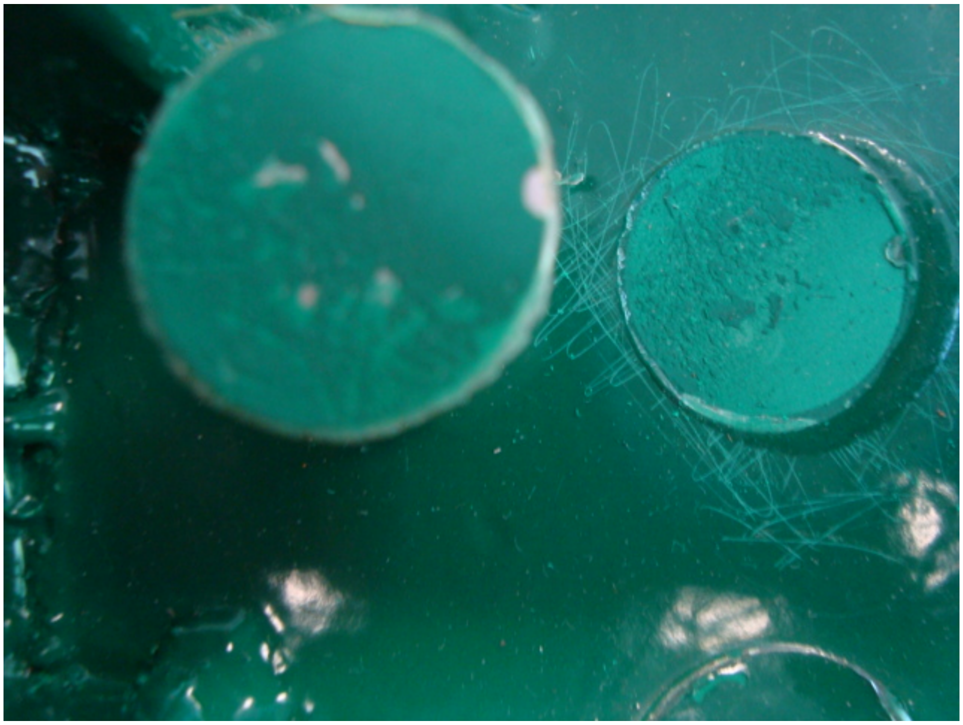
Pull-off Test	G0m-I
Panel#-Test#	Strength (psi)
257-1	2844
257-2	2421
257-3	2770
258-1	2660
258-2	2912
258-3	2448
259-1	2423
259-2	2582
259-4	3170
260-1	680
260-2	2835
260-3	2551
Average	2525
Standard Dev	597
Confidence	338



1.b.3 Enlarged photos of the pull-off dolly on the panel, and a description of the break layers.

1.b.3.1 Panel #257, G0m-I, Test 2

1.b.3.1.1 Panel #257, G0m-I, Test 1



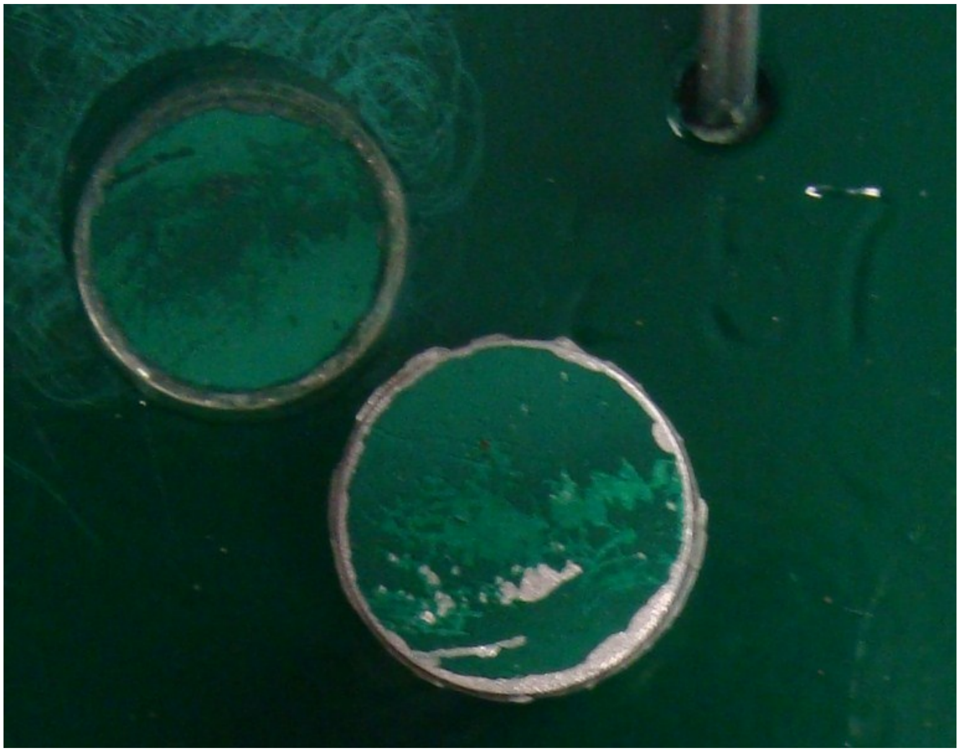
Panel 257 Test 1. G0m-I

Pull-off strength: 2844 psi.

Break: 95% cohesive within Top; 5% adhesive between Glue and Top.

Dolly at left.

1.b.3.1.2 Panel #257, G0m-I, Test 2



Panel 257 Test 2. G0m-I

Pull-off strength: 2421 psi,

Break: 90% cohesive within Top; 10% Glue,

Dolly at lower right.

1.b.3.1.3 Panel #257, G0m-I, Test 3

Panel 257 Test 3. G0m-I

Pull-off strength 2770 psi.

Break: 70% adhesion between Glue and Top; 30% cohesion within Top.

Dolly at left.

1.b.3.2 Panel #258, coating system G0m-I

1.b.3.2.1 Panel #258, coating system G0m-I, Test 1

Panel 258 Test 1. G0m-I

Pull-off strength 2660 psi.

Break: 97% cohesive within Top; 3% adhesive between Glue and Top.

Dolly at right.

1.b.3.2.2 Panel #258, coating system G0m-I, Test 2

Panel 258 Test 2. G0m-I

Pull-off strength 2912 psi.

Break: 80% cohesive within Top; 20% adhesive between Glue and Top.

Dolly at lower right.

1.b.3.2.3 Panel #258, coating system G0m-I, Test 3

The pull-off strength for Panel 258 Test 3 was not recorded. The adhesion between the Glue and Top was too weak to be meaningful. The Top paint surface was too smooth to have sufficient Glue-to-Top adhesion. The top paint surface was roughened by sanding for the other tests and the Glue-to-Top adhesion was sufficient after sanding.

1.b.3.2.4 Panel #258, coating system G0m-I, Test 4

Panel 258 Test 4. G0m-I

Pull-off strength: 2448 psi.

Break: 80% adhesive between Glue and Top; 20% cohesive within Top.

Dolly at left.

1.b.3.3 Panel #259, G0m-I

1.b.3.3.1 Panel #259, G0m-I, Test 1

Panel 259 Test 1. G0m-I

Pull-off strength: 2423 psi.

Break: 70% cohesive within Top; 30% adhesive between Glue and Top.

Dolly at left.

1.b.3.3.2 Panel #259, G0m-I, Test 2

Panel 259 Test 2. G0m-I

Pull-off strength: 2582 psi.

Break: 85% adhesive between Glue and Top; 15% cohesive within Top.

Dolly at lower left, test spot at right.

1.b.3.3.3 Panel #259, G0m-I, Test 3

Panel 259 Test 3 was not recorded.

The pull-off strength for Panel 259 Test 3 was not recorded. The adhesion between the Glue and Top was too weak to be meaningful. The Top paint surface was too smooth to have sufficient Glue-to-Top adhesion. The top paint surface was roughened by sanding for the other tests, and the Glue-to-Top adhesion was sufficient after sanding.

1.b.3.3.4 Panel #259, G0m-I, Test 4

Panel 259 Test 4. G0m-I

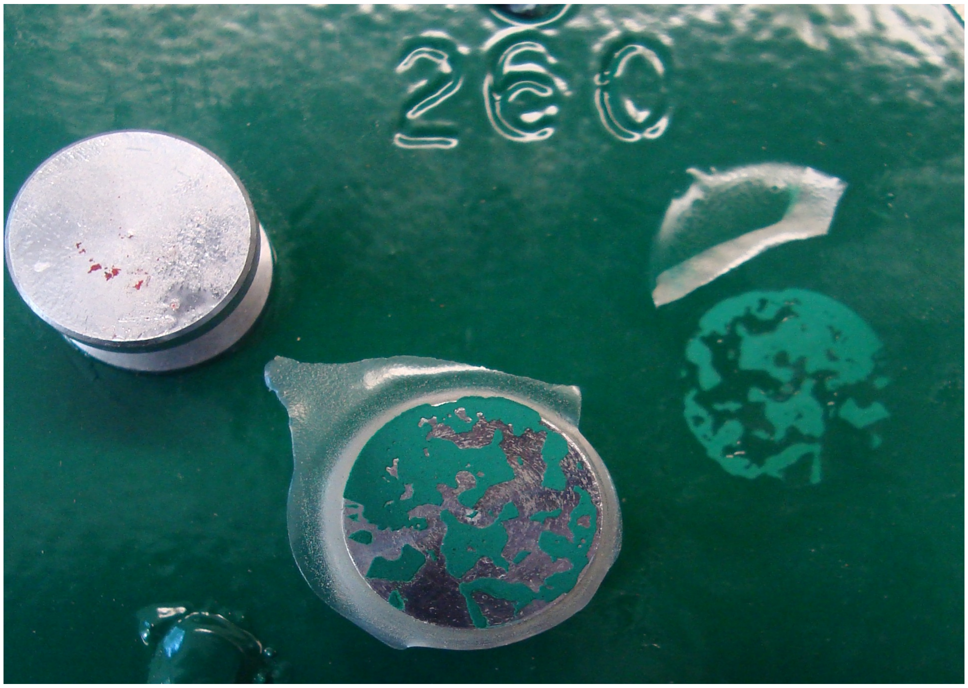
Pull-off strength: 3170 psi.

Break: 100% cohesive within Top.

Dolly at left, test spot at right.

1.b.3.4 Panel #260, G0m-I

1.b.3.4.1 Panel #260, G0m-I, Test 1



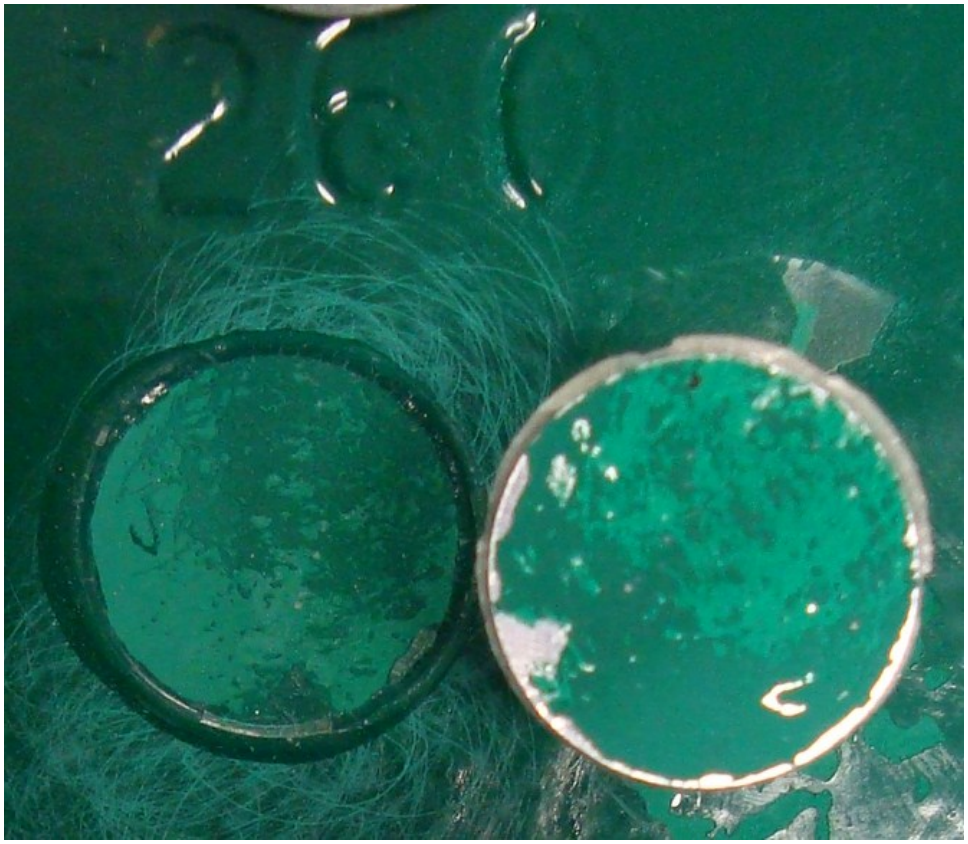
Panel 260 Test 1. G0m-I

Pull-off strength 680 psi.

Break: 50% adhesive between Glue and Top; 50% cohesive within Top.

Dolly at lower center, test spot at right.

1.b.3.4.2 Panel #260, G0m-I, Test 2



Panel 260 Test 2. G0m-I

Pull-off strength: 2835 psi.

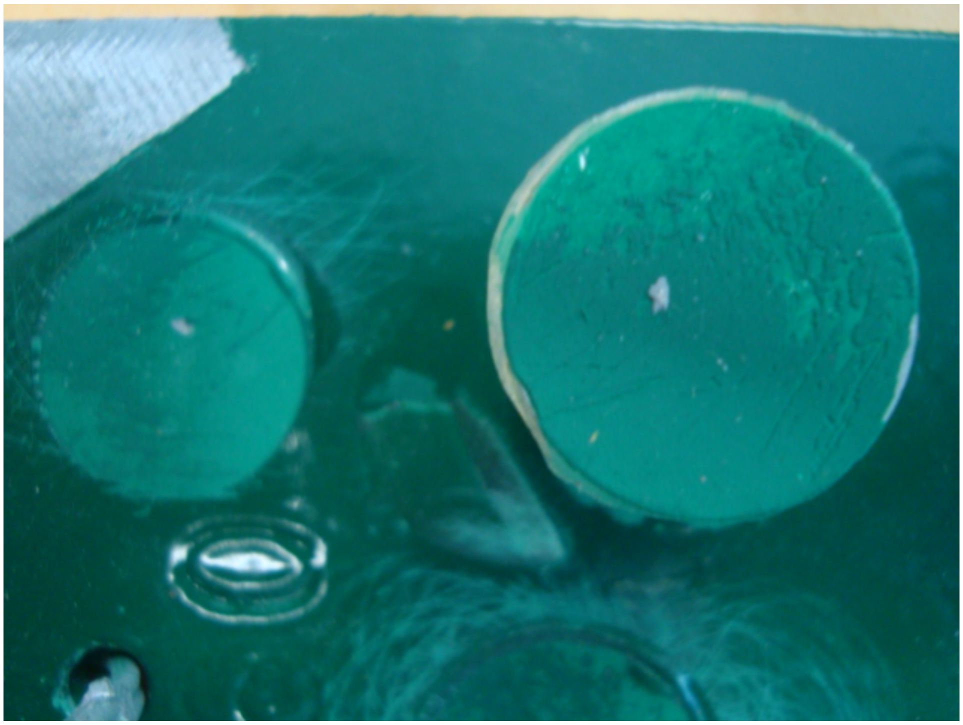
Break: 95% cohesive within Top; 5% adhesive between Glue and Top.

Dolly at right.

1.b.3.4.3-4 Panel #260, G0m-I, Test 3-4

Panel 260 Test 3 and 4 were not recorded. The bonding between the Glue and the Top paint surface were too week because the Top paint surface was very smooth. We did not roughen the surface sufficiently by sanding. This might be the reason for the failing at the Glue-to-Top adhesion.

1.b.3.4.5 Panel #260, G0m-I, Test 5



Panel 260 Test 5. G0m-I

Pull-off strength: 2551 psi.

Break: 97% cohesive within Top; 3% adhesive between Glue and Top.

Dolly at right.

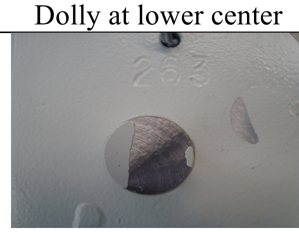
1.c Test panel subgroup G0m-S1

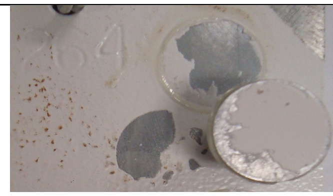
Primer:	Galvanized, mechanical profiling
Intermediate:	Macropoxy 646 Fast Cure Epoxy
Finish:	Acrolon 218 HS Acrylic Polyurethane

Panel numbers 261, 262, 263, 264, stored in box 3.

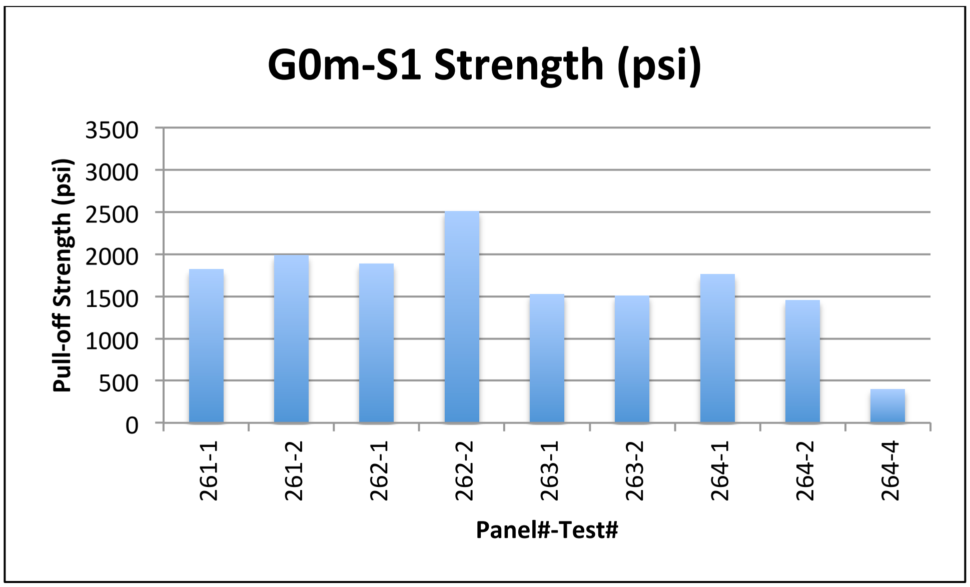
1.c.1 Photos of G0m-S1 test panels.

1.c.2 Adhesive strength test results for G0m-S1 test panels

Test Panel	Pull Test 1	Pull Test 2	X-cut1 Score	X-cut2
261			5	5
	Strength: 1818 psi	Strength: 1987 psi		
	90% adhesive between Glue and Top; 10% adhesive between Top and Int.	Break: 70% adhesive between Int and Zn-G; 30% adhesive between Int and Zn-G.		
	Dolly at left	Dolly at lower right		
262			5	5
	Strength: 1887 psi	Strength: 2511 psi		
	Break: 85% adhesive between Top and Glue, 15% adhesive between Int and Zn-G	Break: 60% adhesive between Glu and Top, 40% adhesive between Int and Zn-G		
	Dolly at left.	Dolly at lower center		
263			5	5
	Strength: 1525 psi	Strength: 1506 psi		
	Break: 60% adhesive between Top and Int; 40% between Glue and Top	Break: 70% adhesive between Glue and Top; 30% between Int and Zn-G		
	Dolly at lower right	Dolly at lower center.		

1.c.2- Adhesive strength test results for G0m-S1 test panel 264 (continued)					
Test Panel	Pull Test 1	Pull Test 3	Pull Test 4	X-cut 1 Score	X-cut 2 Score
264				5	5
	Strength: 1759 psi	Strength: 1456 psi	Strength: 400 psi		
	Break: 90% adhesive between Glue and Top; 10% adhesive between Int and Zn-G	Break: 70% adhesive between Int and Zn-G; 30% adhesive between Glue and Top.	Break: 55% adhesive between Glue and Top; 45% adhesive between Int and Zn-G		
	Dolly at upper right	Dolly at lower right.	Dolly at center. Note: Test 4 shown		

Pull-off Test	G0m-S1
Panel#-Test#	Strength (psi)
261-1	1818
261-2	1987
262-1	1887
262-2	2511
263-1	1525
263-2	1506
264-1	1759
264-2	1456
264-4	400
Average	1818
Standard Dev	536
Confidence	338



1.c.3 Enlarged photos of the pull-off dolly placed near the test spot on the G0m-S1 panels, and a description of the break layers.

1.c.3.1 Panel 261, G0m-S1

1.c.3.1.1 Panel 261, G0m-S1, Test 1

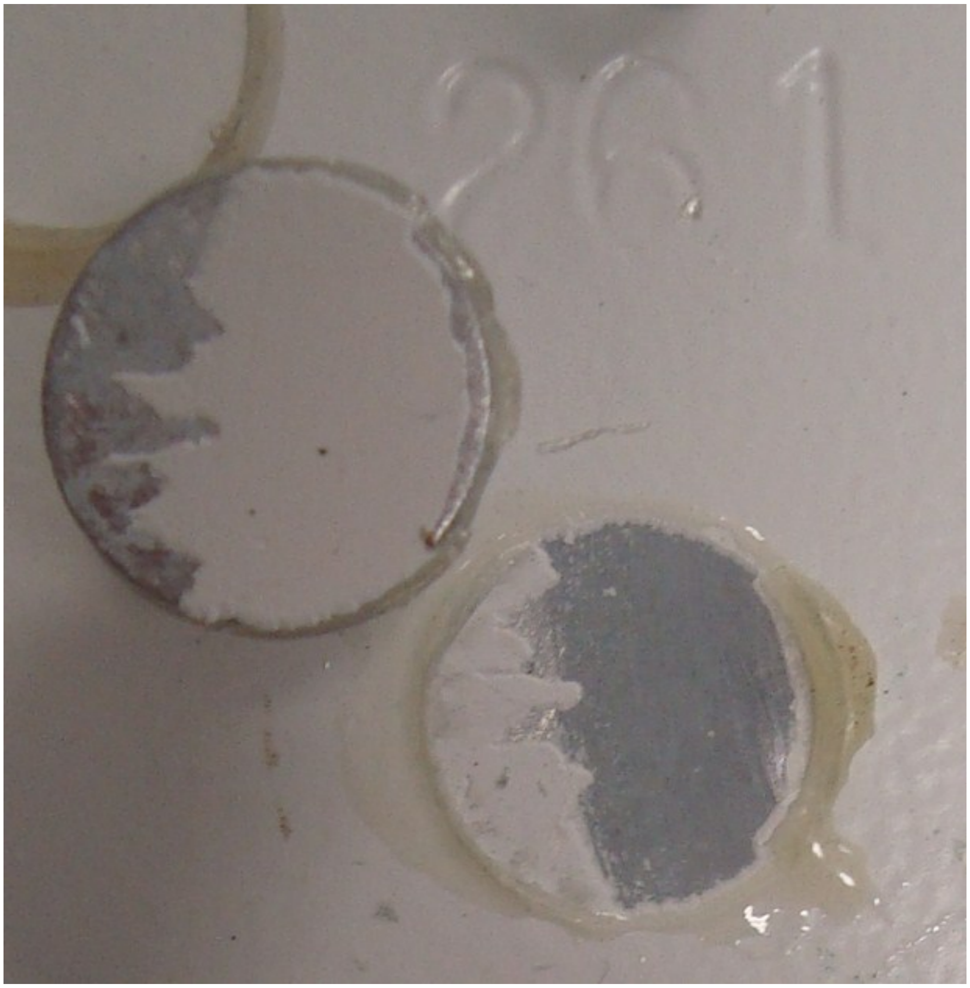
Panel 261 Test 1. G0m-S1

Pull-off strength: 1818 psi.

Break: 90% adhesive between Glue and Top; 10% adhesive between Top and Int.

Dolly at left.

1.c.3.1.2 Panel 261, G0m-S1, Test 2



Panel 261 Test 2. G0m-S1

Pull-off strength: 1987 psi.

Break: 70% adhesive between Int and Zn-G; 30% adhesive between Int and Zn-G.

Dolly at upper left, test spot at lower right.

1.c.3.1.3 Panel 261, G0m-S1, Test 3

Test 3 was invalid. The glue between dolly and topcoat was not set properly.

1.c.3.2 Panel 262, G0m-S1

1.c.3.2.1 Panel 262, G0m-S1, Test 1

Panel 262, Test 1, G0m-S1

Pull-off strength: 1887 psi

Break: 85% adhesive between Top and Glue, 15% adhesive between Int and Zn-G.

Dolly at left.

1.c.3.2.2 Panel 262, G0m-S1, Test 2

Panel 262, Test 2 was invalid. The glue between the dolly and the top coat was not set properly.

1.c.3.2.3 Panel 262, G0m-S1, Test 3

Panel 262, Test 3, G0m-S1

Pull-off strength: 2511 psi

Break: 60% adhesive between Glu and Top, 40% adhesive between Int and Zn-G.

Dolly at lower center.

1.c.3.3 Panel 263, G0m-S1

1.c.3.3.1 Panel 263, G0m-S1, Test 1

Panel 263 Test1, G0m-S1

Pull-off strength: 1525 psi

Break: 60% adhesive between Top and Int; 40% between Glue and Top

Dolly at lower right.

1.c.3.3.2 Panel 263, G0m-S1, Test 2

Panel 263 Test 3, G0m-S1

Pull-off strength: 1506 psi

Break: 70% adhesive between Glue and Top; 30% between Int and Zn-G,

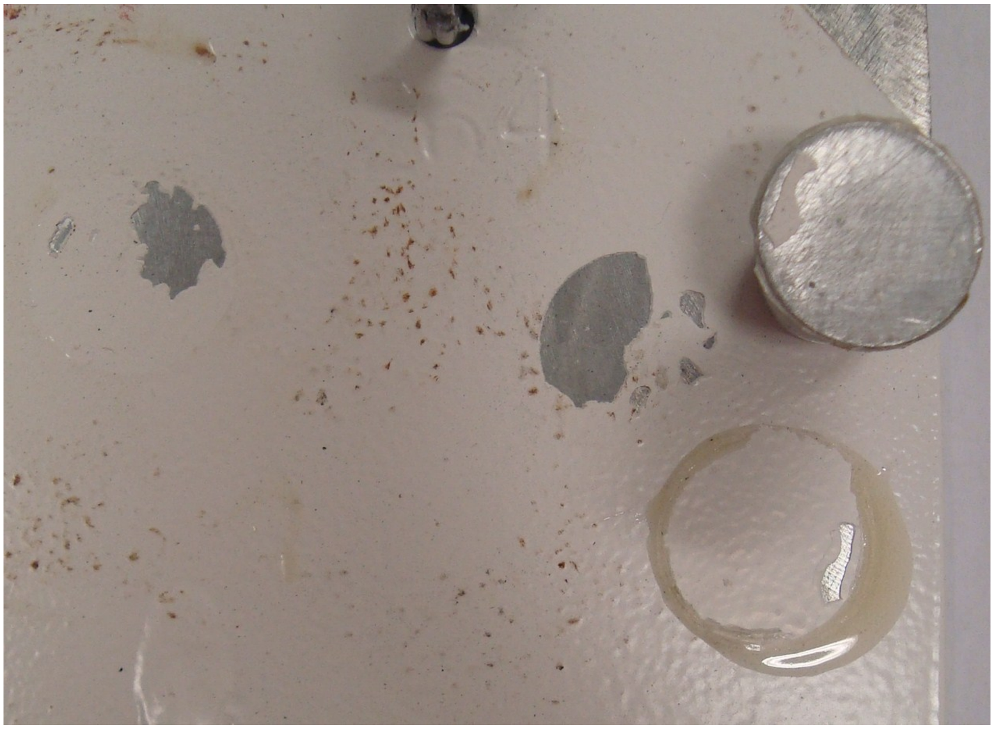
Dolly at lower center

1.c.3.3.3 Panel 263, G0m-S1, Test 3

Panel 263, Test 3 was invalid. The glue between dolly and top coat was not set correctly.

1.c.3.4 Panel 264, G0m-S1

1.c.3.4.1 Panel 264, G0m-S1, Test 1



Panel 264, Test 1, G0m-S1

Pull-off strength: 1759 psi

Break: 90% adhesive between Glue and Top; 10% adhesive between Int and Zn-G

Dolly at upper right, test spot at lower right.

1.c.3.4.2 Panel 264, G0m-S1, Test 2

Panel 264 Test 2. G0m-S1

Pull-off strength: 400 psi

Break: 55% adhesive between Glue and Top; 45% adhesive between Int and Zn-G

Dolly at center.

1.c.3.4.3 Panel 264, G0m-S1, Test 3

Test 3 for Panel 264 was not recorded because the glue between dolly and the topcoat was not set properly.

1.c.3.4.4 Panel 264, G0m-S1, Test 4

Panel 264, Test 4, G0m-S1

Pull-off strength: 1456 psi

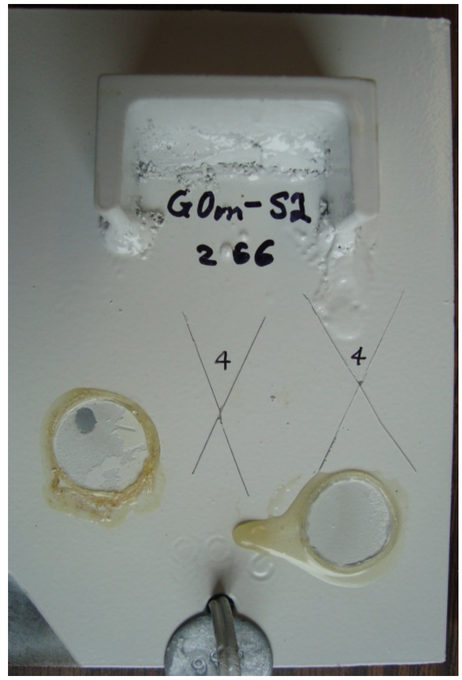
Break: 70% adhesive between Int and Zn-G; 30% adhesive between Glue and Top

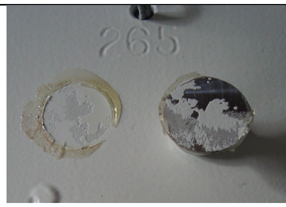
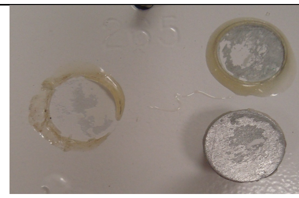
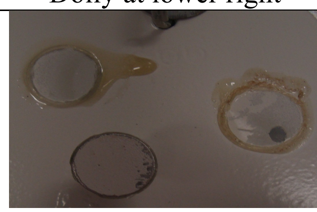
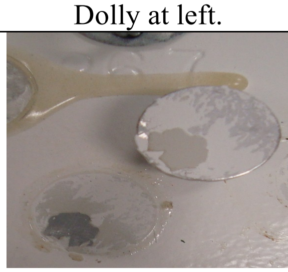
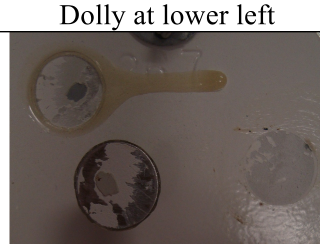
Dolly at lower right, test spot at upper middle.

1.d. Test panel subgroup G0m-S2

Primer: Thermal sprayed zinc metallizing coating
Intermediate: Recoatable Epoxy Primer Series B67
Finish: High Solids Polyurethane Series B58
Panel numbers 265, 266, 267 268, stored in box 4.

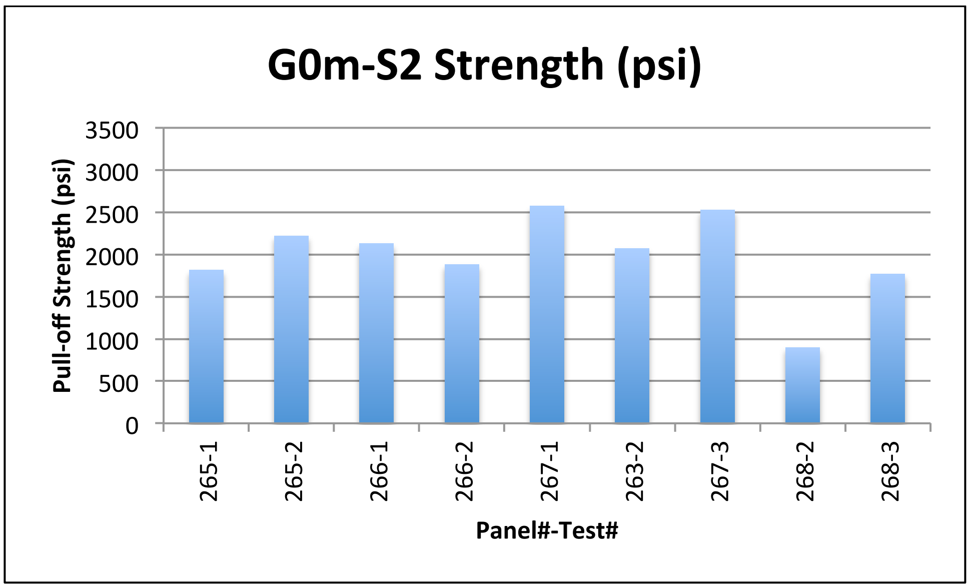
1.d.1 Photos of G0m-S2 test panels.



1.d.2 Adhesive strength test results for G0m-S2 test panels					
Test Panel	Pull Test 1	Pull Test 2	Pull Test 3 (or Test 4 if Test 3 is missing)	X-cut 1 Score	X-cut 2 Score
265				5	5
	Strength: 1846 psi	Strength: 2222 psi			
	Break: 60% cohesive within Top; 40% adhesive between Glue and Top	Break: 70% adhesive between Int and Zn-G; 30% adhesive between Glue and Zn-G.			
	Dolly at right	Dolly at lower right			
266				5	5
	Strength: 2132 psi	Strength: 1884 psi			
	Break: 60% cohesive within Top; 25% adhesive between Glue and Top; 15% adhesive between Int and Zn-G	Break: 95% cohesive within Top; 5% adhesive between Glue and Top			
	Dolly at left.	Dolly at lower left			
267				5	5
	Strength: 2572 psi	Strength: 2072 psi	Strength: 2525 psi		
	Break: 75% cohesive within Top; 25% adhesive between Top and Zn-G	Break: 50% cohesive within Top; 40% adhesive between Glue and Top; 10% adhesive between Int and Zn-G.	95% cohesive within Top; 5% adhesive between Glue and Zn-G		
	Dolly at upper right.	Dolly at lower center.	Dolly at left,		

1.d.2 Adhesive strength test results for G0m-S2 test panel					
Test Panel	Pull Test 1	Pull Test 2	Pull Test 3 (or Test 4 or Test 5 if Test 3 is missing)	X-cut 1 Score	X-cut 2 Score
268	Test 1 was invalid. Glue between dolly and top paint was not set correctly.			5	5
		Strength: 900 psi	Strength: 1767 psi		
		Break (observed on panel): 50% cohesive within Top; 45% adhesive between Glue and Top; 5% adhesive between Int and Zn-G	60% adhesive between Glue and Top; 40% cohesive within Top		
		Dolly not photographed	Dolly at lower right.		

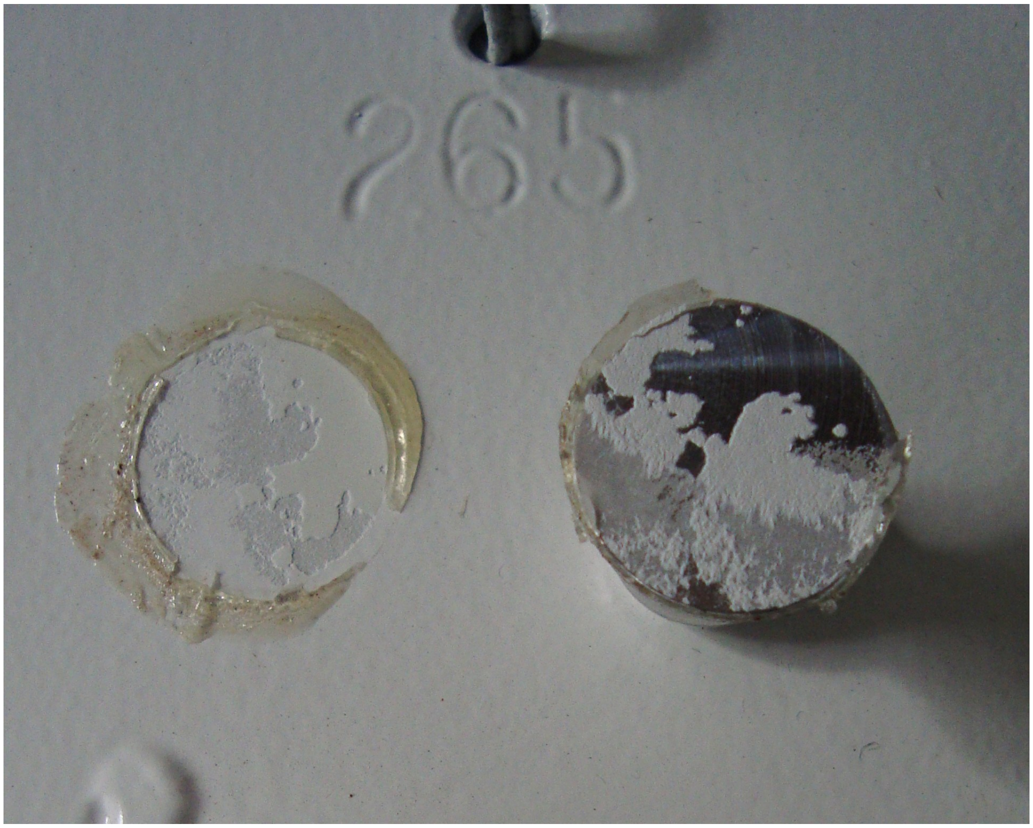
Pull-off Test	G0m-S2
Panel#-Test#	Strength (psi)
265-1	1818
265-2	2222
266-1	2132
266-2	1884
267-1	2572
263-2	2072
267-3	2525
268-2	900
268-3	1767
Average	1988
Standard Dev	470
Confidence	307



1.d.3 Enlarged photos of the pull-off dolly placed near the test spot on the G0m-S2 panels, and a description of the break layers.

1.d.3.1 Panel 265 G0m-S2

1.d.3.1.1 Panel 265, G0m-S2, Test 1



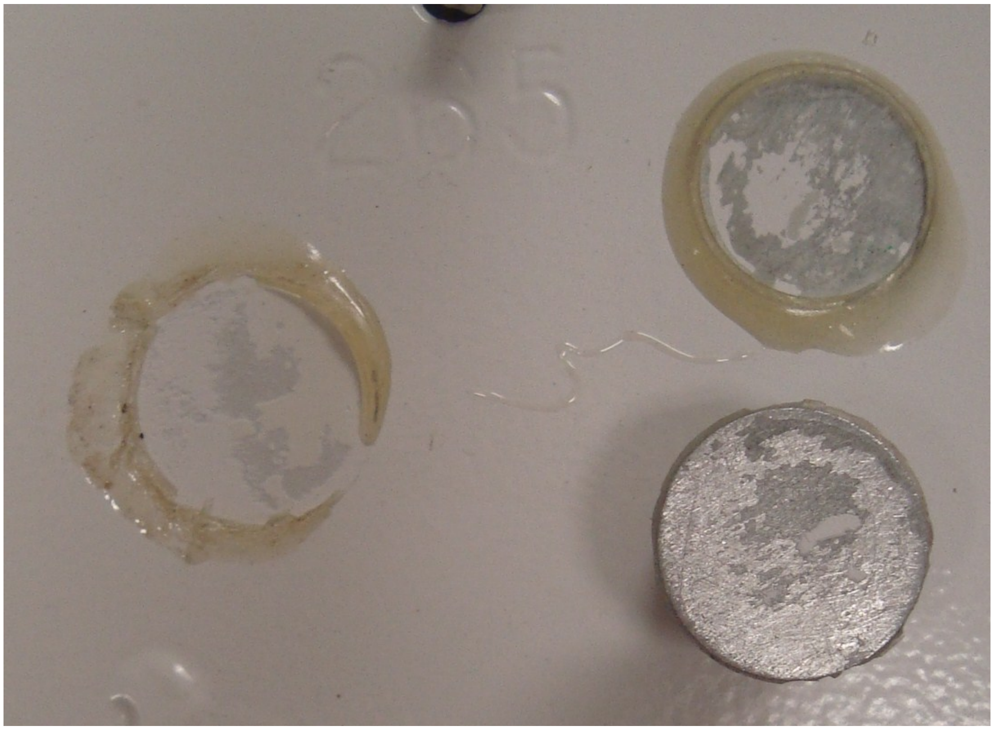
Panel 265 Test 1, G0m-S2

Pull-off strength: 1846 psi

Break: 60% cohesive within Top; 40% adhesive between Glue and Top

Dolly at right

1.d.3.1.2 Panel 265, G0m-S2, Test 2



Panel 265, Test 2, G0m-S2

Pull-off strength: 2222 psi

Break: 70% adhesive between Int and Zn-G; 30% adhesive between Glue and Zn-G

Dolly at lower right.

1.d.3.2 Panel 266 G0m-S2

1.d.3.2.1 Panel 266 G0m-S2, Test 1

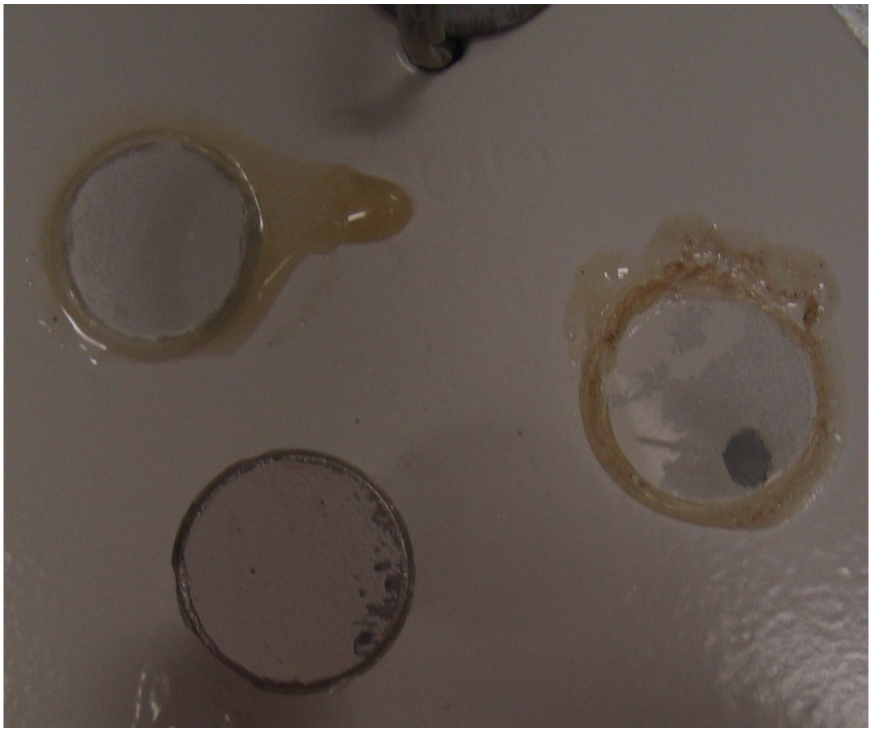
Panel 266 Test 2, G0m-S2

Pull-off strength: 2132 psi

Break: 60% cohesive within Top; 25% adhesive between Glue and Top; 15% adhesive between Int and Zn-G

Dolly at left.

1.d.3.2.2 Panel 266 G0m-S2, Test 2



Panel 266 G0m-S2, Test 2

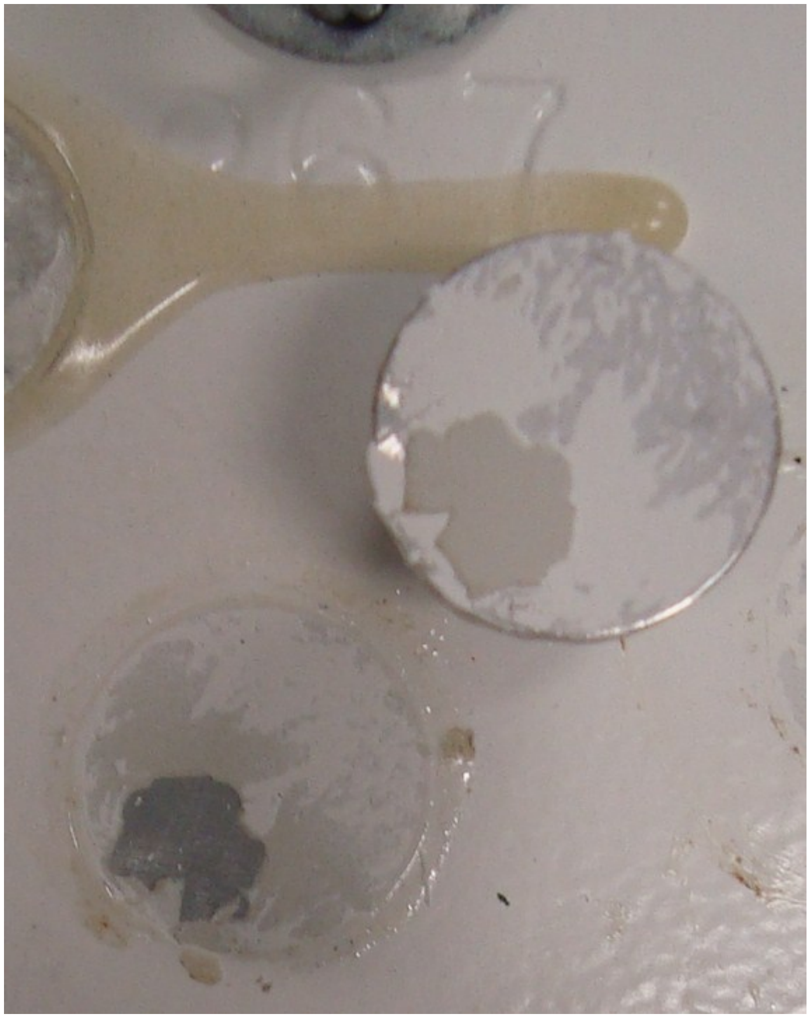
Pull-off strength: 1884 psi

Break: 95% cohesive within Top; 5% adhesive between Glue and Top

Dolly at lower left.

1.d.3.3 Panel 267 G0m-S2

1.d.3.3.1 Panel 267 G0m-S2, Test 1



Panel 267 Test 1, G0m-S2

Pull-off strength: 2572 psi

Break: 75% cohesive within Top; 25% adhesive between Top and Zn-G

Dolly at upper right.

1.d.3.3.2 Panel 267 G0m-S2, Test 2

Panel 267 Test 2, G0m-S2

Pull-off strength: 2072 psi

Break: 50% cohesive within Top; 40% adhesive between Glue and Top; 10% adhesive between Int and Zn-G

Dolly at lower center.

1.d.3.3.3 Panel 267 G0m-S2, Test 3

Panel 267 Test 3, G0m-S2

Pull-off strength: 2525 psi

Break: 95% cohesive within Top; 5% adhesive between Glue and Zn-G

Dolly at left.

1.d.3.4 Panel 268 G0m-S2

1.d.3.4.1 Panel 268 G0m-S2, Test 1

Panel 268 Test 1 was not valid. The Glue between dolly and topcoat was not properly set.

1.d.3.4.2 Panel 268 G0m-S2, Test 2

Panel 268 Test 2, G0m-S2

Pull-off strength: 900 psi

Break: 50% cohesive within Top; 45% adhesive between Glue and Top; 5% adhesive between Int and Zn-G

Dolly not photographed.

1.d.3.4.3 Panel 268 G0m-S2, Test 3

Panel 268 Test 3, G0m-S2

Pull-off strength: 1767 psi

Break: 60% adhesive between Glue and Top; 40% cohesive within Top.

Dolly at lower right.

2. Group G0b, List and Photographic images of tested panels.

This group of test panels was made from galvanized steel with blast profiled zinc surface. The galvanizing, surface profiling and the application of the (intermediate) epoxy paint were performed on the same day.

This group of test panels is labeled as group “G0b” on the test panels. In this label “G” signifies the Galvanizing process, “0” signifies “zero delay time (same day)” between galvanizing and the blast profiling / painting of the epoxy layer. The finish paint was done according to the manufacturer’s specification after the epoxy intermediate layer was cured. Four different paint systems were used for the subgroups with the following designations for the subgroups and the test panels.

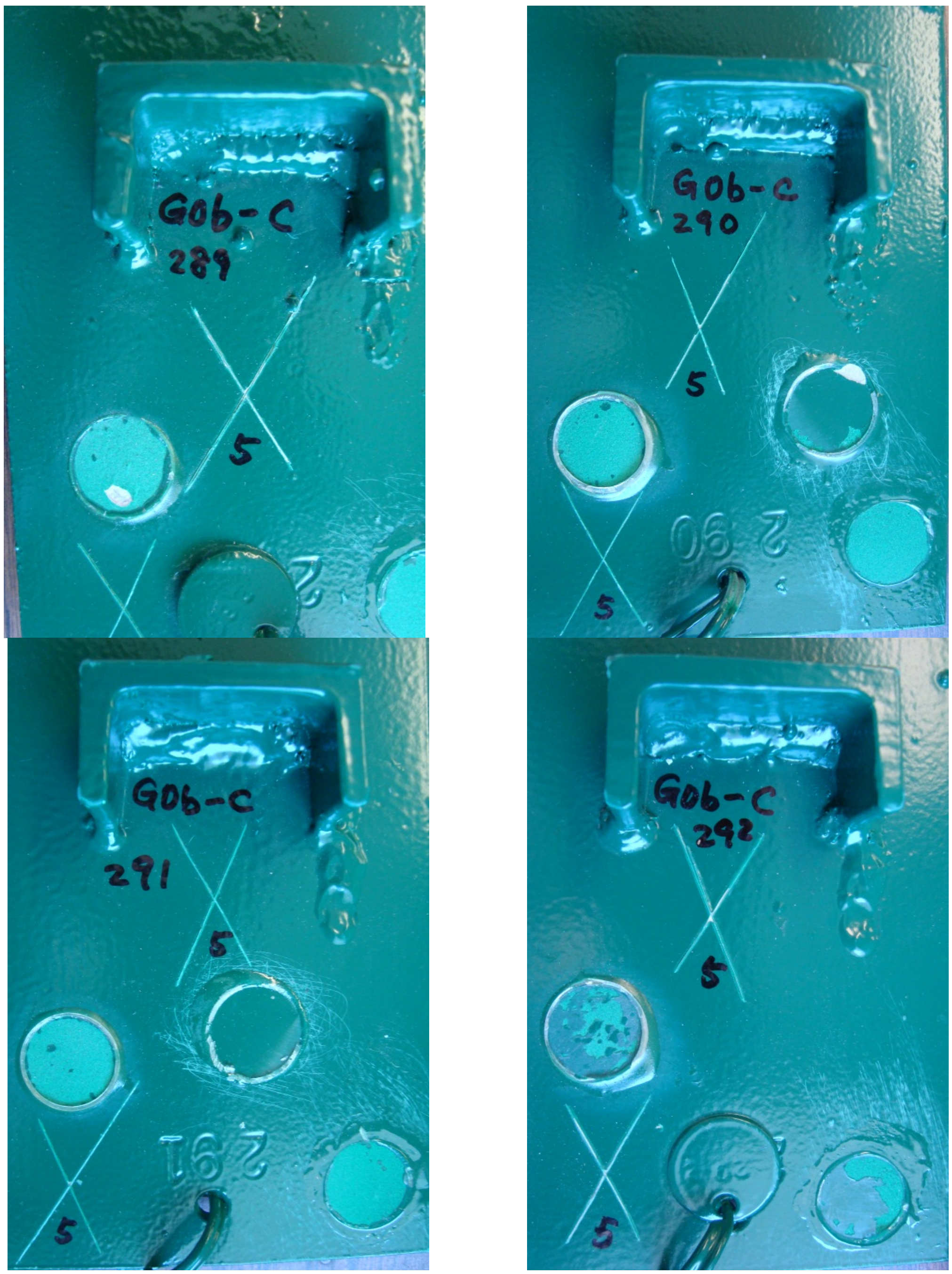
Each pull-off test spot on a test panel is given an identification number according to the following convention: We assign the uppermost test spot in the images of the panels as test sample #1. Pretending that sample #1 is at the 12-oclock position of a clock, the remaining test spots are ordered according to its position in the clockwise rotation order. Occasionally, a pull-off test is omitted from the list because of technical problems observed during the test. For example the dolly was not property glued to the paint surface, or the surface near the test spot is too close to a welding burr so that the tester cannot be seated correctly. A replacement test is listed (using a different test spot identification number) is listed in the table in place of the omitted test.

2.a G0b-C: G0b panels with paint system C

Primer: galvanizing followed by blast surface profiling
Intermediate: Carboline 888 Epoxy
Finish: Carboline 133 LH Aliphatic Polyurethane

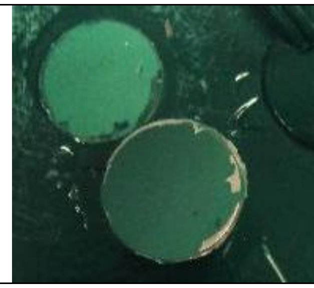
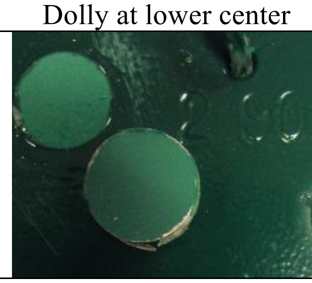
Test panel tag numbers: 289, 290, 291, 292 stored in box 10.

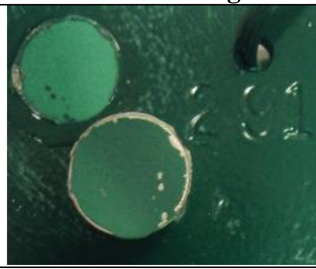
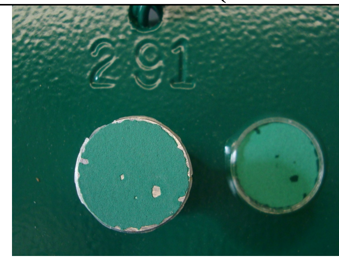
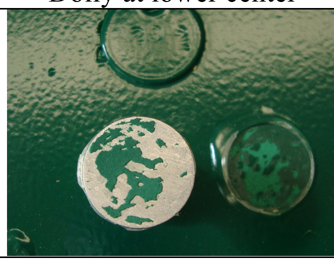
2.a.1 Photo Images of test panels for subgroup G0b-C, after adhesive tests.



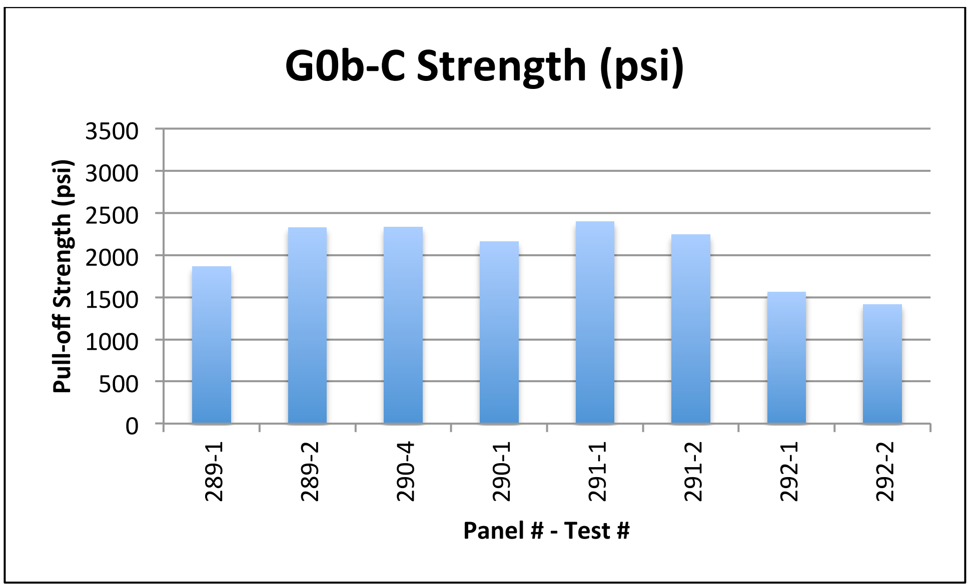
2.a.2 Table of the adhesive strength test results for the G0b-C Test Panels.

2.a.2 Table of the adhesive strength test results for the G0b-C Test Panels.

Test Panel	Pull Test 1 (Exception: Pull Test 2 for panel 291)	Pull Test 2 (Exception: Pull Test 3 for Panels 290 and 291)	X-cut 1 Tape Test Score	X-cut 2 Tape Test Score
289			5	5
	Pull-off Strength: 1865 psi	Pull-off Strength: 2326 psi		
	Break: 90% cohesive within Top; 6% adhesive between Int and Zn-G; 4% adhesive between Glue and Top.	Break: 95% cohesive within Top; 5% adhesive between Glue and Top		
	Dolly at left, test spot at right	Dolly at lower center		
290			5	5
	Pull-off Strength: 2333 psi	Pull-off strength: 2162 psi		
	Break: 97% cohesive within Top; 3% adhesive between Glue and Top	Surface: 100% Top (CO)		
	Dolly at left	Dolly at lower right		

2.a.2 Table of the adhesive strength test results for the G0b-C Test Panels. (Continued)				
291			5	5
	Pull-off Strength: 2398 psi	Pull-off Strength: 2242 psi		
	Break: 97% cohesive within Top; 3% adhesive between Glue and Top	Break: 97% cohesive within Top; 3% adhesive between Glue and Top		
	Dolly at lower center	Dolly at lower left		
292			5	5
	Pull-off Strength: 1561 psi	Pull-off Strength: 1415 psi		
	Break: 60% adhesive between Glue and Top; 40% cohesive within Top	Break: 60% adhesive between Glue and Top; 40% cohesive within Top		
	Dolly at left	Dolly at lower left.		

Pull-off Test	G0b-C
Panel#-Test#	Strength (psi)
289-1	1865
289-2	2326
290-4	2333
290-1	2162
291-1	2398
291-2	2242
292-1	1561
292-2	1415
Average	2038
Stand Dev	354
Confidence	209



2.a.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

2.a.3.1 G0b-C Panel 289

2.a.3.1.1 G0b-C Panel 289 Test 1

Pull-off strength: 1865 psi.

Break: 90% cohesive within Top; 6% adhesive between Int and Zn-G; 4% adhesive between Glue and Top.

Dolly at left

2.a.3.1.2 G0b-C Panel 289 Test 2

G0b-C Panel 289 Test 2

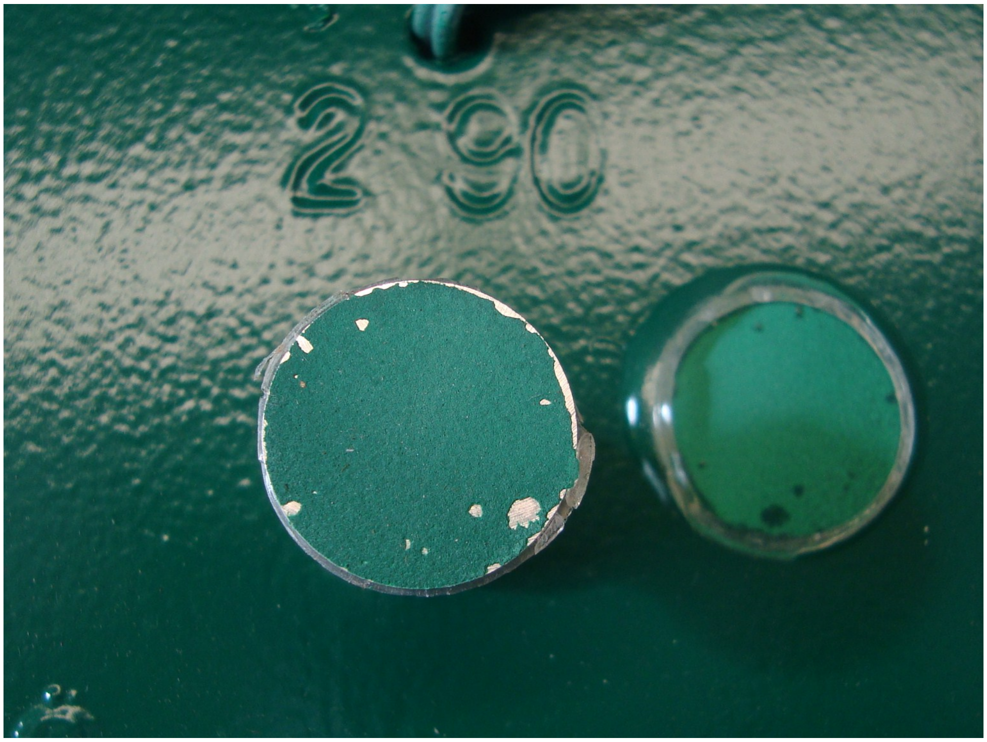
Pull-off strength: 2326 psi.

Break: 95% cohesive within Top; 5% adhesive between Glue and Top

Dolly at lower center.

2.a.3.2 G0b-C Panel 290

2.a.3.2.1 G0b-C Panel 290 Test 1



G0b-C Panel 290 Test 1

Pull-off strength: 2333 psi.

Break: 97% cohesive within Top; 3% adhesive between Glue and Top

Dolly at left.

2.a.3.2.2 G0b-C Panel 290 Test 2

G0b-C Panel 290 Test 2

The pull-off strength for this test spot was not recorded. The base of the pull-off tester was tilted. The surface near the lower right corner of the test spot was uneven due to the presence of a welding residue.

2.a.3.2.3 G0b-C Panel 290 Test 3

G0b-C Panel 290 Test 3

Pull-off strength: 2162 psi.

Break: 100% cohesive within Top.

Dolly at lower center.

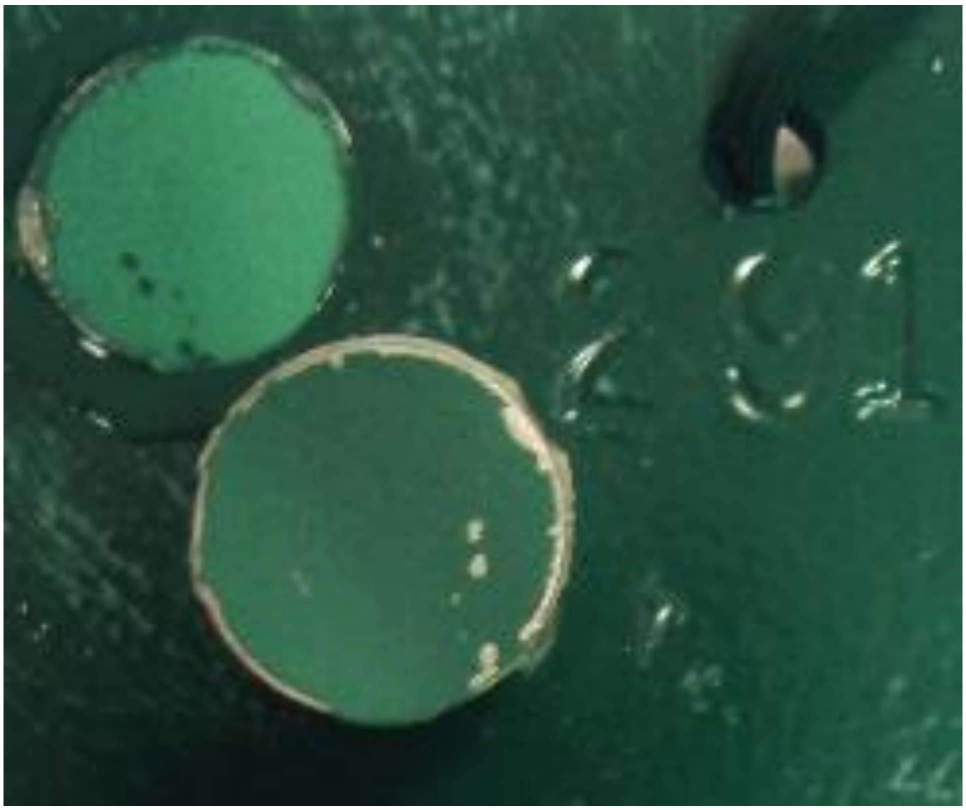
2.a.3.3 G0b-C Panel 291

2.a.3.3.1 G0b-C Panel 291 Test 1

G0b-C Panel 291 Test 1

The pull-off strength for this test spot was not recorded. The base of the pull-off tester was tilted. The surface near the lower right corner of the test spot was uneven due to the presence of a welding residue.

2.a.3.3.2 G0b-C Panel 291 Test 2



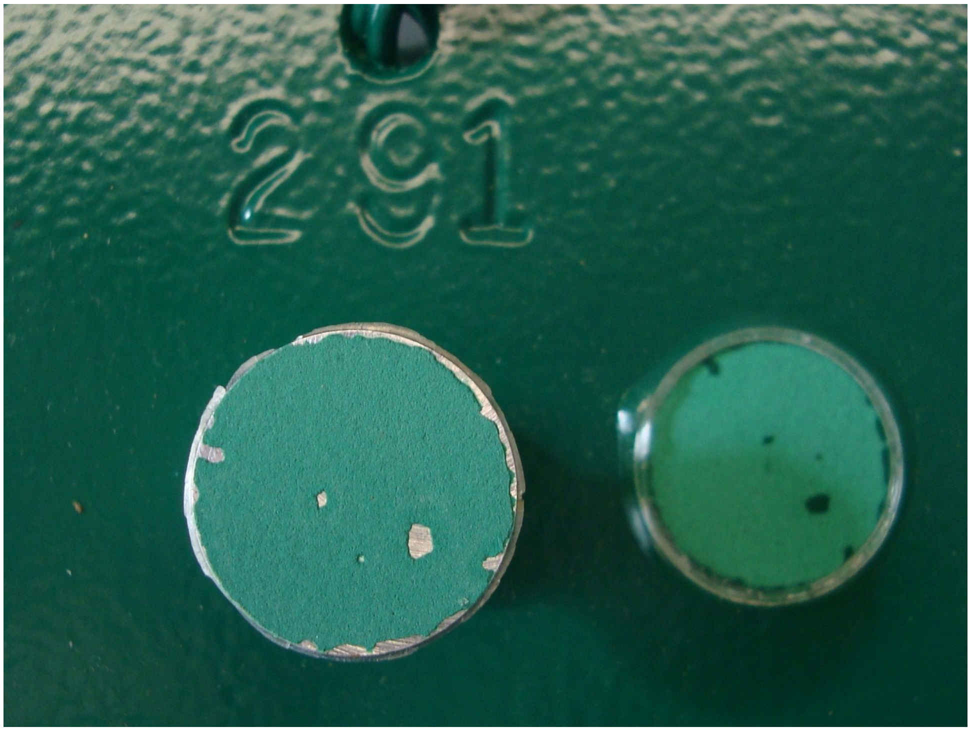
G0b-C Panel 291 Test 2

Pull-off strength: 2398 psi.

Break: 97% cohesive within Top; 3% adhesive between Glue and Top

Dolly at lower center.

2.a.3.3.3 G0b-C Panel 291 Test 3



G0b-C Panel 291 Test 3

Pull-off Strength: 2242 psi.

Break: 97% cohesive within Top; 3% adhesive between Glue and Top

Dolly at left

2.a.3.4 G0b-C Panel 292

2.a.3.4.1 G0b-C Panel 292 Test 1

G0b-C Panel 292 Test 1

Pull-off strength: 1561 psi.

Break: 60% adhesive between Glue and Top; 40% cohesive within Top

Dolly at left

2.a.3.4.2 G0b-C Panel 292 Test 2

G0b-C Panel 292 Test 2

Pull-off strength: 1415 psi.

Break: 60% adhesive between Glue and Top; 40% cohesive within Top

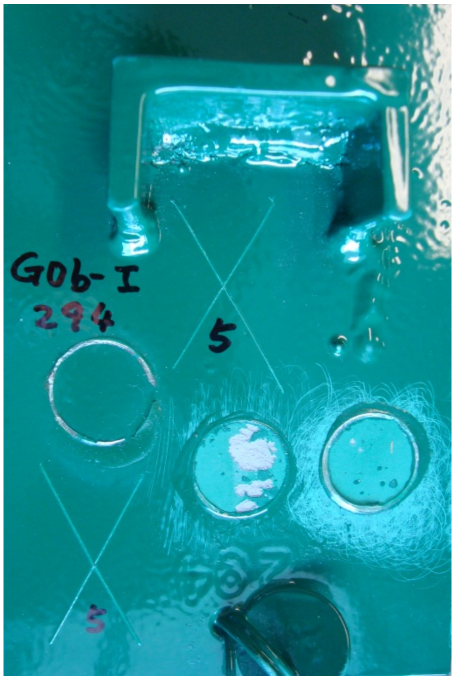
Dolly at lower left

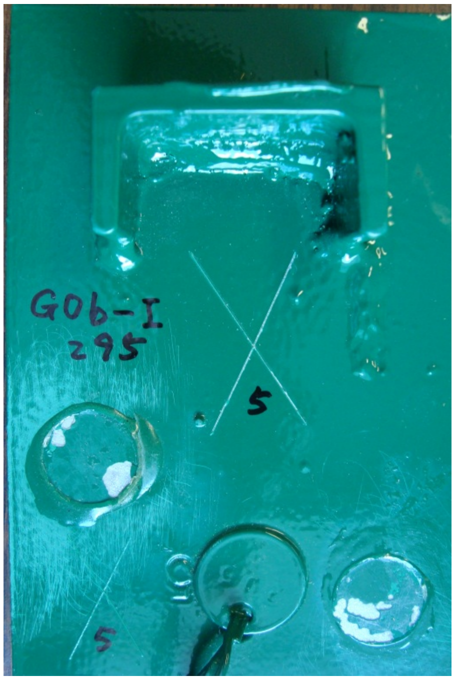
2.b. Test panel subgroup G0b-I

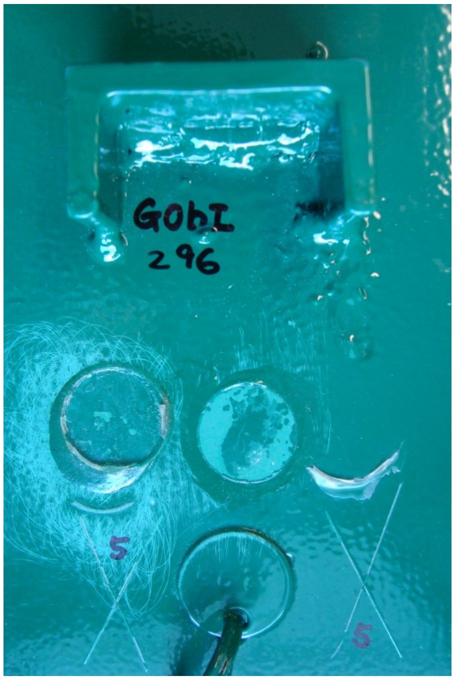
Primer:	galvanizing followed by blast surface profiling
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

Test panel tag numbers: 293, 294, 295, 296 stored in box 11.

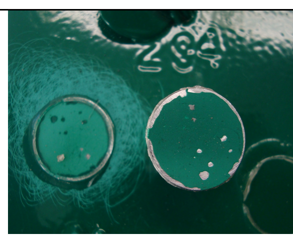
2.b.1 Photos of test panels

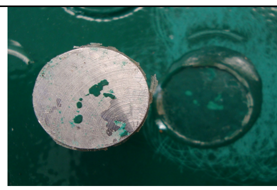




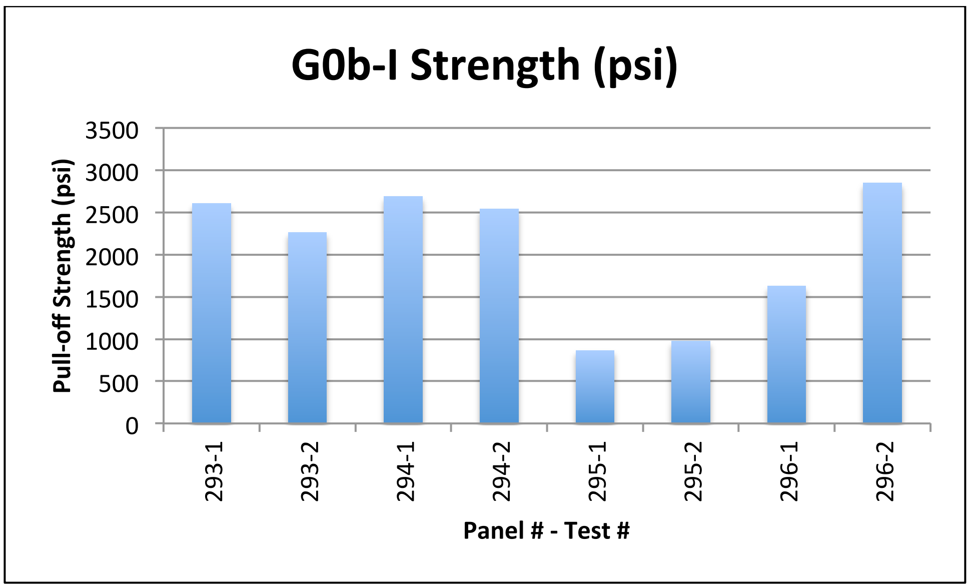


2.b.2 Table of the adhesive strength test results for the G0b-C Test Panels.

Test Panel	Test 1	Test 2	X-cut 1 Score	X-cut 2 Score
293			5	5
	Strength: 2606 psi	Strength: 2263 psi		
	Break: 80% cohesive within Top; 15% adhesive between Glue and Top; 5% adhesive between Int and Zn-G	Break: 60% cohesive within Top; 40% adhesive between Glue and Top		
	Dolly at lower right	Dolly at lower left		
294			5	5
	Strength: 2689 psi	Strength: 2538 psi		
	Break: 95% cohesive within Top; 5% adhesive between Glue and Top	Break: 95% cohesive within Top; 5% adhesive between Glue and Top		
	Dolly at right	Dolly at upper left		

295			5	5
	Strength: 866 psi	Strength: 975 psi		
	Break: 80% adhesive between Glue and Top; 20% adhesive between Int and Zn-G	Break: 80% adhesive between Glue and Top; 20% adhesive between Int and Zn-G		
	Dolly at lower left	Dolly at lower center		
296			5	5
	Strength: 1629 psi	Strength: 2850 psi		
	Break: 95% adhesive between Glue and Top; 5% cohesive within Top	Break: 70% cohesive within Top; 30% adhesive between Glue and Top		
	Dolly at left	Dolly at left.		

Pull-off Test	G0b-I
Panel#-Test#	Strength (psi)
293-1	2606
293-2	2263
294-1	2689
294-2	2538
295-1	866
295-2	975
296-1	1629
296-2	2850
Average	2052
Stand Dev	740
Confidence	437



2.b.3 Enlarged photos of the pull-off dolly placed near the test spot on the G0b-I panel, and a description of the break layers.

2.b.3.1 G0b-I Panel 293

2.b.3.1.1 G0b-I Panel 293 Test 1

G0b-I Panel 293 Test 1

Pull-off Strength: 2606 psi

Break: 80% cohesive within Top; 15% adhesive between Glue and Top; 5% adhesive between Int and Zn-G

Dolly at lower right

2.b.3.1.2 G0b-I Panel 293, Test 2

M0b-I Panel 293 Test 2

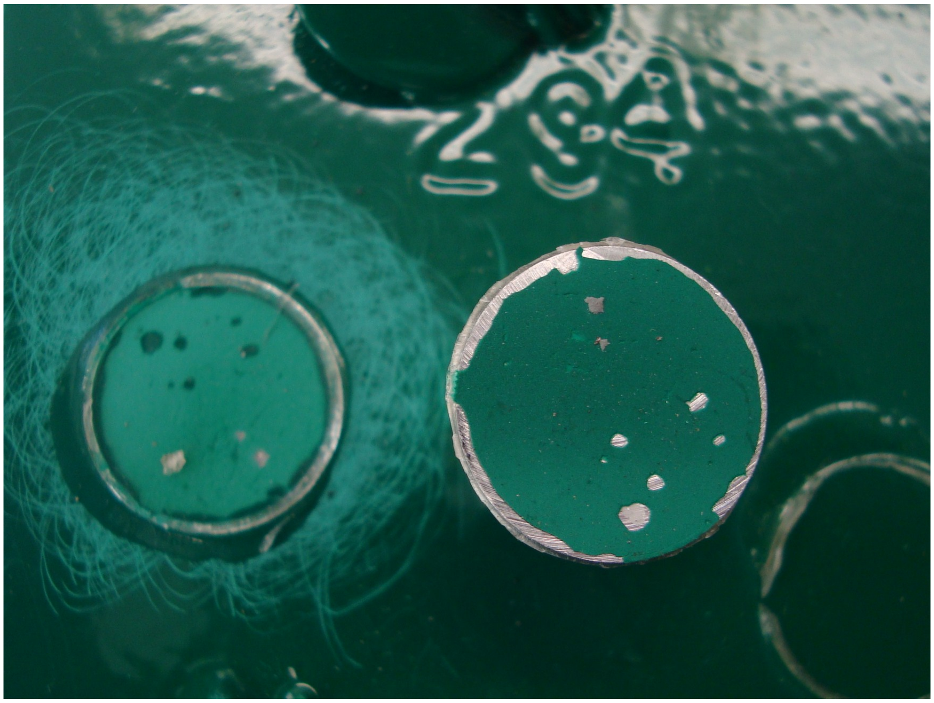
Pull-off Strength: 2263 psi

Break: 60% cohesive within Top; 40% adhesive between Glue and Top

Dolly at lower left

2.b.3.2 G0b-I Panel 294

2.b.3.2.1 G0b-I Panel 294, Test 1



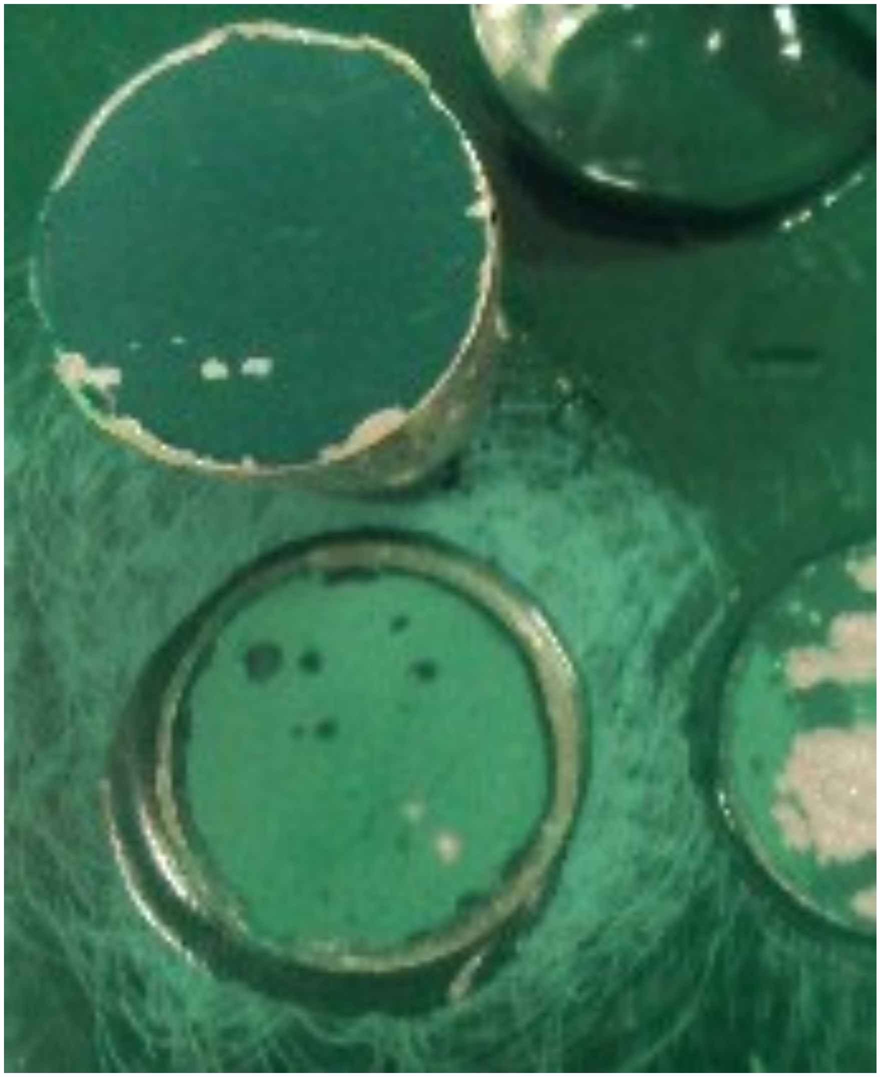
G0b-I Panel 294 Test 1

Pull-off Strength: 2689 psi

Break: 95% cohesive within Top; 5% adhesive between Glue and Top

Dolly at right

2.b.3.2.2 G0b-I Panel 294, Test 2



G0b-I Panel 294 Test 2

Pull-off Strength 2538 psi

Break: 95% cohesive within Top; 5% adhesive between Glue and Top

Dolly at upper left

2.b.3.3 G0b-I Panel 295

2.b.3.3.1 G0b-I Panel 295, Test 1

G0b-I Panel 295 Test 1

Pull-off Strength: 866 psi

Break: 80% adhesive between Glue and Top; 20% adhesive between Int and Zn-G

Dolly at left.

2.b.3.3.2 G0b-I Panel 295, Test 2

G0b-I Panel 295 Test 2

Pull-off Strength: 975 psi

Break: 80% adhesive between Glue and Top; 20% adhesive between Int and Zn-G

Dolly at lower center

2.b.3.4 G0b-I Panel 296

2.b.3.4.1 G0b-I Panel 296, Test 1

G0b-I Panel 296 Test 1

Pull-off Strength: 1629 psi

Break: 95% adhesive between Glue and Top; 5% cohesive within Top

Dolly at left

2.b.3.4.2 G0b-I Panel 296, Test 2

G0b-I Panel 296 Test 2

Pull-off Strength: 2850 psi

Break: 70% cohesive within Top; 30% adhesive between Glue and Top

Dolly at left

2.c Test panel subgroup G0b-S1

Primer: galvanizing followed by blast surface profiling

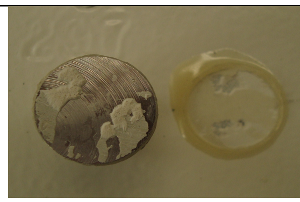
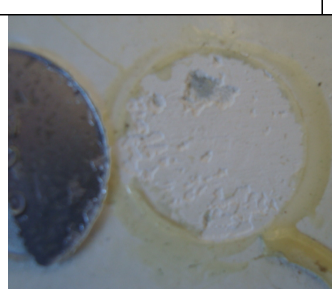
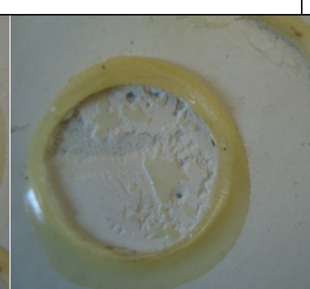
Intermediate: Macropoxy 646 Fast Cure Epoxy

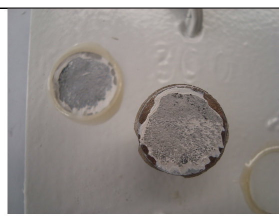
Finish: Acrolon 218 HS Acrylic Polyurethane

Test panel tag numbers: 297, 298, 299, 300, stored in box 12, photographed

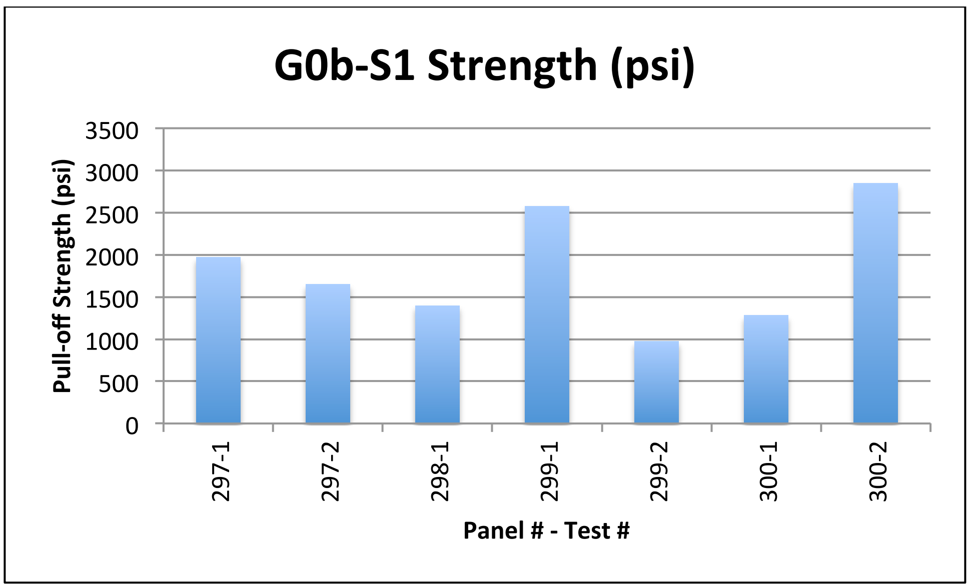
2.c.1 Photographs of the G0b-S1 test panels

2.c.2 Table of the adhesive strength test results for the G0b-S1 Test Panels.

Test Panel	Test 1	Test 2	X-cut 1 Score	X-cut 2 Score
297			5	5
	Strength: 1968 psi	Strength: 1653 psi		
	Break: 70% adhesive between Glue and Top; 15% cohesive within Top; 15% cohesive within Int	Break: 50% cohesive within Top; 50% adhesive between Glue and Top		
	Dolly at left	Dolly at lower right		
298			4 Revised	4 Revised
	Strength: 1398 psi	Strength: not recorded		
	Break: 80% cohesive within Top; 20% adhesive between Top and Int.	Break: 70% cohesive within Top; 20% adhesive between Top and Int; 10% adhesive between Glue and Top		
	Dolly not photographed	Dolly not photographed		

Test Panel	Test 1	Test 2	X-cut 1 Score	X-cut 2 Score
299			5	5
	Strength: 2578 psi	Strength: 975 psi		
	Break: 50% cohesive within Top; 40% cohesive within Int; 10% adhesive between Glue and Top	Break: 80% adhesive between Glue and Top; 20% adhesive between Int and Zn-G		
	Dolly at center left	Dolly at lower center		
300			5	5
	Strength: 1283 psi	Strength: 2850 psi		
	Break: 85% adhesive between Int and Zn-G; 10% adhesive between Glue and Top; 5% cohesive within Top;	Break: 70% cohesive within Top; 30% adhesive between Glue and Top		
	Dolly at center	Dolly at left.		

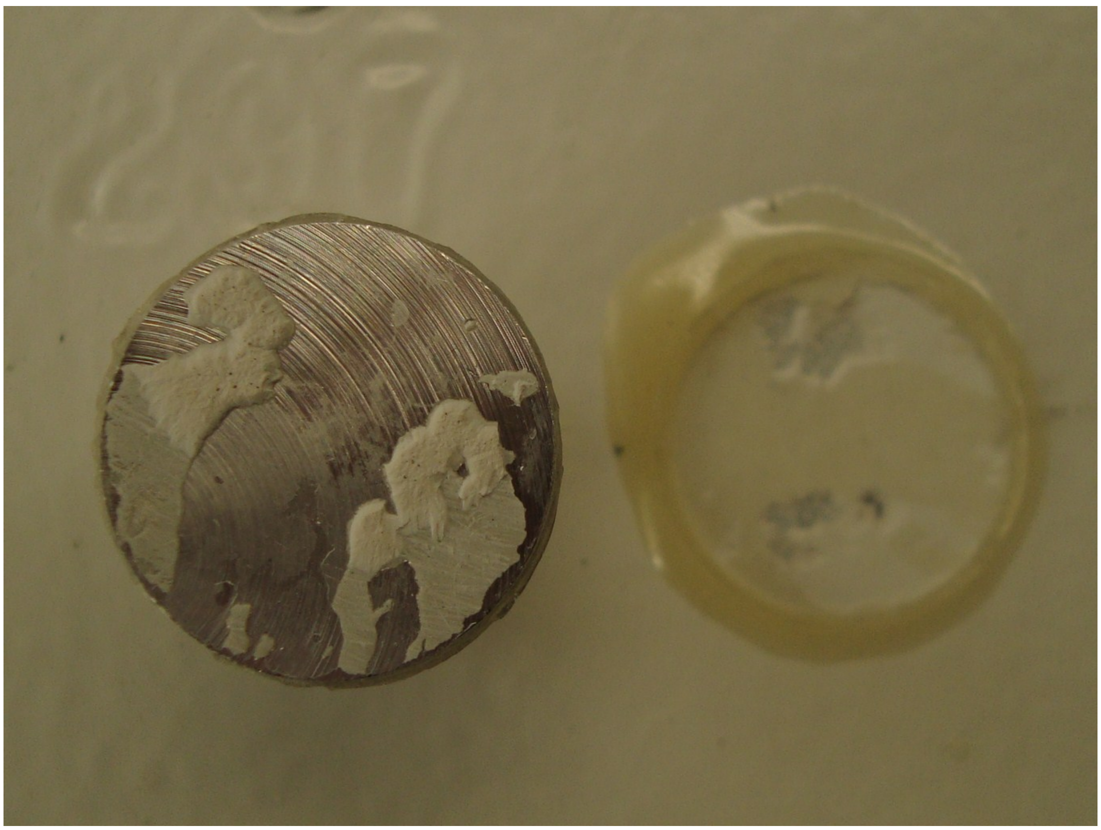
Pull-off Test	G0b-S1
Panel#-Test#	Strength (psi)
297-1	1968
297-2	1653
298-1	1398
299-1	2578
299-2	975
300-1	1283
300-2	2850
Average	1815
Stand Dev	640
Confidence	474



2.c.3 Enlarged photos of the pull-off dolly placed near the test spot on the G0b-S1 panel, and a description of the break layers.

2.c.3.1 G0b-S1 Panel 297

2.c.3.1.1 G0b-S1 Panel 297 Test 1



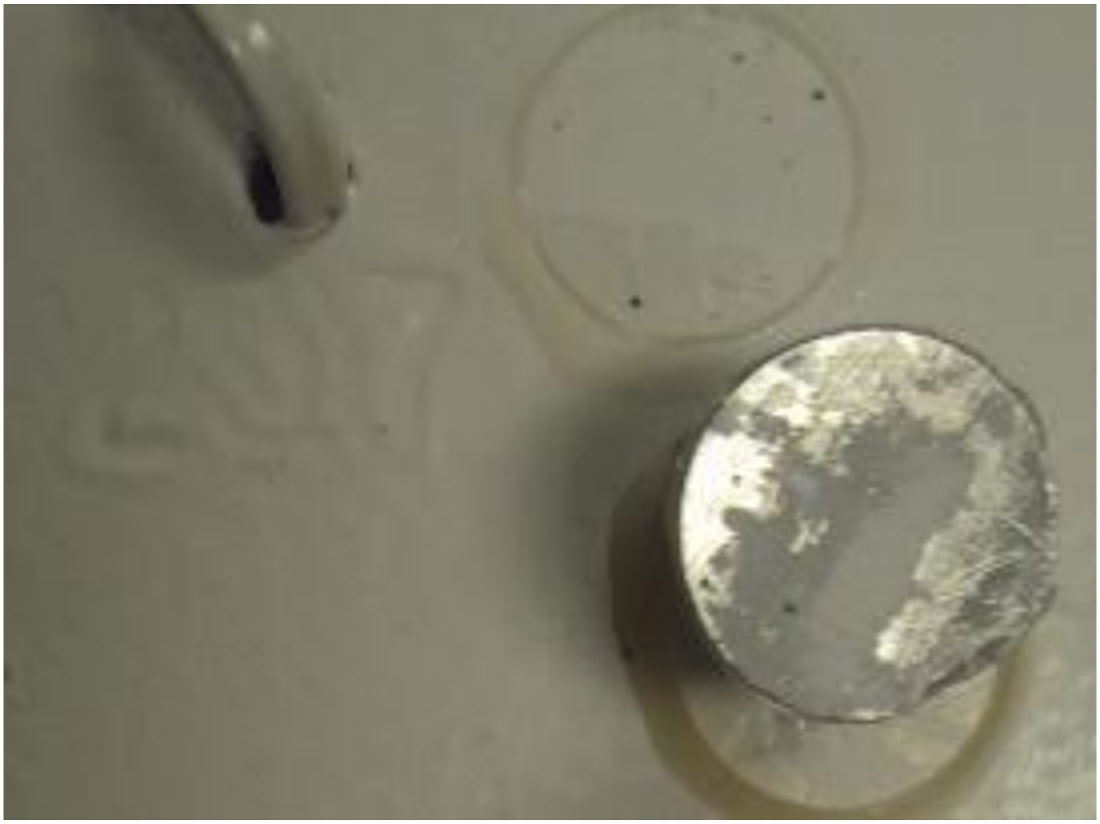
G0b-S1 Panel 297 Test 1

Pull-off Strength: 1968 psi

Break: 70% adhesive between Glue and Top; 15% cohesive within Top; 15% cohesive within Int

Dolly at left

2.c.3.1.2 G0b-S1 Panel 297 Test 2



G0b-S1 Panel 297 Test 2

Pull-off Strength: 1653 psi

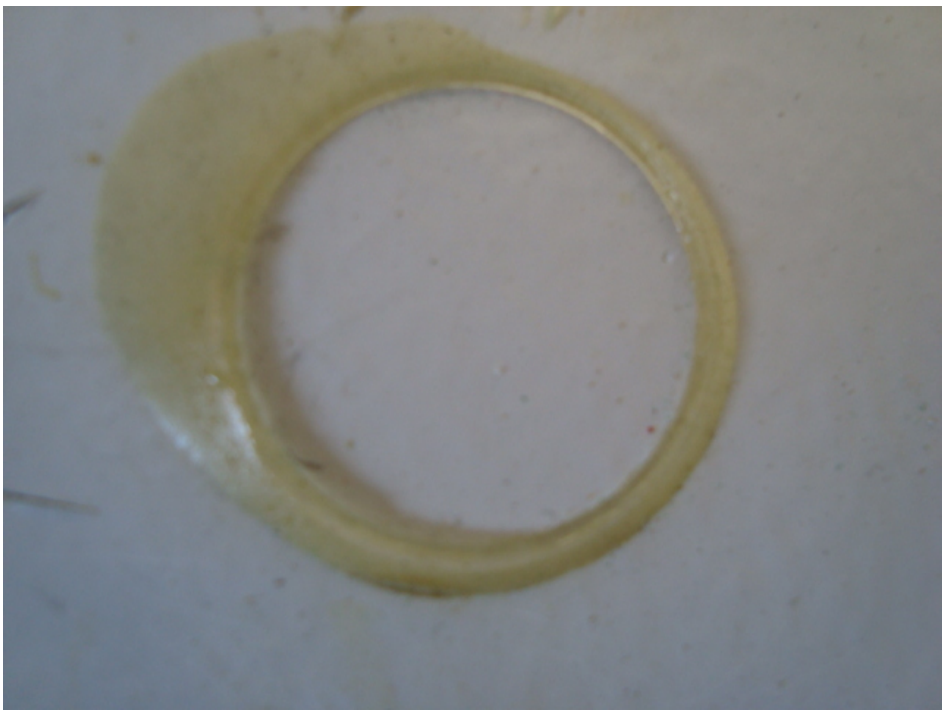
Break: 50% cohesive within Top; 50% adhesive between Glue and Top

Dolly at lower right

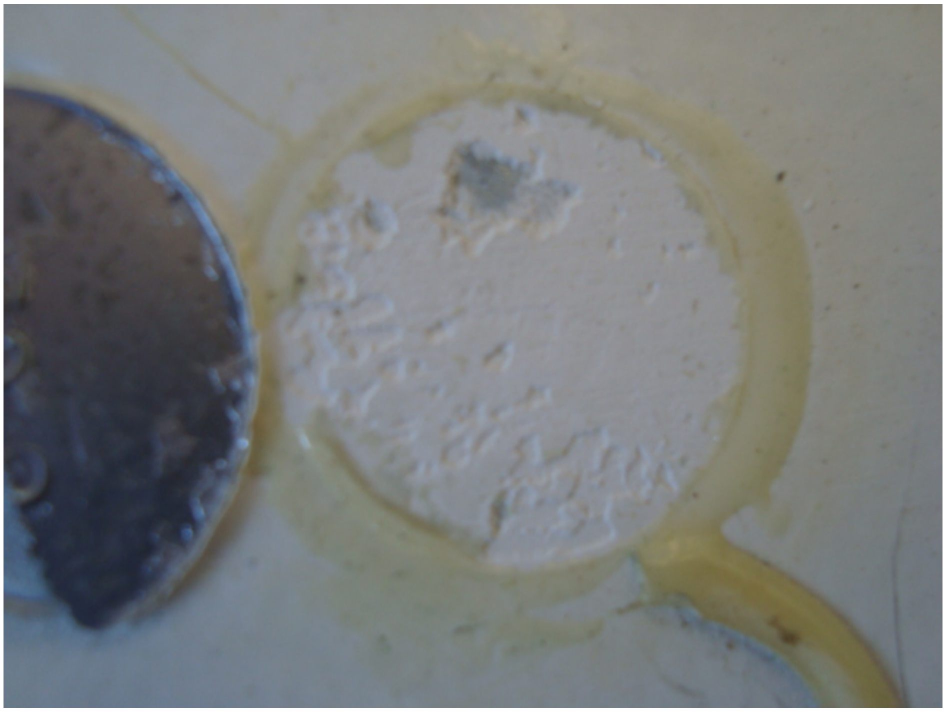
2.c.3.2 G0b-S1 Panel 298

2.c.3.2.1 G0b-S1 Panel 298 Test 1

The Glue to Top adhesion was too weak. The separation between Glue and Top occurred immediately after pull pressure was applied. The following picture of the test spot after pull is shown here:



2.c.3.2.2 G0b-S1 Panel 298 Test 2



Panel 298, Test 2, G0b-S1

Pull-off Strength: 1398 psi

Break: 80% cohesive within Top; 20% adhesive between Top and Int.

Dolly not photographed.

2.c.3.2.3 G0b-S1 Panel 298 Test 3

Panel 298 Test 3, G0b-S1

Pull-off Strength: not recorded

Break: 70% cohesive within Top; 20% adhesive between Top and Int; 10% adhesive between Glue and Top.

Dolly not photographed.

2.c.3.3 G0b-S1 Panel 299

2.c.3.3.1 G0b-S1 Panel 299 Test 1

G0b-S1 Panel 299 Test 1

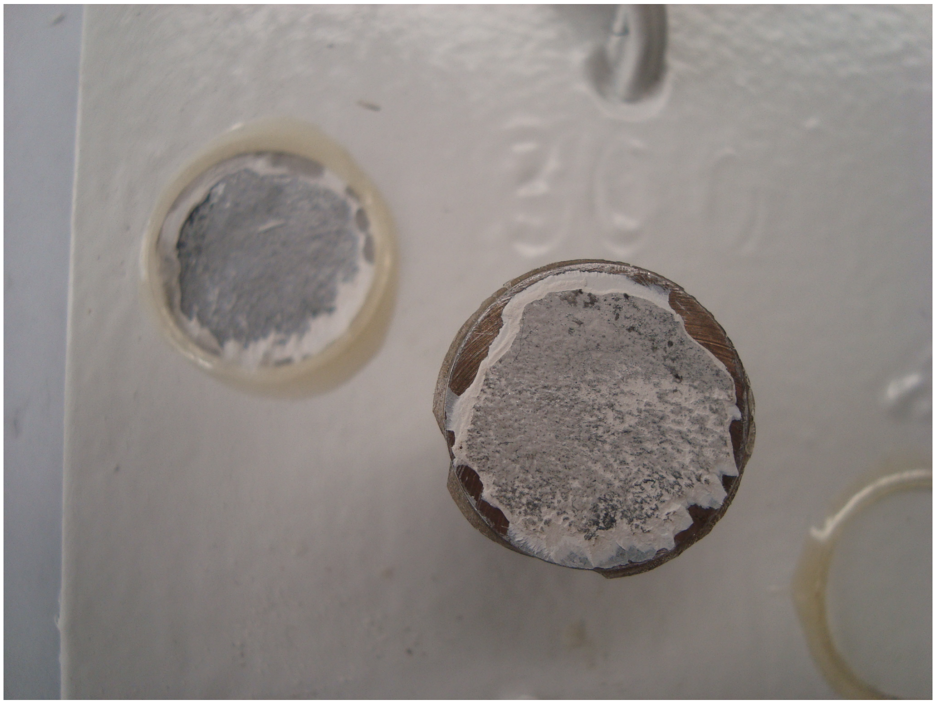
Pull-off Strength: 2578 psi

Break: 50% cohesive within Top; 40% cohesive within Int; 10% adhesive between Glue and Top

Dolly at center left

2.c.3.4 G0b-S1 Panel 300

2.c.3.4.1 G0b-S1 Panel 300 Test 1



G0b-S1 Panel 300 Test 1

Pull-off Strength: 1283 psi

Break: 85% adhesive between Int and Zn-G; 10% adhesive between Glue and Top; 5% cohesive within Top;

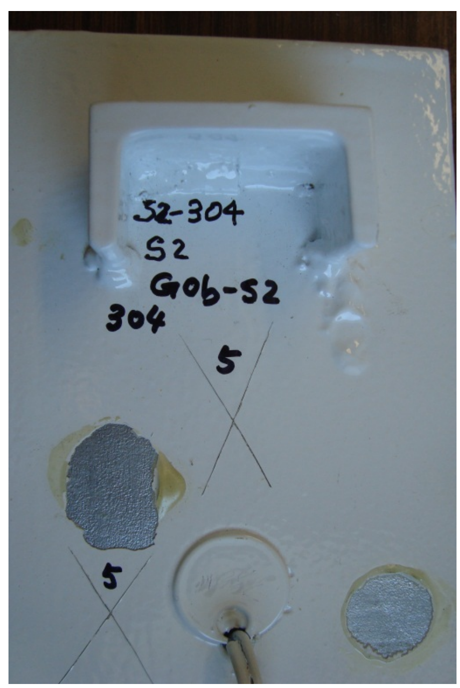
Dolly at lower right

2.d. Test panel subgroup G0b-S2

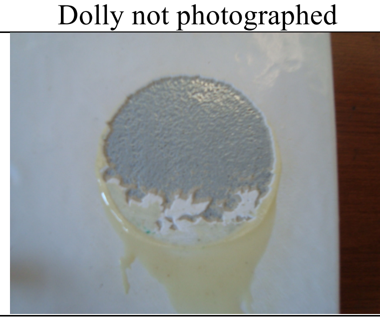
Primer: galvanizing followed by blast surface profiling
Intermediate: Recoatable Epoxy Primer Series B67
Finish: High Solids Polyurethane Series B58

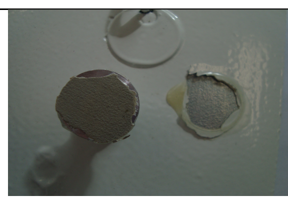
Test panel tag numbers: 301, 302, 303, 304, stored in box 13

2.d.1 Photographs of test panels

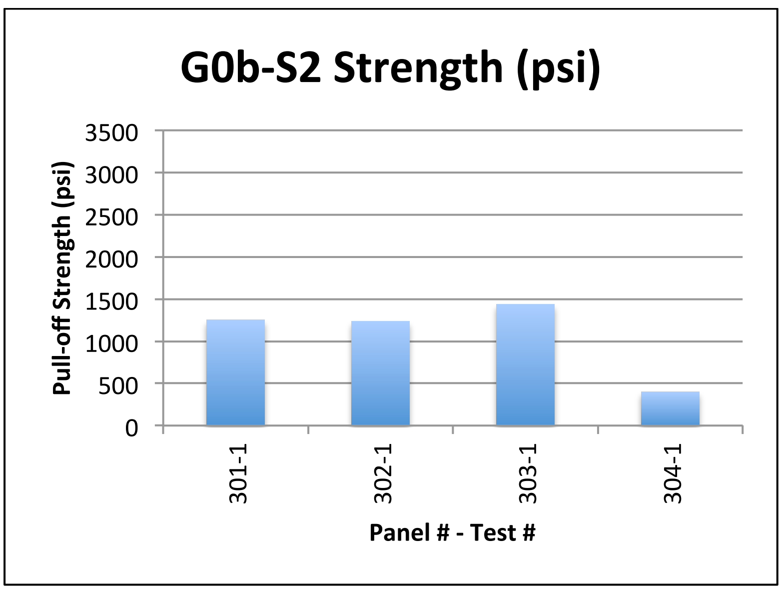


2.d.2 Table of the adhesive strength test results for the G0b-S2 Test Panels.

Test Panel	Pull Test 1	Pull Test 2	X-cut 1 Tape Test Score	X-cut 2 Tape Test Score
301			5	5
	Pull-off Strength: 1253 psi	Pull-off Strength: Data lost		
	Break: 100% adhesive between Int and Zn-G.	Break: 100% adhesive between Int and Zn-G.		
	Dolly at lower left	Dolly not photographed		
302			5	5
	Pull-off Strength: 1236 psi	Pull-off Strength: Data lost		
	Break: 100% adhesive between Int and Zn-G	Break: 80% Adhesive between Int and Zn-G; 20% adhesive between Glue and Top.		
	Dolly at left	Dolly not photographed		

Test Panel	Test 1	Test 2	X-cut 1 Score	X-cut 2 Score
303			5	5
	Strength: 1439 psi	Strength: Data lost		
	Break: 92% adhesive between Int and Zn-G; 8% adhesive between Top and Int.	Break: 80% Adhesive between Int and Zn-G; 20% adhesive between Glue and Top.		
	Dolly at left	Dolly not photographed		
304			5	5
	Strength: 403 psi			
	Break: 100% adhesive between Int and Zn-G			
	Dolly at left			

Pull-off Test	G0b-S2
Panel#-Test#	Strength (psi)
301-1	1253
302-1	1236
303-1	1439
304-1	403
Average	1083
Stand Dev	400
Confidence	392



2.d.3 Enlarged photos of the pull-off dolly placed near the test spot on the G0b-S2 panel, and a description of the break layers.

2.d.3.1 G0b-S2 Panel 301

2.d.3.1.1 G0b-S2 Panel 301 Test 1

Panel 301 Test 1, G0b-S2

Pull-off Strength: 1253 psi

Break: 100% adhesive between Int and Zn-G.

Dolly at left.

2.d.3.1.2 G0b-S2 Panel 301 Test 2

Panel 301 Test 1 G0b-S2

Pull-off Strength: Data lost

Break: 100% cohesive within Int.

Dolly not photographed

2.d.3.2 G0b-S2 Panel 302

2.d.3.2.1 Panel 302 G0b-S2 Test 1

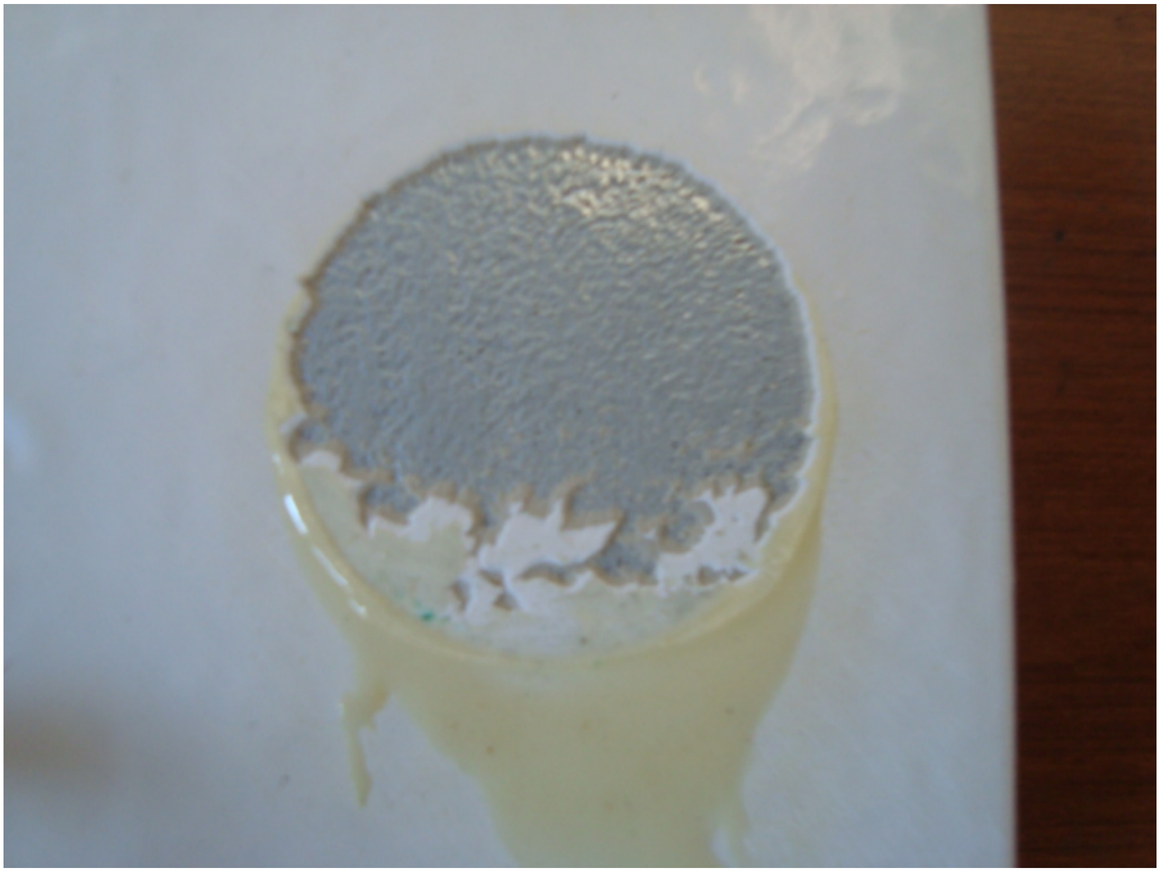
Panel 301 Test 1, G0b-S2

Pull-off Strength 1236 psi

Break: 100% adhesive between Int and Zn-G

Dolly at left.

2.d.3.2.2 Panel 302 G0b-S2 Test 2



Panel 302 Test 2 G0b-S2

Pull-off Strength: Data lost

Break: 80% Adhesive between Int and Zn-G; 20% adhesive between Glue and Top.

Dolly not photographed.

2.d.3.3 G0b-S2 Panel 303

2.d.3.3.1 Panel 303 G0b-S2 Test 1

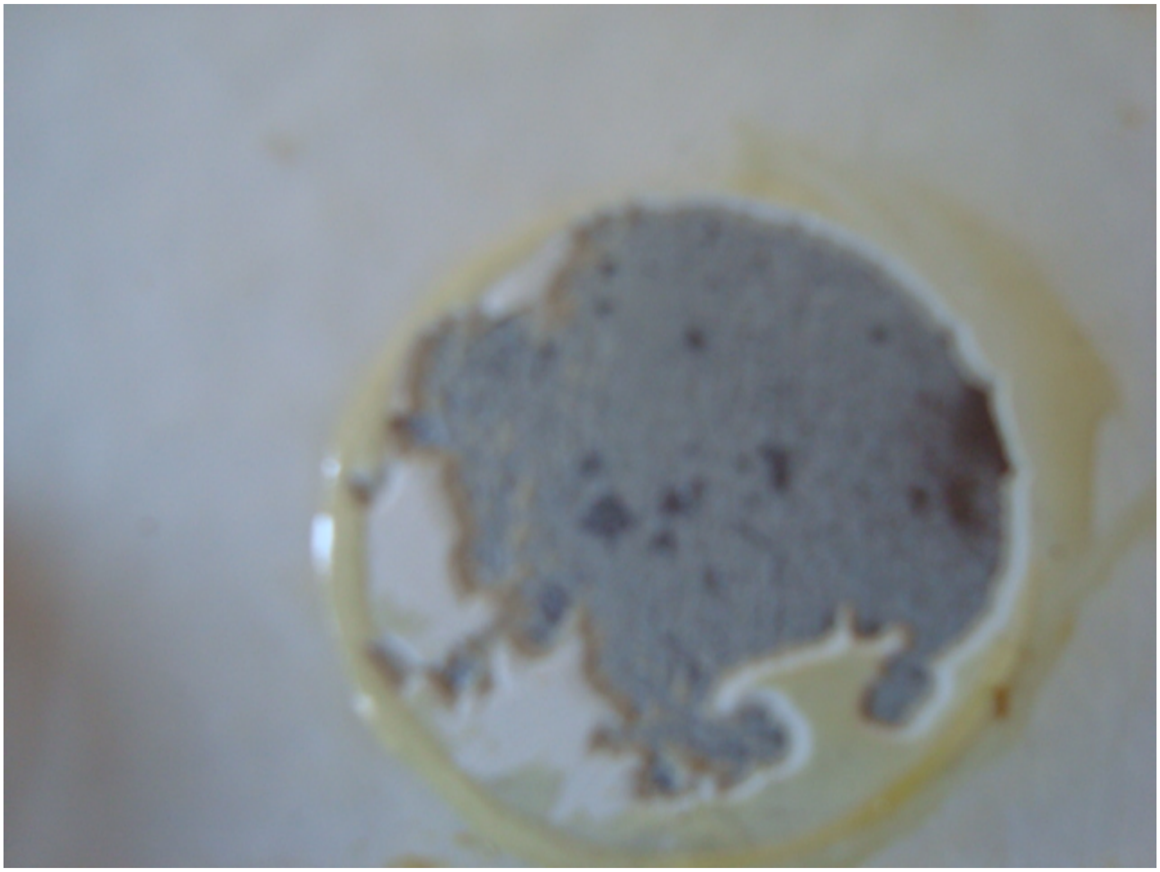
Panel 303 Gb0-S2 Test 1

Pull-off Strength: 1439 psi

Break: 92% adhesive between Int and Zn-G; 8% adhesive between Top and Int.

Dolly at left.

2.d.3.3.2 Panel 303 G0b-S2 Test 2



Panel 303 Test 2, G0b-S2

Pull-off Strength: Data lost

Break: 80% adhesive between Int and Zn-G, 20% adhesive between Glue and Top

Dolly not photographed

2.d.3.4 G0b-S2 Panel 304

2.d.3.4.1 Panel 303 G0b-S2 Test 1

Panel 304 G0b-S2 Test 1

Pull-off Strength: 403 psi

Break: 100% adhesive between Int and Zn-G

Dolly at left.

3. Group M0, List and photographic image of tested panels.

This group of test panels is made from the thermal sprayed zinc metallized surface. The metallizing and the application of the epoxy paint (or sealer) were performed on the same day. This group of test panels is labeled as group “M0”. In this group label “M” stands for zinc metallized steel, “0” stands for zero delay time (same day) between metallizing and the painting of the epoxy layer. Five different paint systems were used for the subgroups with the following designations for the subgroups and the test panels.

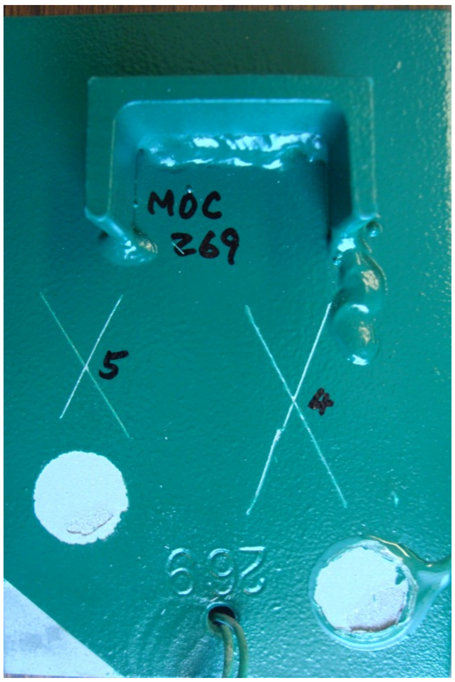
Each pull-off test spot on a test panel is given an identification number according to the following convention: We assign the uppermost test spot in the images of the panels as test sample #1. Pretending that sample #1 is at the 12-oclock position of a clock, the remaining test spots are ordered according to its position in the clockwise rotation order. Occasionally, a pull-off test is omitted from the list because of technical problems observed during the test. For example the dolly was not property glued to the paint surface, or the surface near the test spot is too close to a welding burr so that the tester cannot be seated correctly. A replacement test is listed (using a different test spot identification number) is listed in the table in place of the omitted test.

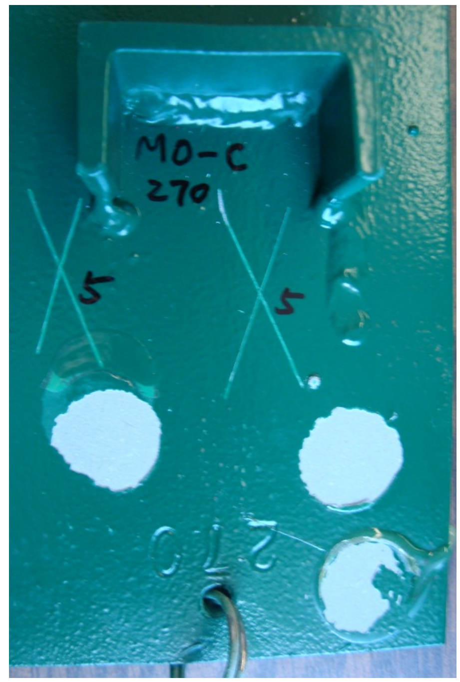
3.a M0-C: M0 panels with paint system C

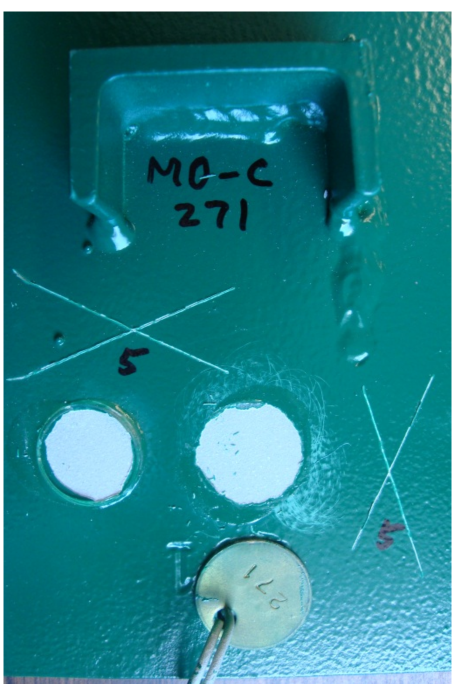
Primer: Thermal sprayed zinc metallizing coating
Intermediate: Carboline 888 Epoxy
Finish: Carboline 133 LH Aliphatic Polyurethane

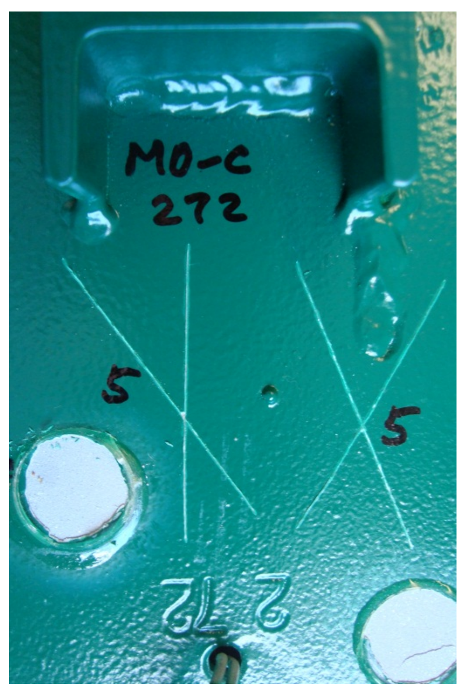
Test panel tag numbers: 269, 270, 271, 272 stored in box 5.

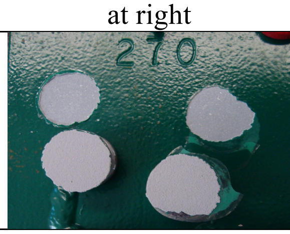
3.a.1 Photographs of the M0-C test panels

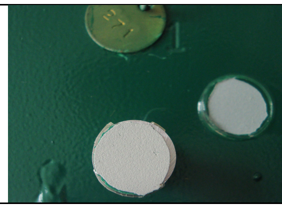
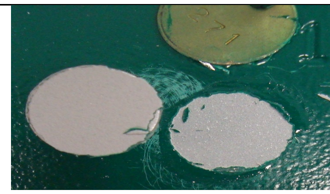




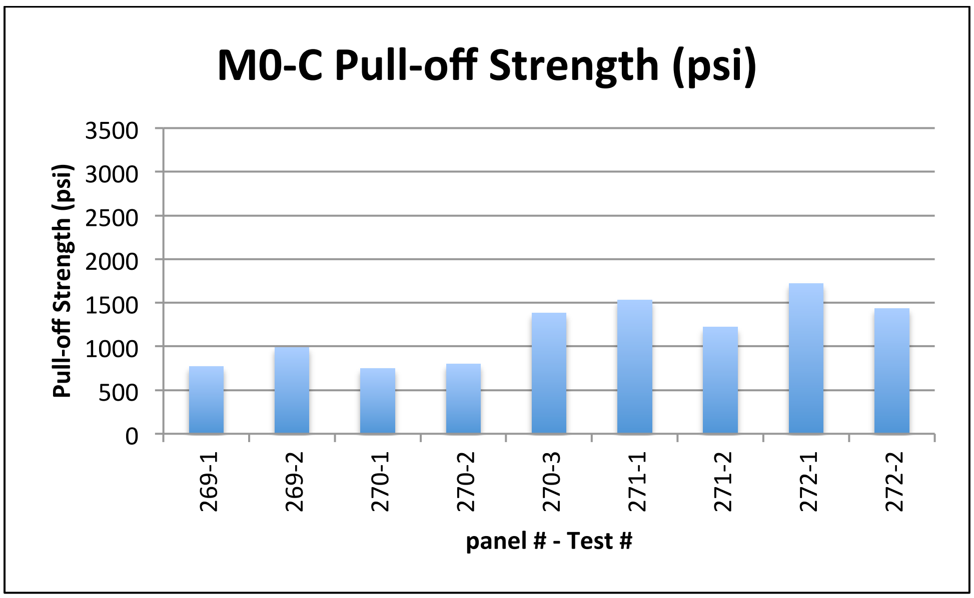




3.a.2 Adhesive strength test results for M0-C test panels					
Test Panel	Pull Test 1	Pull Test 2 (or Test 3 if Test 2 is not shown)	Pull Test 3 (or Test 4 if Test 3 is not shown)	X-cut 1 Score	X-cut 2 Score
269				5	4
	Strength: 772 psi	Strength: 990 psi			
	Break: 80% cohesive within Int; 20% adhesive between Int and Zn-M.	Break: 60% cohesive within Int; 40% adhesive between Int and Zn-M			
	Dolly was not photographed, test spot at right	Dolly at lower left	.		
270				5	5
	Strength: 750 psi	Strength: 800 psi	Strength: 1382 psi		
	Break: 90% adhesive between Int and Zn-M; 10% adhesive between Glue and Top	Break: 100% adhesive between Int and Zn-M	Break: 70% adhesive between Int and Zn-M; 30% adhesive between Glue and Top		
	Dolly at lower right. (Note this photograph shows tests 1 and 2. Test 1 spot/dolly are on the right.)	Dolly at lower left. (Note this photograph shows tests 1 and 2. Test 2 spot/dolly are on the left.)	Dolly at lower center; Test spot at upper left		

Test Panel	Pull Test 1	Pull Test 2	X-cut 1 score	X-cut 2 score
271			5	5
	Strength: 1533 psi	Strength: 1220 psi		
	Break: 95% cohesive within Int; 5% adhesive between Glue and Top	Break: 95% adhesive between Int and Zn-M; 5% adhesive between Glue and Top		
	Dolly at lower center	Dolly at lower left		
272			5	5
	Strength: 1718 psi	Strength: 1437 psi		
	Break: 100% adhesive between Int and Zn-M	Break: 95% adhesive between Int and Zn-M, 5% adhesive between Glue and Top		
	Dolly at lower left	Dolly at lower left		

Pull-off Test	M0-C
Panel#-Test#	Strength (psi)
269-1	772
269-2	990
270-1	750
270-2	800
270-3	1382
271-1	1533
271-2	1220
272-1	1718
272-2	1437
Average	1178
Standard Dev	342
Confidence	224



3.a.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

3.a.3.1 M0-C Panel #269

3.a.3.1.1 M0-C Panel #269, Test 1

M0-C Panel 269 Test 1

Pull-off strength: 772 psi

Break: 80% cohesive within Int; 20% adhesive between Int and Zn-M.

Dolly was not photographed, test spot at right

3.a.3.1.2 M0-C Panel #269, Test 2

M0-C Panel 269 Test 2

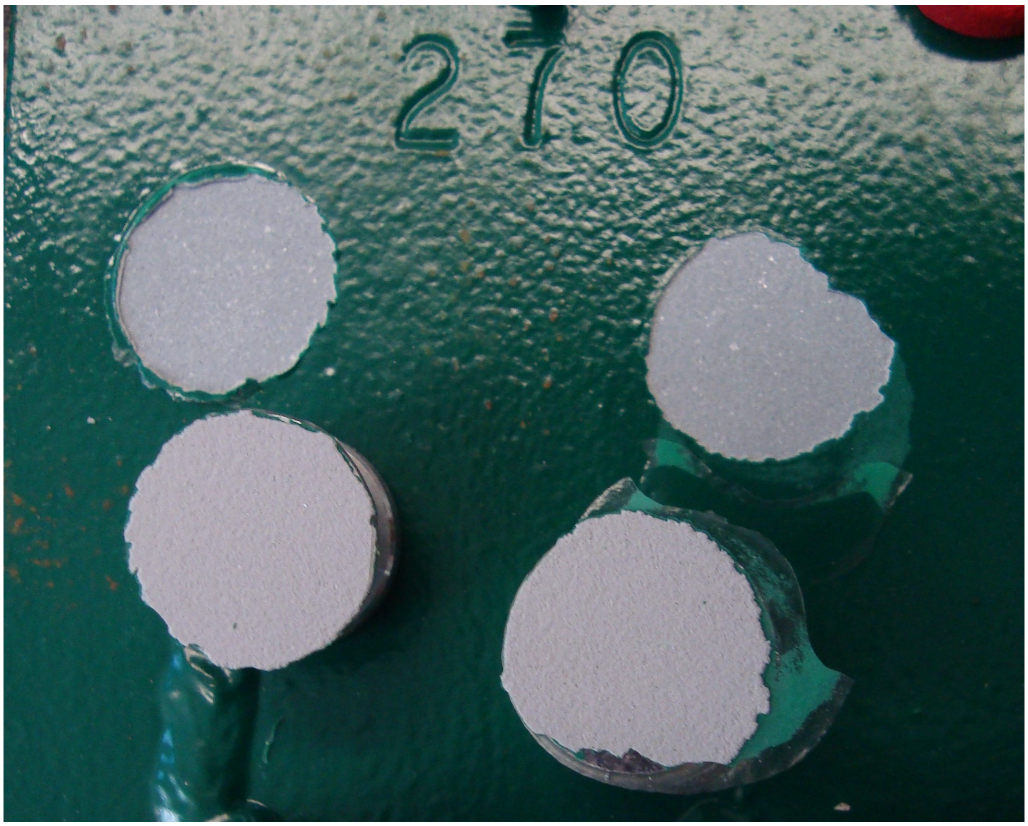
Pull-off strength: 990 psi

Break: 60% cohesive within Int; 40% adhesive between Int and Zn-M.

Dolly at lower left.

3.a.3.2 M0-C Panel #270

3.a.3.2.1 M0-C Panel 270 Test 1



M0-C Panel 270 Test 1

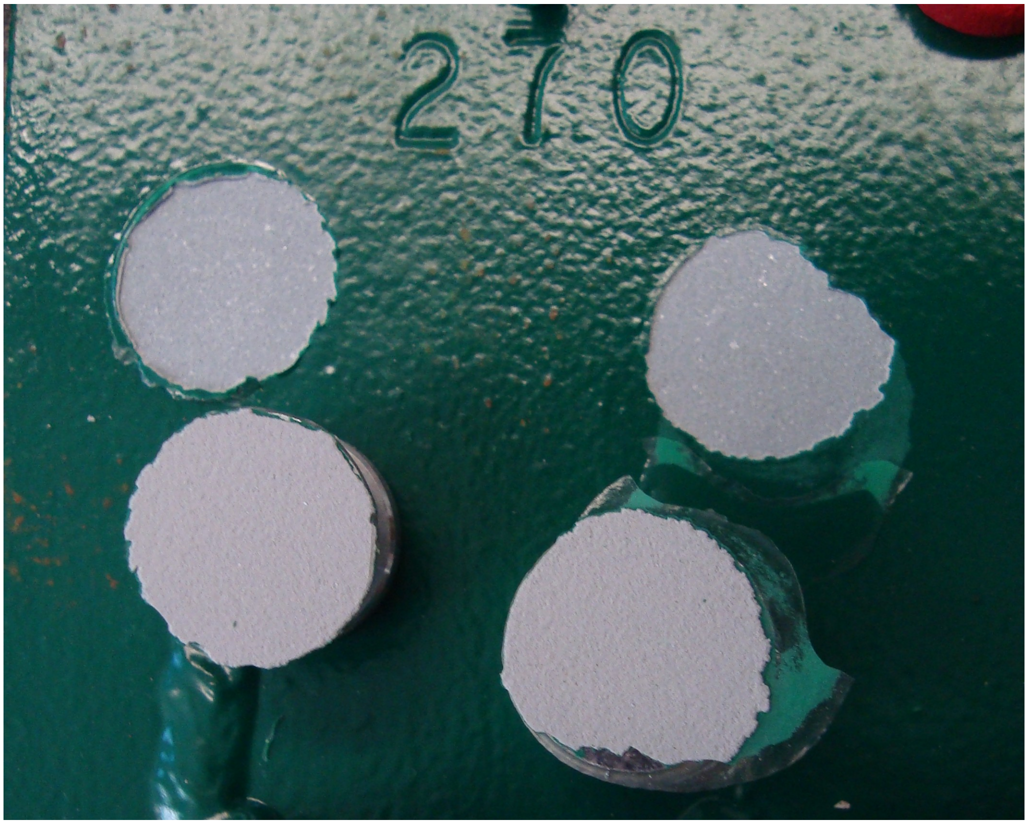
Pull-off strength: 750 psi

Break: 90% adhesive between Int and Zn-M; 10% adhesive between Glue and Top

Dolly at lower right

(Note this photograph shows tests 1 and 2. Test 1 spot and dolly are on the right.)

3.a.3.2.2 M0-C Panel 270 Test 2



M0-C Panel 270 Test 2

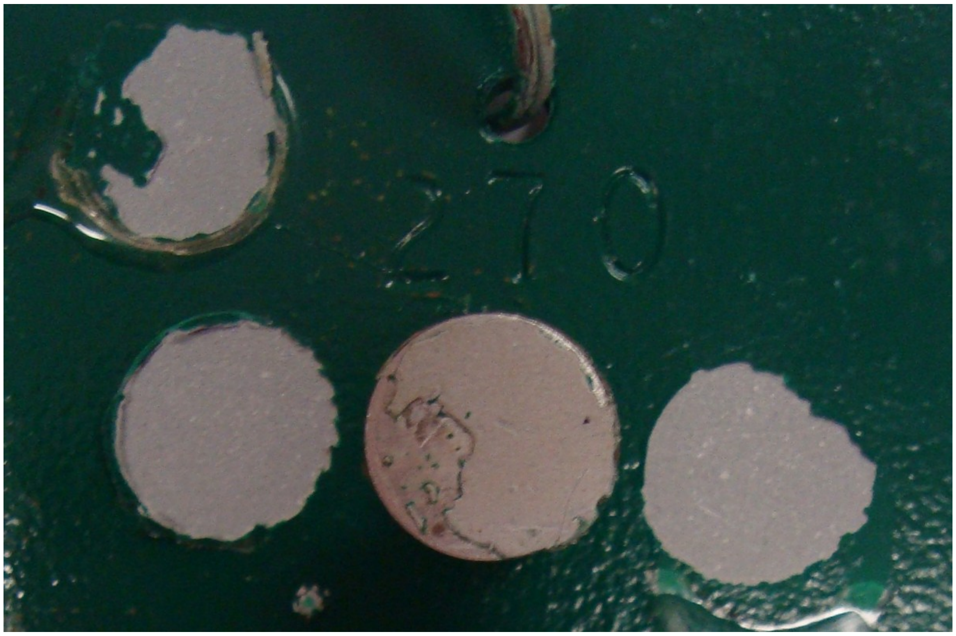
Pull-off strength: 800 psi

Break: 100% adhesive between Int and Zn-M

Dolly at lower left.

(Note this photograph shows tests 1 and 2. Test 2 spot and dolly are on the left.)

3.a.3.2.3 M0-C Panel 270 Test 2



M0-C Panel 270 Test 3

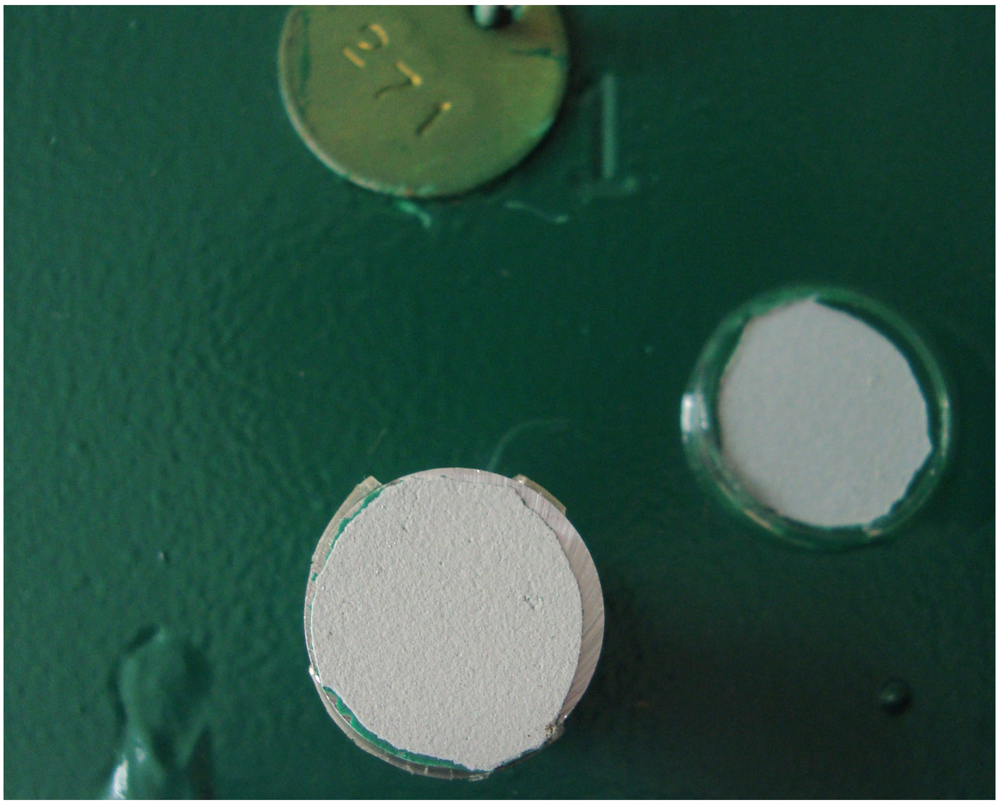
Pull-off strength: 1382 psi

Break: 70% adhesive between Int and Zn-M; 30% adhesive between Glue and Top.

Dolly at lower center; Test spot at upper left.

3.a.3.3 M0-C Panel #271

3.a.3.3.1 M0-C Panel 271 Test 1



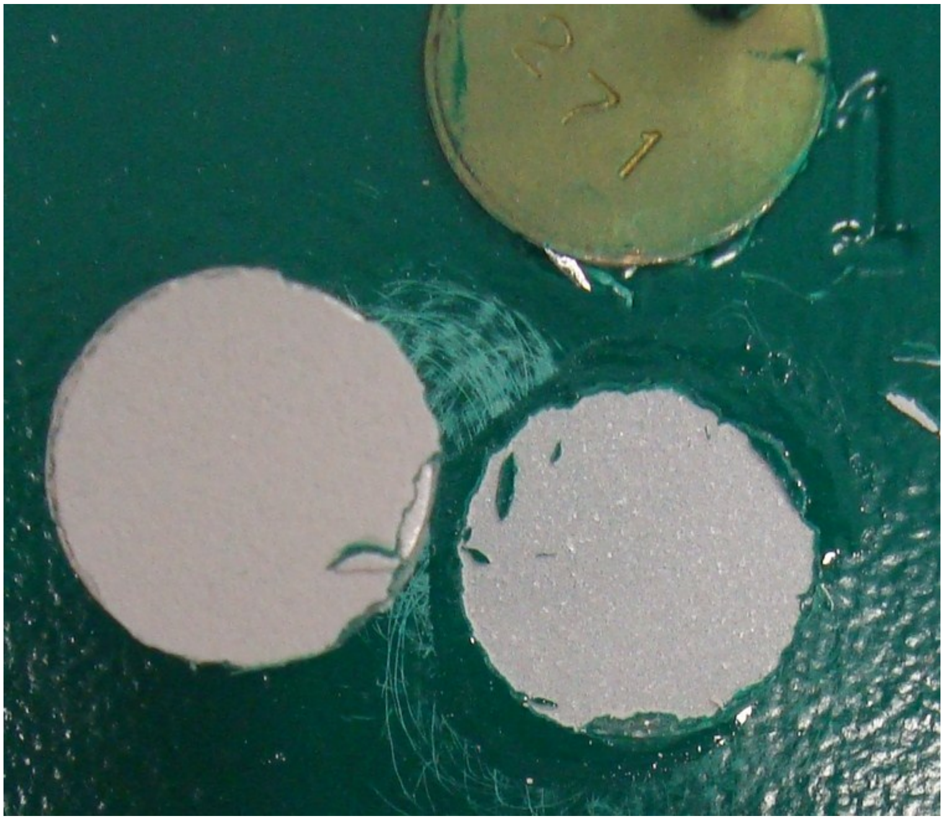
M0-C Panel 271 Test 1

Pull-off strength: 1533 psi

Break: 95% cohesive within Int; 5% adhesive between Glue and Top

Dolly at lower center.

3.a.3.3.2 M0-C Panel 271 Test 2



M0-C Panel 271 Test 2

Pull-off strength 1220 psi

Break: 95% adhesive between Int and Zn-M; 5% adhesive between Glue and Top

Dolly at lower left.

3.a.3.4 M0-C Panel #272

3.a.3.4.1 M0-C Panel 272 Test 1

M0-C Panel 272 Test 1

Pull-off Strength: 1718 psi

Break: 100% adhesive between Int and Zn-M

Dolly at left

3.a.3.4.2 M0-C Panel 272 Test 2

M0-C Panel 272 Test 2

Pull-off strength: 1437 psi

Break: 95% adhesive between Int and Zn-M, 5% adhesive between Glue and Top

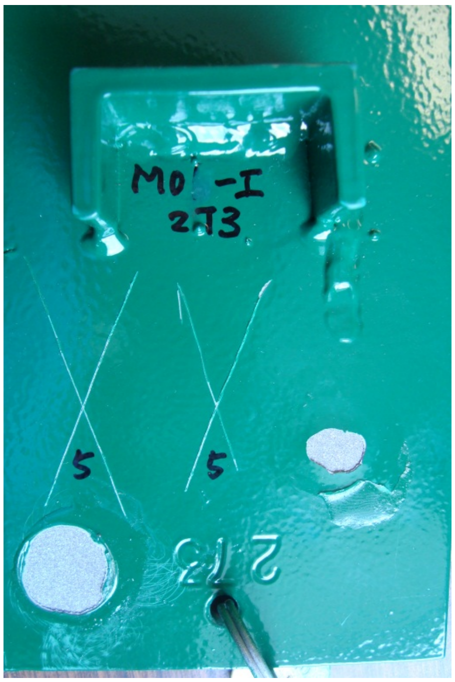
Dolly at lower left.

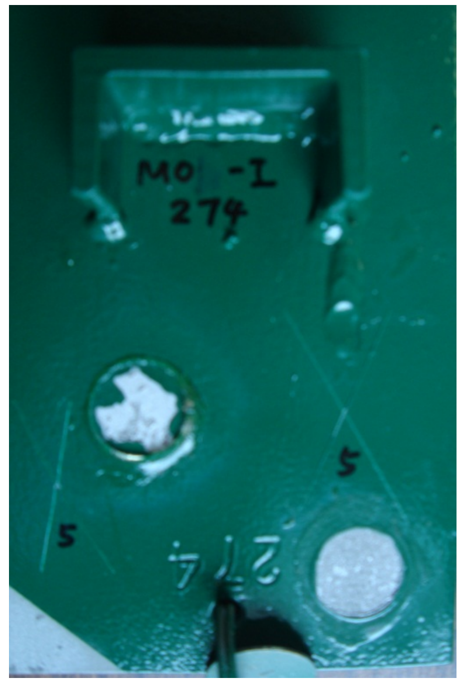
3.b Test panel subgroup M0-I

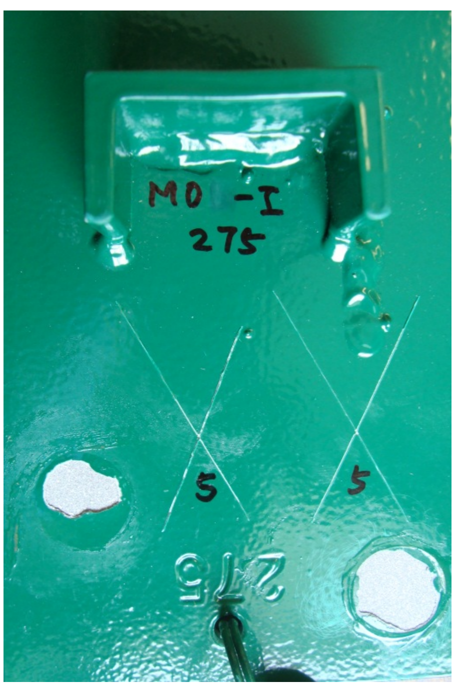
Primer:	Thermal sprayed zinc metallizing coating
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

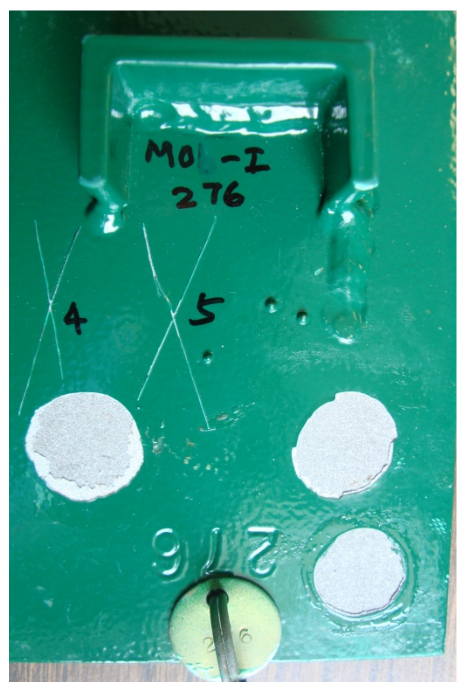
Panel numbers 273, 274, 275, 276, stored in box 6.

3.b.1 Photographs of the M0-I test panels

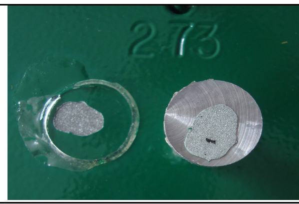
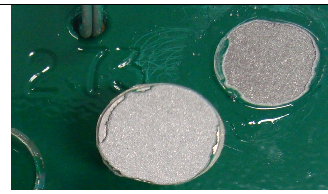
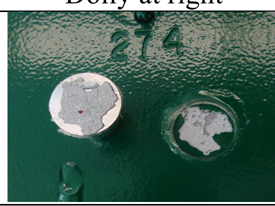




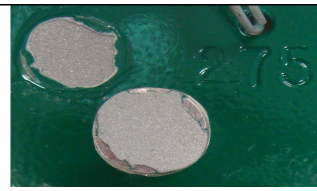
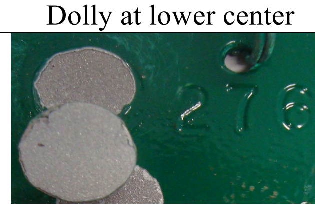




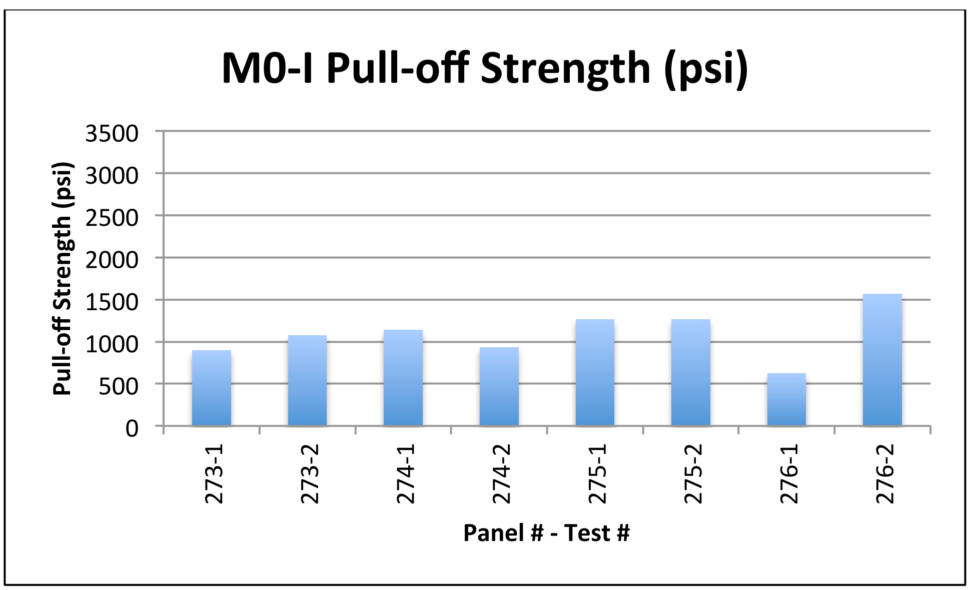
3.b.2 Adhesive strength test results for M0-I test panels

Test Panel	Pull Test 1	Pull Test 2 (or Test 3 if Test 2 is not shown)	X-cut 1 Score	X-cut 2 Score
273			5	5
	Strength: 839 psi	Strength: 1075 psi		
	Break: 60% adhesive between Glue and Top; 40% adhesive between Int and Zn-M	Break: 95% adhesive between Int and Zn-M, 5% adhesive between Glue and Top		
	Dolly at right	Dolly at lower left		
274			5	5
	Strength: 1141 psi	Strength: 931 psi		
	Break: 80% adhesive between Int and Zn-M; 20% adhesive between Glue and Top	Break: 100% adhesive between Int and Zn-M		
	Dolly at left.	Dolly at lower center.		

3.b.2 Adhesive strength test results for M0-I test panels (Part II)

Test Panel	Pull Test 1	Pull Test 2 (or Test 3)	X-cut 1 score	X-cut 2 score
275			5	5
	Strength: 1263 psi	Strength: 1262 psi		
	Break: 60% adhesive between Int and Zn-M; 40% adhesive between Glue and Top	Break: 90% adhesive between Int and Zn-M; 10% adhesive between Glue and Top		
	Dolly at center	Dolly at lower center		
276			4	5
	Strength: 620 psi	Strength: 1568 psi		
	Break: 85% adhesive between Int and Zn-M; 15% cohesive within Int.	Break: 100% adhesive between Int and Zn-M (Test 3)		
	Dolly at lower center Test spot at upper right	Dolly at lower left Test spot at upper left		

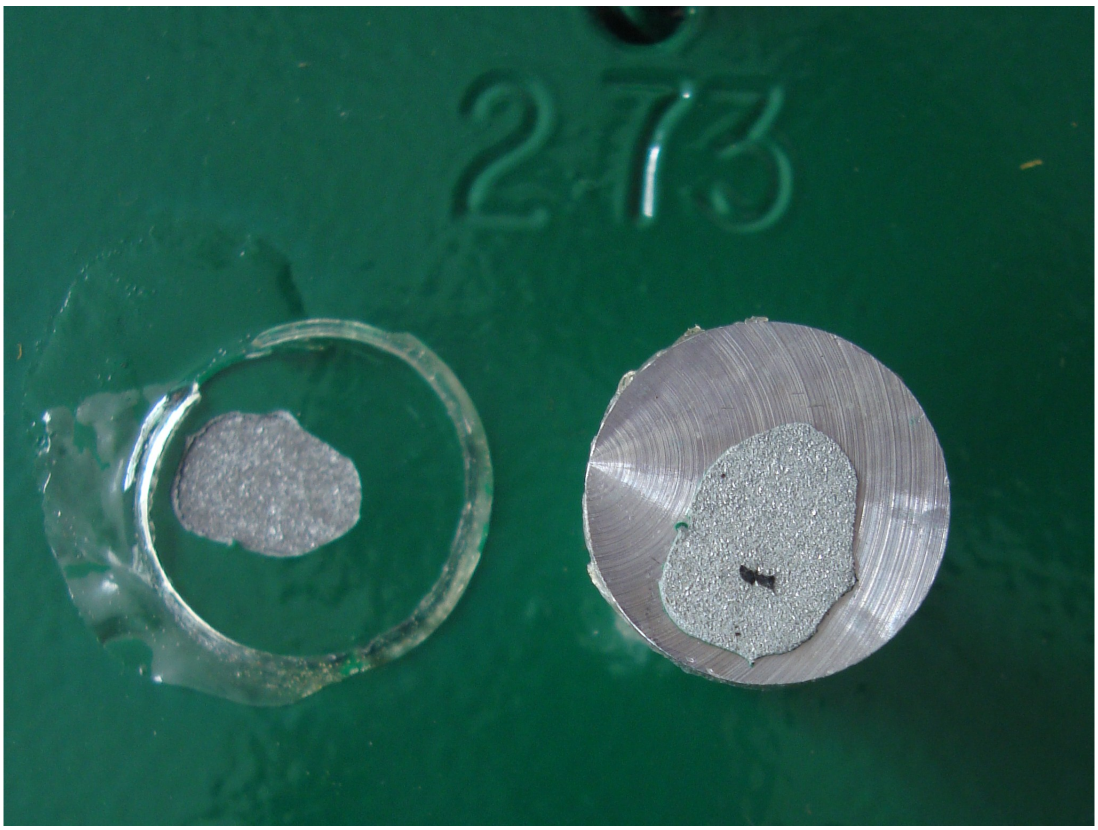
Pull-off Test M0-I	
Panel#-Test#	Strength (psi)
273-1	893
273-2	1075
274-1	1141
274-2	931
275-1	1263
275-2	1262
276-1	620
276-2	1568
Average	1094
Standard Dev	268



3.b.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers. M0-I panels.

3.b.3.1 M0-I panel 273

3.b.3.1.1 Panel 273 Test 1, M0-I



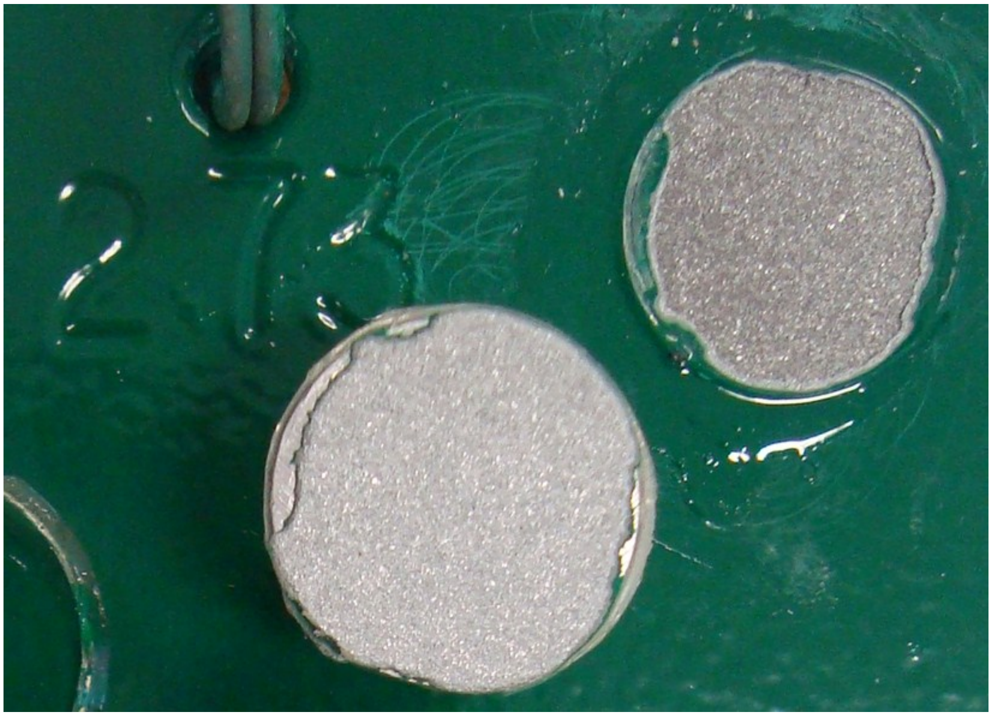
Panel 273 Test 1

Pull-off strength: 839 psi

Break: 60% adhesive between Glue and Top; 40% adhesive between Int and Zn-M

Dolly at right.

3.b.3.1.2 M0-I Panel 273 Test 2



M0-I Panel 273 Test 2

Pull-off strength: 1175 psi

Break: 95% adhesive between Int and Zn-M, 5% adhesive between Glue and Top.

Dolly at lower center.

3.b.3.2 M0-I panel 274

3.b.3.2.1 M0-I Panel 274 Test 1

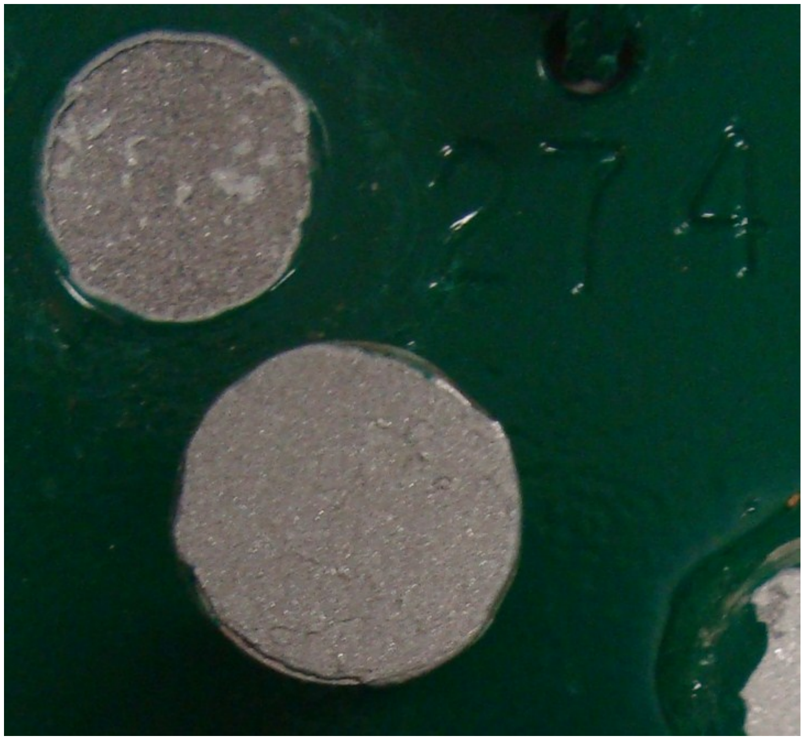
M0-I Panel 274 Test 1

Pull-off strength:

Break: 80% adhesive between Int and Zn-M; 20% adhesive between Glue and Top

Dolly at left.

3.b.3.2.2 M0-I Panel 274 Test 2



M0-I Panel 274 Test 2

Pull-off strength: 931 psi

Break: 100% adhesive between Int and Zn-M

Dolly at lower center.

3.b.3.3 M0-I panel 275

3.b.3.3.1 M0-I Panel 275 Test 1

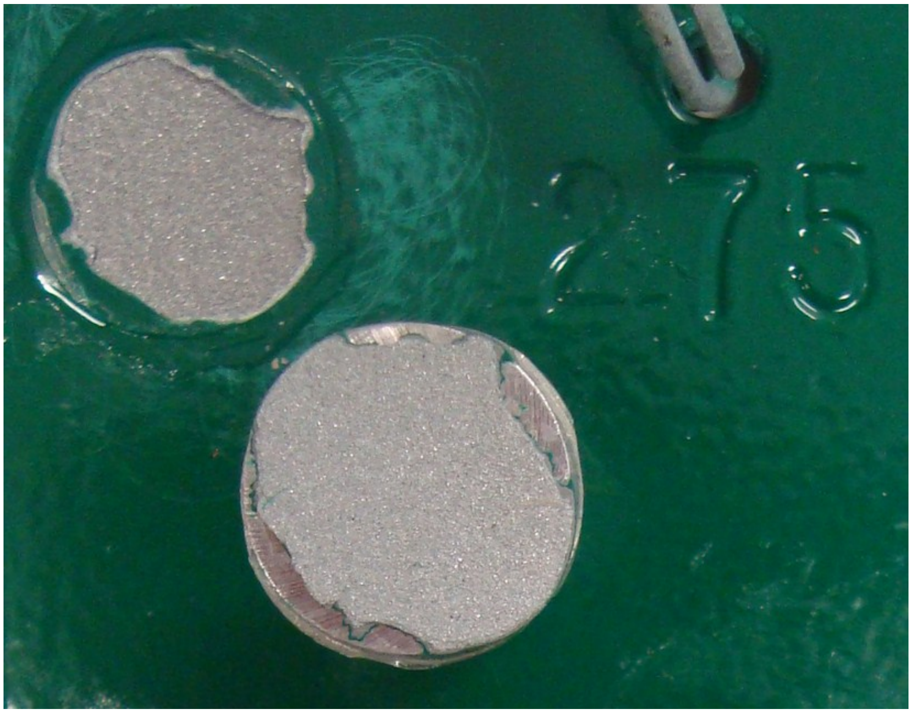
M0-I Panel 275 Test 1

Pull-off strength: 1263 psi

Break: 60% adhesive between Int and Zn-M; 40% adhesive between Glue and Top.

Dolly at center.

3.b.3.3.2 M0-I Panel 275 Test 2



M0-I Panel 275 Test 2

Pull-off strength: 1262 psi

Break: 90% adhesive between Int and Zn-M; 10% adhesive between Glue and Top

Dolly at lower center.

3.b.3.4 M0-I panel 276

3.b.3.4.1 M0-I Panel 276 Test 1

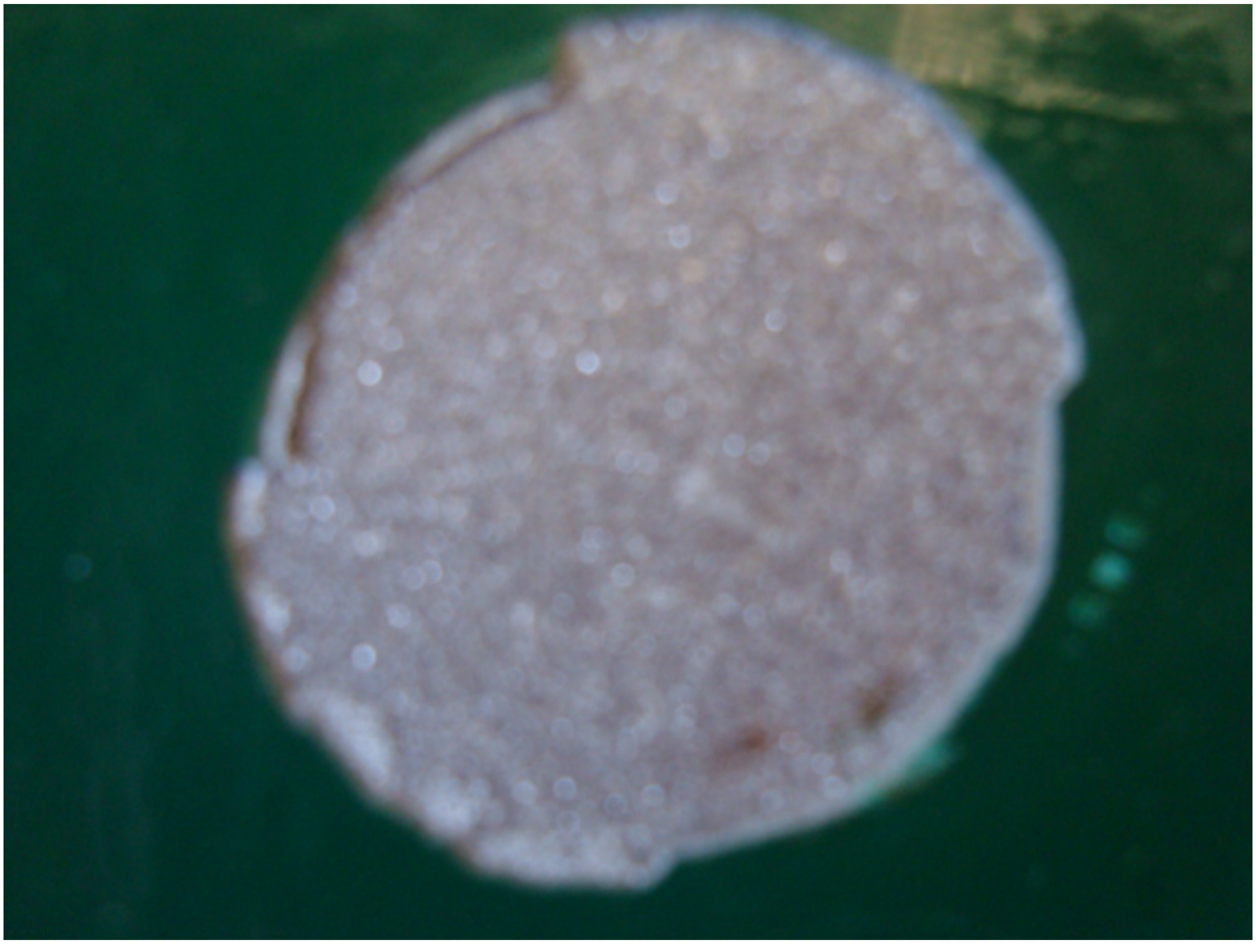
M0-I Panel 276 Test 1

Pull-off strength: 620 psi

Break: 85% adhesive between Int and Zn-M; 15% cohesive within Int.

Dolly at lower center.

3.b.3.4.2 M0-I Panel 276 Test 2



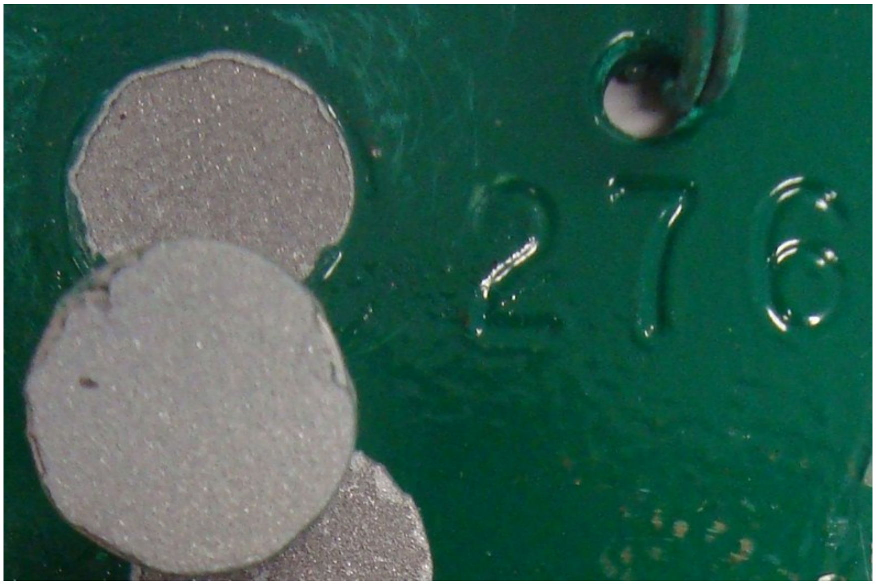
Panel 276 Test 2, M0-I

Pull-off Strength: Data Lost

Break: 100 % adhesive between Int and Zn-M

Dolly not photographed.

3.b.3.4.3 M0-I Panel 276 Test 3



M0-I Panel 276 Test 3

Pull-off strength: 1568 psi

Break: 100% adhesive between Int and Zn-M

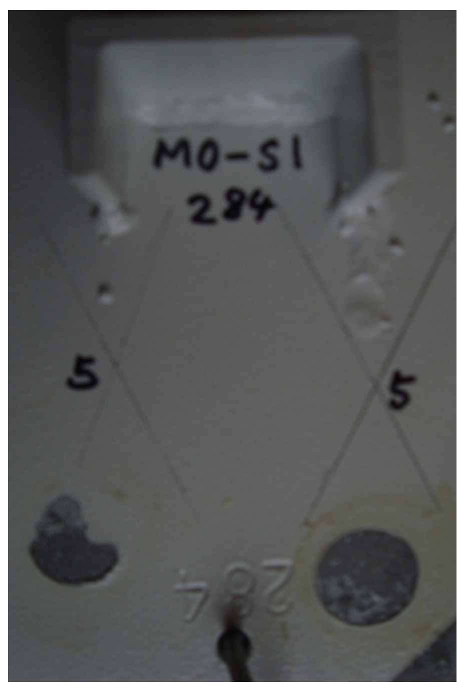
Dolly at lower left.

3.c Test panel subgroup M0-S1

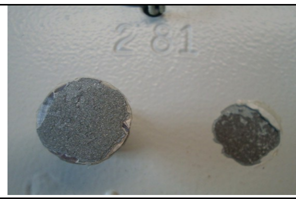
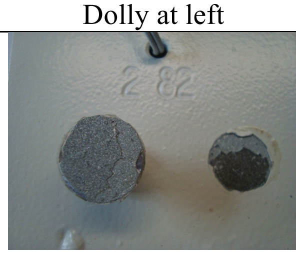
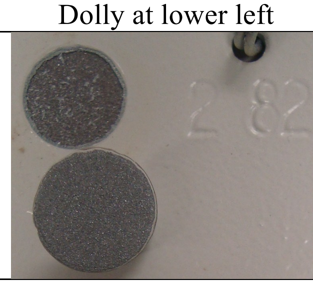
Primer: galvanizing followed by blast surface profiling
Intermediate: Macropoxy 646 Fast Cure Epoxy
Finish: Acrolon 218 HS Acrylic Polyurethane

Test panel tag numbers: 281, 282, 283, 284, stored in box 12

3.c.1 Photographs of the M0-S1 test panels

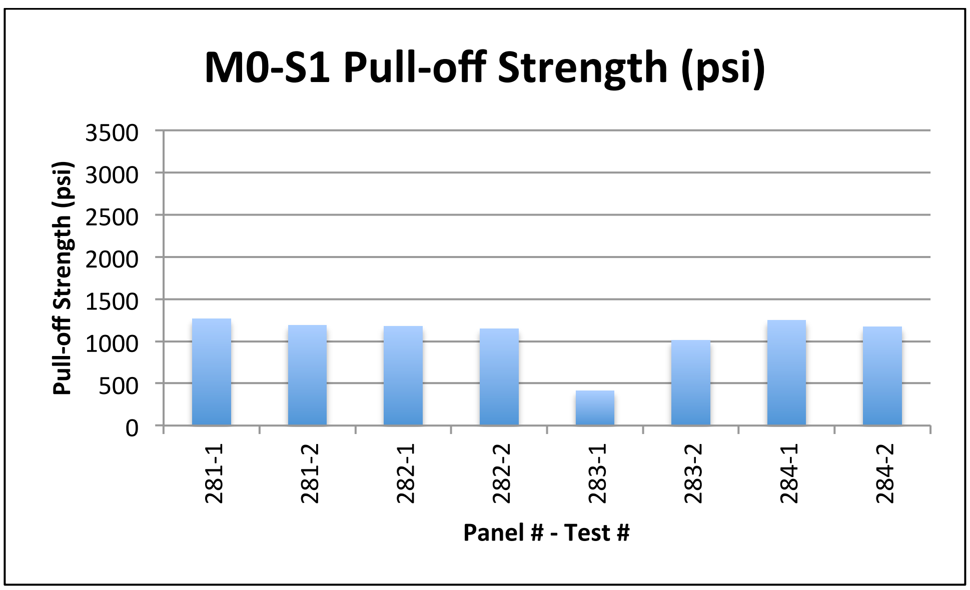


3.c.2 Adhesive strength test results for M0-S1 test panels

3.c.2 Adhesive strength test results for M0-S1 test panels (Part I)				
Test Panel	Pull Test 1	Pull Test 2 (or Test 3 if Test 2 is not shown)	X-cut 1 Score	X-cut 2 Score
281			5	4
	Strength: 1266 psi	Strength: 1192 psi		
	Break: 90% adhesive between Int and Zn-M; 10% adhesive between Glue and Top	Break: 90% adhesive between Int and Zn-M; 10% cohesive within Int		
	Dolly at left	Dolly at lower left		
282			5	5
	Strength: 1179 psi	Strength: 1150 psi		
	Break: 70% cohesive within Int; 30% adhesive between Int and Zn-M	100% adhesive between Int and Zn-M		
	Dolly at left.	Dolly at lower left.		

3.c.2 Adhesive strength test results for M0-S1 test panels (Part II)				
Test Panel	Pull Test 1	Pull Test 2	X-cut 1 score	X-cut 2 score
283			5	5
	Strength: 415 psi	Strength: 1010 psi		
	Break: 90% cohesive within Int; 10% adhesive between Int and Zn (Note: Paint beyond the dolly glued area were torn off from panel)	Break: 100% adhesive between Int and Zn-M		
	Dolly at lower center	Dolly at center right, Test spot at upper right		
284			5	5
	Strength: 1249 psi	Strength: 1172 psi		
	Break: 60% adhesive between Int and Zn-M; 10% cohesive within Int; 30% adhesive between Glue and Top	Break: 80% adhesive between Int and Zn-M, 20% cohesive within Int		
	Dolly at left	Dolly at lower right		

Pull-off Test M0-S1	
Panel#-Test#	Pull-off Strength (psi)
281-1	1266
281-2	1192
282-1	1179
282-2	1150
283-1	415
283-2	1010
284-1	1249
284-2	1172
Average	1079
Standard Dev	261
Confidence	181



3.c.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers. M0-S1 panels.

3.c.3.1 M0-S1 panel 281

3.c.3.1.1 M0-S1 Panel 281 Test 1

M0-S1 Panel 281 Test 1

Pull-off strength: 1266psi

Break: 90% adhesive between Int and Zn-M; 10% adhesive between Glue and Top

Dolly at left.

3.c.3.1.2 M0-S1 Panel 281 Test 2

M0-S1 Panel 281 Test 2

Pull-off strength: 1192 psi

Break: 90% adhesive between Int and Zn-M; 10% cohesive within Int.

Dolly at lower left.

3.c.3.2 M0-S1 panel 282

3.c.3.2.1 M0-S1 panel 282 Test 1

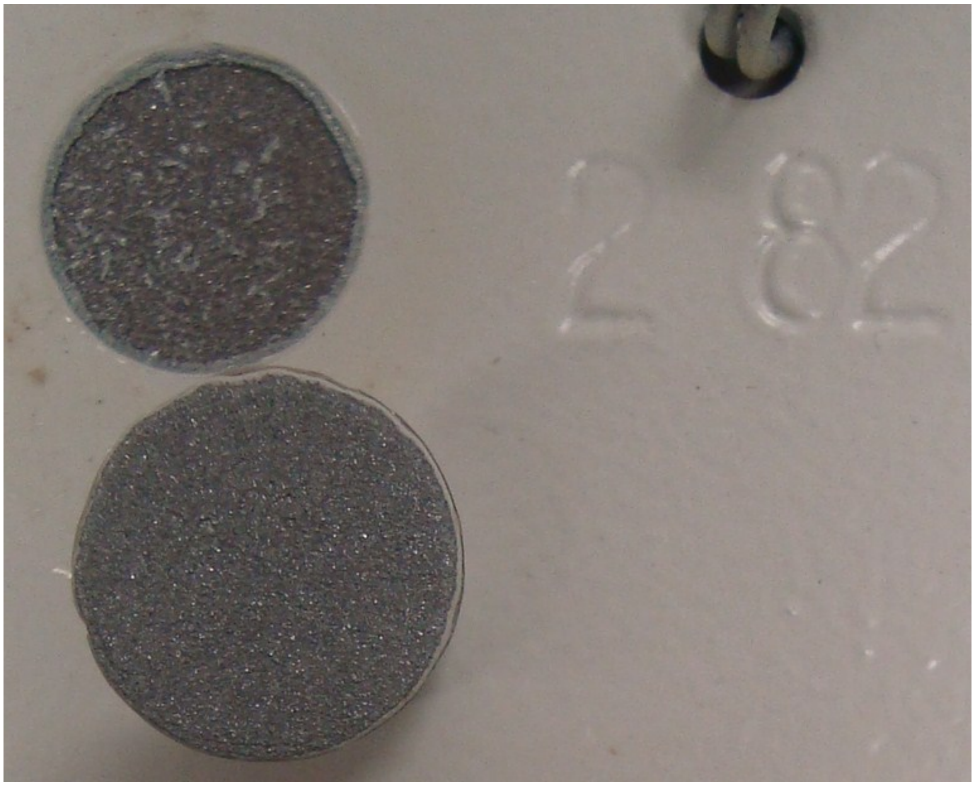
M0-S1 panel 282 Test 1

Pull-off strength: 1179 psi

Break: 70% cohesive within Int; 30% adhesive between Int and Zn-M

Dolly at left.

3.c.3.2.2 M0-S1 Panel 282 Test 2



M0-S1 Panel 282 Test 2

Pull-off Strength: 1150 psi

Break: 100% adhesive between Int and Zn-M

Dolly at lower left.

3.c.3.3 M0-S1 panel 283

3.c.3.3.1 M0-S1 Panel 283 Test 1

M0-S1 Panel 283 Test 1

Pull-off strength: 415 psi

Break: 90% cohesive within Int; 10% adhesive between Int and Zn-M

(Note: Paint beyond the dolly footprint were torn off from panel. This observation is consistent with the poor adhesion between Int and Zn-M)

Dolly at lower center.

3.c.3.3.2 M0-S1 Panel 283 Test 2

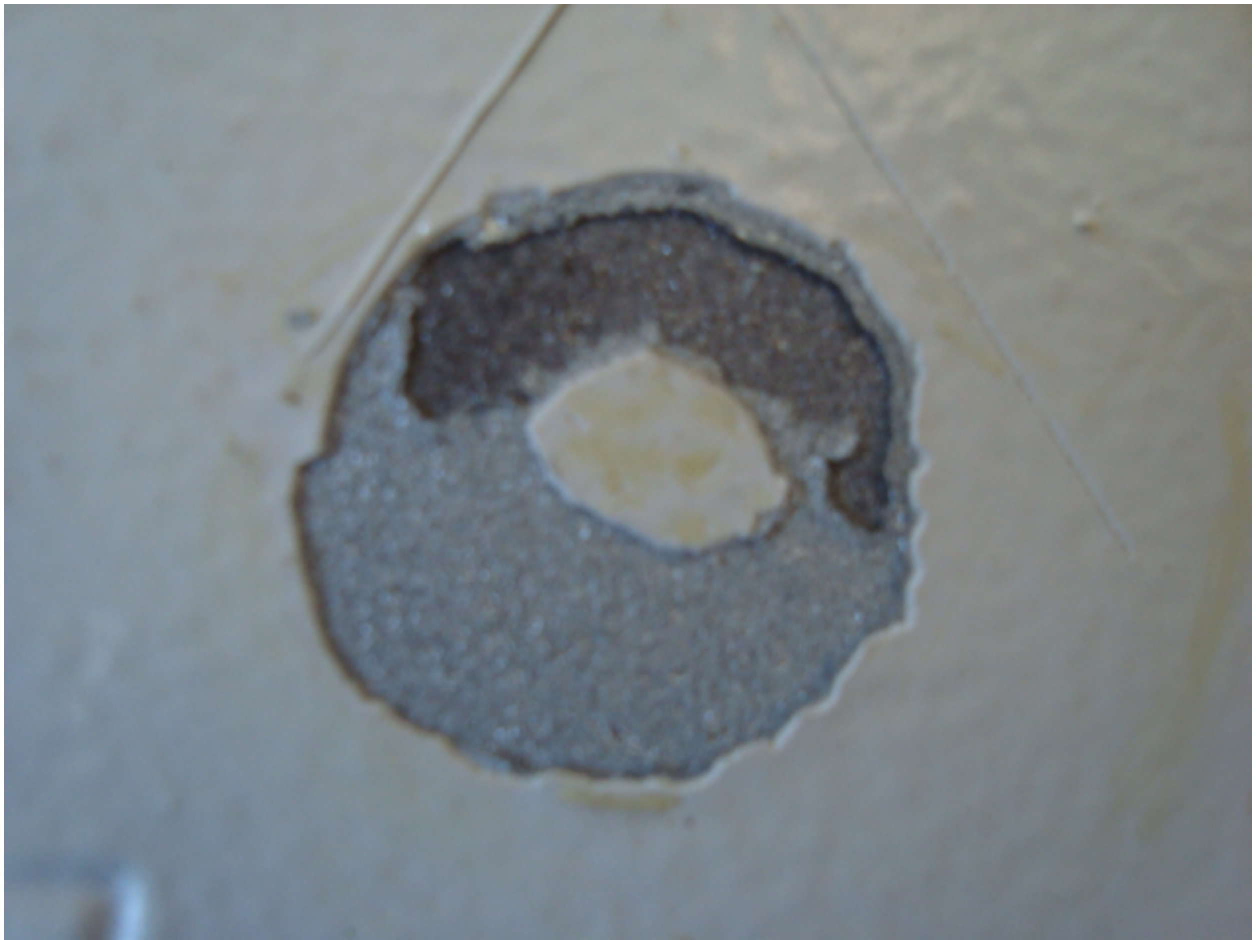
M0-S1 Panel 283 Test 2

Pull-off Strength: 1010 psi

Break: 100% adhesive between Int and Zn-M

Dolly at center right, test spot at upper right.

3.c.3.3.3 M0-S1 Panel 283 Test 3



Panel 283 Test 3, M0-S1

Pull-off Strength: Data lost

Break: 60% adhesive between Top and Int; 25% adhesive between Int and Zn-M; 15% adhesive between Glue and Top.

Dolly not photographed.

3.c.3.4 M0-S1 panel 284

3.c.3.4.1 M0-S1 Panel 284 Test 1

M0-S1 Panel 284 Test 1

Pull-off Strength: 1249 psi

Break: 60% adhesive between Int and Zn-M; 10% cohesive within Int; 30% adhesive between Glue and Top.

Dolly at left.

3.c.3.4.2 M0-S1 Panel 284 Test 2

M0-S1 Panel 284 Test 2

Pull-off Strength: 1172 psi

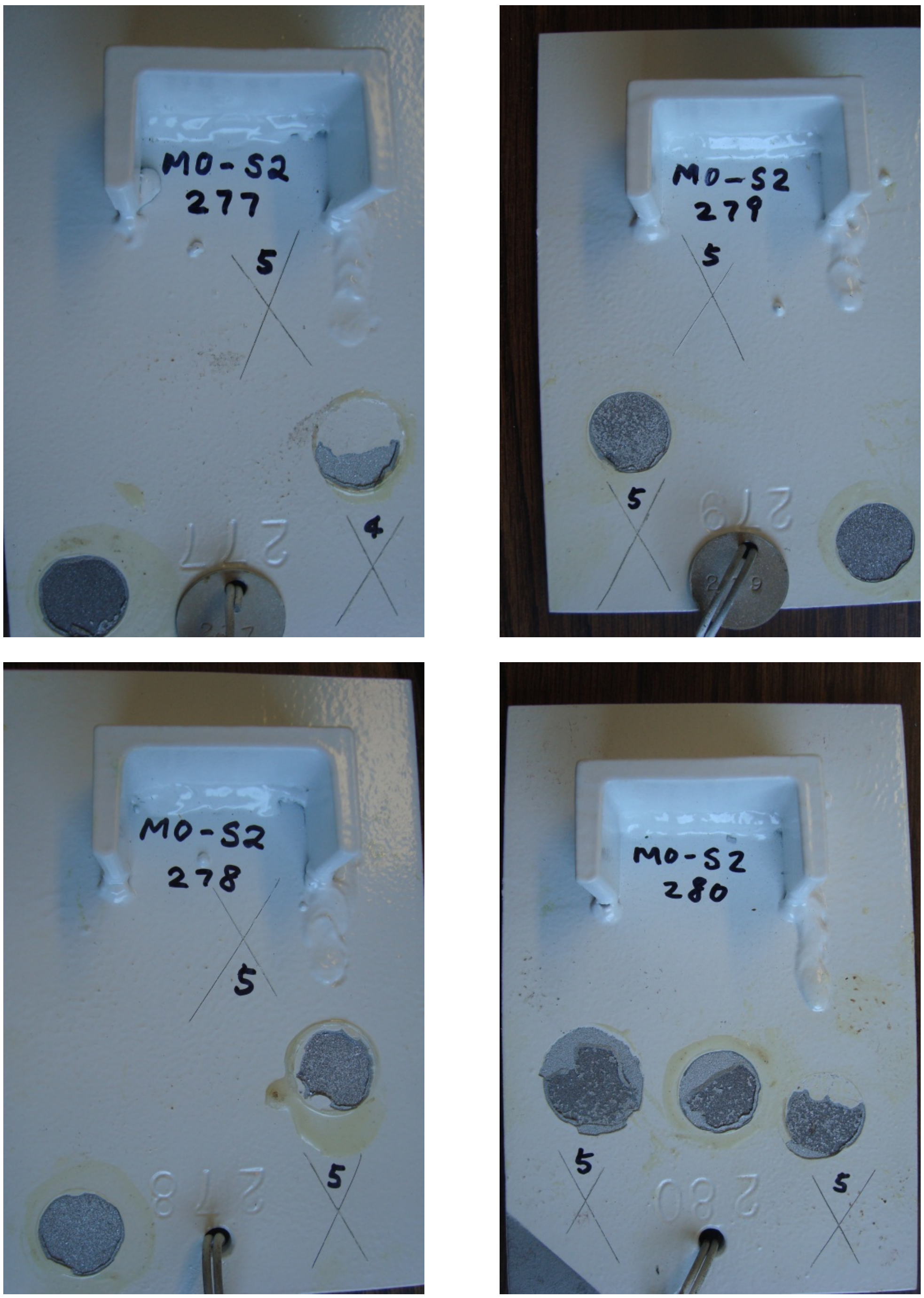
Break: 80% adhesive between Int and Zn-M, 20% cohesive within Int

Dolly at lower right

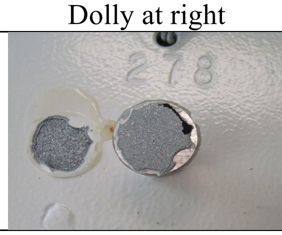
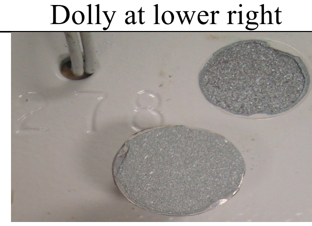
3.d. Test panel subgroup M0-S2

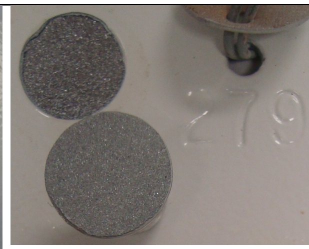
Primer: Thermal sprayed zinc metallizing coating
Intermediate: Recoatable Epoxy Primer Series B67
Finish: High Solids Polyurethane Series B58
Test panels 277, 278, 279, 280, stored in box 7

3.d.1 Photographs of the M0-S2 test panels

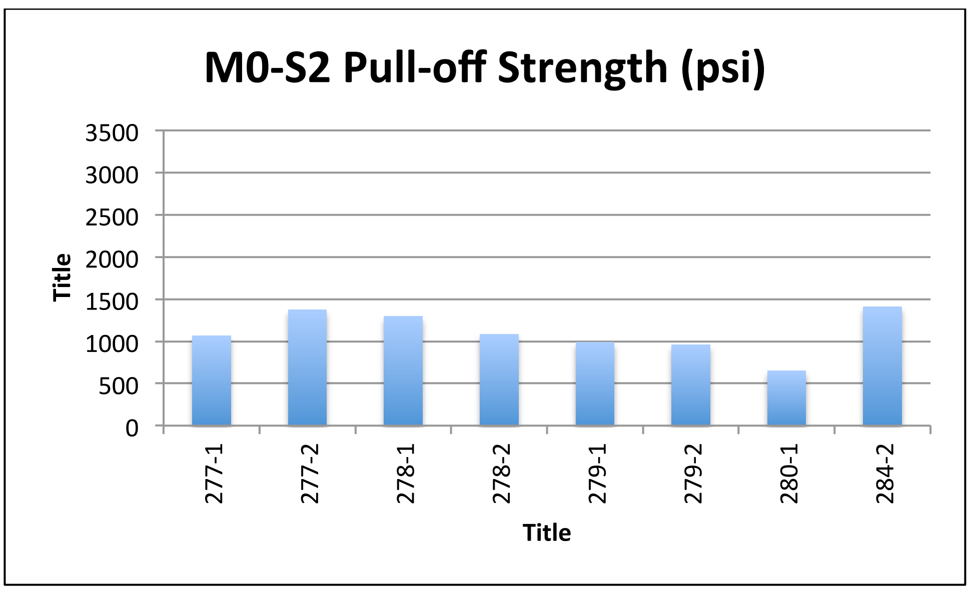


3.d.2 Adhesive strength test results for M0-S2 test panels

3.d.2 Adhesive strength test results for M0-S2 test panels (Part I)				
Test Panel	Pull Test 1	Pull Test 2 (or Test 3 if Test 2 is not shown)	X-cut 1 Score	X-cut 2 Score
277			5	4
	Strength: 1063 psi	Strength: 1373 psi		
	Break: 60% adhesive between Glue and Top; 40% adhesive between Int and Zn-M.	Break: 100% adhesive between Int and Zn-M.		
	Dolly at right	Dolly at lower right		
278			5	5
	Strength: 1297 psi	Strength: 1083 psi		
	Break: 80% adhesive between Int and Zn-M; 20% adhesive between Glue and Top.	Break: 100% adhesive between Int and Zn-M		
	Dolly at right.	Dolly at lower center.		

3.d.2 Adhesive strength test results for M0-S2 test panels (Part II)				
	Pull Test 1	Pull Test 2	X-cut 1 score	X-cut 2 score
279			5	4
	Strength: 990 psi	Strength: 958 psi		
	Break: 100% adhesive between Int and Zn-M	Break: 100% adhesive between Int and Zn-M		
	Dolly at left	Dolly at lower left		
280			5	5
	Strength: 650 psi	Strength: 1408 psi		
	Break: 70% adhesive between Int and Zn-M, 30% cohesive within Int	Break: 60% adhesive between Int and Zn-M; 40% cohesive within Int.		
	Dolly at lower center	Dolly at left		

Pull-off Test M0-S2	
Panel#-Test#	M0-S2 Pull-off Strength (psi)
277-1	1063
277-2	1373
278-1	1297
278-2	1083
279-1	990
279-2	958
280-1	650
284-2	1408
Average	1103
Standard Dev	236
Confidence	163



3.d.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers. M0-S2 panels.

3.d.3.1 M0-S2 panel 277

M0-S2 Panel 277 Test 1

M0-S2 Panel 277 Test 1

Pull-off strength: 1063 psi

Break: 60% adhesive between Glue and Top; 40% adhesive between Int and Zn-M.

Dolly at right.

M0-S2 Panel 277 Test 2

M0-S2 Panel 277 Test 2

Pull-off strength: 1373 psi

Break: 100% adhesive between Int and Zn-M

Dally at lower right

3.d.3.2 M0-S2 panel 278

M0-S2 Panel 278 Test 1

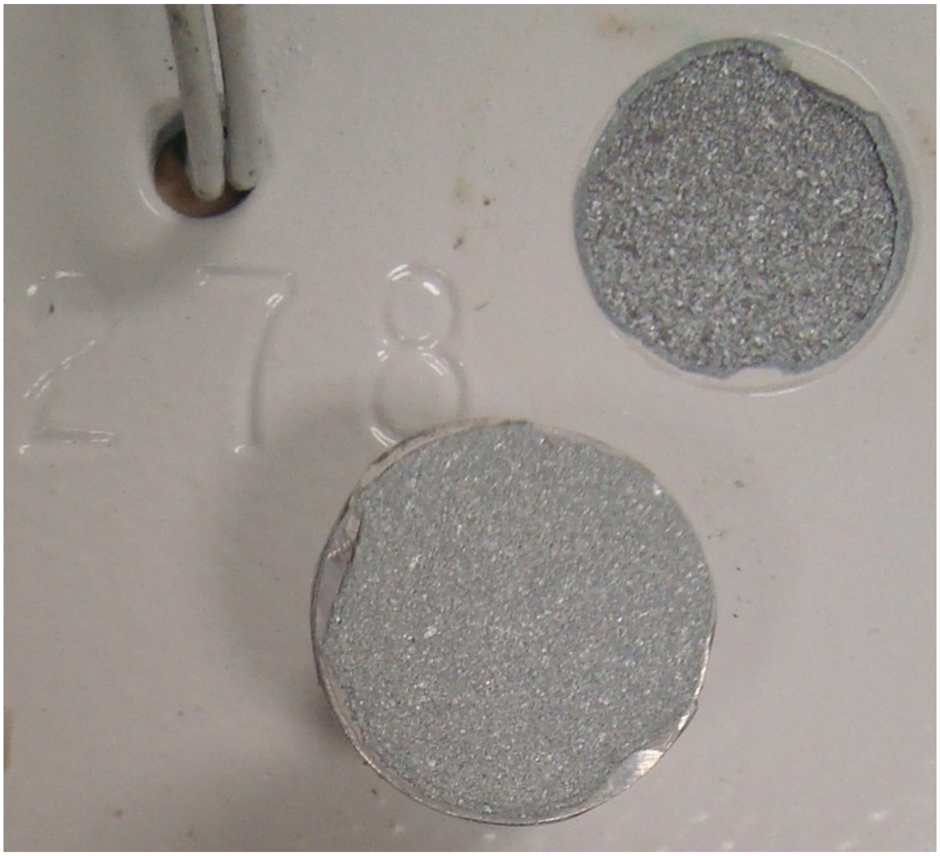
M0-S2 Panel 278 Test 1

Pull-off strength: 1297 psi

Break: 80% adhesive between Int and Zn-M.

Dolly at right.

M0-S2 Panel 278 Test 2



M0-S2 Panel 278 Test 2

Pull-off strength: 1083 psi

Break: 100% adhesive between Int and Zn-M

Dolly at lower center.

3.d.3.3 M0-S2 panel 279

M0-S2 Panel 279 Test 1

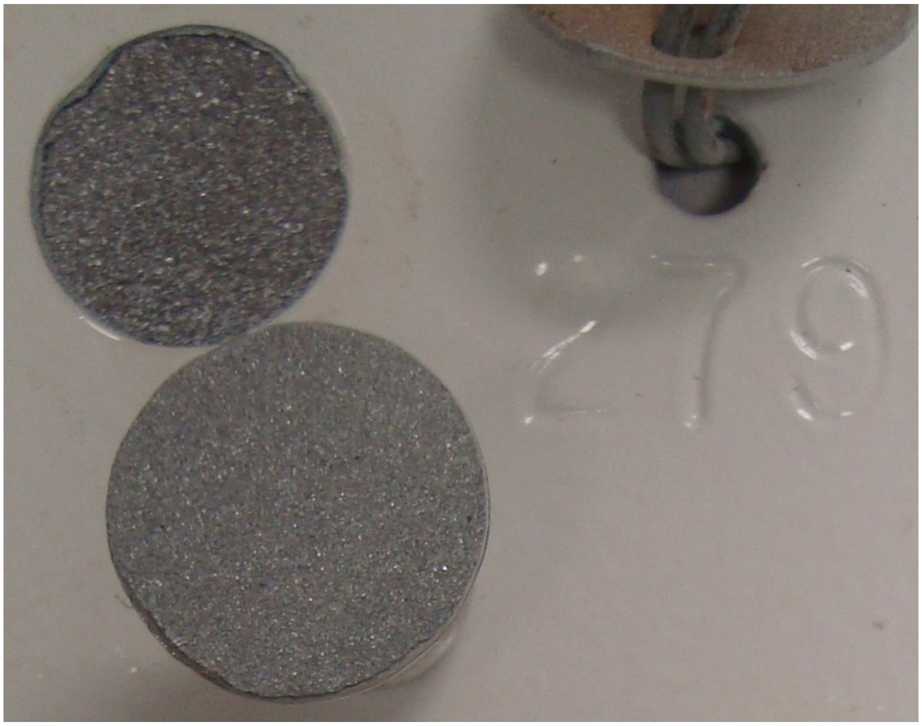
M0-S2 Panel 279 Test 1

Pull-off Strength: 990 psi

Break: 100% adhesive between Int and Zn-M

Dolly at left.

M0-S2 Panel 279 Test 2



M0-S2 Panel 279 Test 2

Pull-off Strength: 958 psi

Break: 100% adhesive between Int and Zn-M

Dolly at lower left

3.d.3.4 M0-S2 panel 280

M0-S2 Panel 280 Test 1

M0-S2 Panel 280 Test 1

Pull-off Strength: 650 psi

Break: 70% adhesive between Int and Zn-M, 30% cohesive within Int

Dolly at lower center

M0-S2 Panel 280 Test 2

M0-S2 Panel 280 Test 2

Pull-off Strength: 1408 psi

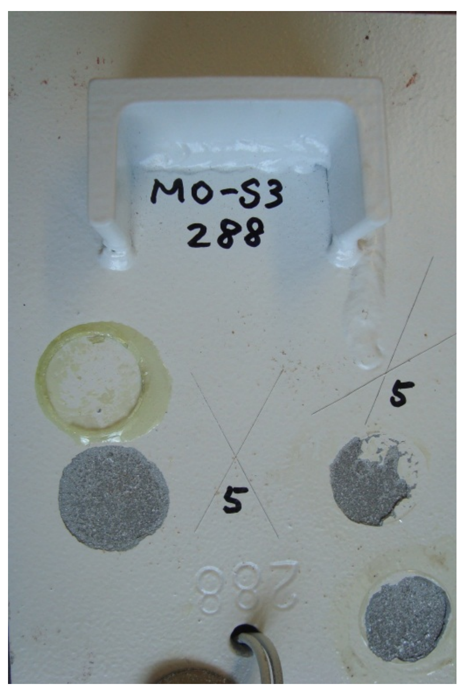
Break: 60% adhesive between Int and Zn-M; 40% cohesive within Int.

Dolly ant left.

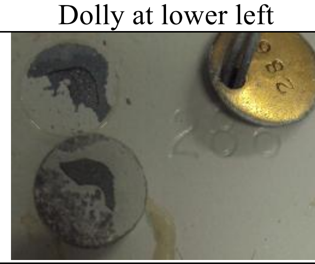
3.e. Test panel subgroup M0-S3

Primer: Thermal sprayed zinc metallizing coating
Intermediate: Macropoxy 920 penetrating pre-primer
Finish: Acrolon 218 HS Acrylic Polyurethane
Test panel numbers 285 286, 287, 288, stored in box 8.

3.e.1 Photographs of the M0-S3 test panels

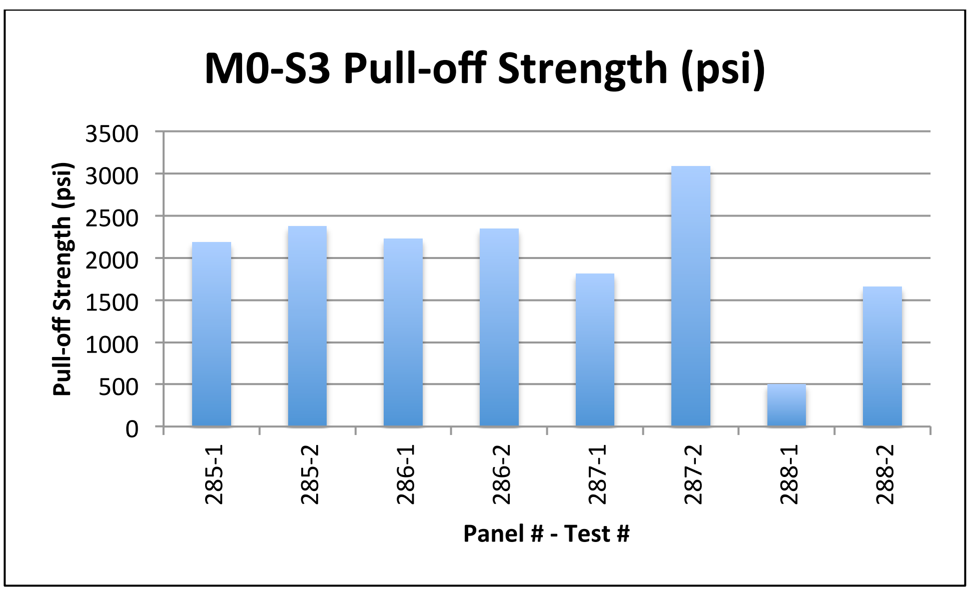


3.e.2 Adhesive strength test results for M0-S3 test panels

3.e.2 Adhesive strength test results for M0-S3 test panels (Part I)				
Test Panel	Pull Test 1	Pull Test 2 (or Test 3 if Test 2 is not shown)	X-cut 1 Score	X-cut 2 Score
285			5	5
	Strength: 2182 psi	Strength: 2373 psi		
	Break: 90% adhesive between Glue and Top;.	Break: 60% adhesive between Glue and Top; 40% cohesive within Top		
	Dolly at lower left	Dolly at lower left		
286			5	5
	Strength: 2227 psi	Strength: 2345 psi		
	Break: 85% adhesive between Glue and Top; 15% adhesive between Int and Zn-M	Break: 40% adhesive between Top and Int; 30% between Glue and Top; 30% cohesive within Int		
	Dolly at lower center. Test spot at upper right	Dolly at lower left.		

3.e.2 Adhesive strength test results for M0-S3 test panels (Part II)				
Test Panel	Pull Test 1	Pull Test 2	X-cut 1 score	X-cut 2 score
287			5	5
	Strength: 1811 psi	Strength: 3086 psi		
	Break: 50% adhesive between Glue and Top; 40% adhesive between Int and Zn-M, 10% adhesive between Top and Int.	Break: 80% adhesive between Glue and Top; 15% adhesive between Top and Int; 5% cohesive within Top		
	Dolly at lower center	Dolly at lower left		
288			5	5
	Strength: 500 psi	Strength: 1658 psi		
	Break: 100% adhesive between Int and Zn-M	Break: 95% adhesive between Int and Zn-M, 5% adhesive between Glue and Top		
	Dolly at lower center Test spot at upper right	Dolly at lower center		

Pull-off Test M0-S3	
Panel#-Test#	M0-S3 Pull-off Strength (psi)
285-1	2182
285-2	2373
286-1	2227
286-2	2345
287-1	1811
287-2	3086
288-1	500
288-2	1658
Average	2023
Standard Dev	700
Confidence	485



3.e.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers. M0-S3 panels.

3.e.3.1 M0-S3 panel 285

3.e.3.1.1 M0-S3 Panel 285 Test 1

M0-S3 Panel 285 Test 1

Pull-off Strength: 2182 psi

Break: 90% adhesive between Glue and Top; 10% between Int and Zn-M

Dolly at left.

3.e.3.1.2 M0-S3 Panel 285 Test 2

M0-S3 Panel 285 Test 2

Pull-off Strength: 2373 psi

Break: 60% adhesive between Glue and Top; 40% cohesive within Top

Dolly at lower left.

3.e.3.2 M0-S3 panel 286

3.e.3.2.1 M0-S3 Panel 286 Test 1

M0-S3 Panel 286 Test 1

Pull-off Strength: 2227 psi

Break: 85% adhesive between Glue and Top; 15% adhesive between Int and Zn-M

Dolly at lower center.

3.e.3.2.2 M0-S3 Panel 286 Test 2

M0-S3 Panel 286 Test 2

Pull-off Strength: 2345 psi

Break: 40% adhesive between Top and Int; 30% between Glue and Top; 30% cohesive within Int

Dolly at lower left

3.e.3.3 M0-S3 panel 287

3.e.3.3.1 M0-S3 Panel 287 Test 1

M0-S3 Panel 287 Test 1

Pull-off Strength: 1811 psi

Break: 50% adhesive between Glue and Top; 40% adhesive between Int and Zn-M; 10% adhesive between Top and Int

Dolly at center right.

3.e.3.3.2 M0-S3 Panel 287 Test 2

M0-S3 Panel 287 Test 2

Pull-off Strength: 3086 psi

Break: 80% adhesive between Glue and Top; 15% adhesive between Top and Int; 5% cohesive within Top

Dolly at lower left

3.e.3.4 M0-S3 panel 288

3.e.3.4.1 M0-S3 Panel 288 Test 1

M0-S3 Panel 288 Test 1

Pull-off Strength: 500 psi

Break: 100% adhesive between Int and Zn-M

Dolly at lower center, test spot at upper right.

3.e.3.4.2 M0-S3 Panel 288 Test 2

M0-S3 Panel 288 Test 2

Pull-off Strength: 1658 psi

Break: Break: 95% adhesive between Int and Zn-M, 5% adhesive between Glue and Top

Dolly at lower center

4. Group G2b, List of panels and photographic images of the tested panels.

This group of test panels was made from galvanized steel with blast profiled zinc surface and coated with 4 different paint systems. After galvanizing the panels were stored indoor in open air for 2 weeks before surface profiling by sweep blasting. The application of the epoxy paint was performed immediately (within 4 hours) after the surface profiling.
This group of test panels is labeled as group “G2b” on the test panels. In this group label “G” stands for the Galvanizing process, “2” stands for 2 weeks of indoor storage between the time of galvanizing and blast profiling / painting. The finish paint was done after the epoxy layer was cured. Four different paint systems were used for the subgroups with the following designations for the subgroups and the test panels.

Each pull-off test spot on a test panel is given an identification number according to the following convention: We assign the uppermost test spot in the images of the panels as test sample #1. Pretending that sample #1 is at the 12-oclock position of a clock, the remaining test spots are ordered according to its position in the clockwise rotation order. Occasionally, a pull-off test is omitted from the list because of technical problems observed during the test. For example the dolly was not property glued to the paint surface, or the surface near the test spot is too close to a welding burr so that the tester cannot be seated correctly. A replacement test is listed (using a different test spot identification number) is listed in the table in place of the omitted test.

Section 4.a.1 contains a description of the paint system used for coating the test panels, the labels stamped or attached to the test panels, and the storage box number for the test panels, and the photographic image of the test panels after the adhesive strength tests were completed.

Section 4.a.2 contains a table summarizing the test results of the ASTM D4541 pull-off strength tests and the ASTM D3359 Type A X-cut tape tests. In the table we summarize the pull-off strengths (in the unit of psi), a description of the surface of breakage on the test dolly.

We photographed the dolly placed near the test spot on the panel to show the surface of break after the pull-off strength test. A small photographic image of the break surfaces are shown in the table for the purpose of associating the pull-off strength data with the images of the tested panels shown in section 2.a.1.

Each test spot on a test panel is given an identification number according to the following convention: We assign the uppermost test spot in the images of the panels in Section 2.a.1 as test sample #1. Pretending that sample #1 is at the 12-oclock position of a clock, the remaining test spots are ordered according to its position in the clockwise rotation order.

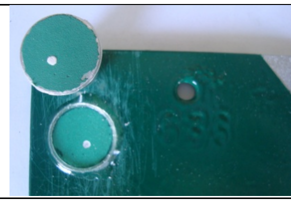
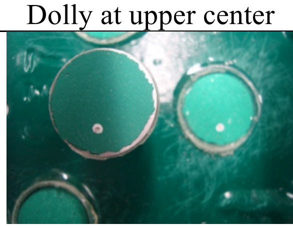
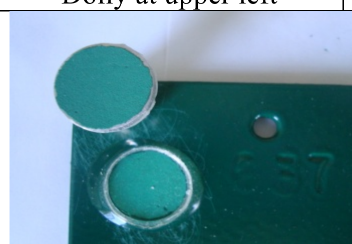
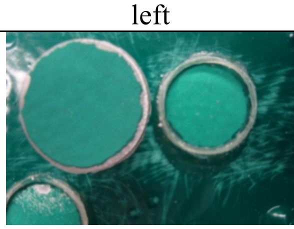
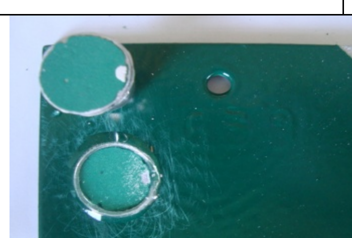
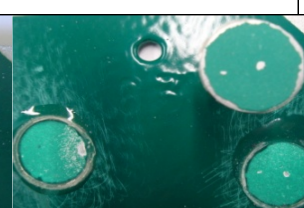
Section 4.a.3 contains the enlarged copies of the pictures in the Table of Section 4.a.2. The enlarged pictures are posted to enable closer examination of the surfaces of both the dolly and the pull-off surface on the panel, and for the readers to verify the description of the break surface in the table of Section 2.a.2.

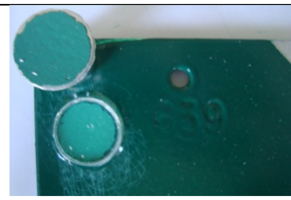
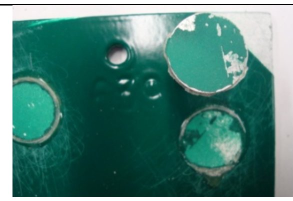
4.a G2b-C: G2b panels with paint system C

4.a.1 Photo Images of test panels for subgroup G2b-C, after adhesive tests.

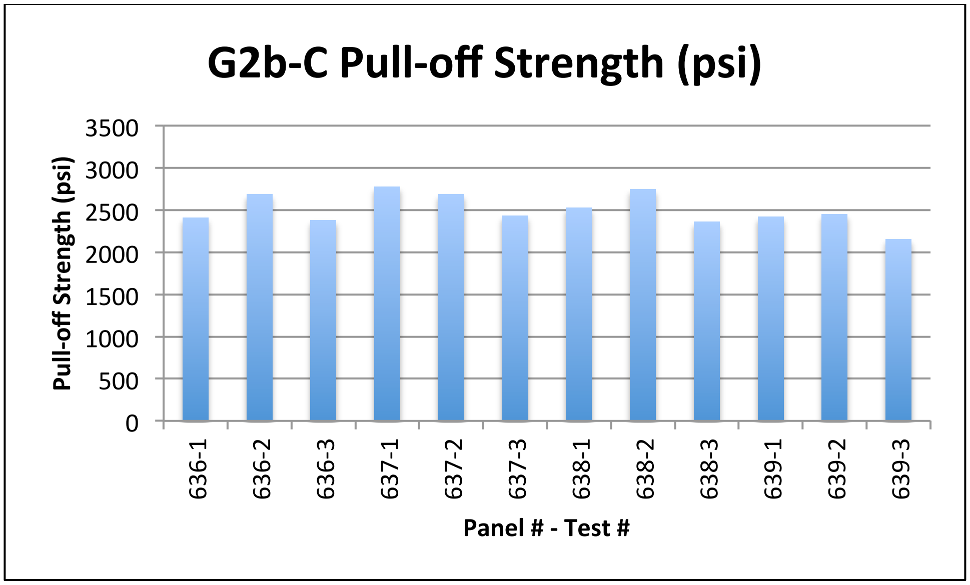
Primer: (galvanizing or metallizing)
Intermediate: Carboline 888 Epoxy
Finish: Carboline 133 LH Aliphatic Polyurethane
Test panel numbers: 636, 637, 638, 639, stored in Box 14.
(label "G2C" on the photograph is a short hand for "G2b-C")

4.a.2 Adhesive strength test results for G2b-C test panels

4.a.2 Adhesive strength test results for G2b-C test panels (Part I)					
Test Pane	Pull Test 1	Pull Test 2	Pull Test 3	X-cut 1 Score	X-cut 2 Score
636				5	5
	Strength: 2410 psi	Strength: 2685 psi	Strength: 2380 psi		
	Break: 95% cohesive within Top; 5% adhesive between Top and Int.	Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G	Break: 90% cohesive within Top; 10% adhesive between Top and Int.		
	Dolly at upper center	Dolly at upper left	Dolly at upper right		
637				5	5
	Strength: 2775 psi	Strength: 2687 psi	Strength: 2433 psi		
	Break: 100% cohesive within Top	Break: 100% cohesive within Top	Break: 97% cohesive within Top; 3% adhesive between Top and Int		
	Dolly image at middle left	Dolly at upper left	Dolly at upper left		
638				5	5
	Strength: 2527 psi	Strength: 2747 psi	Strength: 2360 psi		
	Break: 100% cohesive within Top	Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G	Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G		
	Dolly at upper left	Dolly at upper left	Dolly at upper right		

4.a.2 Adhesive strength test results for G2b-C test panels (Part II)					
Test Pane	Pull Test 1	Pull Test 2	Pull Test 3	X-cut 1 Score	X-cut 2 Score
639				5	5
	Strength: 2422 psi	Strength: 2447 psi	Strength: 2153 psi		
	Break: 80% codhesive within Top; 20% adhesive between Int and Zn-G	Break: 98% cohesive within Top; 2% adhesive between Int and Zn-G	Break: 70% cohesive within Top; 15% adhesive between Glue and Top; 15% adhesive between Top and Int.		
	Doly image at left	Dolly at Upper left.	Dolly at upper right		

Pull-off Test G2b-C	
Panel#-Test#	G2b-C Pull-off Strength (psi)
636-1	2410
636-2	2685
636-3	2380
637-1	2775
637-2	2687
637-3	2433
638-1	2527
638-2	2747
638-3	2360
639-1	2422
639-2	2447
639-3	2153
Average	2502
Standard Dev	179
Confidence	101



G2b-C Pull-off Strength (psi)
Pull-off Strength (psi)
3500
3000
2500
2000
1500
1000
500
0
636-1
636-2
636-3
637-1
637-2
637-3
638-1
638-2
638-3
639-1
639-2
639-3
Panel # - Test #

4.a.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

4.a.3.1 Panel #636 G2b-C

4.a.3.1.1 Panel 636 Test 1, G2b-C

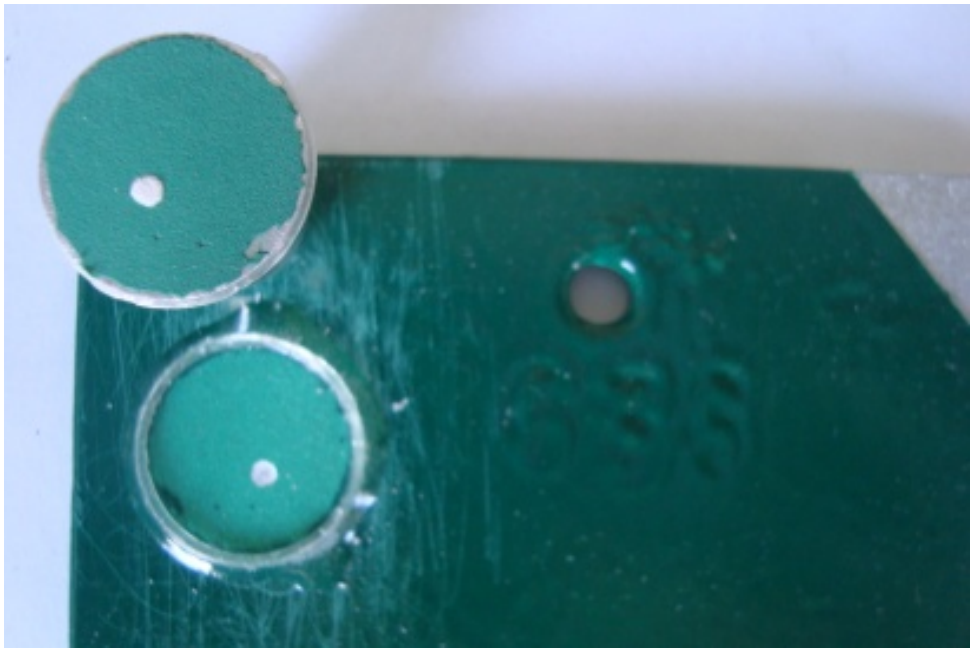
Panel 636 Test 1

Pull-off Strength: 2410 psi

Break: 95% cohesive within Top; 5% adhesive between Top and Int.

Dolly at upper center

4.a.3.1.2 Panel 636 Test 2, G2b-C



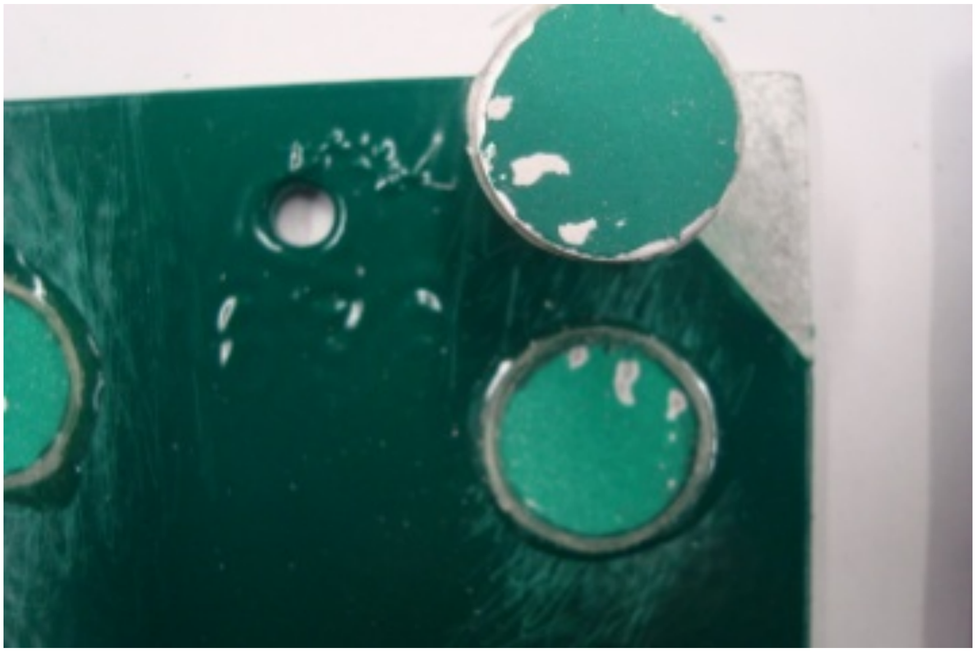
Panel 636 Test 2, G2b-C

Pull-off Strength: 2685 psi

Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G

Dolly at upper left.

4.a.3.1.3 Panel 636 Test 3, G2b-C



Panel 636 Test 3, G2b-C

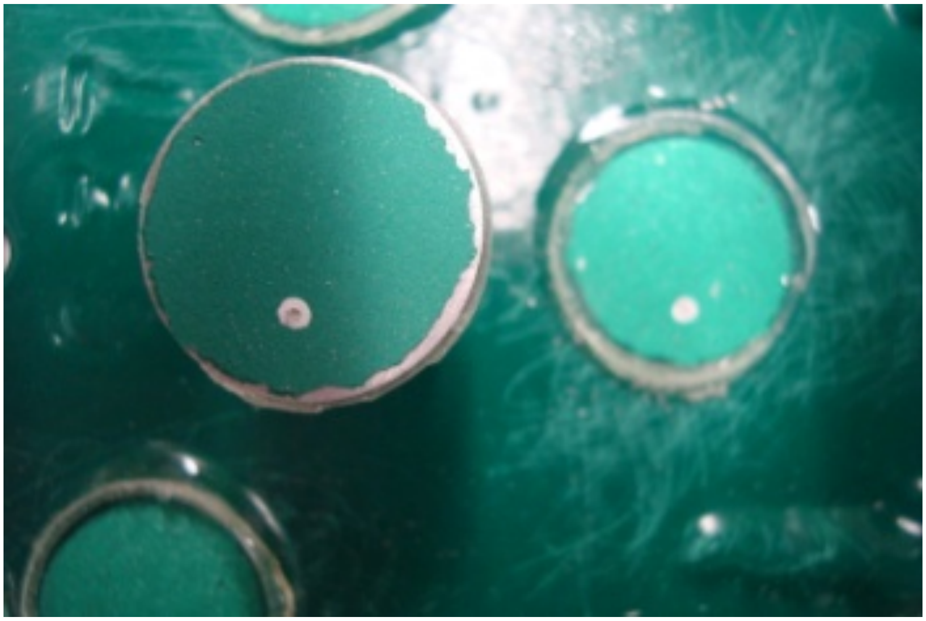
Pull-off Strength: 2380 psi

Break: 90% cohesive within Top; 10% adhesive between Top and Int.

Dolly at upper right.

4.a.3.2 Panel #637, Gb2-C

4.a.3.2.1 Panel 637 Gb2-C, Test 1



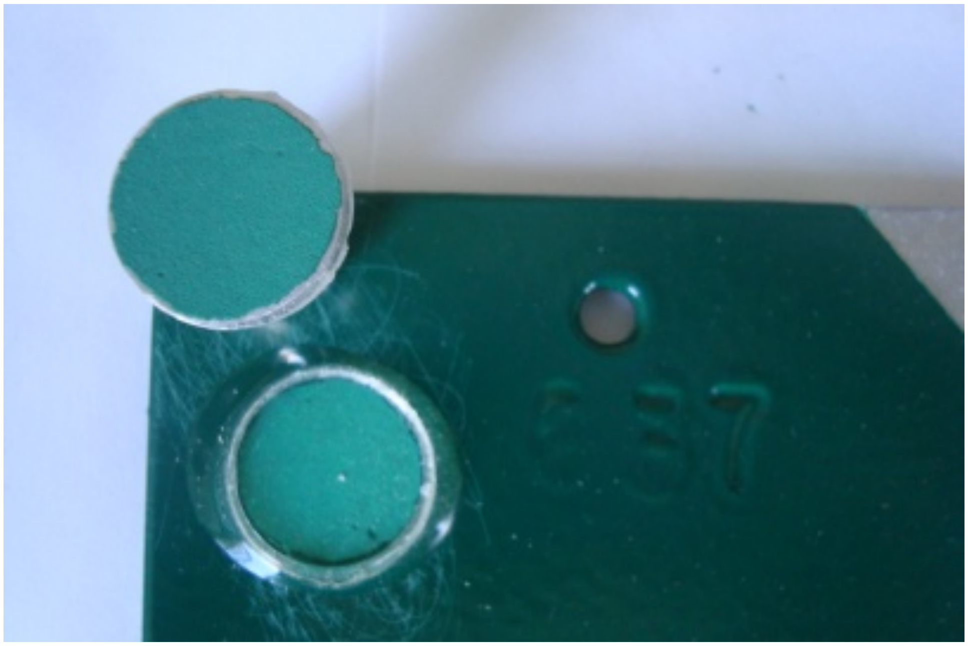
Panel 673 G2b-C Test 1

Pull-off Strength: 2775 psi

Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G

Dolly at middle left

4.a.3.2.2 Panel 637 Gb2-C, Test 2



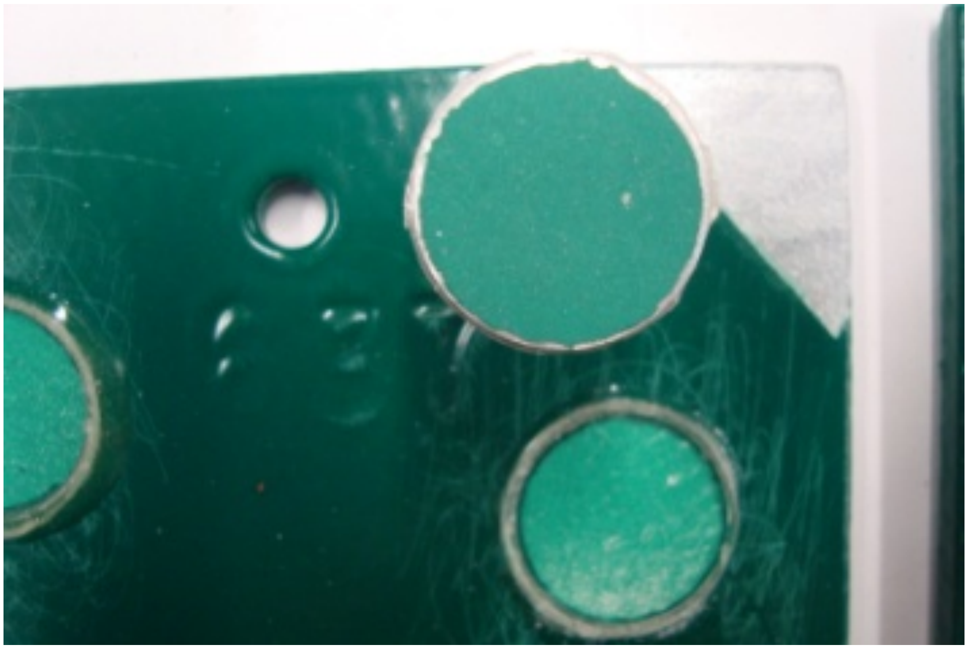
Panel 637 G2b-C Test 2

Pull-off Strength: 2687 psi

Break: 100% cohesive within Top

Dolly at upper left.

4.a.3.2.3 Panel 637 Gb2-C, Test 3



Panel 337 G2b Test 3

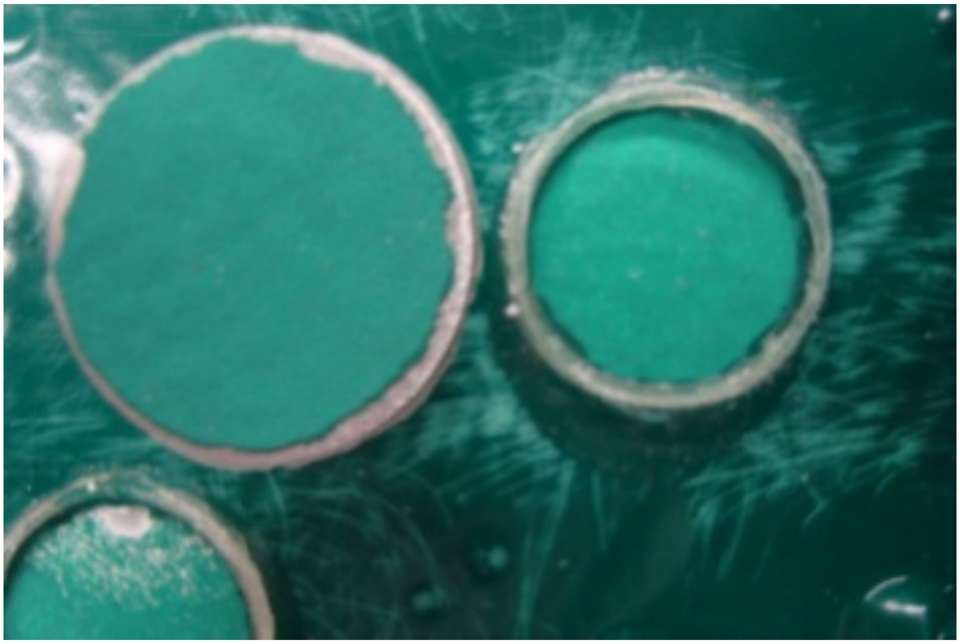
Pull-off Strength: 2443 psi

Break: 97% cohesive within Top; 3% adhesive between Top and Int

Dolly at upper right.

4.a.3.3 Panel #638 G2b-C

4.a.3.3.1 Panel 638 G2b-C Test 1



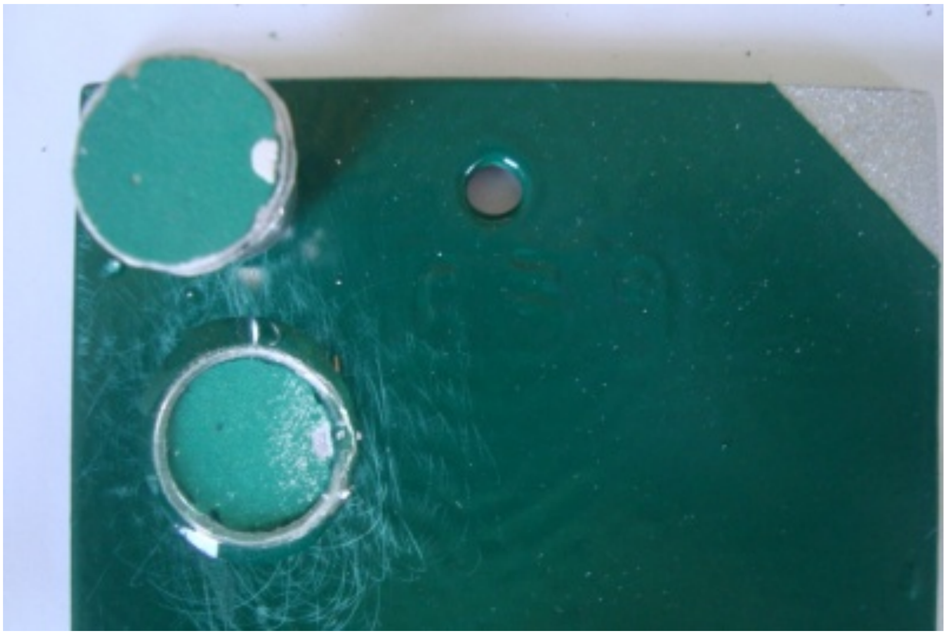
Panel 638 G2b-C Test 1

Pull-off Strength: 2527 psi

Break: 100% cohesive within Top

Dolly at upper left.

4.a.3.3.2 Panel 638 G2b-C Test 2



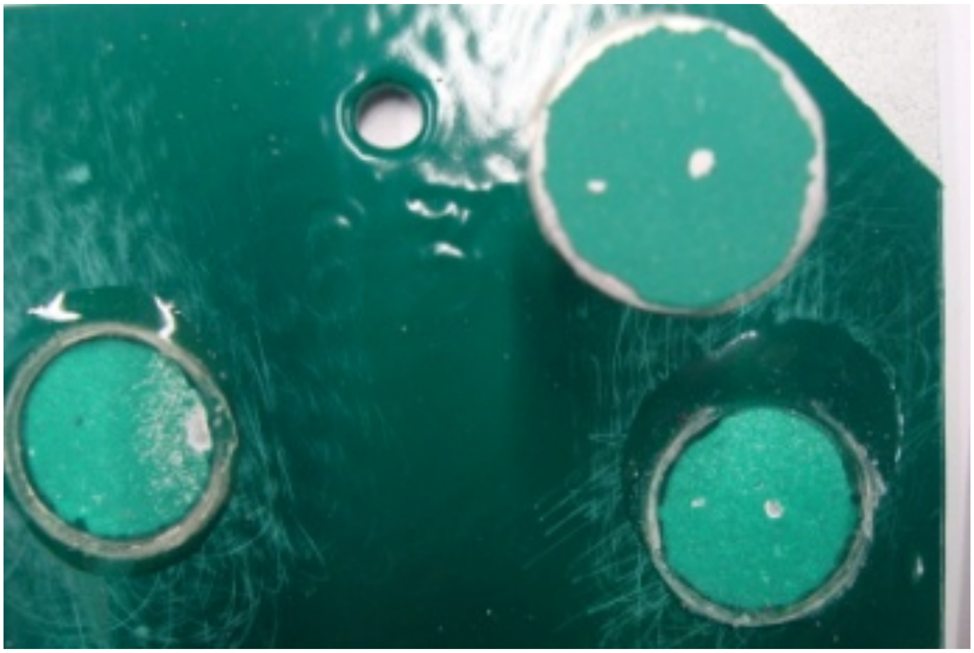
Panel 638 G2b-C Test 2

Pull-off Strength: 2747 psi

Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G

Dolly at upper left.

4.a.3.3.3 Panel 638 G2b-C Test 3



Panel 638 G2b-C Test 3

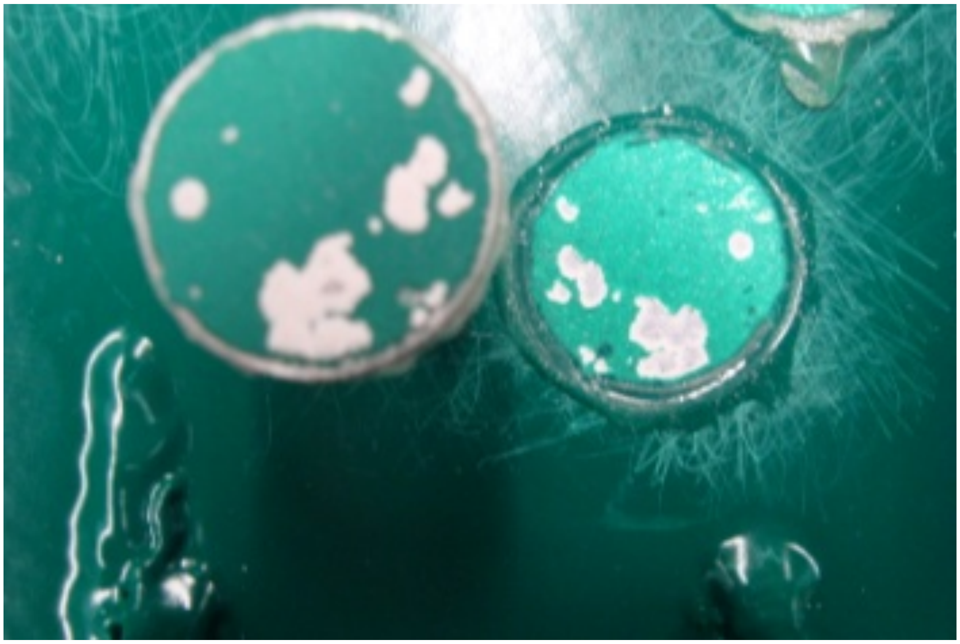
Pull-off Strength: 2360 psi

Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G

Dolly at upper right.

4.a.3.4 Panel #639 G2b-C

4.a.3.4.1 Panel 639 G2b-C Test 1



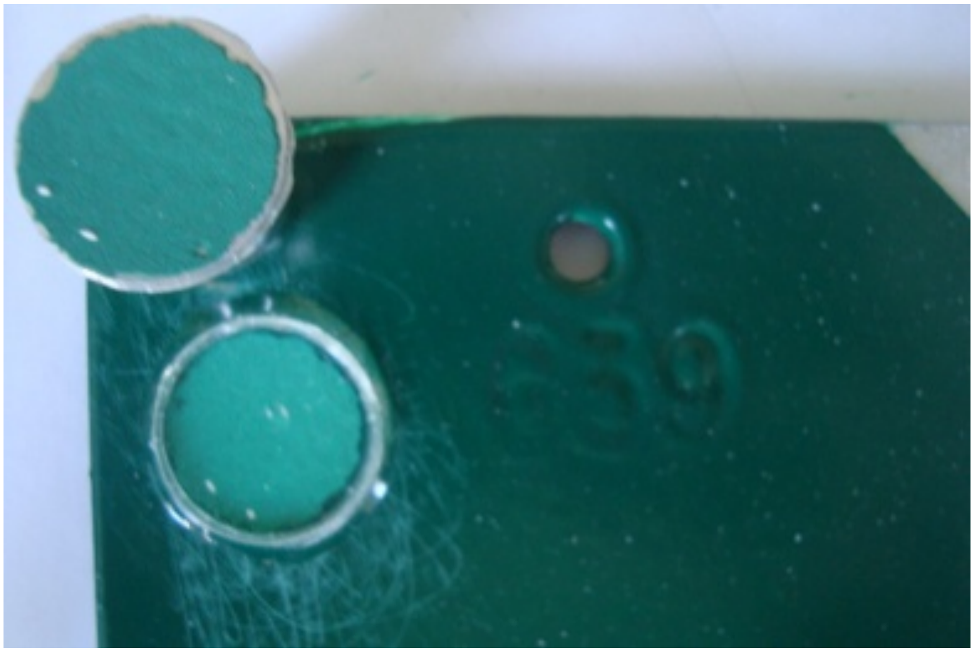
Panel 639 G2b-C Test 1

Pull-off Strength: 2422 psi

Break: 80% codhesive within Top; 20% adhesive between Int and Zn-G

Dolly at left

4.a.3.4.2 Panel 639 G2b-C Test 2



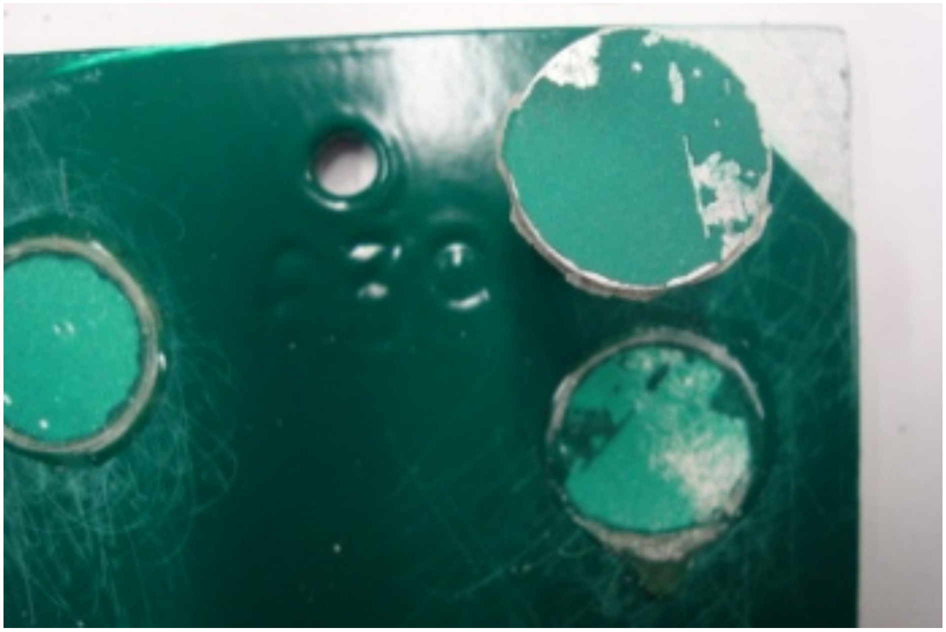
Panel 639 G2b-C Test 2

Pull-off Strength: 2447 psi

Break: 98% cohesive within Top; 2% adhesive between Int and Zn-G

Dolly at upper left.

4.a.3.4.3 Panel 639 G2b-C Test 3



Panel 639 G2b-C Test 3

Pull-off Strength: 2153 psi

Break: 70% cohesive within Top; 15% adhesive between Glue and Top; 15% adhesive between Top and Int.

Dolly at upper right.

4.b G2b-I: G2b panels with paint system I

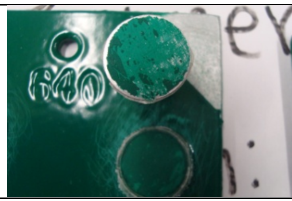
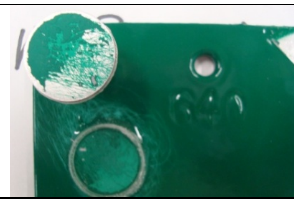
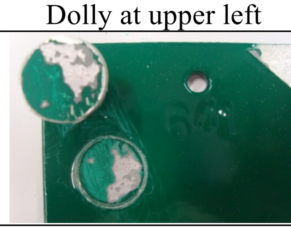
4.b.1 Photo Images of test panels for subgroup G2b-I, after adhesive tests.

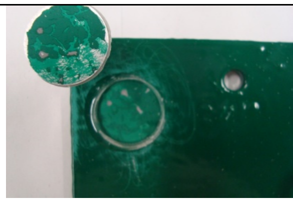
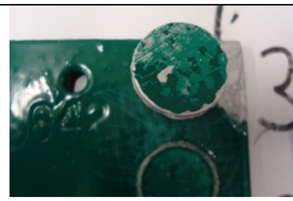
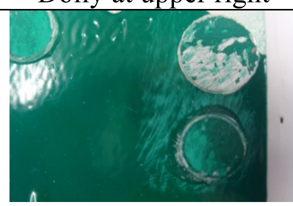
Test panel subgroup G2b-I

Primer:	(galvanizing or metallizing)
Intermediate:	Intergard 345 Epoxy
Finish:	Interthane 870 UHS

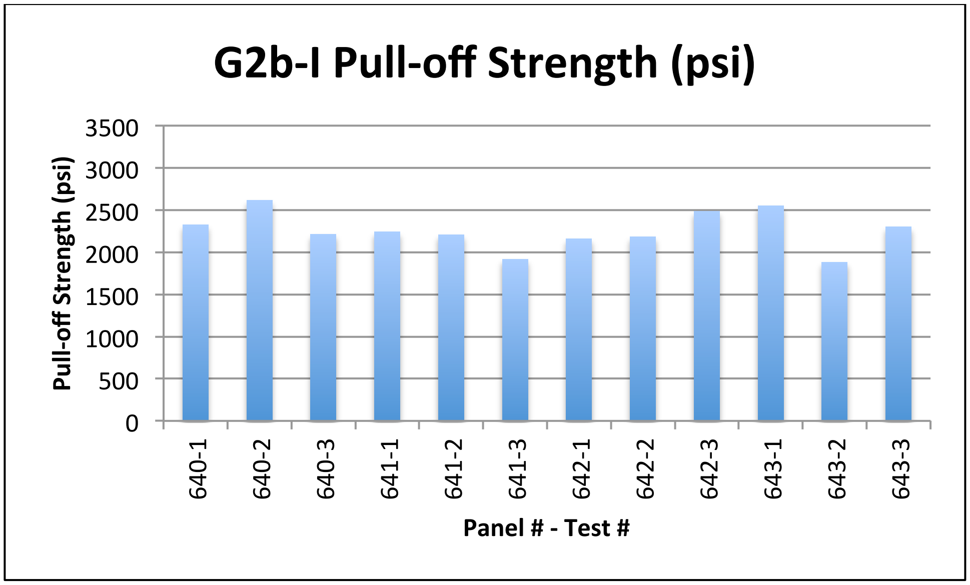
Test panel numbers: 640, 641, 642, 643 (Labels G2I should be "G2b-I) Box 15

4.b.2 Adhesive strength test results for G2b-I test panels

4.b.2 Adhesive strength test results for G2b-I test panels (Part I)					
Panel	Test 1	Test 2	Test 3	X-cut 1 Score	X-cut 2 Score
640				5	5
	Strength: 2326 psi	Strength: 2615 psi	Strength: 2210 psi		
	Break: 80% cohesive within Top; 20% adhesive between Glue and Top	Break: 80% cohesive within Top; 20% adhesive between Glue and Top	Break: 100% cohesive within Top		
	Dolly at left	Dolly at upper left	Dolly at upper center		
641				5	5
	Strength: 2241 psi	Strength: 2207 psi	Strength: 1919 psi		
	Break: 80% cohesive within Top; 10 % adhesive between Top and Int; 10% adhesive between Int and Zn-G	Break: 60% cohesive within Top; 20% adhesive between Int and Zn-G; 10% adhesive between Top and Int	Break: 85% cohesive within Top; 15% adhesive between Int and Zn-G		
	Dolly at left	Dolly at upper left	Dolly at upper right		

4.b.2 Adhesive strength test results for G2b-I test panels (Part II)					
Panal	Test 1	Test 2	Test 3	X-cut 1	X-cut 2
642				5	5
	Strength: 2161 psi	Strength: 2182 psi	Strength: 2484 psi		
	Break: 50% cohesive within Int; 40% adhesive between Top and Int; 10% adhesive between Int and Zn-G.	Break: 95% cohesive within Top; 5% adhesive between glue and Zn-G	Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G.		
	Dolly at upper left	Dolly at upper right	Dolly at right		
643				5	5
	Strength: 2553 psi	Strength: 1882 psi	Strength: 2302 psi		
	Break: 97% cohesive within Top; 3% adhesive between glue and Top	Break: 50% cohesive within Top; 50% adhesive between Glue and Top	Surf: 80% Top / 10% Int / 10% Adh		
	Dolly at upper left	Dolly at Upper right.	Dolly at left		

Pull-off Test G2b-I	
Panel#-Test#	G2b-I Pull-off Strength (psi)
640-1	2326
640-2	2615
640-3	2210
641-1	2241
641-2	2207
641-3	1919
642-1	2161
642-2	2182
642-3	2484
643-1	2553
643-2	1882
643-3	2302
Average	2257
Standard Dev	214
Confidence	121


G2b-I Pull-off Strength (psi)
Pull-off Strength (psi)
3500
3000
2500
2000
1500
1000
500
0
640-1
640-2
640-3
641-1
641-2
641-3
642-1
642-2
642-3
643-1
643-2
643-3
Panel # - Test #

4.b.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

4.b.3.1 Panel #640 G2b-I

4.b.3.1.1 Panel 640 G2b-I Test 1

Panel 640 G2b-I Test 1

Pull-off Strength: 2326 psi

Break: 80% cohesive within Top; 20% adhesive between Glue and Top

Dolly at left

4.b.3.1.2 Panel 640 G2b-I Test 2

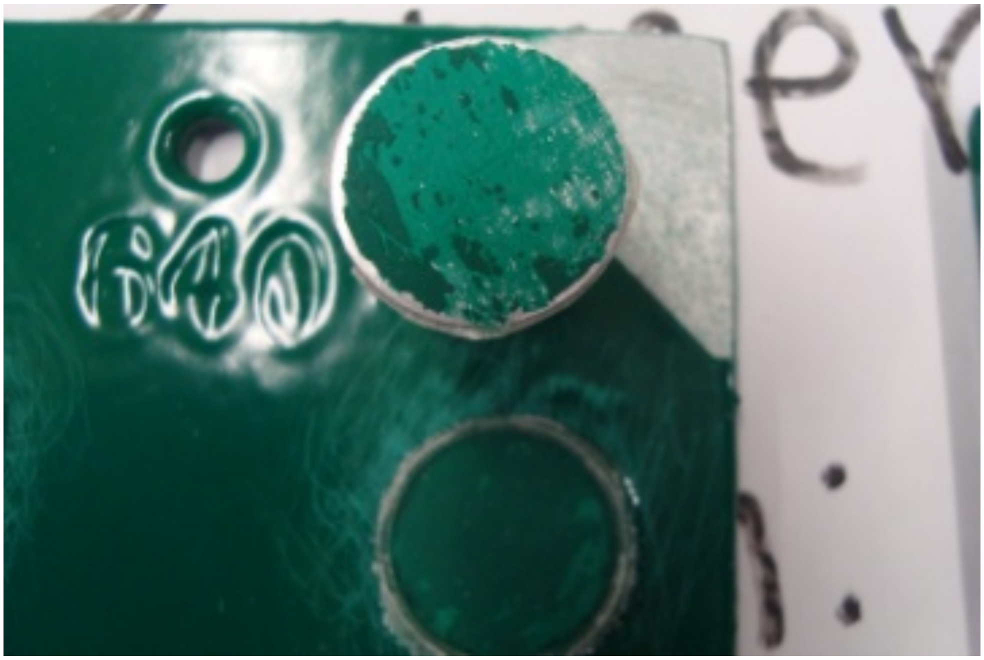
Panel 640 G2b-I Test 2

Pull-off Strength: 2615 psi

Break: 80% cohesive within Top; 20% adhesive between Glue and Top

Dolly at upper left.

4.b.3.1.3 Panel 640 G2b-I Test 3



Panel 640 G2b-I Test 3

Pull-off Strength: 2210 psi

Break: 100% cohesive within Top

Dolly at upper center.

4.b.3.2 Panel #641 G2b-I

4.b.3.2.1 Panel 641 G2b-I Test 1

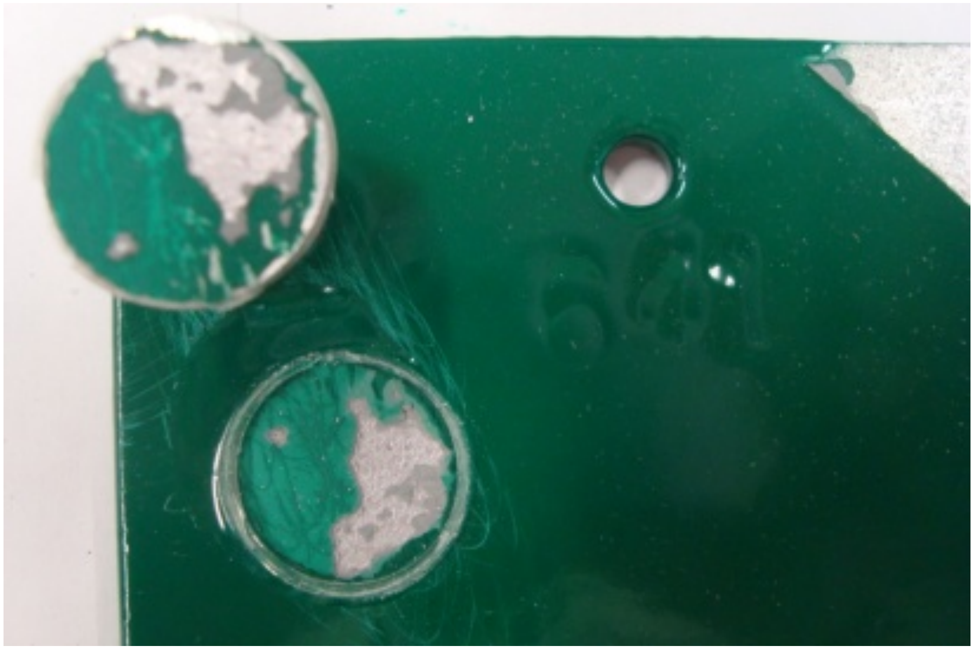
Panel 641 G2b-I Test 1

Pull-off Strength: 2241 psi

Break: 80% cohesive within Top; 10 % adhesive between Top and Int; 10% adhesive between Int and Zn-G

Dolly at left.

4.b.3.2.2 Panel 641 G2b-I Test 2



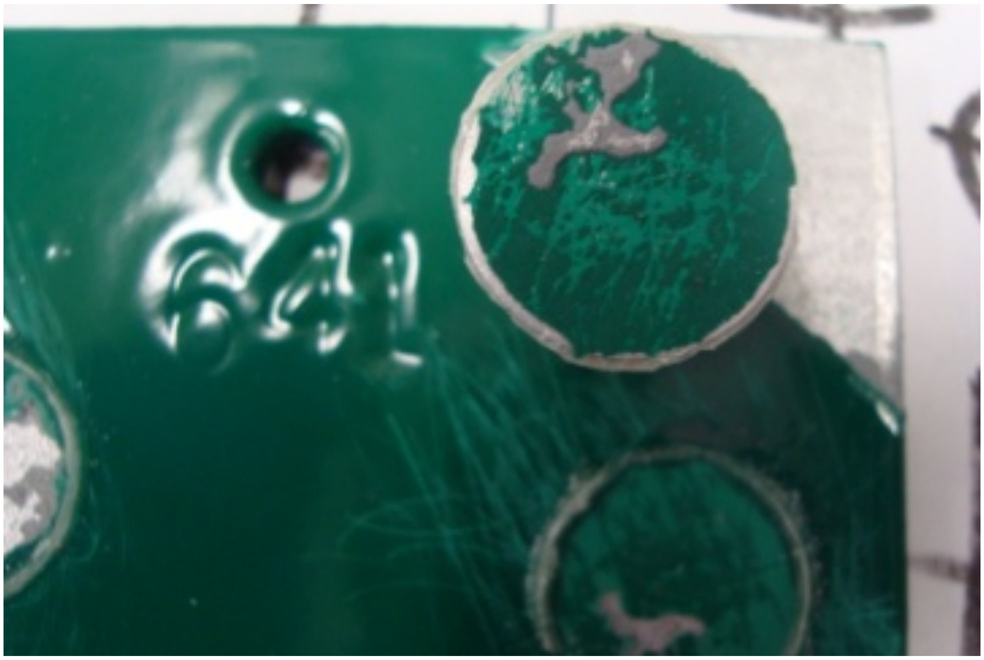
Panel 641 G2b-I Test 2

Pull-off Strength: 2207 psi

Break: 60% cohesive within Top; 20% adhesive between Int and Zn-G; 10% adhesive between Top and Int

Dolly at upper left

4.b.3.2.3 Panel 641 G2b-I Test 3



Panel 641 G2b-I Test 3

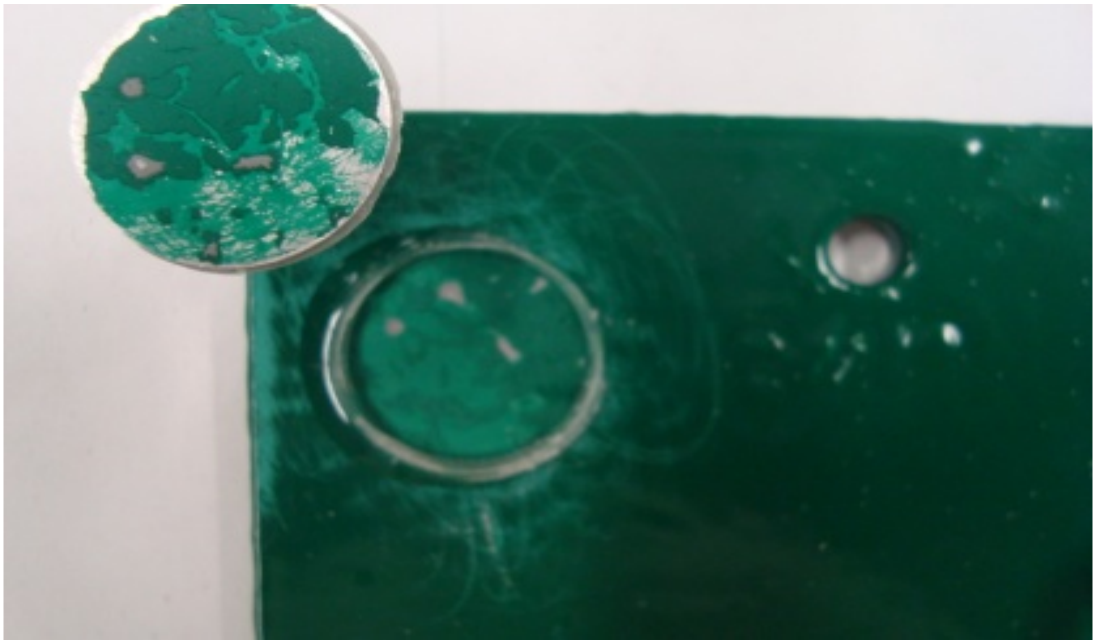
Pull-off Strength: 1919 psi

Break: 85% cohesive within Top; 15% adhesive between Int and Zn-G

Dolly at upper right

4.b.3.3 Panel #642 G2b-I

4.b.3.3.1   Panel 642, G2b-I, Test 1



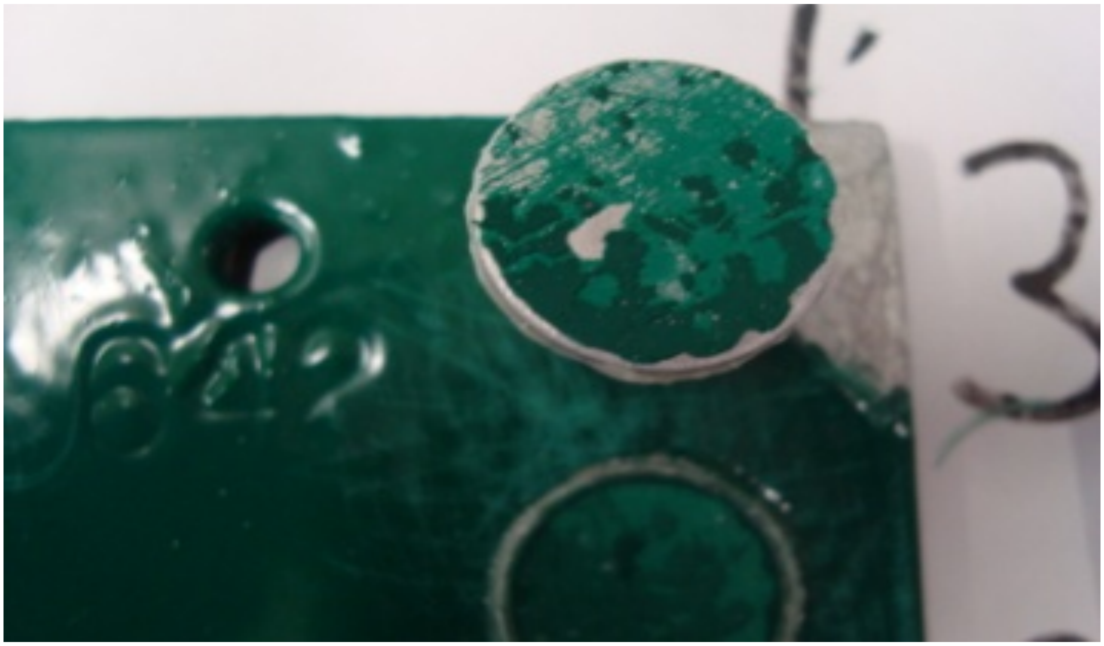
G2b-I, Panel 642, Test 1

Pull off strength: 2161 psi

Break: 50% cohesive within Int; 40% adhesive between Top and Int; 10% adhesive between Int and Zn-G.

Dolly at upper left

4.b.3.3.2 Panel 642, G2b-I, Test 2



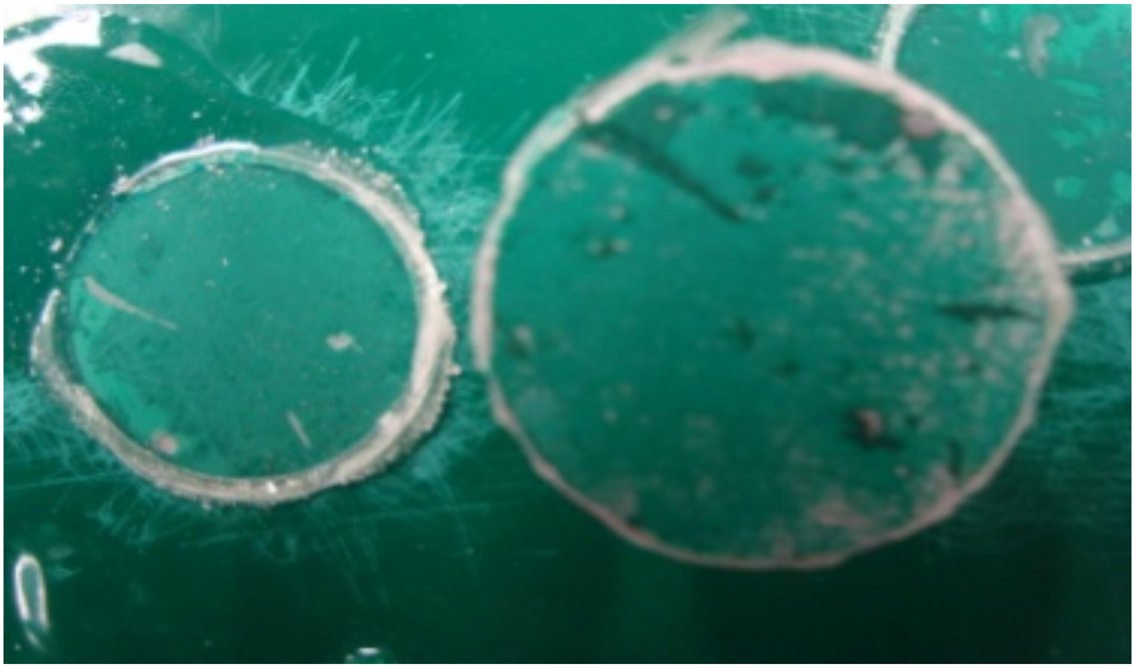
G2b-I, Panel 642, Test 2

Pull off strength: 2182 psi,

Break: 95% cohesive within Top; 5% adhesive between glue and Zn-G

Dolly at upper right

4.b.3.3.3 Panel 642, G2b-I, Test 3



G2b-I, Panel 642, Test 3

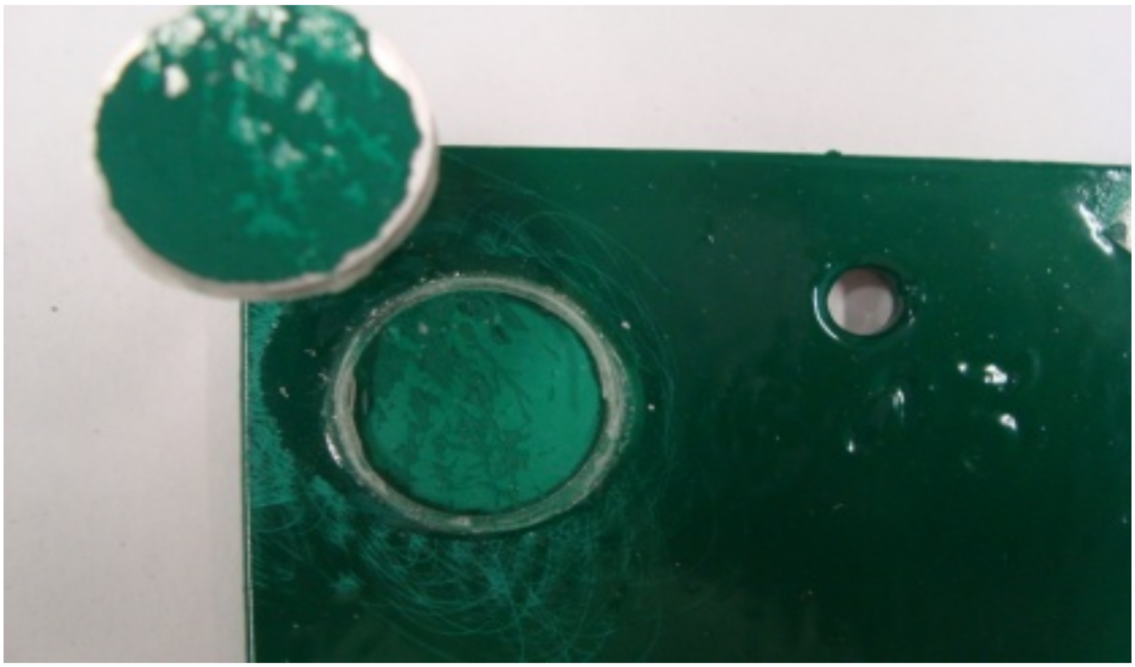
Pull off strength: 2484 psi,

Break: 95% cohesive within Top; 5% adhesive between Int and Zn-G.

Dolly at right.

4.b.3.4 Panel #643 G2b-I

4.b.3.4.1 Panel 643, G2b-I, Test 1



G2b-I, Panel 643

Pull off strength: 2553 psi,

Break: 97% cohesive within Top; 3% adhesive between glue and Top.

Dolly at upper left

4.b.3.4.2 Panel 643, G2b-I, Test 2

G2b-I, Panel 643, Test 2

Pull off strength: 1882 psi,

Break: 50% cohesive within Top; 50% adhesive between Glue and Top

Dolly at upper right

4.b.3.4.3 Panel 643, G2b-I, Test 3

G2b-I, Panel 643, Test 3

Pull off strength: 2302 psi,

Break: 80% cohesive within Top; 10% adhesive between Top and Int; 10% adhesive between Glue and Top.

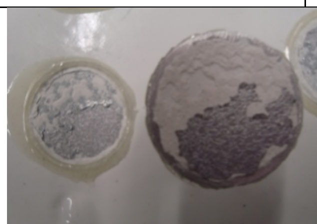
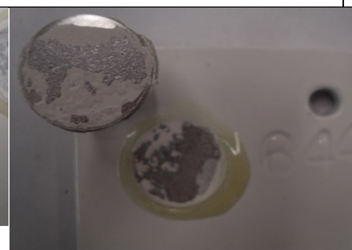
Dolly at left

4.c.1 Test panel subgroup G2b-S1

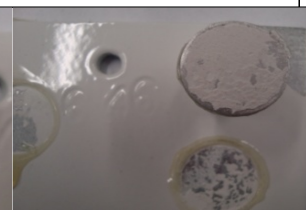
Primer: (galvanizing) or (metallizing w/ and w/o Macropoxy 920 sealer)
Intermediate: Macropoxy 646 Fast Cure Epoxy
Finish: Acrolon 218 HS Acrylic Polyurethane

Test panel numbers: 644,645,646,647 (the labels "G2-S1" should be read as G2b-S1) Box 16

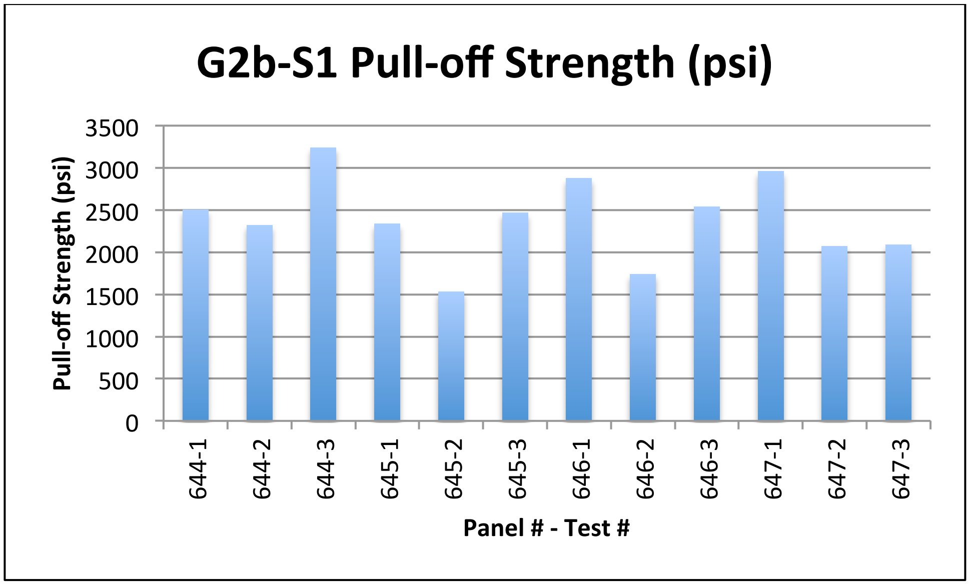
4.c.2 Adhesive strength test results for G2b-S1 test panels

4.c.2 Adhesive strength test results for G2b-S1 test panels (Part I)					
Panel	Test 1	Test 2	Test 3	X-cut 1 Score	X-cut 2 Score
644				5	5
	Strength: 2505 psi	Strength: 2320 psi	Strength: 3240 psi		
	Break: 50% cohesive within Top; 50% cohesive within Int.	Break: 40% cohesive within Int ; 30% cohesive within Top; 20% cohesive within Top; 10% adhesive between Top and Glue.	Break: 60% cohesive within Top; 40% cohesive within Int.		
	Dolly at right	Dolly at upper left	Dolly at upper right		
645				5	5
	Strength: 2335 psi	Strength: 1529 psi	Strength: 2466 psi		
	Break: 95% cohesive within Top; 5% adhesive between Glue and Top	Break: 60 % adhesive between Top and Int; 20% cohesive within Top; 20% adhesive between Glue and Top.	Break: 85% cohesive within Top; 15% adhesive between Int and Zn-G		
	Dolly at right	Dolly at upper left	Dolly at upper right		

4.c.2 Adhesive strength test results for G2b-S1 test panels (Part II)

Panel	Test 1	Test 2	Test 3	X-cut 1 Score	X-cut 2 Score
646				5	5
	Strength: 2875 psi	Strength: 1740 psi	Strength: 2541 psi		
	Break: 80% cohesive within Top; 20% adhesive between Glue and Top	Break: 70% cohesive within Top; 30% adhesive between Glue and Top	Break: 90% cohesive within Top; 10% adhesive between Top and Int.		
	Dolly at right	Dolly at upper left	Dolly at upper right		
647				5	5
	Strength: 2959 psi	Strength: 2069 psi	Strength: 2088 psi		
	Break: 100% cohesive within Top.	Break: 85% cohesive within Top; 15% adhesive between Glue and Top	Break: 85% adhesive between Glue and Top; 15% cohesive within Top		
	Dolly at right	Dolly at upper right	Dolly at upper right		

Pull-off Test G2b-S1	
Panel#-Test#	G2b-S1 Pull-off Strength (psi)
644-1	2505
644-2	2320
644-3	3240
645-1	2335
645-2	1529
645-3	2466
646-1	2875
646-2	1740
646-3	2541
647-1	2959
647-2	2069
647-3	2088
Average	2389
Standard Dev	473
Confidence	268


G2b-S1 Pull-off Strength (psi)
3500
3000
2500
2000
1500
1000
500
0
Pull-off Strength (psi)
644-1
644-2
644-3
645-1
645-2
645-3
646-1
646-2
646-3
647-1
647-2
647-3
Panel # - Test #

4.c.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

4.c.3.1 Panel #644

4.c.3.1.1 Panel 644 G2b-S1 Test 1

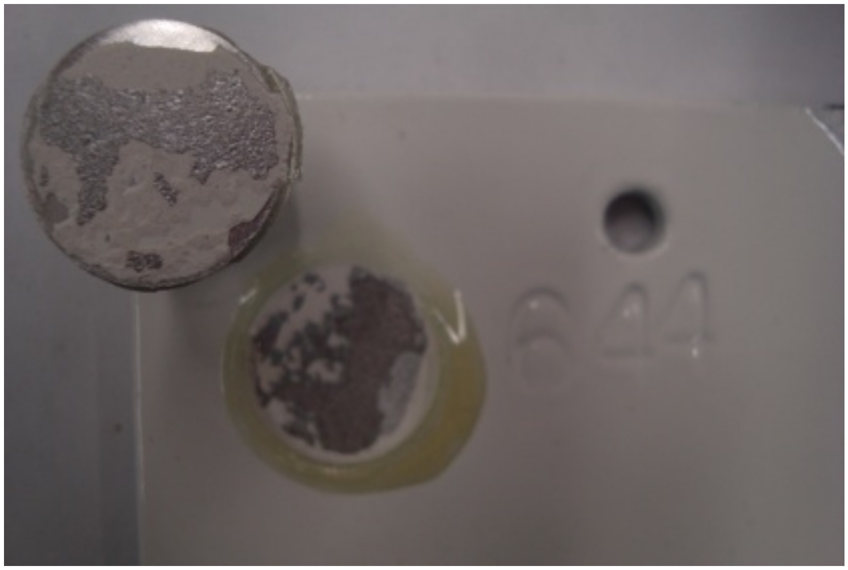
G2b-S1 Panel 644 Test 1

Pull-off strength: 2505 psi

Break: 50% cohesive within Top; 50% cohesive within Int.

Dolly at right.

4.c.3.1.2 Panel 644 G2b-S1 Test 2



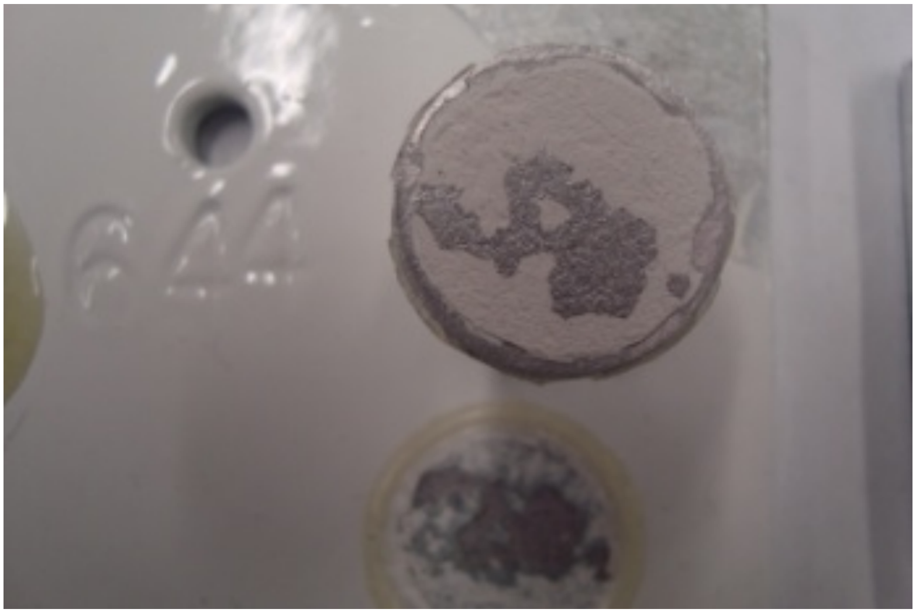
G2b-S1 Panel 644 Test 2

Pull off strength: 2320 psi

Break: 40% cohesive within Int; 30% cohesive within Top; 20% adhesive between Top and Int; 10% adhesive between Top and Glue.

Dolly at upper left.

4.c.3.1.3 Panel 644 G2b-S1 Test 3



G2b-S1 Panel 644 Test 3

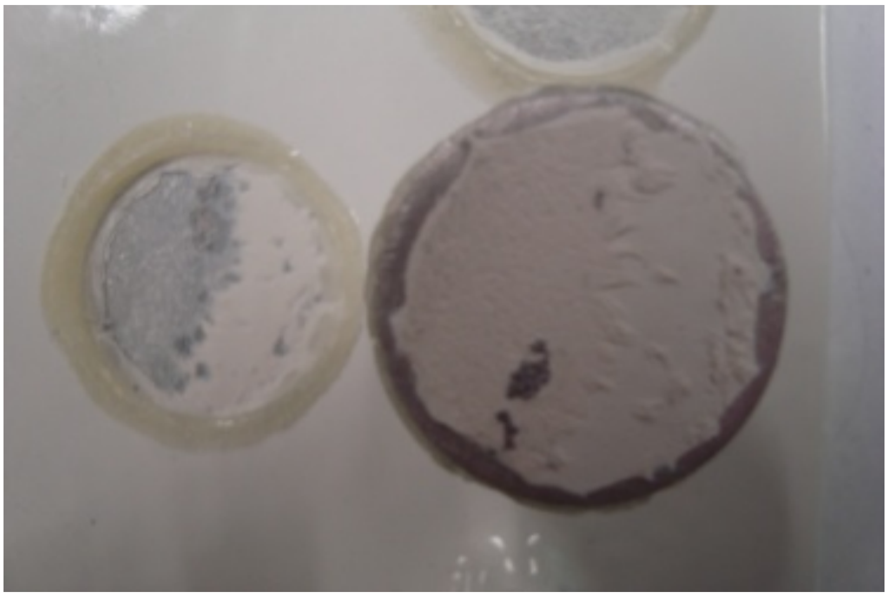
Pull off strength: 3240 psi

Break: 60% cohesive within Top; 40% cohesive within Int.

Dolly at upper right.

4.c.3.2 Panel #645

4.c.3.2.1 Panel 645, G2b-S1, Test 1



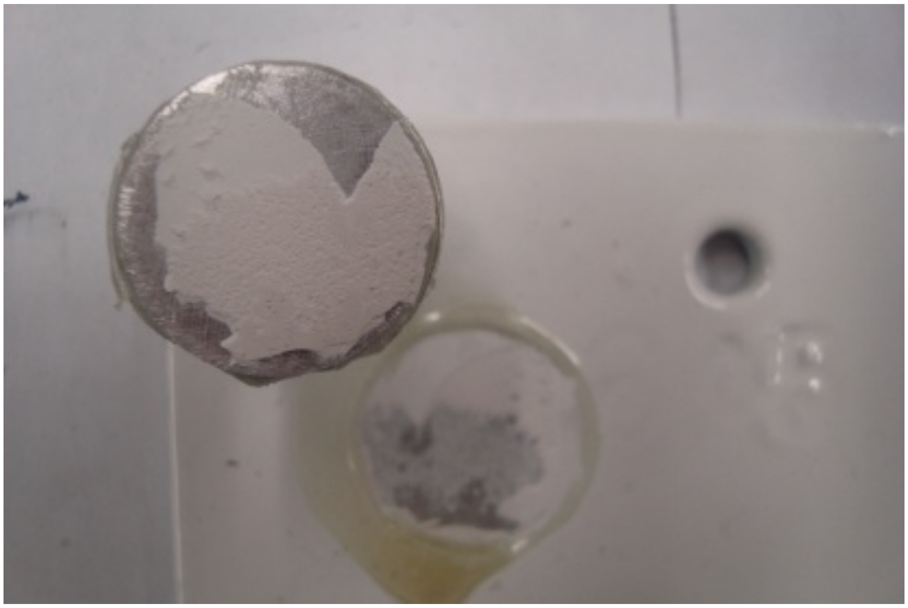
G2b-S1 Panel 645 Test 1

Pull off strength: 2335 psi

Break: 95% cohesive within Top; 5% adhesive between Glue and Top

Dolly at right

4.c.3.2.2 Panel 645, G2b-S1, Test 2



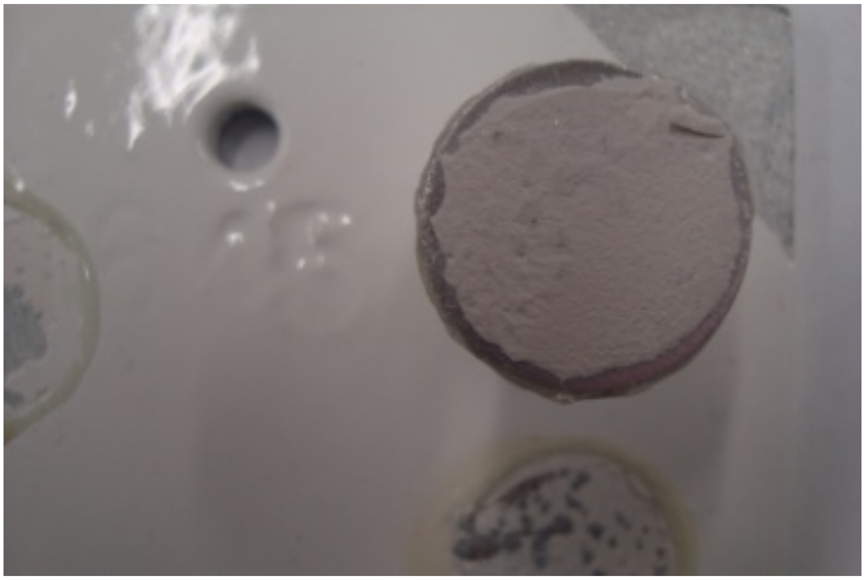
G2b-S1, Panel 645, Test 2

Pull off strength: 1529 psi

Break: 60 % adhesive between Top and Int; 20% cohesive within Top; 20% adhesive between Glue and Top.

Dolly at upper right

4.c.3.2.3 Panel 645, G2b-S1, Test 3



G2b-S1, Panel 645, Test 3

Pull off strength: 2466 psi

Break: 90% cohesive within Top; 10% adhesive between Top and Int.

Dolly at upper right.

4.c.3.3 Panel #646

4.c.3.3.1 Panel 646, G2b-S1, Test 1

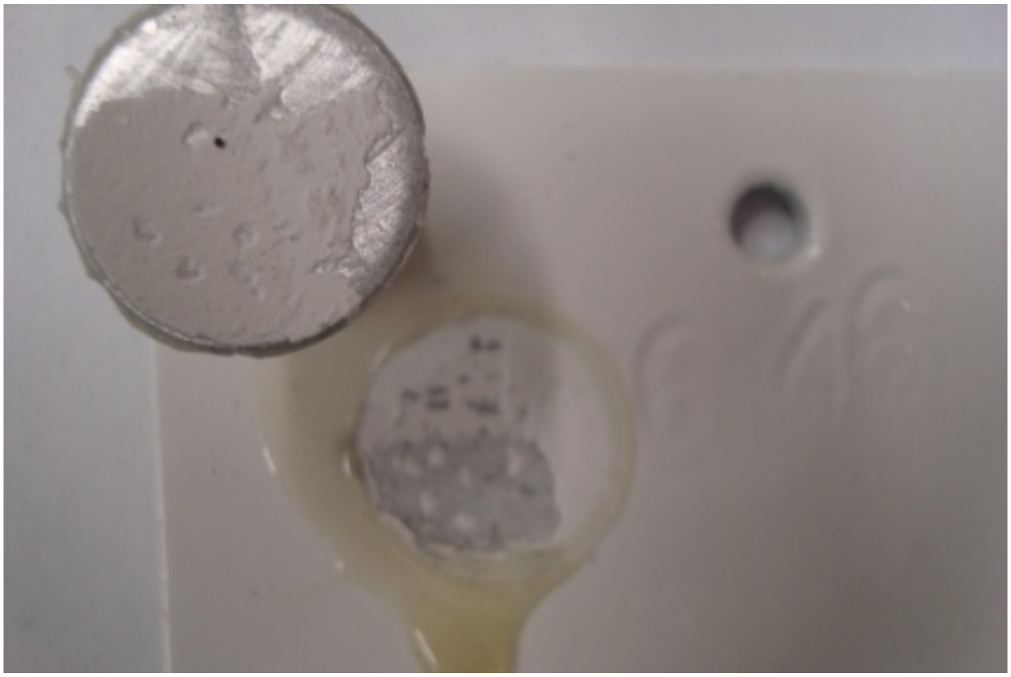
G2b-S1, Panel 646, Test 1

Pull off strength: 2876 psi

Break: 80% cohesive within Top; 20% adhesive between Glue and Top.

Dolly at right.

4.c.3.3.2 Panel 646, G2b-S1, Test 2



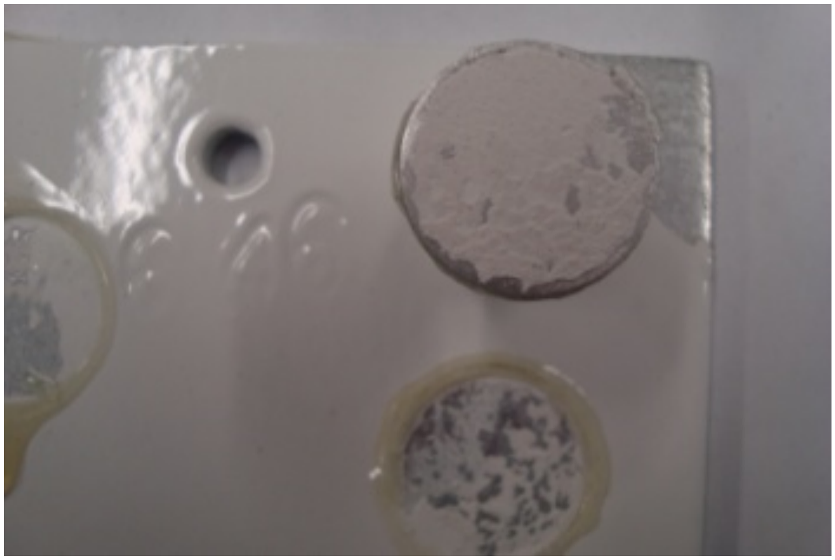
G2b-S1, Panel 646 Test 2

Pull off strength: 1740 psi

Break: 70% cohesive within Top; 30% adhesive between Glue and Top.

Dolly at upper left.

4.c.3.3.3 Panel 646, G2b-S1, Test 3



G2b-S1, Panel 646, Test 3

Pull off strength: 2541 psi

Break: 90% cohesive within Top; 10% adhesive between Top and Int.

Dolly at upper right.

4.c.3.4 Panel #647

4.c.3.4.1 Panel 647, G2b-S1, Test 1

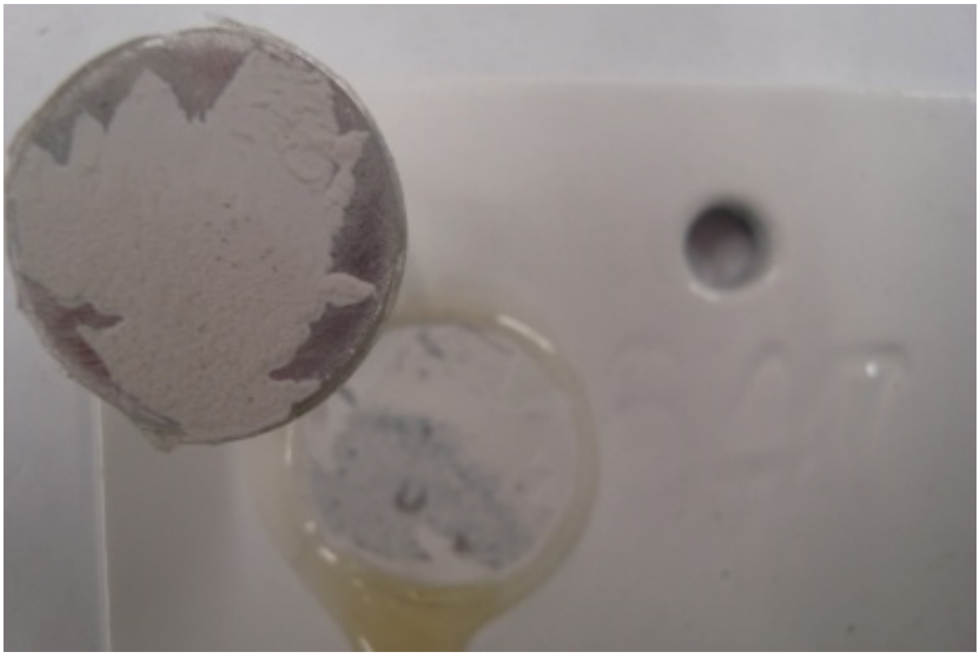
G2b-S1, Panel 647, Test 1

Pull off strength: 2959 psi

Break: 100% cohesive within Top.

Dolly at right

4.c.3.4.2 Panel 647, G2b-S1, Test 2



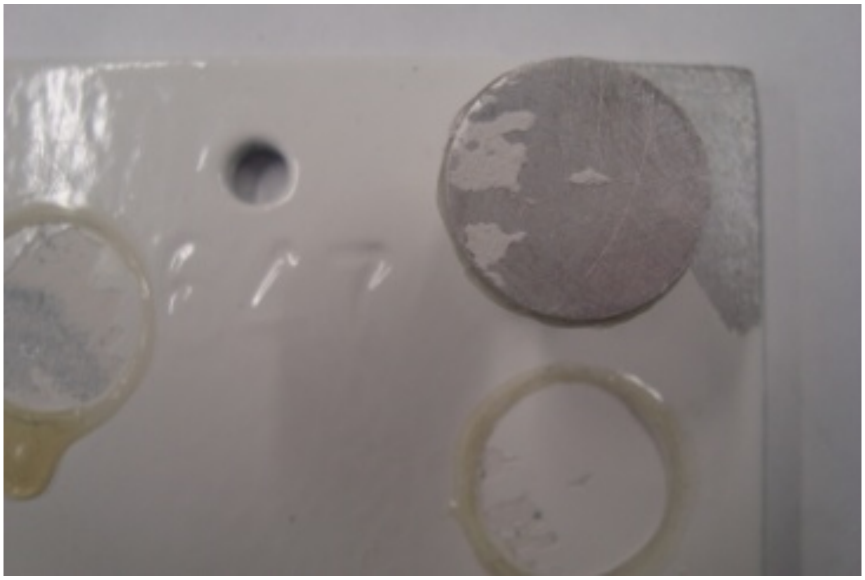
G2b-S1, Panel 647, Test 2

Pull off strength: 2069 psi

Break: 85% cohesive within Top; 15% adhesive between Glue and Top.

Dolly at upper left.

4.c.3.4.3 Panel 647, G2b-S1, Test 3



G2b-S1, Panel 647, Test 3

Pull off strength: 2088 psi

Break: 85% adhesive between Glue and Top; 15% cohesive within Top.

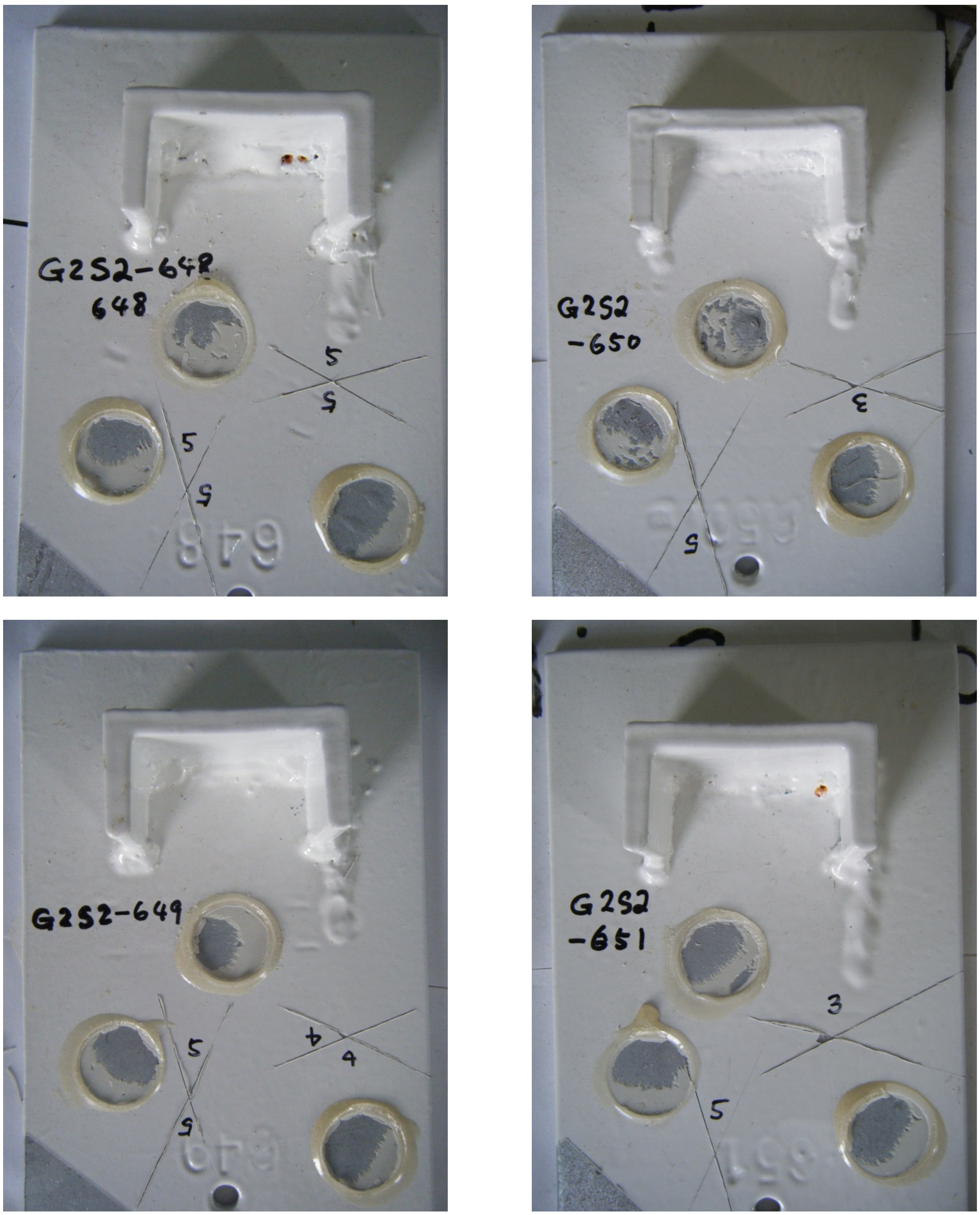
Dolly at upper right.

4.d. Test panel subgroup G2b-S2

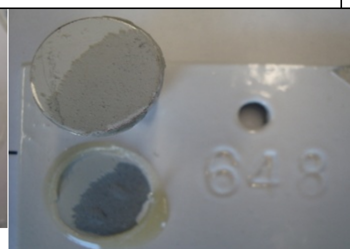
Primer:	(galvanizing or metallizing)
Intermediate:	Recoatable Epoxy Primer Series B67
Finish:	High Solids Polyurethane Series B58

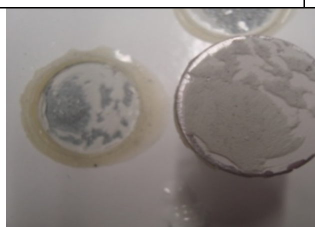
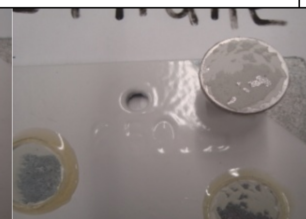
Test panel numbers: 648,649,650,651 (G2b-S2) Box 1

4.d.1 Photographs of the G2b-S2 test panels

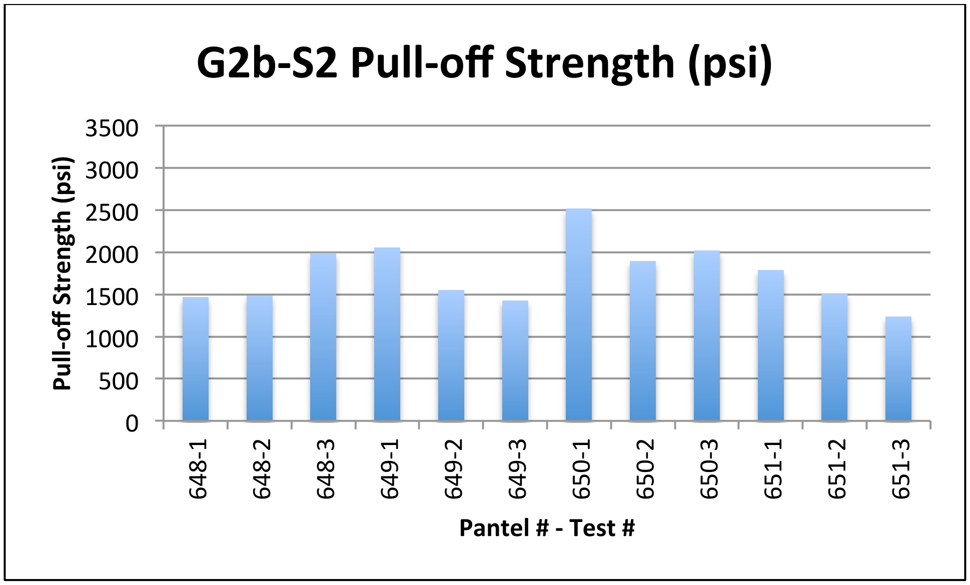


4.d.2 Adhesive strength test results for G2b-S2 test panels

4.d.2 Adhesive strength test results for G2b-S2 test panels (Part I)					
Panel	Test 1	Test 2	Test 3	X-cut 1 Score	X-cut 2 Score
648				5	5
	Strength: 1468 psi	Strength: 1481 psi	Strength: 1986 psi		
	Break: 80% cohesive within Top; 20% adhesive between Glue and Top	Break: 70% adhesive between Int and Zn-G; 30% adhesive between Top and Int.	Break: 50% adhesive between Top and Int., 50% cohesive within Top		
	Dolly at left	Dolly at upper left	Dolly at upper right		
649				5	5
	Strength: 2055 psi	Strength: 1549 psi	Strength: 1424 psi		
	Break: 70% adhesive between Top and Int; 30% adhesive between Int and Zn-G.	Break: 80% adhesive between Int and Zn-G; 20% adhesive between Top and Int.	Break: 60% adhesive between Int and Zn-G, 40% adhesive between Top and Int		
	Dolly at right	Dolly at upper left	Dolly at upper right		

4.d.2 Adhesive strength test results for G2b-S2 test panels (Part II)					
Panel	Test 1	Test 2	Test 3	X-cut 1 Score	X-cut 2 Score
650				5	5
	Strength: 2513 psi	Strength: 1894 psi	Strength: 2016 psi		
	Break: 50% adhesive between Int and Zn-G; 50% adhesive between Top and Int.	Break: 70% adhesive between Int and Zn-G; 30% adhesive between Top and Int.	Break: 60% adhesive between Int and Zn-G; 40% adhesive between Top and Int.		
	Dolly at right	Dolly at upper left	Dolly at upper right		
651				5	5
	Strength: 1785 psi	Strength: 1504 psi	Strength: 1232 psi		
	Break: 80% adhesive between Int and Zn-G; 20% adhesive between Top and Int.	Break: 70% adhesive between Int and Zn-G; 30% adhesive between Top and Int.	Break: 70% adhesive between Int and Zn-G; 30% adhesive between Top and Int.		
	Dolly at left	Dolly at upper left	Dolly at upper right		

Pull-off Test G2b-S2	
Panel#-Test#	G2b-S2 Pull-off Strength (psi)
648-1	1468
648-2	1481
648-3	1986
649-1	2055
649-2	1549
649-3	1424
650-1	2513
650-2	1894
650-3	2016
651-1	1785
651-2	1504
651-3	1232
Average	1742
Standard Dev	348
Confidence	197



G2b-S2 Pull-off Strength (psi)
Pull-off Strength (psi)
3500
3000
2500
2000
1500
1000
500
0
648-1
648-2
648-3
649-1
649-2
649-3
650-1
650-2
650-3
651-1
651-2
651-3
Pantel # - Test #

4.d.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers for G2b-S2 coated panels.

4.d.3.1 Panel #648

4.d.3.1.1 Panel 648 G2b-S2 Test 1

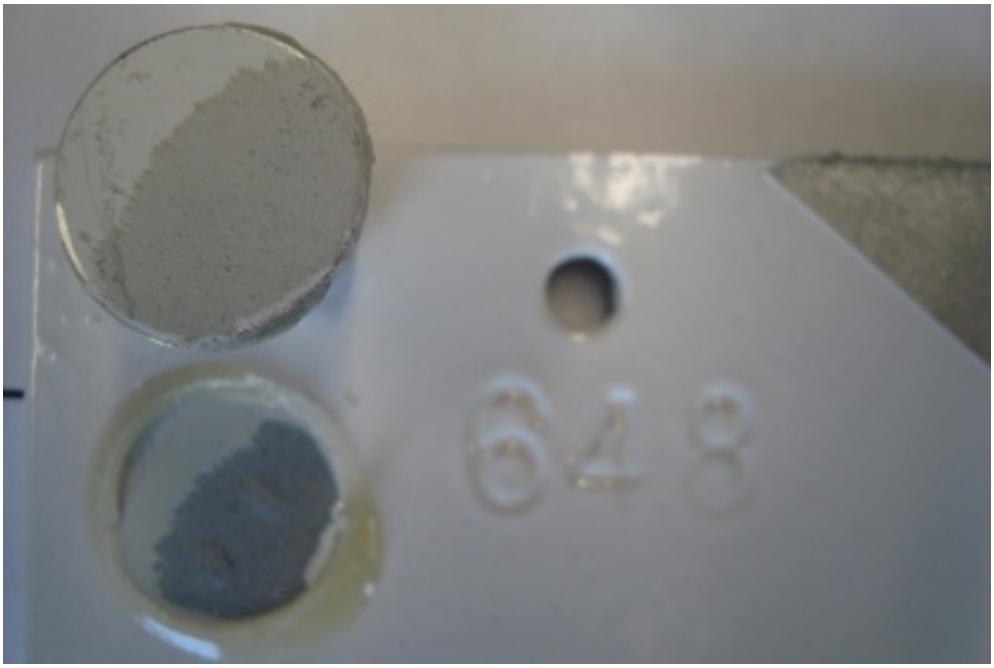
G2b-S2, Panel 648, Test 1

Pull off strength: 1468 psi.

Break: 60% cohesive within Top; 40% adhesive between Top and Int.

Dolly at left.

4.d.3.1.2 Panel 648 G2b-S2 Test 2



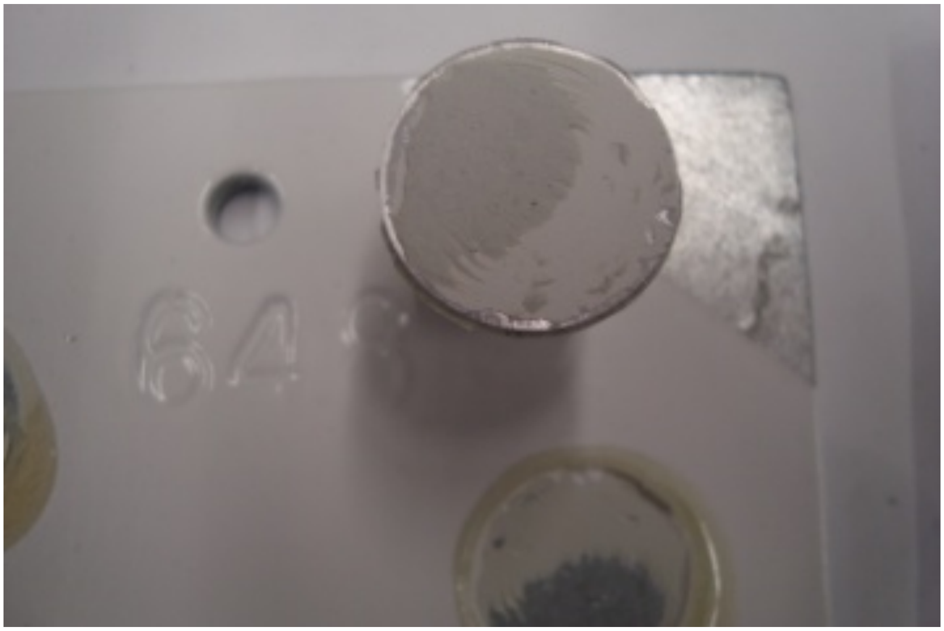
G2b-S2, Panel 648, Test 2

Pull off strength: 1481 psi

Break: 70% adhesive between Int and Zn-G; 30% adhesive between Top and Int.

Dolly at upper left.

4.d.3.1.3 Panel 648 G2b-S2 Test 3



G2b-S2, Panel 648, Test 3

Pull off strength: 1986 psi

Break: 50% adhesive between Top and Int., 50% cohesive within Top

Dolly at upper right.

4.d.3.2 Panel #649

4.d.3.2.1 Panel 649 G2b-S2 Test 1

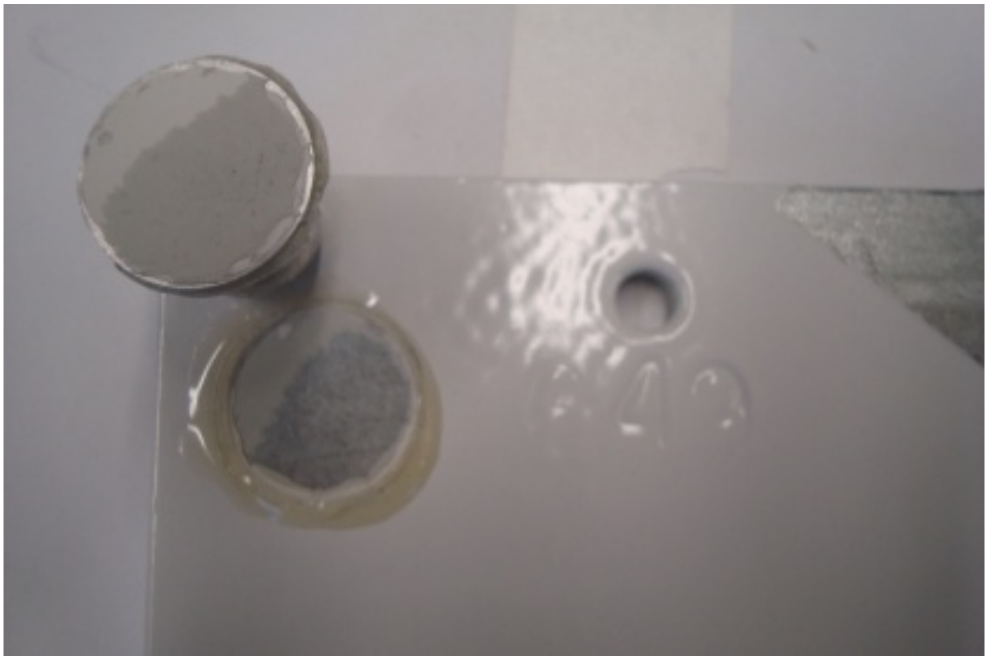
G2b-S2, Panel 649, Test 1

Pull off strength: 2055 psi

Break: 70% adhesive between Top and Int; 30% adhesive between Int and Zn-G.

Dolly at right.

4.d.3.2.2 Panel 649 G2b-S2 Test 2



G2b-S2, Panel 649, Test 2

Pull off strength: 1549 psi

Break: 80% adhesive between Int and Zn-G; 20% adhesive between Top and Int.

Dolly at upper left.

4.d.3.2.3 Panel 649 G2b-S2 Test 3

G2b-S2, Panel 649, Test 3

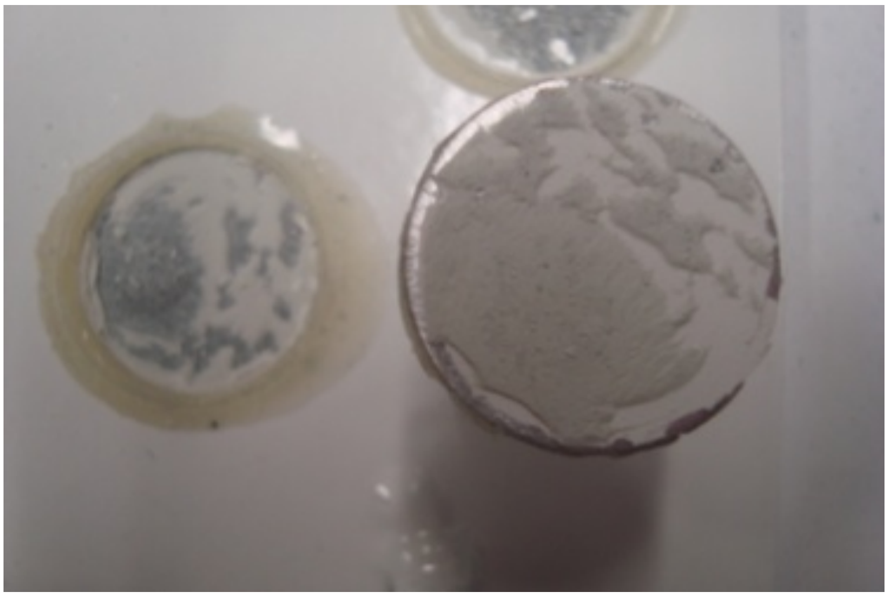
Pull off strength: 1424 psi

Break: 60% adhesive between Int and Zn-G, 40% adhesive between Top and Int.

Dolly at upper right.

4.d.3.3 Panel #650

4.d.3.3.1 Panel 650 G2b-S2 Test 1



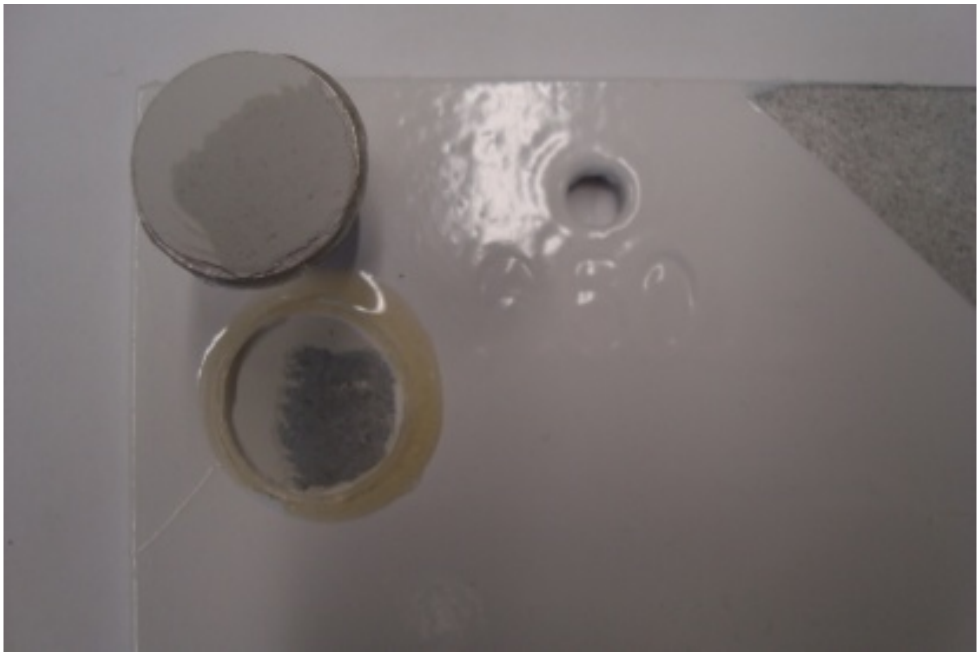
G2b-S2, Panel 650, Test 1

Pull off strength: 2513 psi

Break: 50% adhesive between Int and Zn-G; 50% adhesive between Top and Int.

Dolly at right.

4.d.3.3.2 Panel 650 G2b-S2 Test 2



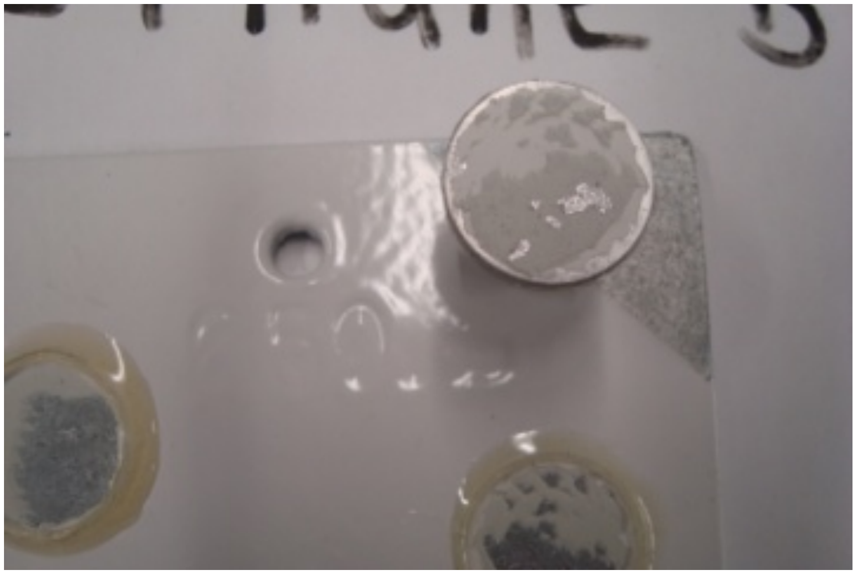
G2b-S2, Panel 650, Test 2

Pull off strength: 1894 psi

Break: 70% adhesive between Int and Zn-G; 30% adhesive between Top and Int.

Dolly at upper left.

4.d.3.3.3 Panel 650 G2b-S2 Test 3



G2b-S2, Panel 650, Test 3

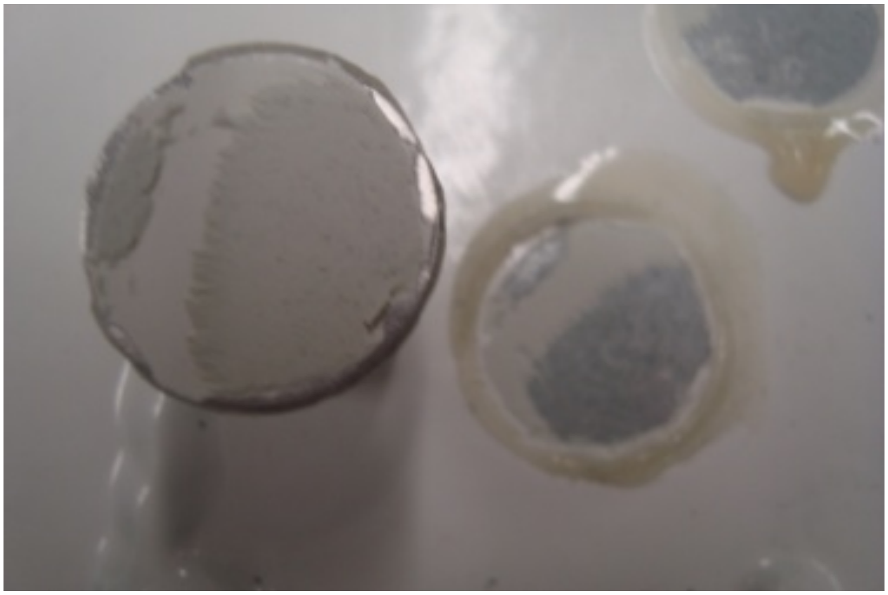
Pull off strength: 2016 psi

Break: 60% adhesive between Int and Zn-G; 40% adhesive between Top and Int.

Dolly at upper right.

4.d.3.4 Panel #651

4.d.3.4.1 Panel 651 G2b-S2 Test 1



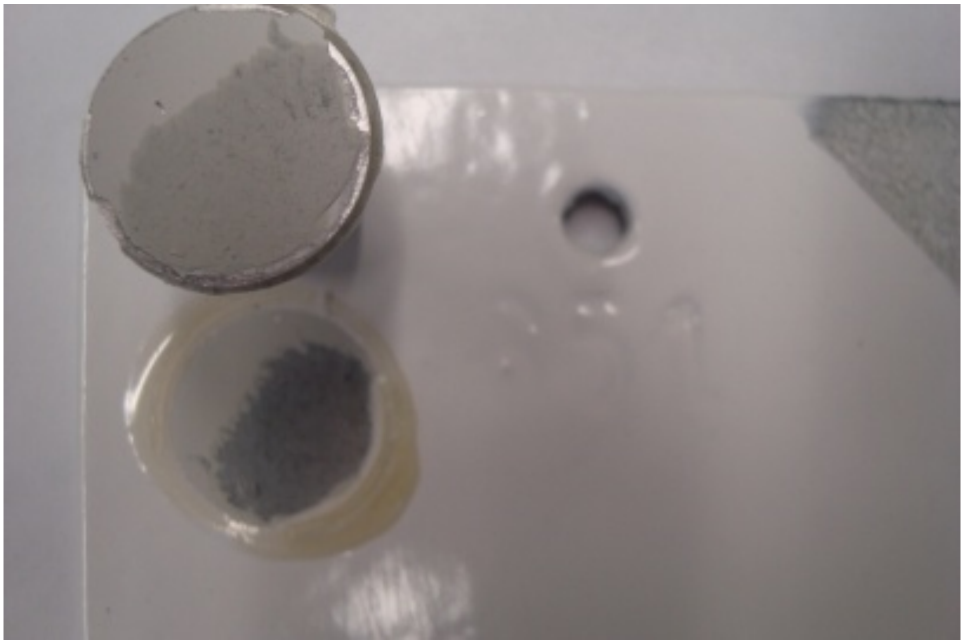
G2b-S2, Panel 651, Test 1

Pull off strength: 1785 psi

Break: 80% adhesive between Int and Zn-G; 20% adhesive between Top and Int.

Dolly at left.

4.d.3.4.2 Panel 651 G2b-S2 Test 2



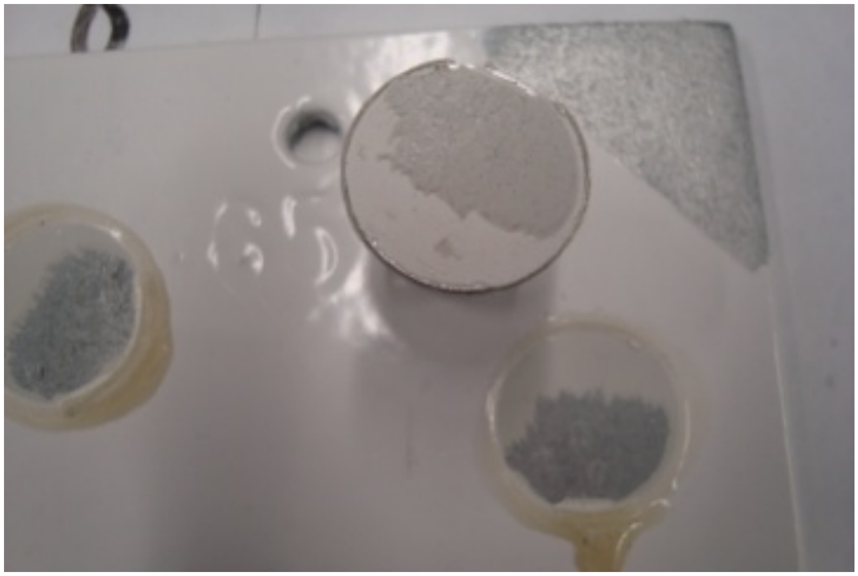
G2b-S2, Panel 651, Test 2

Pull off strength: 1504 psi

Break: 70% adhesive between Int and Zn-G; 30% adhesive between Top and Int.

Dolly at upper left.

4.d.3.4.3 Panel 651 G2b-S2 Test 3



G2b-S2, Panel 651, Test 3

Pull off strength: 1232 psi

Break: 70% adhesive between Int and Zn-G; 30% adhesive between Top and Int.

Dolly at upper left.

5. Group Z, List and photographic images of the tested panels.

This group of test panels used zinc rich primer instead of the galvanized or metallized zinc as the corrosion protection layer. The steel test panels were fabricated by performing on the same day the near-white blasting (SSPC-SP10/NACE 2 Near white blasting) of steel panels and the painting of the steel panels with zinc rich organic primer coating. The intermediate and the top paints were applied according to the manufacturer's specification after the zinc rich epoxy layer was cured. Four different paint systems were used for the subgroups with the following designations for the subgroups and the test panels. See the following pages for photographs of the tested panels.

Each pull-off test spot on a test panel is given an identification number according to the following convention: We assign the uppermost test spot in the images of the panels as test sample #1. Pretending that sample #1 is at the 12-oclock position of a clock, the remaining test spots are ordered according to its position in the clockwise rotation order. Occasionally, a pull-off test is omitted from the list because of technical problems observed during the test. For example the dolly was not property glued to the paint surface, or the surface near the test spot is too close to a welding burr so that the tester cannot be seated correctly. A replacement test is listed (using a different test spot identification number) is listed in the table in place of the omitted test.

Section 5.a.1 contains a description of the paint system used for coating the test panels, the labels stamped or attached to the test panels, and the storage box number for the test panels, and the photographic image of the test panels after the adhesive strength tests were completed.

Section 5.a.2 contains a table summarizing the test results of the ASTM D4541 pull-off strength tests and the ASTM D3359 Type A X-cut tape tests. In the table we summarize the pull-off strengths (in the unit of psi), a description of the surface of breakage on the test dolly.

We photographed the dolly placed near the test spot on the panel to show the surface of break after the pull-off strength test. In some test spots, the dollies were not photographed. For these samples, only the areas of the panel with pull-off spot were shown in the table. A small photographic image of the break surfaces are shown in the table for the purpose of associating the pull-off strength data with the images of the tested panels shown in section 5.a.1.

Each test spot on a test panel is given an identification number according to the following convention: We assign the uppermost test spot in the images of the panels in Section 5.a.1 as test sample #1. Pretending that sample #1 is at the 12-oclock position of a clock, the remaining test spots are ordered according to its position in the clockwise rotation order.

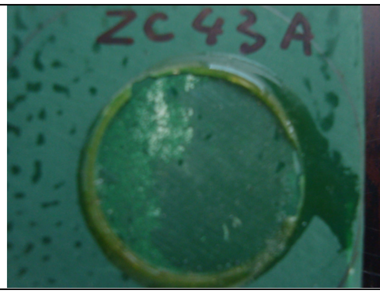
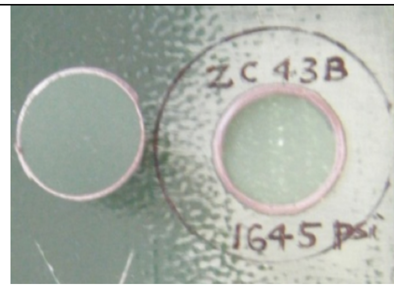
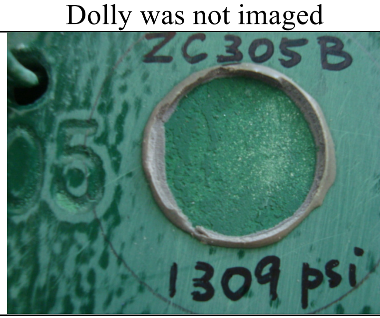
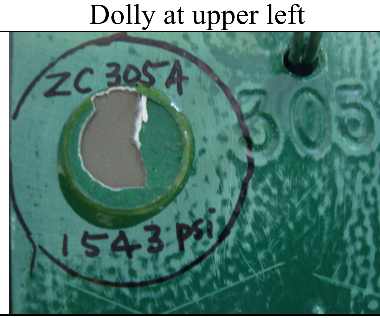
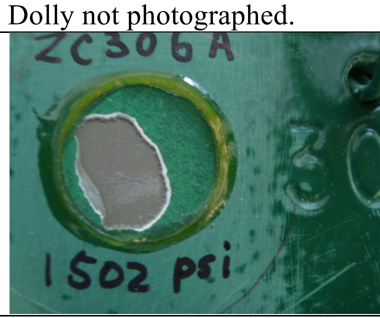
Section 5.a.3 contains the enlarged copies of the pictures in the Table of Section 5.a.2. The enlarged pictures are posted to enable closer examination of the surfaces of both the dolly and the pull-off surface on the panel, and for the readers to verify the description of the break surface in the table of Section 5.a.2.

5.a.1 Test panels subgroup ZC

Primer:	Carbozinc 859 Organic Zinc Rich Epoxy Primer
Intermediate:	Carboline 888 Epoxy
Finish:	Carboline 133 LH Aliphatic Polyurethane

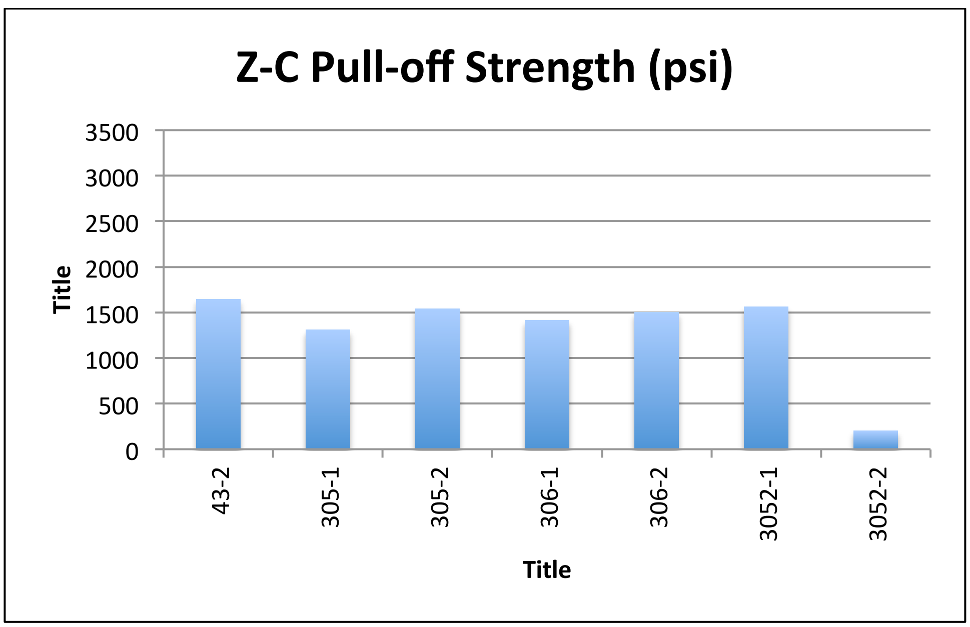
Test panels: ZC-43, ZC-305, ZC-3052, ZC-306, in Box 18

5.a.2 Adhesive strength Test results for Z-C test panels

5.a.2 Adhesive strength Test results for Z-C test panels (Part I)				
Test Pane	Pull Test 1	Pull Test 2	X-cut 1 Score	X-cut 2 Score
43			5	5
	Strength: N/A	Strength: 1645 psi		
	Test result is not counted because of failure of adhesive glue.	Break: 80% cohesive within Top; 20% adhesive between Top and Int		
	Dolly was not imaged	Dolly at upper left		
305			5	5
	Strength: 1309 psi	Strength: 1543 psi		
	Break: 60% cohesive within Top; 20% adhesive between Top and Int; 20% adhesive between Glue and Top	Break: 60% adhesive between Zn-P and St; 40% cohesive within Top.		
	Dolly not photographed.	Dolly not photographed.		
306			5	5
	Strength: 1415 psi	Strength: 1502 psi		
	Break: 70% cohesive within Top; 30% adhesive between Zn-P and St	Break: 60% cohesive within Top; 40% adhesive between Zn-P and St		
	Dolly at lower left	Dolly not photogrphed		

5.a.2 Adhesive strength Test results for Z-C test panels (Part II)				
Test Pane	Pull Test 1	Pull Test 2	X-cut 1 Score	X-cut 2 Score
3052			5	5
	Strength: 1521 psi	Strength: 200 psi		
	Break: 80% adhesive between Zn-P and St; 20% adhesive between Top and Int	Break: 80% adhesive between Zn-P and St; 20% adhesive between Glue and Top.		
	Doly at left	Dolly not photographed		

Pull-off Test	Z-C
Panel#-Test#	Z-C Pull-off Strength (psi)
43-2	1645
305-1	1309
305-2	1543
306-1	1415
306-2	1502
3052-1	1561
3052-2	200
Average	1311
Stand Dev	464
Confidence	344

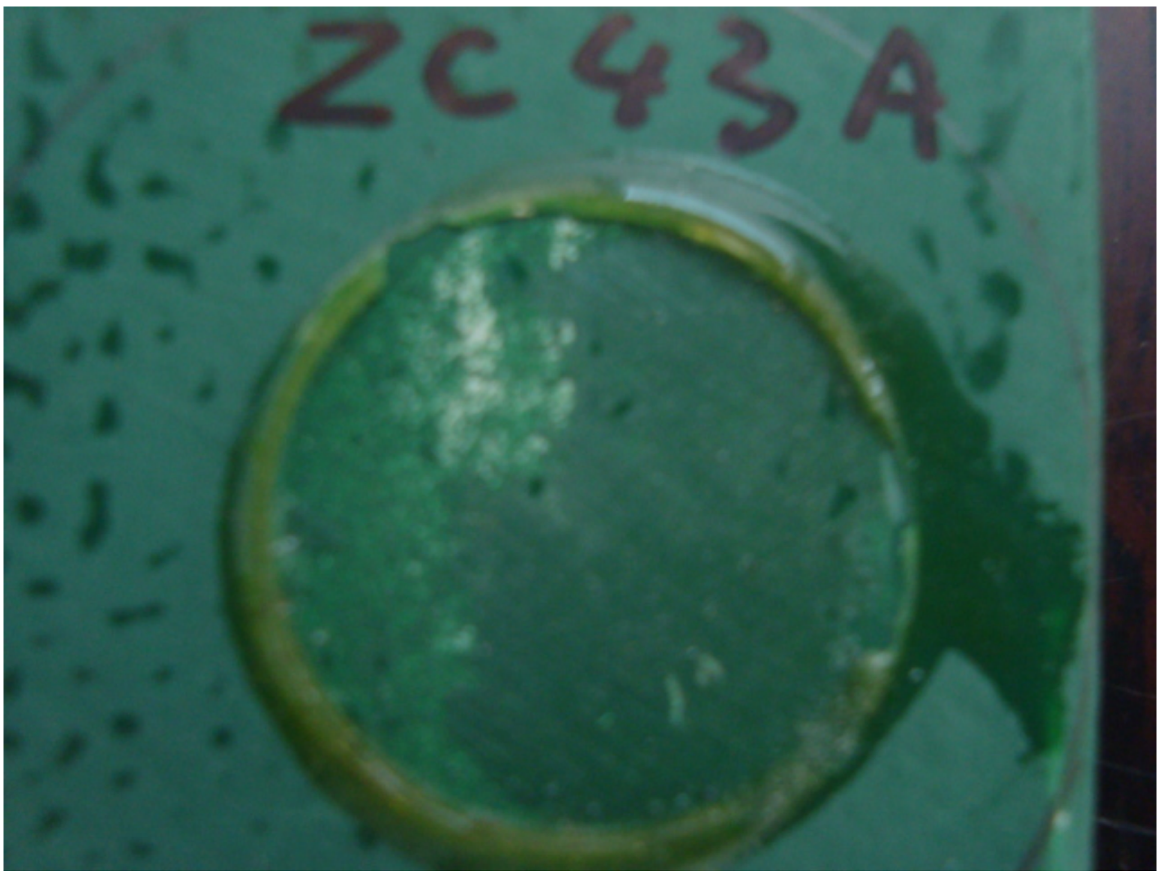


5.a.3 Enlarged photos of the pull-off dolly placed near the test spot on the Z-C panel, and a description of the break layers.

5.a.3.1 Panel #43, Z-C

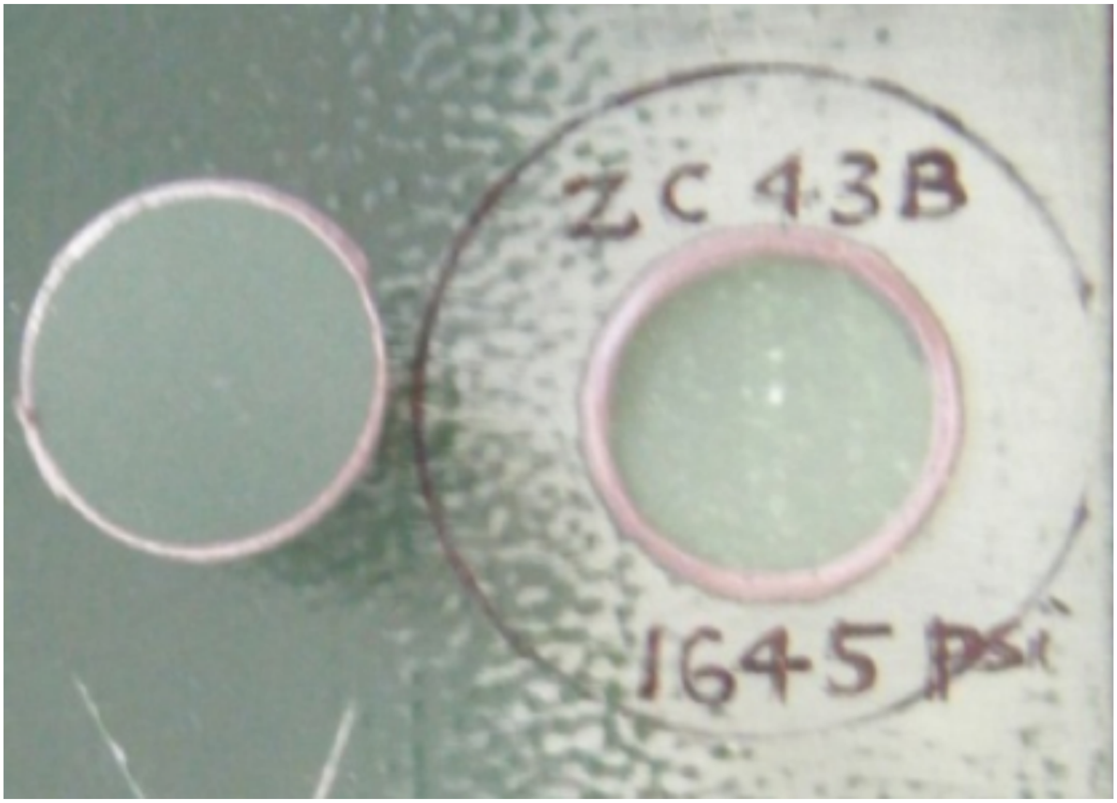
5.a.3.1.1 Panel 43 Test 1, Z-C

This test failed because the glue for dolly to panel attachment was not properly set. Consequentially, the pull-off break occurred at the dolly to top coat interface and the pull off strength registered was 0 psi.



No pull-off strength recorded.

5.a.3.1.2 Panel 43 Test 2, Z-C



Pull-off Strength: 1645 psi

Break: 80% cohesive within Top; 20% adhesive between Top and Int.

Dolly at left

5.a.3.2 Panel #305

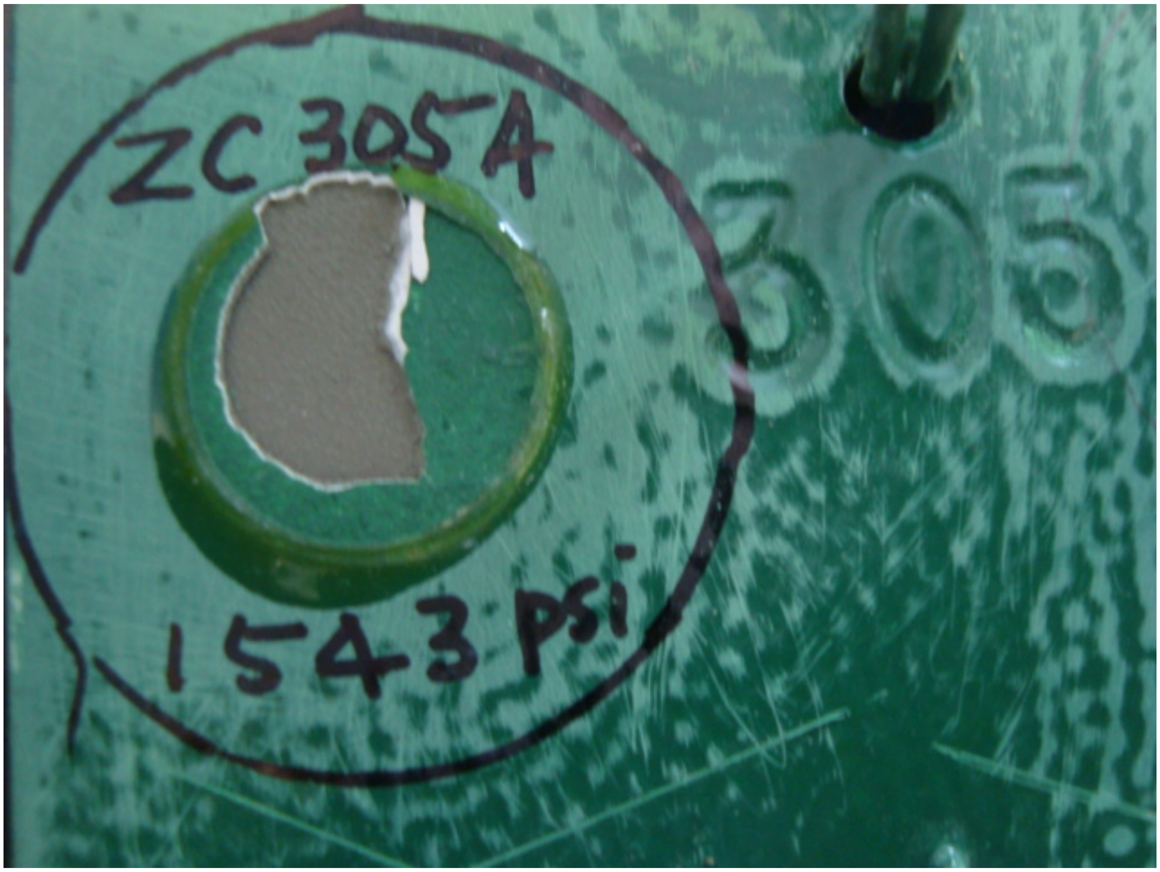
5.a.3.2.1 Panel 305 Z-C Test 1

Pull-off Strength: 1309 psi

Break: 60% cohesive within Top; 20% adhesive between Top and Int; 20% adhesive between Glue and Top

Dolly not photographed.

5.a.3.2.2 Panel 305 Z-C Test 2



Panel 305 Test 2, Z-C

Pull-off Strength: 1543 psi

Break: 60% adhesive between Zn-P and St; 40% cohesive within Top.

Dolly not photographed.

5.a.3.3 Panel #306

5.a.3.3.1 Panel 306 Z-C Test 1

Test 1 Panel 306 Z-C

Pull-off Strength: 1415 psi

Break: 70% cohesive within Top; 30% adhesive between Zn-P and St.

Dolly at lower left.

5.a.3.3.2 Panel 306 Z-C Test 2

Panel 306 Test 2, Z-C

Pull-off Strength 1502 psi

Break: 60% cohesive within Top; 40% adhesive between Zn-P and St

Dolly not photographed.

5.a.3.4 Panel #3052

5.a.3.4.1 Panel 3052 Test 1 Z-C

Panel 3052 Test 1, Paint Z-C

Pull-off Strength: 1521 psi

Break: 80% adhesive between Int and St; 20% adhesive between Top and Int

Dolly at left.

5.a.3.4.2. Panel 3052 Z-C Test 2

Pull-off Strength: 200 psi

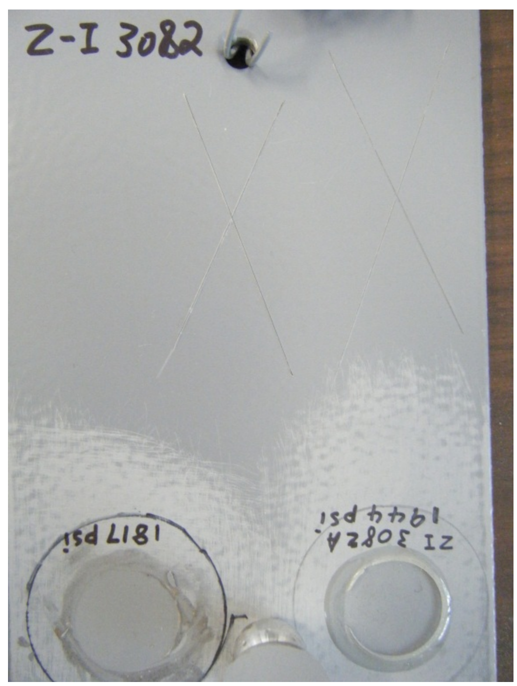
Break: 80% adhesive between Zn-P and St; 20% adhesive between Glue and Top.

Dolly not photographed.

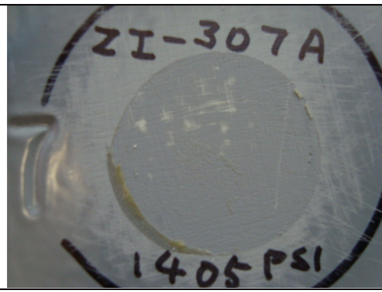
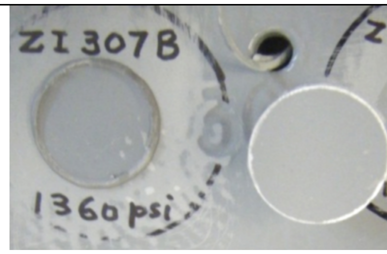
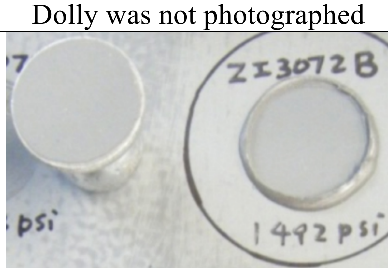
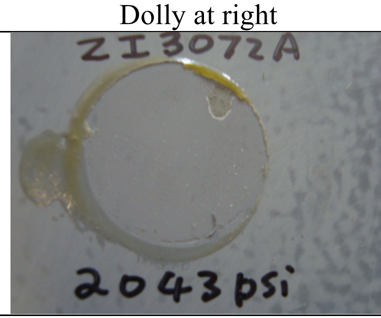
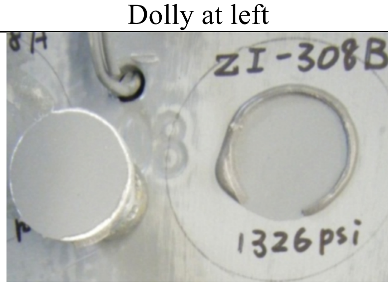
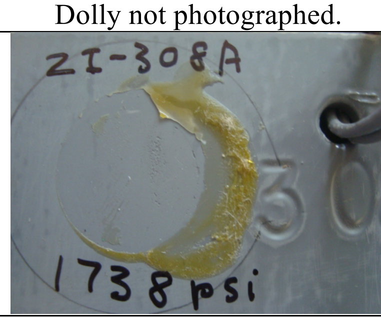
5.b.1 Test panels subgroup Z-I.

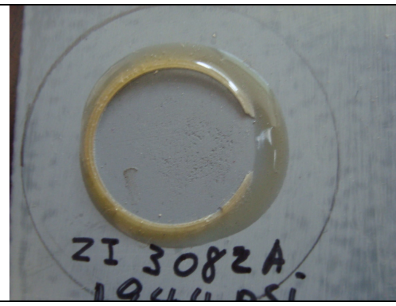
Primer: Interzinc® 52 Epoxy Zinc Rich (Green)
Intermediate: Intergard 345 Epoxy
Finish: Interthane 870 UHS

Test panels: ZI 307, 3072, 308, 3082, Box 19

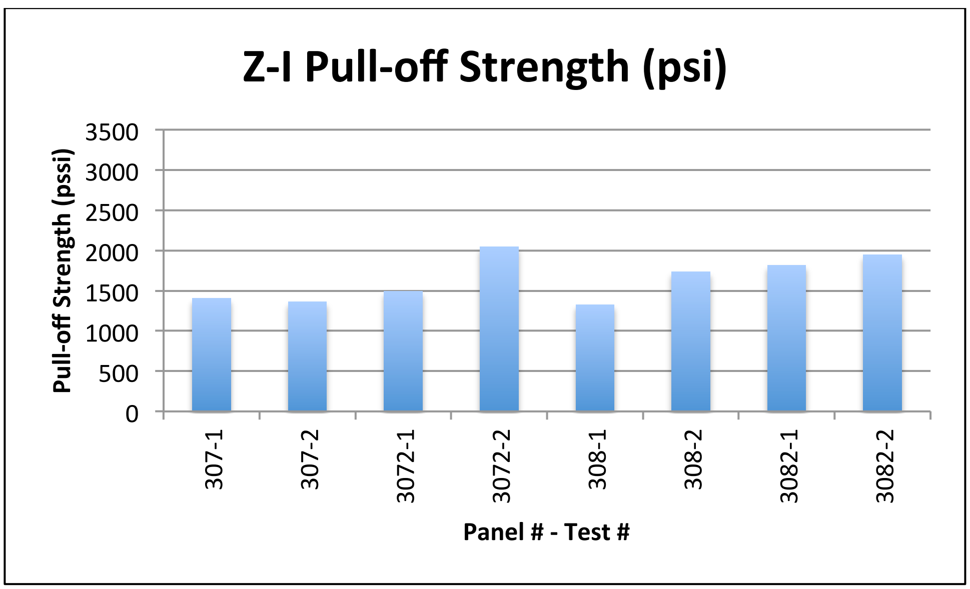


5.b.2 Adhesive strength Test results for Z-I test panels

5.b.2 Adhesive strength Test results for Z-I test panels (Part I)				
Test Pane	Pull Test 1	Pull Test 2	X-cut 1 Score	X-cut 2 Score
307			5	5
	Strength: 1405 psi	Strength: 1360 psi		
	Break: 95% cohesive within Top; 5% adhesive between Top and Int	Break: 95% cohesive within Top; 5% adhesive between Top and Int		
	Dolly was not photographed	Dolly at right		
3072			5	5
	Strength: 1492 psi	Strength: 2043 psi		
	Break: 100% cohesive within Top	Break: 95% cohesive within Top; 5% adhesive between Zn-P and St		
	Dolly at left	Dolly not photographed.		
308			5	5
	Strength: 1326 psi	Strength: 1738 psi		
	Break: 100% cohesive within Top	Break: 95% adhesive between Glue and Top; 5% cohesive within Top		
	Dolly at left	Dolly not photographed		

5.b.2 Adhesive strength Test results for Z-I test panels (Part II)				
Test Pane	Pull Test 1	Pull Test 2	X-cut 1 Score	X-cut 2 Score
3082			5	5
	Strength: 1817 psi	Strength: 1944 psi		
	Break: 100% cohesive within Top	Break: 100% cohesive within Top.		
	Doly at upper left	Dolly not photographed		

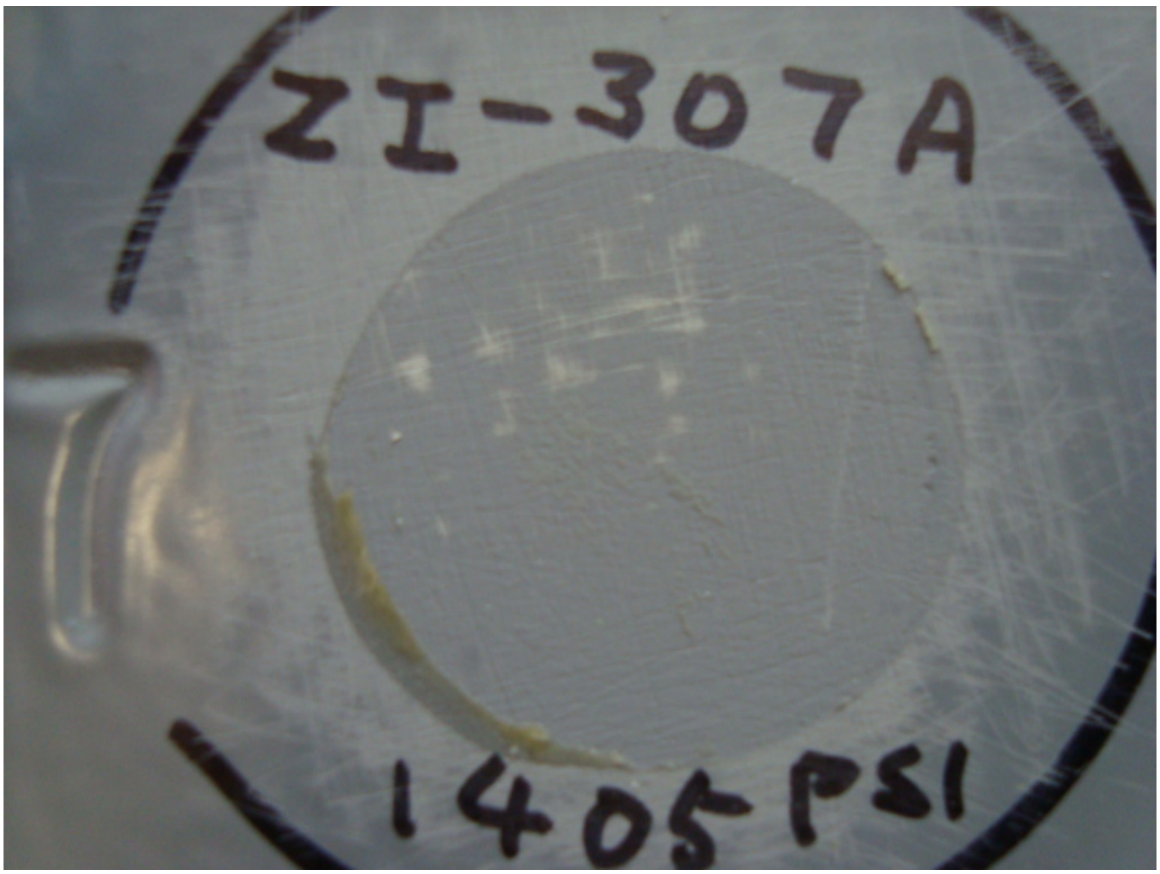
Pull-off Test	G0b-I
Panel#-Test#	Strength (psi)
307-1	1405
307-2	1360
3072-1	1492
3072-2	2043
308-1	1326
308-2	1738
3082-1	1817
3082-2	1944
Average	1641
Stand Dev	262
Confidence	155



5.b.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

5.b.3.1 Panel #307, Paint Z-I

5.b.3.1.1 Panel 307, Paint Z-I, Test 1



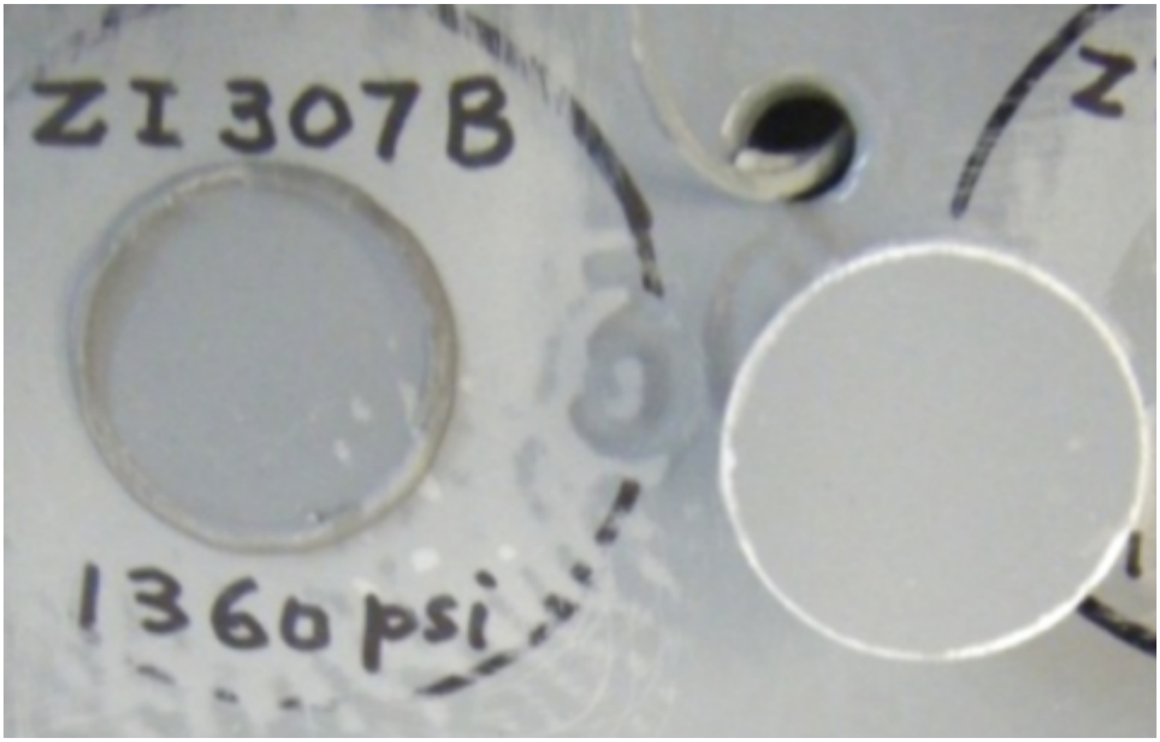
Panel 307 Test 1, Paint Z-I

Pull-off Strength: 1405 psi

Break: 95% cohesive within Top; 5% adhesive between Top and Int

Dolly not photographed.

5.b.3.1.2 Panel 307, Paint Z-I, Test 2



Panel 370 Test 1, Paint Z-I

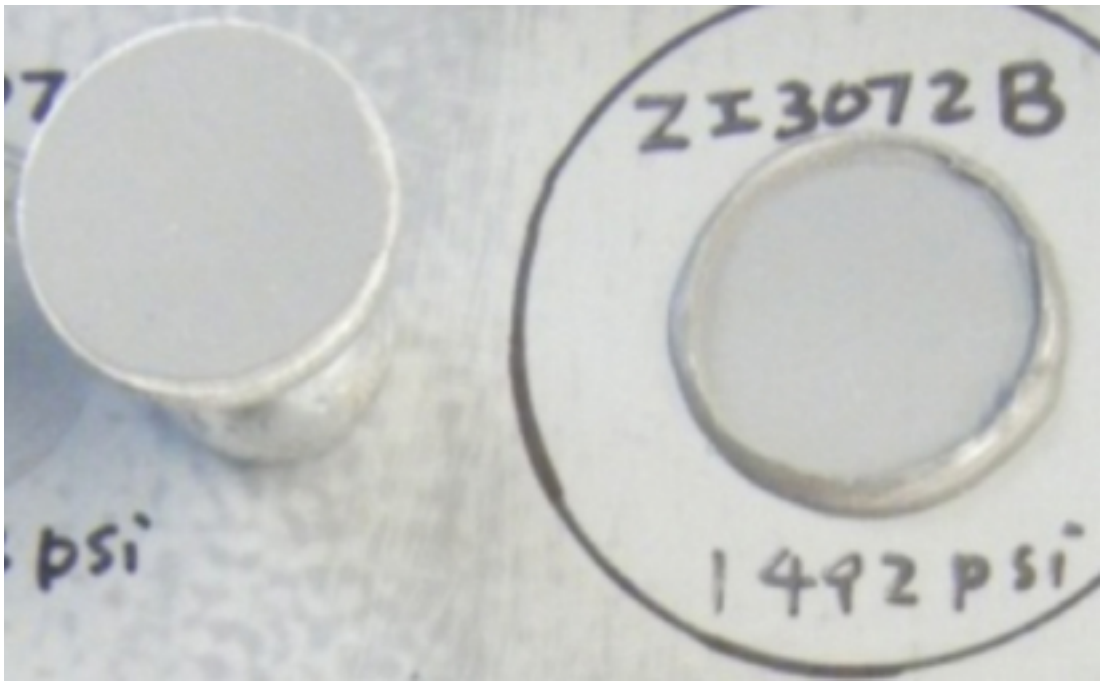
Pull-off Strength: 1360 psi

Break: 95% cohesive within Top; 5% adhesive between Top and Int

Dolly at right

5.b.3.2 Panel #307, Paint Z-I

5.b.3.2.1 Panel 3072, Paint Z-I, Test 1



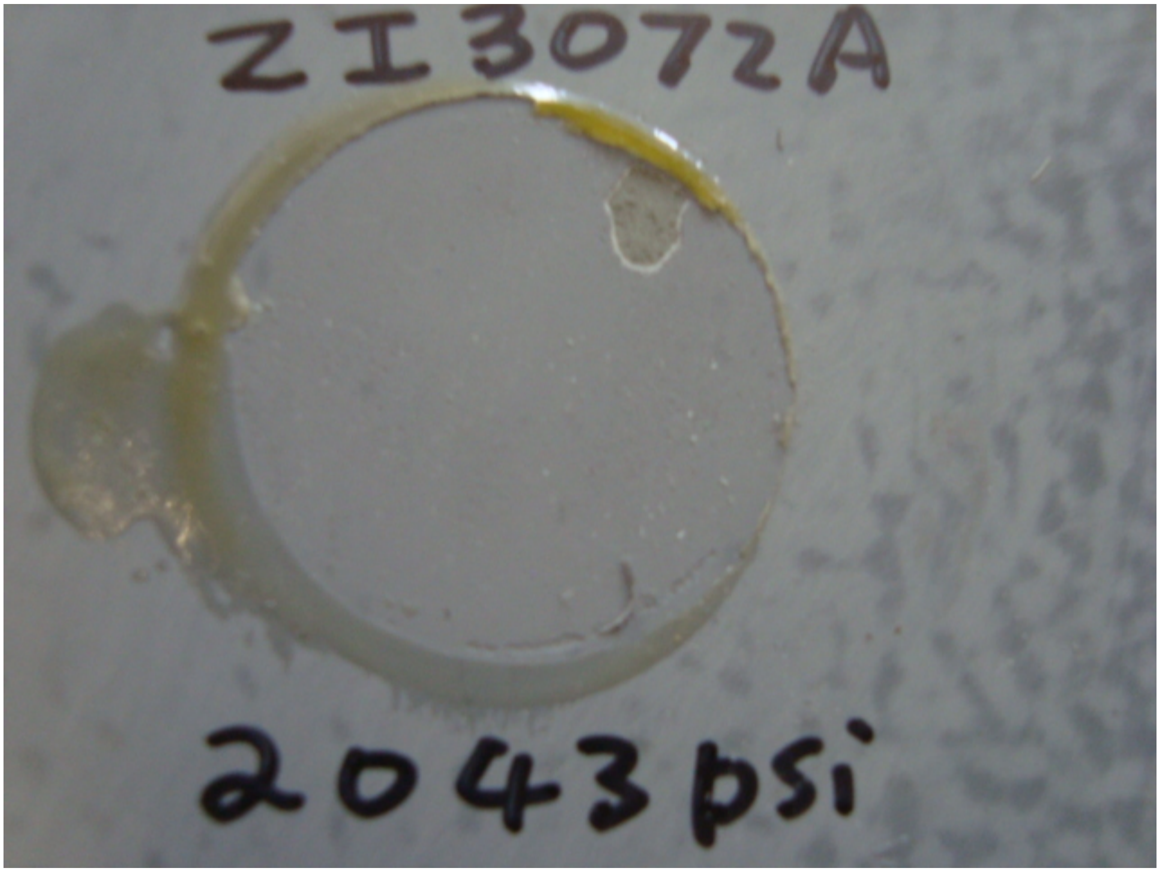
Panel 3072 Test 1; Paint Z-I

Pull-off strength 1492 psi

Break: 100% cohesive within Top

Dolly at left

5.b.3.2.2 Panel 3072, Paint Z-I, Test 2



Panel 3072 Test 2; Paint Z-I

Pull-off strength: 2043 psi

Break: 95% cohesive within Top; 5% adhesive between Zn-P and St

Dolly not photographed.

5.b.3.3 Panel #308

5.b.3.3.1 Panel 308 Z-I Test 1

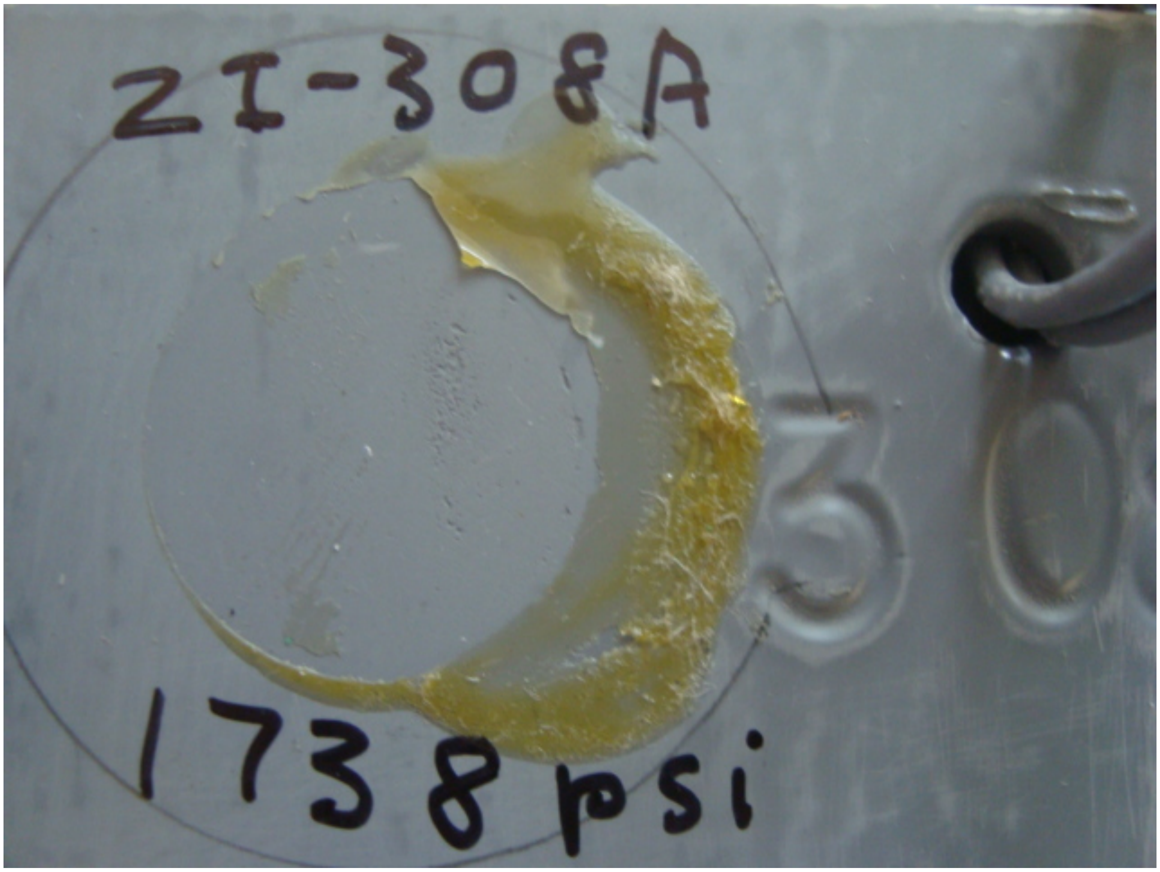
Panel 308, Test 1; Paint Z-I

Pull-off Strength: 1326 psi

Break: 100% cohesive within Top

Dolly at left

5.b.3.3.2 Panel 308 Z-I Test 2



Panel 308 Test 2, Paint Z-I

Pull-off strength: 1738 psi

Break: 95% adhesive between Glue and Top; 5% cohesive within Top

Dolly not photographed

5.b.3.4 Panel #3082

5.b.3.4.1 Panel 3082 Z-I, Test 1

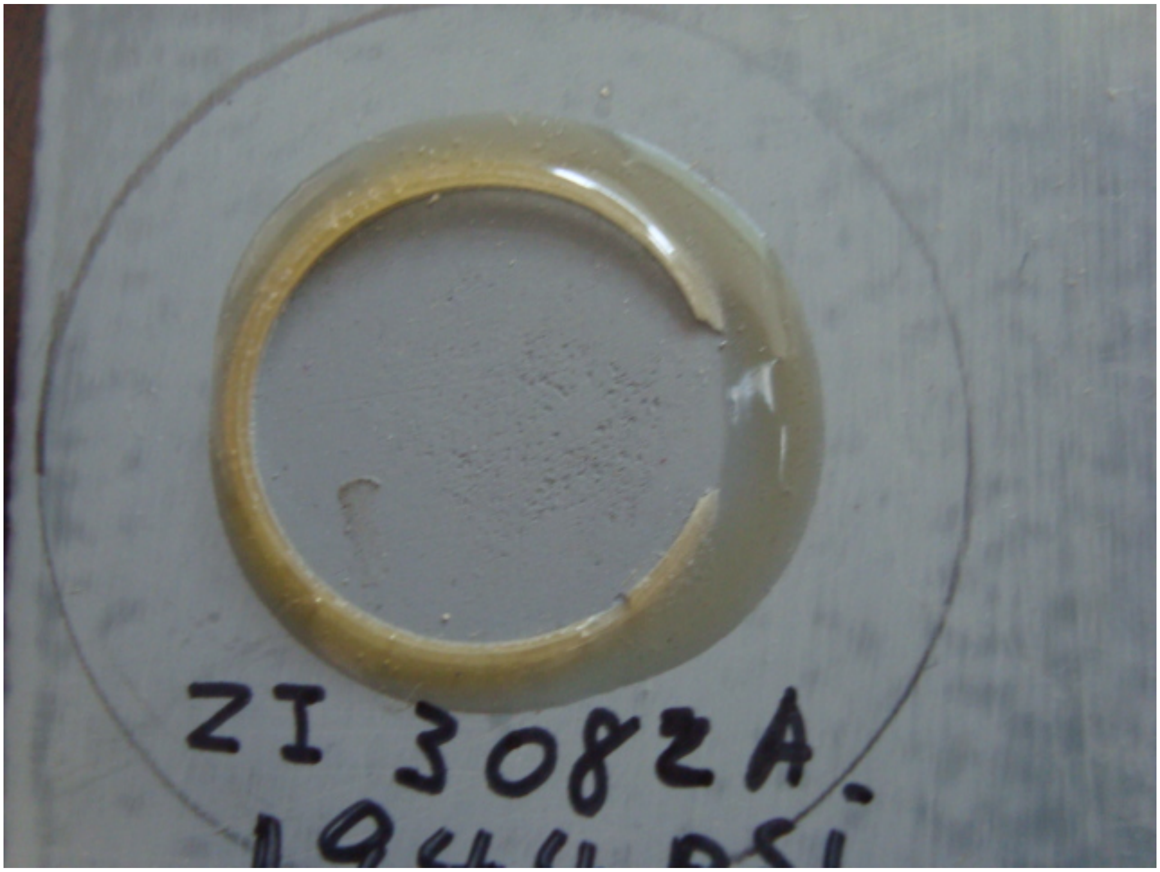
Panel 3052. Test 1, Paint Z-I

Pull-off Strength: 1817 psi

Break: 100% cohesive within Top

Dolly at upper left.

5.b.3.4.2 Panel 3082 Test 2 Z-I



Panel 3082 Z-I Test 2

Pull-off Strength: 1944 psi

Break: 100% cohesive within Top.

Dolly not photographed.

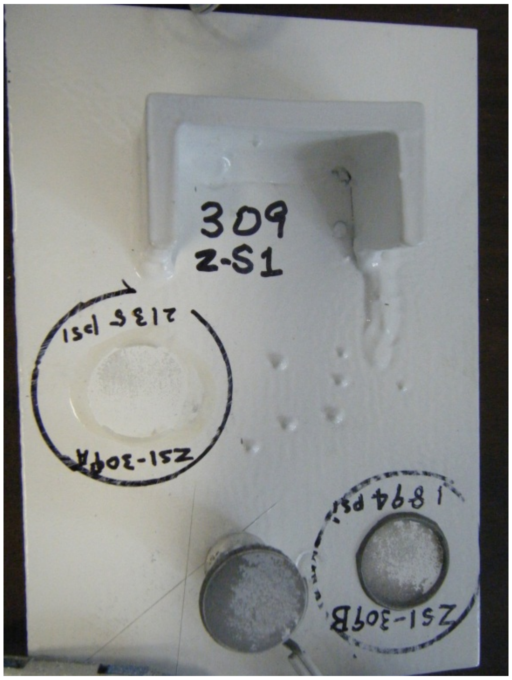
5.c.1 Test panels subgroup Z-S1

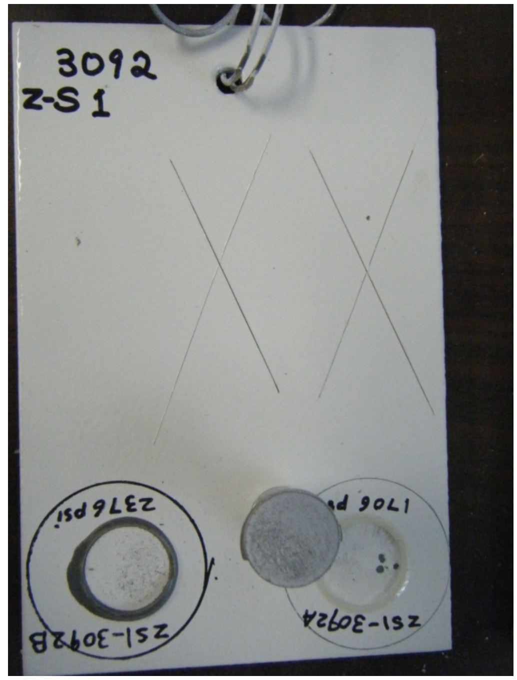
Primer: Zinc Clad III HS Organic Zinc Rich Epoxy Primer

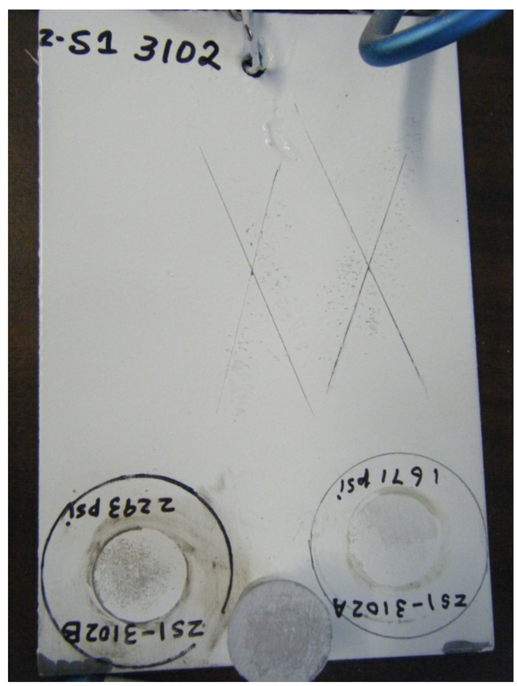
Intermediate: Macropoxy 646 Fast Cure Epoxy

Finish: Acrolon 218 HS Acrylic Polyurethane

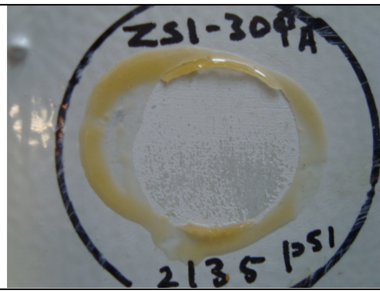
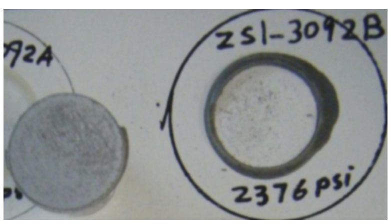
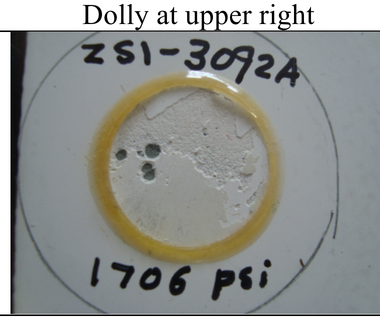
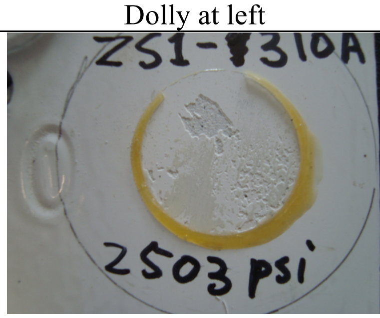
Test panels: ZS1 309, 3092, 310, 3102, in Box 20

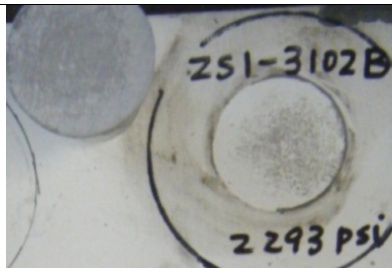




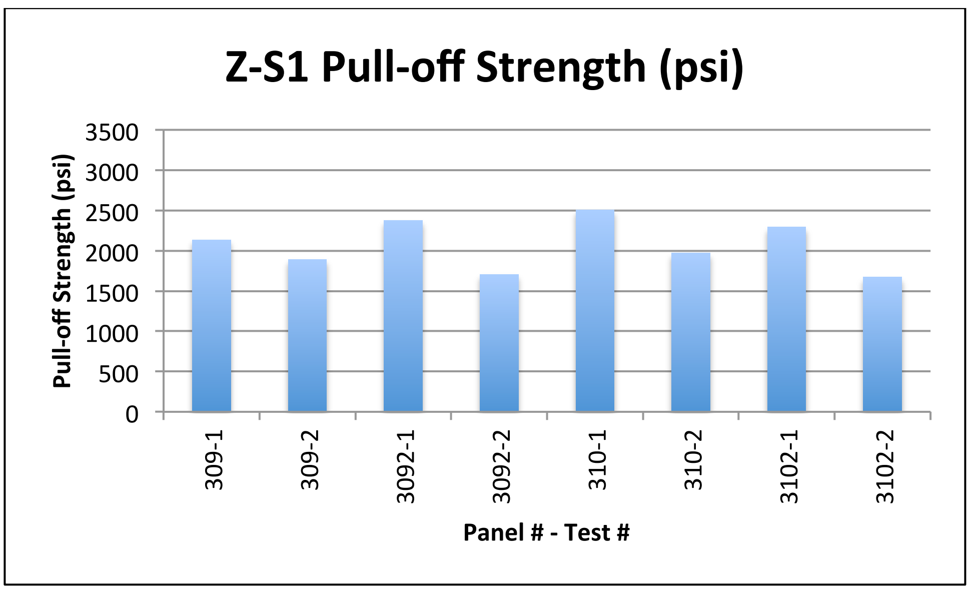


5.c.2 Adhesive strength Test results for Z-S1 test panels

<table>
<tr><td colspan="5">5.c.2 Adhesive strength Test results for Z-S1 test panels (Part I)</td></tr>
<tr><td>Test Pane</td><td>Pull Test 1</td><td>Pull Test 2</td><td>X-cut 1 Score</td><td>X-cut 2 Score</td></tr>
<tr><td rowspan="4">309</td><td>
</td><td>
</td><td rowspan="4">5</td><td rowspan="4">5</td></tr>
<tr><td>Strength: 2135 psi</td><td>Strength: 1894 psi</td></tr>
<tr><td>Break: 60% adhesive between Glue and Top ; 40% cohesive within Top;</td><td>Break: 70% cohesive within Top; 30% adhesive between Glue and Top</td></tr>
<tr><td>Dolly was not photographed</td><td>Dolly at upper right</td></tr>
<tr><td rowspan="4">3092</td><td>
</td><td>
</td><td rowspan="4">5</td><td rowspan="4">5</td></tr>
<tr><td>Strength: 2376 psi</td><td>Strength: 1706 psi</td></tr>
<tr><td>Break: 100% cohesive within Top</td><td>Break: 50% adhesive between Glue and Top; 45% cohesive within Top; 5% cohesive within Zn-P</td></tr>
<tr><td>Dolly at left</td><td>Dolly not photographed.</td></tr>
<tr><td rowspan="4">310</td><td>
</td><td>
</td><td rowspan="4">5</td><td rowspan="4">5</td></tr>
<tr><td>Strength: 2503 psi</td><td>Strength: 1972 psi</td></tr>
<tr><td>Break: 60% cohesive within Top; 40% adhesive between Glue and Top</td><td>Break: 90% cohesive within Top; 10% adhesive between Glue and Top</td></tr>
<tr><td>Dolly not photographed</td><td>Dolly at right</td></tr>
</table>

Test Pane	Pull Test 1	Pull Test 2	X-cut 1 Score	X-cut 2 Score
3102			4	4
	Strength: 2293 psi	Strength: 1671 psi		
	Break: 60% cohesive within Top; 40% adhesive between Glue and Top	Break: 60% adhesive between Glue and Top; 40% cohesive within Top.		
	Doly at upper left	Dolly not photographed		

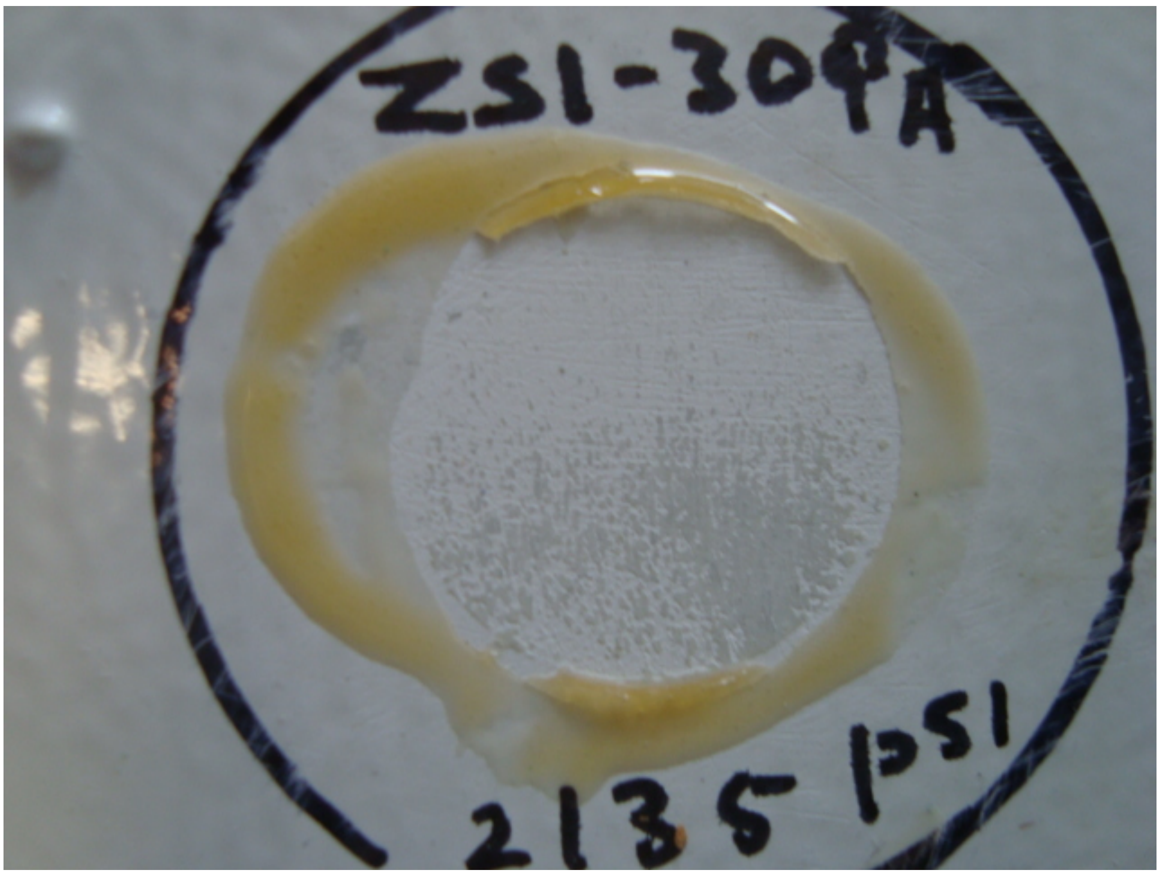
Pull-off Test	Z-S1
Panel#-Test#	Z-S1 Pull-off Strength (psi)
309-1	2135
309-2	1894
3092-1	2376
3092-2	1706
310-1	2503
310-2	1972
3102-1	2293
3102-2	1671
Average	2069
Stand Dev	289
Confidence	200



5.c.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

5.c.3.1 Panel #309, Paint Z-S1

5.c.3.1.1 Panel 309, Paint Z-S1, Test 1



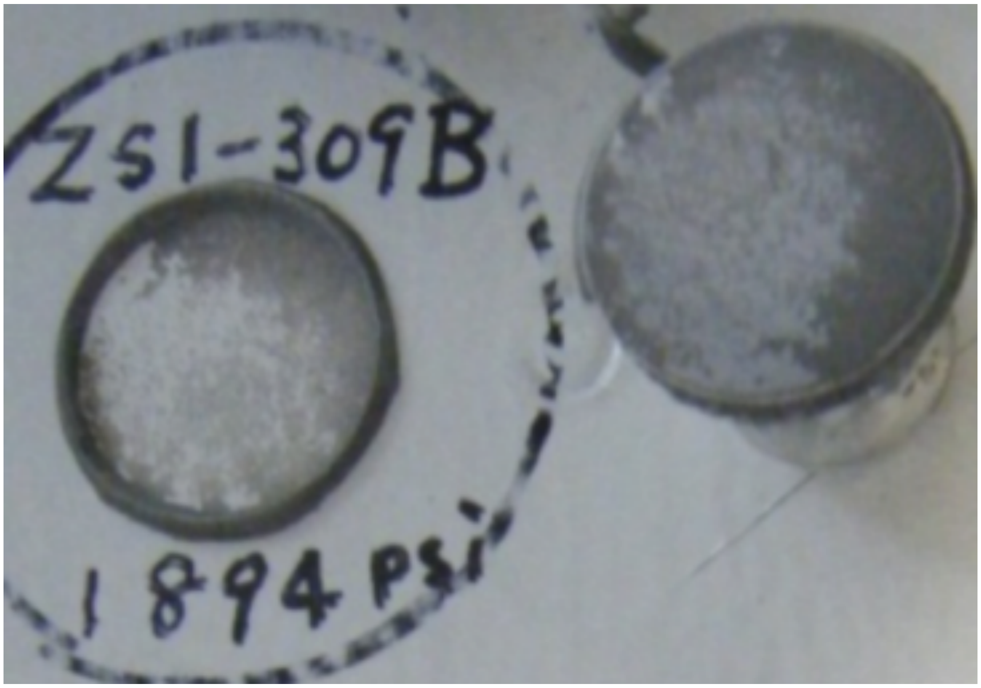
Panel 309 Test 1, Paint Z-S1

Pull-off Strength: 2135 psi

Break: 60% adhesive between Glue and Top ; 40% cohesive within Top;

Dolly not photographed.

5.c.3.1.2 Panel 309, Paint Z-S1, Test 2



Panel 390 Test 2, Paint Z-S1

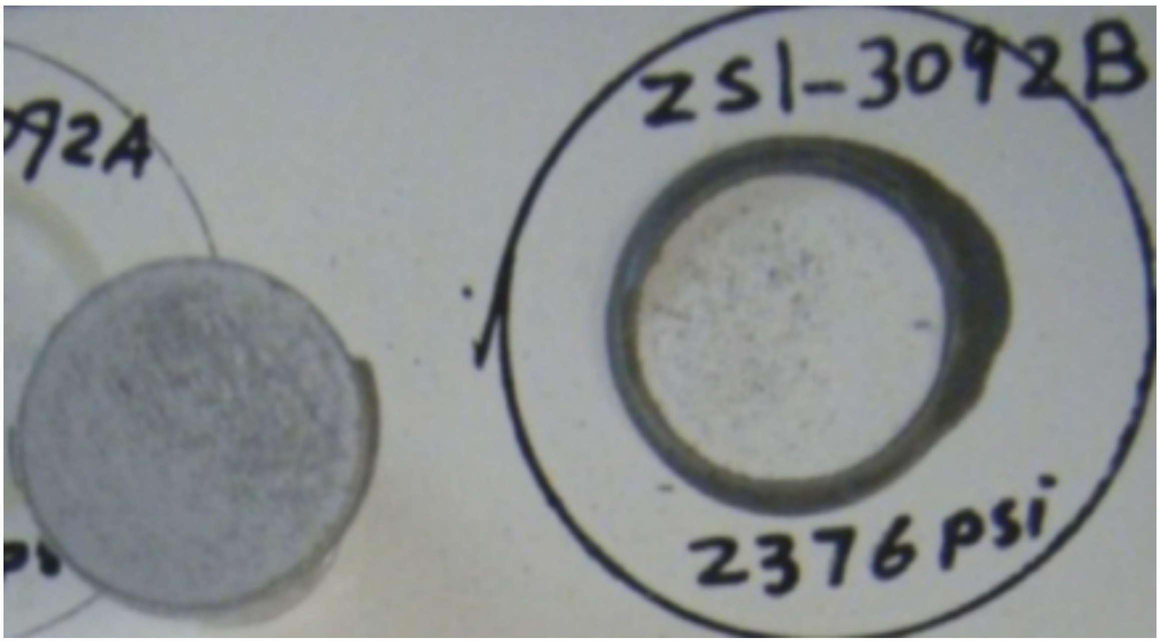
Pull-off Strength: 1894 psi

Break: 70% cohesive within Top; 30% adhesive between Glue and Top

Dolly at upper right

5.c.3.2 Panel #3092, Paint Z-S1

5.c.3.2.1 Panel 3092, Paint Z-S1, Test 1



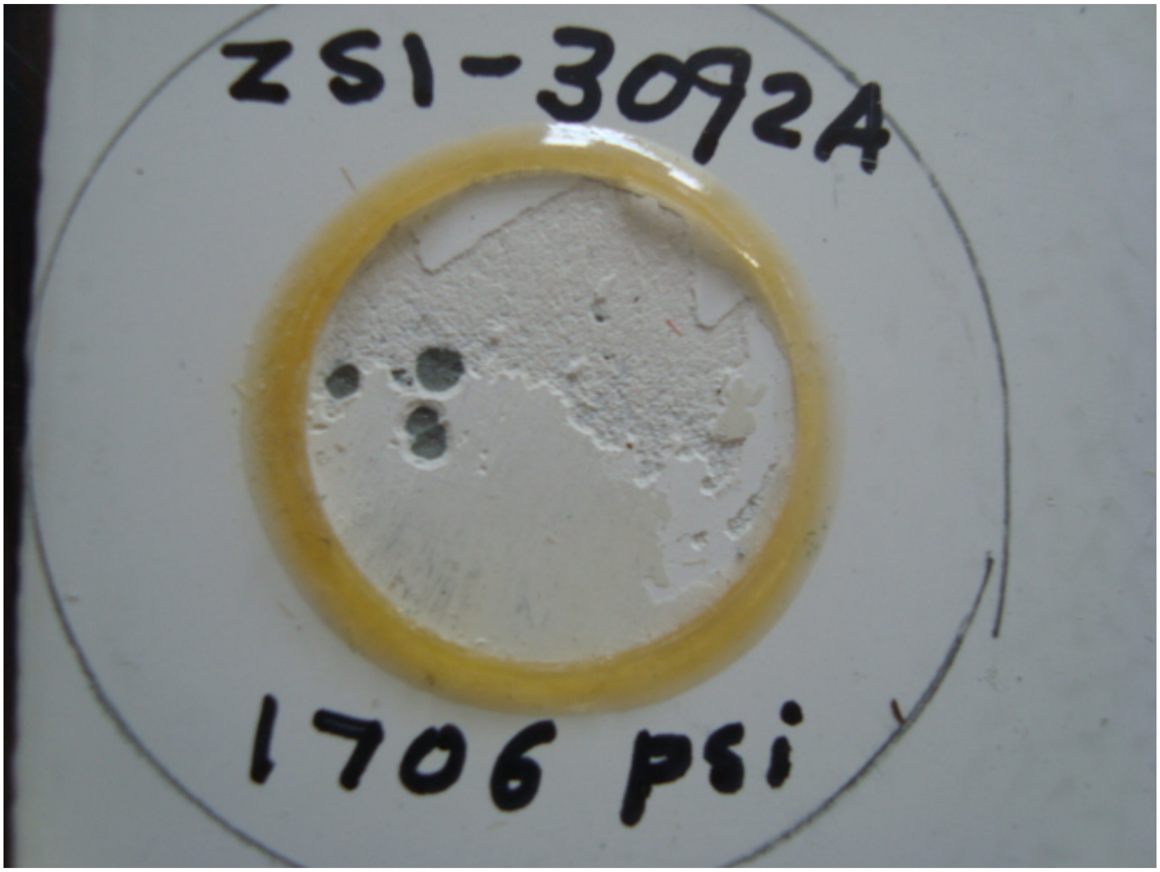
Panel 3092 Test 1; Paint Z-S1

Pull-off strength 2376 psi

Break: 100% cohesive within Top

Dolly at left

5.c.3.2.2 Panel 3092, Paint Z-S1, Test 2



Panel 3092 Test 2; Paint Z-S1

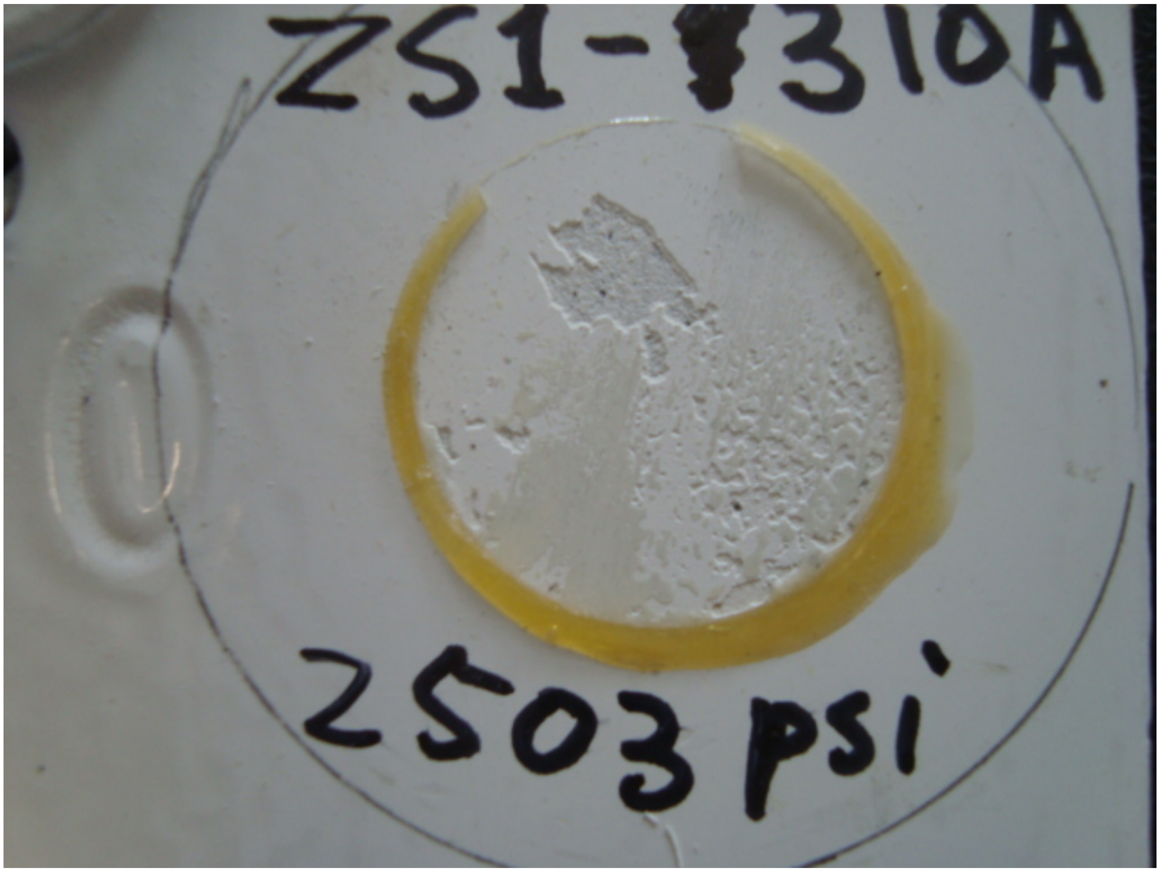
Pull-off strength: 1706 psi

Break: 50% adhesive between Glue and Top; 45% cohesive within Top; 5% cohesive within Zn-P

Dolly not photographed

5.c.3.3 Panel #310

5.c.3.3.1 Panel 310 Z-S1 Test 1



Panel 310, Test 1; Paint Z-S1

Pull-off Strength: 2503 psi

Break: 60% cohesive within Top; 40% adhesive between Glue and Top

Dolly not photographed.

5.c.3.3.2 Panel 310 Z-S1 Test 2

Panel 310 Test 2, Paint Z-S1

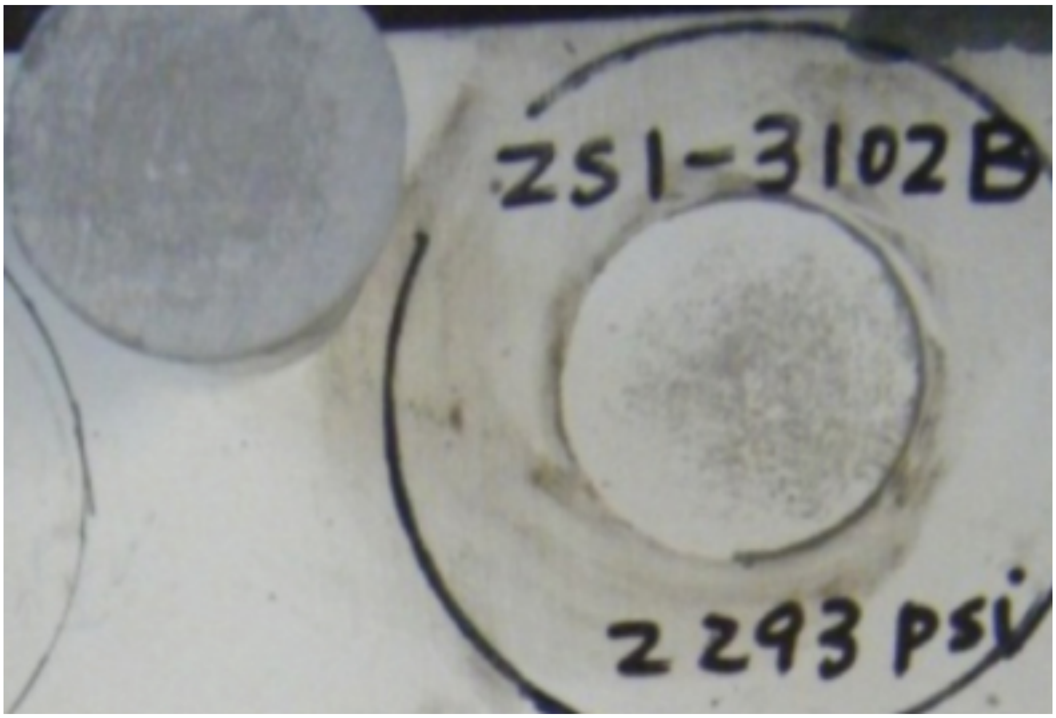
Pull-off strength: 1972 psi

Break: 90% cohesive within Top; 10% adhesive between Glue and Top

Dolly at right

5.c.3.4 Panel #3102

5.c.3.4.1 Panel 3102 Z-S1, Test 1



Panel 3102. Test 1, Paint Z-S1

Pull-off Strength: 2293 psi

Break: 60% cohesive within Top; 40% adhesive between Glue and Top

Dolly at upper left.

5.c.3.4.2 Panel 3102 Test 2 Z-S1

Panel 3102 Z-S1 Test 2

Pull-off Strength: 1671 psi

Break: 60% adhesive between Glue and Top; 40% cohesive within Top.

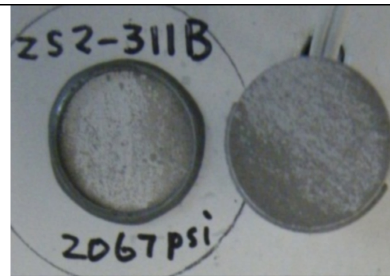
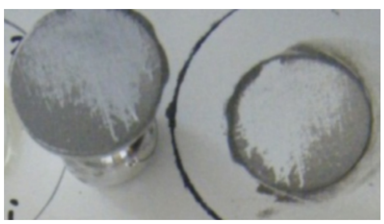
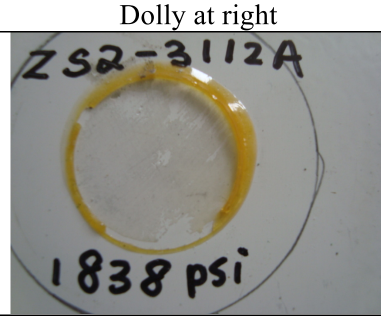
Dolly not photographed.

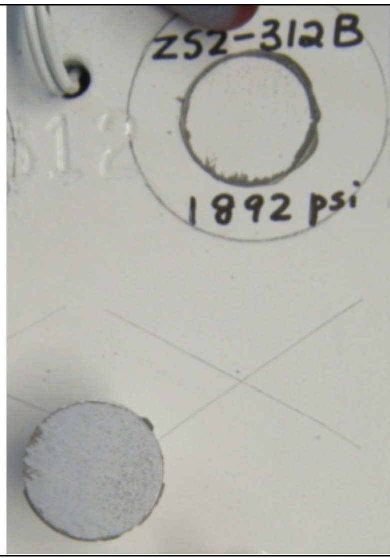
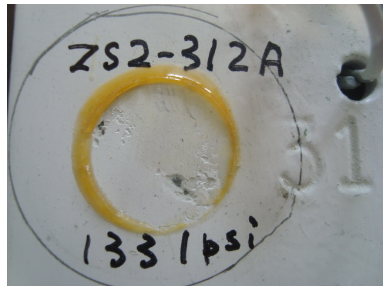
5.d.1 Test panels subgroup Z-S2

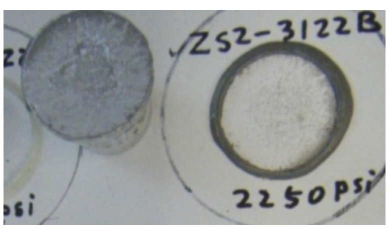
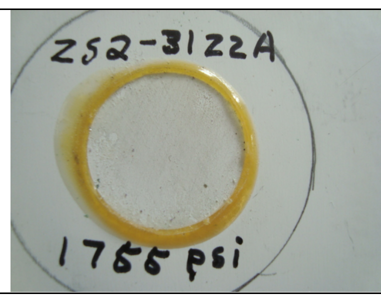
Primer: Zinc Clad III HS Organic Zinc Rich Epoxy Primer
Intermediate: Recoatable Epoxy Primer Series B67
Finish: High Solids Polyurethane Series B58
Test panel numbers: 311, 3112, 312, 3122, in Box 21

Note: Test spot at the lower left of plate ZS2-3112 failed at the adhesive joint between dally and the topcoat. Data for ZS2-3112B was not included in the ZS2 table for pull-off strength.

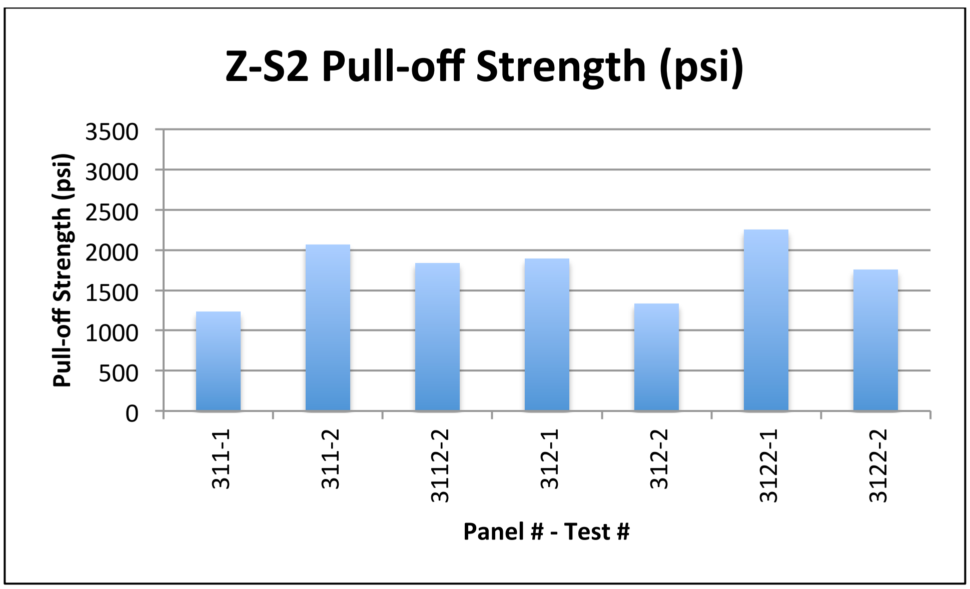
5.d.2 Adhesive strength Test results for Z-S2 test panels

<table>
<tr><td colspan="5">5.d.2 Adhesive strength Test results for Z-S2 test panels (Part I)</td></tr>
<tr><td>Test Pane</td><td>Pull Test 1</td><td>Pull Test 2</td><td>X-cut 1 Score</td><td>X-cut 2 Score</td></tr>
<tr><td rowspan="4">311</td><td>
</td><td>
</td><td rowspan="4">5</td><td rowspan="4">5</td></tr>
<tr><td>Strength: 1234 psi</td><td>Strength: 2067 psi</td></tr>
<tr><td>Break: 60% adhesive between Glue and Top ; 40% cohesive within Top;</td><td>Break: 70% cohesive within Top; 30% adhesive between Glue and Top</td></tr>
<tr><td>Dolly was not photographed</td><td>Dolly at right</td></tr>
<tr><td rowspan="4">3112</td><td></td><td>
</td><td rowspan="4">5</td><td rowspan="4">5</td></tr>
<tr><td>Strength: Not recorded</td><td>Strength: 1838 psi</td></tr>
<tr><td>Glue adhesion failed no pull-off strength was measured</td><td>Break: 100% cohesive within Top</td></tr>
<tr><td>Dolly at left</td><td>Dolly not photographed.</td></tr>
</table>

5.d.2 Adhesive strength Test results for Z-S2 test panels (Part II)				
Test Pane	Pull Test 1	Pull Test 2	X-cut 1 Score	X-cut 2 Score
312			5	5
	Strength: 1892 psi	Strength: 1331 psi		
	Break: 100% cohesive within Top	Break: 90% cohesive within Top; 10% adhesive between Top and Int		
	Dolly at lower left	Dolly not photographed		

Test Pane	Pull Test 1	Pull Test 2	X-cut 1 Score	X-cut 2 Score
3122			4	4
	Strength: 2250 psi	Strength: 1755 psi		
	Break: 70% cohesive within Top; 30% adhesive between Glue and Top	Break: 100% cohesive within Top		
	Doly at upper left	Dolly not photographed		

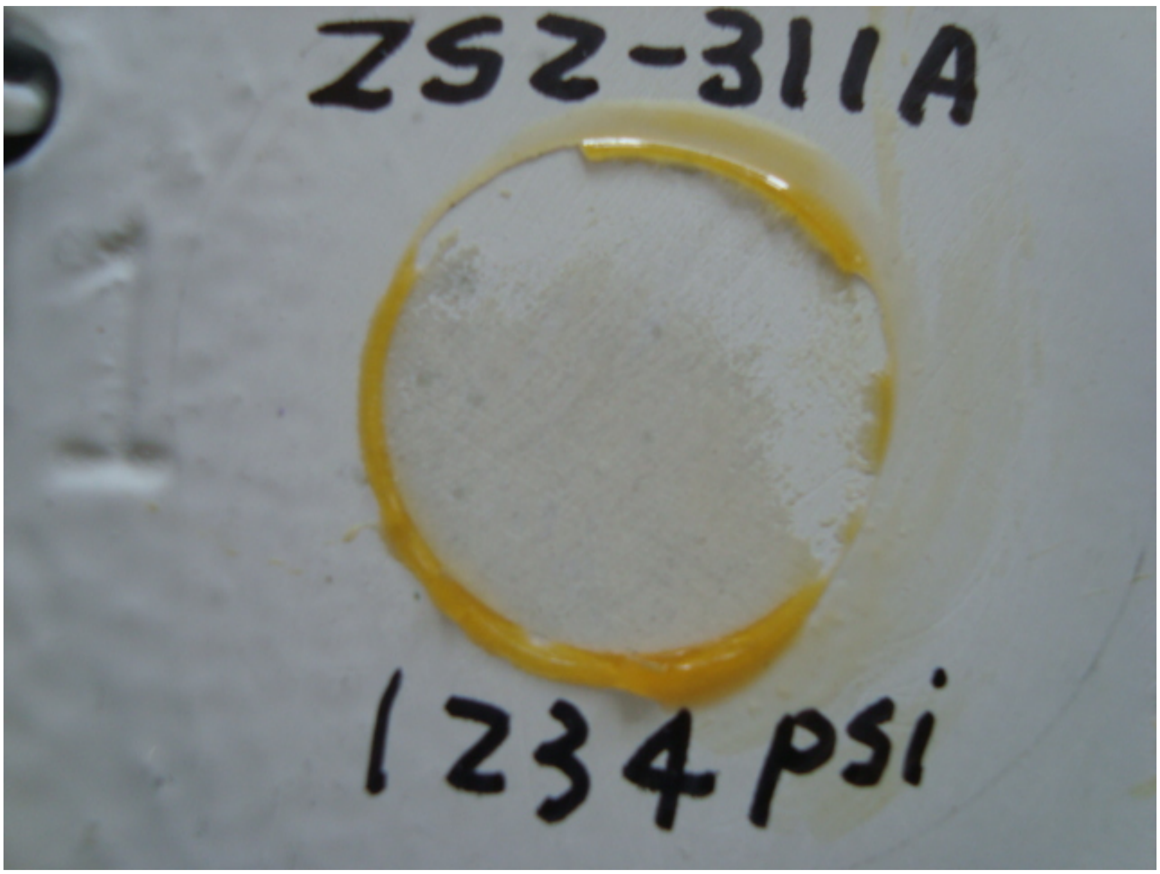
Pull-off Test	Z-S2
Panel #-Test #	Z-S2 Pull-off Strength (psi)
311-1	1234
311-2	2067
3112-2	1838
312-1	1892
312-2	1331
3122-1	2250
3122-2	1755
Average	1767
Stand Dev	342
Confidence	253



5.d.3 Enlarged photos of the pull-off dolly placed near the test spot on the panel, and a description of the break layers.

5.d.3.1 Panel #311, Paint Z-S2

5.d.3.1.1 Panel 311, Paint Z-S2, Test 1



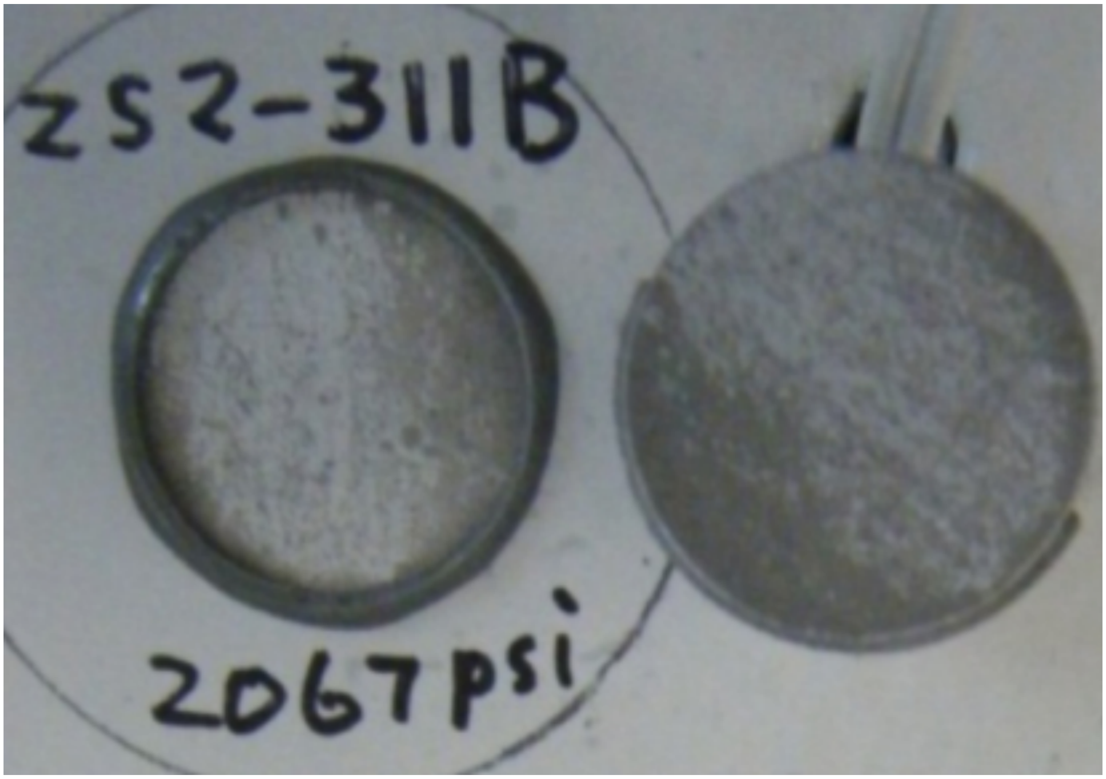
Panel 311 Test 1, Paint Z-S2

Pull-off Strength: 1234 psi

Break: 60% adhesive between Glue and Top ; 40% cohesive within Top;

Dolly not photographed.

5.d.3.1.2 Panel 311, Paint Z-S2, Test 2



Panel 311 Test 2, Paint Z-S2

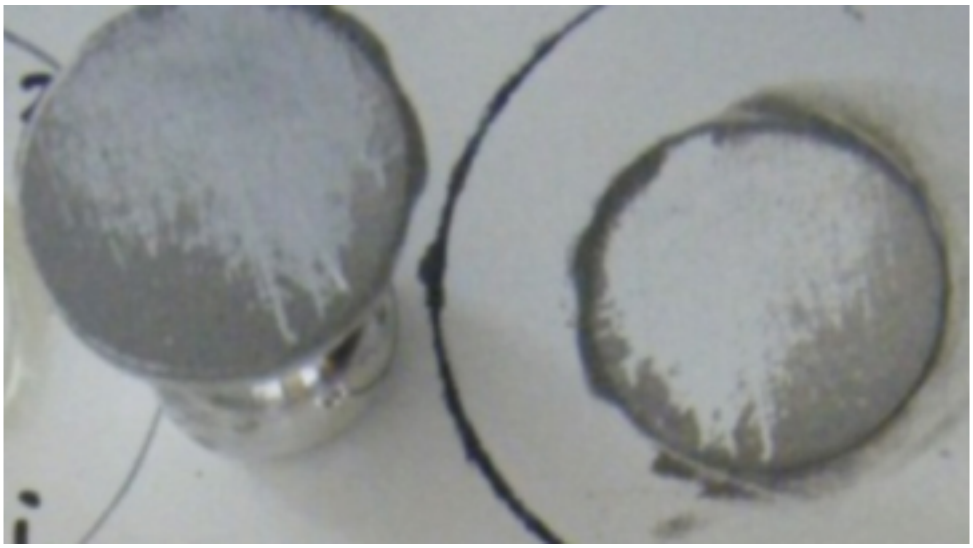
Pull-off Strength: 2067 psi

Break: 70% cohesive within Top; 30% adhesive between Glue and Top

Dolly at right

5.d.3.2 Panel #3112, Paint Z-S2

5.d.3.2.1 Panel 3112, Paint Z-S2, Test 1

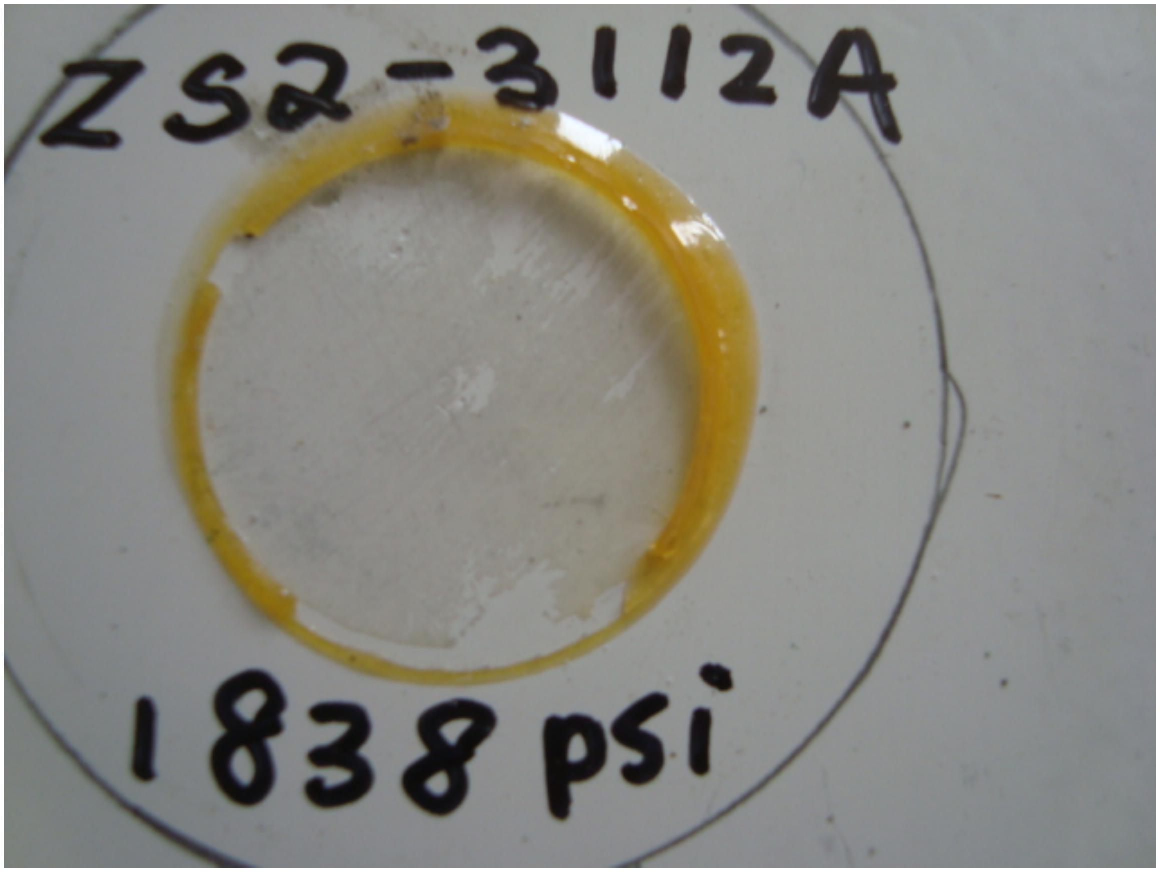


Panel 3112 Test 1; Paint Z-S2

Glue adhesion failed no pull-off strength was measured.

Dolly at left

5.d.3.2.2 Panel 3112, Paint Z-S2, Test 2



Panel 3112 Test 2; Paint Z-S2

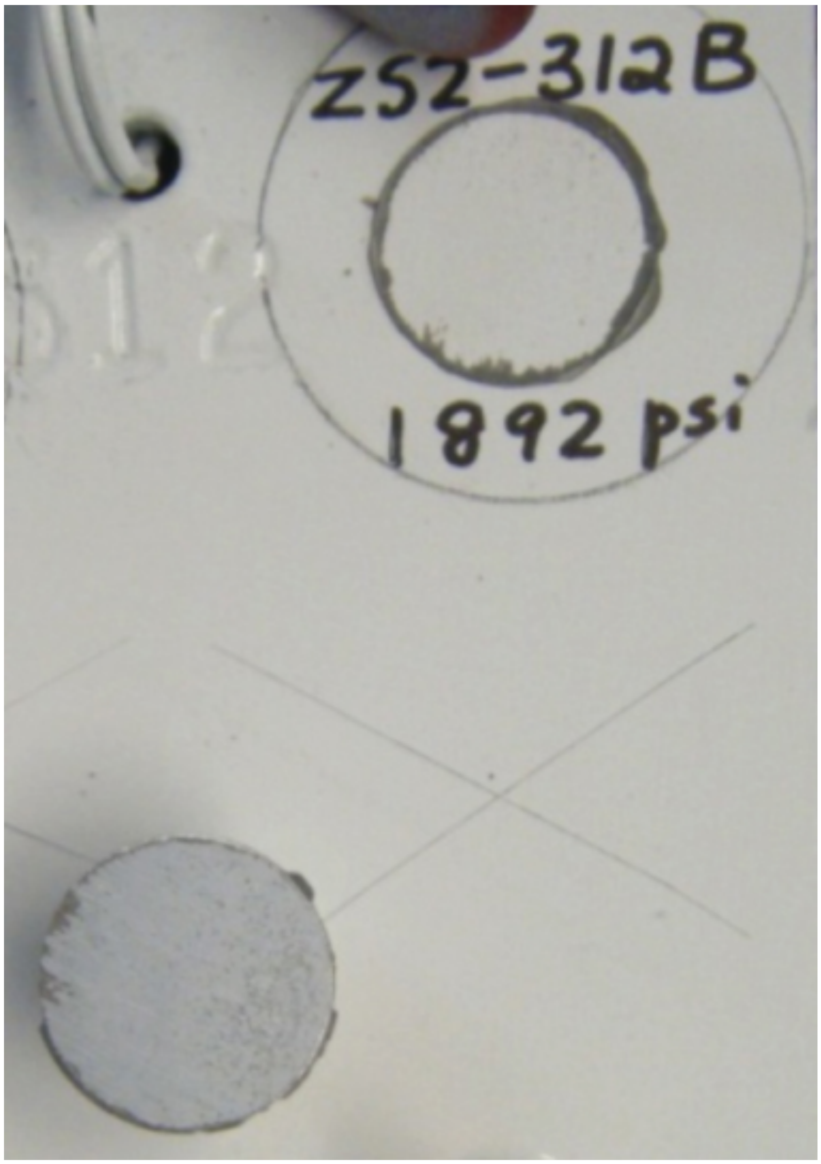
Pull-off strength: 1838 psi

Break: 100% cohesive within Top

Dolly not photographed

5.d.3.3 Panel #312

5.d.3.3.1 Panel 312 Z-S2 Test 1



Panel 312, Test 1; Paint Z-S2

Pull-off Strength: 1892 psi

Break: 100% cohesive within Top

Dolly at lower left

5.d.3.3.2 Panel 312 Z-S2 Test 2

Panel 312 Test 2, Paint Z-S2

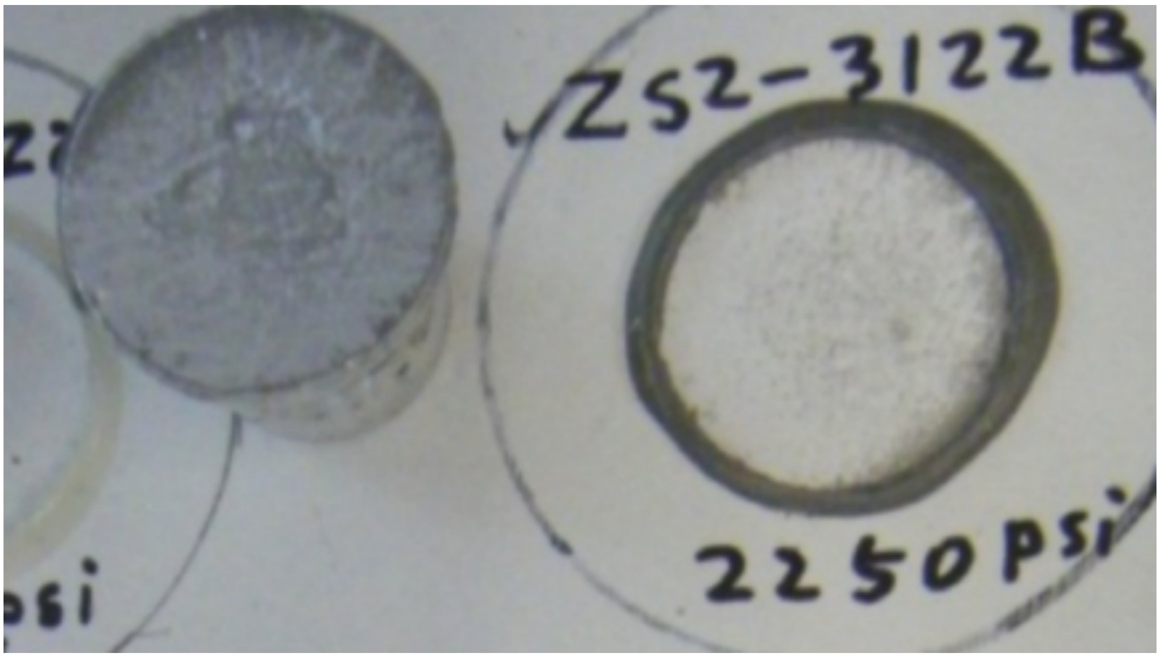
Pull-off strength: 1331 psi

Break: 90% cohesive within Top; 10% adhesive between Top and Int

Dolly not photographed

5.d.3.4 Panel #3122

5.d.3.4.1 Panel 3122 Z-S2, Test 1



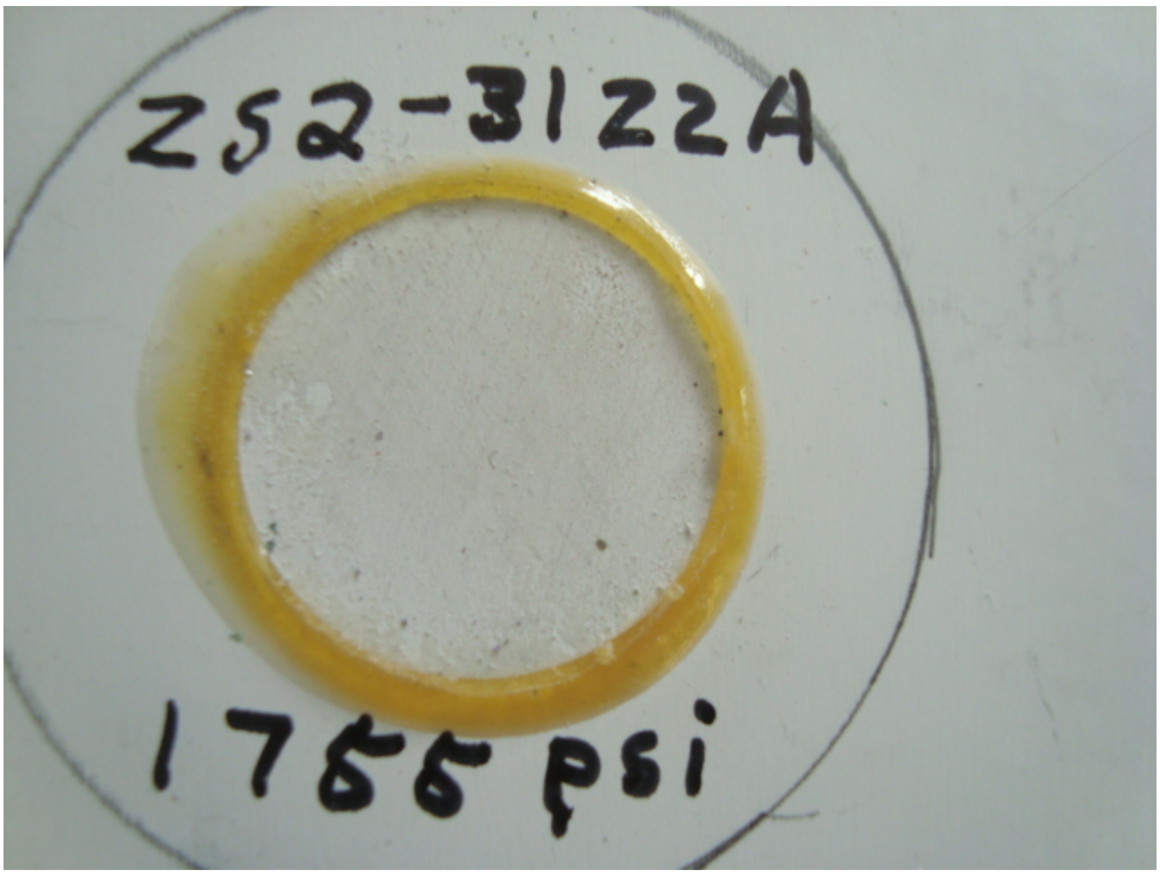
Panel 3122. Test 1, Paint Z-S2

Pull-off Strength: 2250 psi

Break: 70% cohesive within Top; 30% adhesive between Glue and Top

Dolly at upper left.

5.d.3.4.2 Panel 3122 Test 2 Z-S2



Panel 3122 Z-S2 Test 2

Pull-off Strength: 1755 psi

Break: 100% cohesive within Top

Dolly not photographed.

5.e Test panels subgroup Z-S3

This set of panels was not fabricated because we anticipate very thin dried film thickness of S3 on either the white blasted steel surface or on a cured zinc-rich primer.

S3 (Macropoxy 920) is a low viscosity epoxy penetrating sealant. The product data sheet from the paint manufacturer (Sherwin Williams) indicates its use as a sealer (per-primer) for tight rusted steel surface or for porous concrete surfaces. A Sherwin Williams representative recommended us to use as both a sealant and primer for metallized surface but did not recommend the use on either white blasted steel or as an intermediate paint on a zinc-rich primer. Although S3 can spread and penetrate the porous channels within the metallized zinc layer, it is anticipated to be too thin on the white blasted steel surface due to its low viscosity.