Successful corrosion protection of steel depends on good adhesion of a coating to the substrate. Adhesion testing determines how well a coating is bonded to the substrate (i.e., whether it is anchored to the substrate itself or just to a thin layer of material on the surface of the steel).

There are various reasons for wanting to evaluate adhesion. The specifier and contractor would want to assess adhesion when considering or performing overcoating work because the new coating may act more like a paint stripper than a protective coating if adhesion of the existing coating system is poor. Another reason for testing adhesion is for bidding purposes. Knowing the adhesion of the existing coating will tell something about production rates that can be achieved. Adhesion is sometimes measured during application, as required by a specification. In addition, adhesion tests are performed by coating manufacturers when qualifying coating materials. Their test results are given in product data sheets.

The common adhesion tests are performed with a knife or a specialised pull-off adhesion tester. All adhesion tests are destructive, so the test area must be repaired. Therefore, it is best to keep the tests to a minimum. However, when adhesion testing is needed, it is important to know the different ways to perform the tests, precautions for each type of test, and what the results mean. These are the topics of this month’s Applicator Training Bulletin.

**Knife Test**

The simplest method of evaluating adhesion is to pick at the coating with a utility knife. This method has been used for many years, though no formal procedure currently exists. Two cuts are made in the coating to form the letter X, as shown in Fig. 1. The cuts are about 40 mm (1.5 in.) long, and the angle between them is 30–45 degrees. It is important to make sure the cuts go all the way to the steel. The knife blade is then used to pick at the intersection of the cuts with a vertical motion to try and lift the coating. If more than about 5 mm (0.2 in.) of material is removed, the adhesion is considered to be poor.

Another method is to insert the knife blade under the coating at the intersection of the X and push forward with the blade. When this is done with a sharp blade and a lot of pressure, a well-adhered coating may slice, but it will not disbond from the surface.

The knife adhesion test is subjective, and experience is the best teacher. It’s a good idea to run this test on all sorts of coatings, especially the ones that are going to be removed.

**Tape Test**

A more formal knife adhesion test is the tape test. The incisions are made the same as the knife test, but instead of picking at the coating, a piece of semi-transparent, pressure-sensitive tape is used. When this is done with a sharp blade and a lot of pressure, a well-adhered coating may slice, but it will not disbond from the surface. The edges of the cuts are completely smooth; none of the squares of the lattice is detached.

Small flakes of the coating are detached at intersections; less than 5% of the area is affected.

Small flakes of the coating are detached along edges and at intersections of cuts. The area affected is 5 to 15% of the lattice.

The coating has flaked along the edges and on parts of the squares. The area affected is 15 to 35% of the lattice.

Flaking and detachment worse than Grade 1

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**Table 1: Rating Scale for Tape Tests in ASTM D3359**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5A</td>
<td>No peeling or removal</td>
</tr>
<tr>
<td>4A</td>
<td>Trace peeling or removal along incisions or at their intersection</td>
</tr>
<tr>
<td>3A</td>
<td>Jagged removal along incisions up to 1.6 mm (1/16 in.) on either side</td>
</tr>
<tr>
<td>2A</td>
<td>Jagged removal along most of incisions up to 3.2 mm (1/8 in.) on either side</td>
</tr>
<tr>
<td>1A</td>
<td>Removal from most of the area of the X under the tape</td>
</tr>
<tr>
<td>0A</td>
<td>Removal beyond the area of the X</td>
</tr>
<tr>
<td>5B</td>
<td>The edges of the cuts are completely smooth; none of the squares of the lattice is detached.</td>
</tr>
<tr>
<td>4B</td>
<td>Small flakes of the coating are detached at intersections; less than 5% of the area is affected.</td>
</tr>
<tr>
<td>3B</td>
<td>Small flakes of the coating are detached along edges and at intersections of cuts. The area affected is 5 to 15% of the lattice.</td>
</tr>
<tr>
<td>2B</td>
<td>The coating has flaked along the edges and on parts of the squares. The area affected is 15 to 35% of the lattice.</td>
</tr>
<tr>
<td>1B</td>
<td>The coating has flaked along the edges of cuts in large ribbons and whole squares have detached. The area affected is 35 to 65% of the lattice.</td>
</tr>
<tr>
<td>0B</td>
<td>Flaking and detachment worse than Grade 1</td>
</tr>
</tbody>
</table>

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about 25 mm (1 in.) wide is placed on the surface. Before making the incisions, you should clean the surface with water to remove any chalking or other loose material that could interfere with adhesion of the tape. It’s also a good idea to lightly roughen the surface with sandpaper and to wipe it clean to assure good adhesion of the tape. Finally, make sure the surface is dry before running the test.

Remove several laps of tape from the roll when you begin, and then cut off a piece about 75 mm (3 in.) long. Place the centre of the piece of tape at the intersection of the cuts, with the tape running in the same direction as the smaller angles. Smooth the tape into place with a finger and then rub firmly with a pencil eraser. A uniform colour apparent through the tape is a good indication that proper contact has been made.

Remove the tape within 1–2 minutes by grabbing one end and pulling it off rapidly as close to an angle of 180 degrees as possible. Table 1 shows the rating scale from ASTM D3359, Standard Test Methods for Measuring Adhesion by Tape Test, which includes the details of the test procedure.

A number of factors can affect the results obtained. The first is the cut. It must be made with a sharp blade held perpendicular to the surface. It is good practice to replace the blade every 10 tests. If the blade is not perfectly perpendicular, small amounts of coating may be removed, depending on the brittleness of the coating. A rating of 4A or even 3A can be obtained from an otherwise well-adhered coating just by cutting incorrectly. The tape used also can have an effect on the results. Tapes do not have uniform adhesion from roll to roll, and bond strength may change over time. Nevertheless, the X-cut tape test is simple to perform and does not require expensive equipment.

A rating of 3A is the lowest acceptable for a new coating system. (A new coating should actually be 4A or better.) For overcoating work, the existing system should have a rating of 2A or better. A rating of 1A may be acceptable for applying a thin-film, low-stress overcoating system. A 0A rating indicates a coating that should not be overcoated.

Another tape test method uses a cross-hatch pattern rather than the X pattern. If the coating is less than 50 µm (2 mils) thick, 11 parallel cuts are made 1 mm apart, and then 11 more cuts are made at 90 degrees to the first set. If the coating is between 50 µm (2 mils) and 125 µm (5 mils) thick, six sets of cuts are made in a similar manner but 2 mm apart (Fig. 2). A cutting guide or a special cross-hatch cutter with multiple preset blades is needed to make sure the incisions are properly spaced and parallel. The tape is applied and pulled off in the same manner as for the X-cut test. Table 1 shows the rating scale for this method as well. This cutting pattern is not considered suitable for films thicker than 125 µm (5 mils).

A portable adhesion tester, loading fixtures, and adhesive are needed for this test. The first step is to prepare the loading fixtures. They are supplied as smooth steel and must be cleaned so the glue will stick. This usually involves solvent cleaning. It is a good idea to roughen the bonding surface of the loading fixture either with sandpaper or light abrasive blasting. This will minimise the number of glue failures that occur.

The coating surface must also be cleaned. Surface abrasions can induce flaws, so only fine sandpaper (400 grit or finer) should be used, if needed, to remove loose or weakly adherent contaminants such as chalking or dirt that cannot be washed off.

Epoxy or acrylic adhesives are used to glue the loading fixture in place. The adhesive must cure for the amount of time recommended by the manufacturer. This can be several hours to a day, depending on the adhesive and the temperature. Using other adhesive types such as cyanoacrylates that cure in a few minutes may not be acceptable because these materials may contain solvents that can attack the coating. Mix the adhesive and apply it to the base of the loading fixture, making sure a continuous film covers the entire surface. A critical step in the test procedure is positioning the fixture onto the surface. Avoid any movement, especially twisting, that can result in stress dislocation.
continuities during the pull testing. Wipe away any excess adhesive with a cotton swab once the test fixture is in place.

It is important that constant contact pressure be maintained as the adhesive sets and begins to cure. Magnetic or mechanical clamps work best. For pull-off adhesion testing, at least three test fixtures per test area are normally required. The number of areas being tested will determine how many fixtures and clamps are needed. The fixtures can be taped in place with masking tape or duct tape if enough clamps are not available. However, tape can relax with time and allow air to get between the fixture and the test area. Thus, at least three pieces of tape across the top of the fixture in different directions should be used (Fig. 4). Also, it is important to space the fixtures far enough apart so the loading device can be properly positioned when the pull is performed.

There are two main types of commonly used adhesion testers. One is a fixed-alignment, mechanical adhesion tester; the other is a fixed-alignment, pneumatic adhesion tester. These instruments come in different force ranges, so the proper range instrument must be selected.

Now comes the next critical step in the procedure—connecting the loading fixture to the central grip of the tester (sometimes called the detaching assembly). Remove the clamping device or tape. Then follow the manufacturer’s instructions for attaching the tester to the loading fixture, making sure not to bump, hit, bend, or otherwise apply any load to the fixture that will knock it off the vertical.

If the test is being performed on any other surface than a horizontal one (e.g., a vertical web or the underside of a flange), the tester must be supported so its weight does not contribute to the force exerted.

Once the fixture is attached to the instrument, it is time to run the test (Fig. 5). Again, review the manufacturer’s instructions on how this should be done. No matter what instrument is being used, the load to the fixture should be increased continuously and smoothly at a rate not to exceed 1 MPa/s (145 psi/s). Keep applying the load until failure occurs (or until the maximum force has been applied). Any test fixtures that do not detach with the maximum load can be easily removed by tapping them on their side. In fact, this is a good demonstration of how easily the test fixtures can be removed in shear compared to the tensile failure mode of the actual test. Also, make sure you have a firm grip on the loading device, because coatings with high tensile strength can cause the loading device to rebound when the break occurs.

Some instruments come supplied with a circular hole cutter to score through the coating to the substrate around the loading fixture before running the test. Scoring around the fixture violates the fundamental criterion of the test that an unaltered coating be tested. However, the practice is a subject of debate among some adhesion test experts. Therefore, if scoring is required for some reason, be very careful to prevent micro-cracks in the coating because they will give lower pull-off strengths. The hole cutter must be held perpendicular to the surface so that no sideways pressure is placed on the test fixture.


Test Results

Two pieces of information are obtained from a pull-off test. The first is the pull-off strength of the coating. Record the force attained at failure (or the maximum force applied if the test fixture did not disbond). If required by the manufacturer, a calibration conversion chart is used to convert the force reading on the instrument to the actual force applied. If the manufacturer does not require the use of such a chart, then the actual applied force is read directly from the instrument. In either case, the force then must be divided by the surface area of the test fixture to determine the pull-off strength. The test fixtures are circular, so the surface area is $\pi r^2$, where $\pi$ is 3.14 and $r$ is the radius of the test fixture. Some instruments use only one size test fixture, so the instrument scale is already in MPa (psi). Consult the operation manual for the instrument.

The other piece of information is where the split occurs in the coating system. Examine the bottom of the test fixture and the surface where the test was performed. The split could be an adhesive break, a cohesive break, a combination of both, or a failure of the glue. An adhesive failure is a break between coating layers or between the coating and the substrate. If the break occurs between coating layers of a multi-colour coating system, one colour coating will be on

Continued
the back of the test fixture and another colour coating will be on the surface. A cohesive failure is a break within one coating layer, so the colours will be the same. Estimate the percentage of adhesive and cohesive failures. Also, report where these failures occurred in the coating system (i.e., adhesive failure between the steel and primer; adhesive failure between the primer and midcoat; cohesive failure within the primer; glue failure, etc.). Information about the location of the break in the coating system is just as important, if not more important, than the pull-off strength. It identifies the weakest area in the coating system.

Expect to get a number of glue failures until you’ve gained some experience in running the test. When a glue failure occurs, the only information gained is that the pull-off strength is greater than the value obtained. Don’t use results from glue failures in calculating the average of the tests performed in an area.

It’s always good practice to save the test fixture. Mark it so that it can later be identified with the field notes.

**Interpreting Test Results**

Interpreting the pull-off strength results must be done with caution. There is a large variability in the repeatability and reproducibility of the method, and different types of instruments give different results.

It is quite common to run three pulls at one area and get results such as 1.4 MPa (200 psi), 5.2 MPa (750 psi) and 5.5 MPa (800 psi). Comparing the first and last tests, the percent relative difference is 120%. (Percent relative difference is the difference of the readings divided by the average of those readings, multiplied by 100.) The first pull test would be considered suspect no matter which type of instrument was used, but the only valid reasons for discarding results when calculating the average are things such as known misalignment of the apparatus that was not normal (i.e., perpendicular) to the surface, poor definition of the area stressed due to improper application of the adhesive, poorly defined glue lines and boundaries, holidays in the adhesive caused by voids or inclusions, improperly prepared surfaces, and sliding or twisting of the test fixture during the initial adhesive cure. So the average adhesion for the example above would be 4.0 MPa (580 psi) if all the data were used and 5.4 MPa (775 psi) if there was a valid reason for discarding the first result.

Big differences in pull-off strengths also exist among instrument types. Looking at round-robin test results, one coating had an average pull-off strength of 4.04 MPa (586 psi) with the mechanical instrument and 8.00 MPa (1,160 psi) with the pneumatic instrument. Another coating had a pull-off strength of 6.12 MPa (888 psi) with the mechanical instrument and 11.57 MPa (1,680 psi) with the pneumatic instrument. In all cases, higher pull-off strengths were obtained with the pneumatic tester. Therefore, when comparing results, the type of instrument used to perform the test must be considered when looking at the tensile strength.

So, what is an adequate adhesion of a coating when using a pull-off adhesion tester? That is a difficult question to answer. It depends not only on the instrument used but also on the generic type of coating. Because of its good adhesive properties, an epoxy coating would be expected to have an inherently higher pull-off strength than an alkyd, for example. Information on acceptable pull-off strengths (and the type of instrument to use) would have to be obtained from the coating manufacturer.

If a specification or regulation calls for pull-off adhesion testing, the minimum acceptable pull-off strength and the type of instrument should be identified. Some manufacturers report pull-off adhesion test values for their coatings. Remember that these pull-off strengths generally refer to laboratory testing and not field testing.

This does not mean pull-off strength requirements do not exist in some contracts or regulations as a performance requirement. For example, a minimum pull-off strength of 1.4 MPa (200 psi) is required for coatings used in nuclear power plants in the USA. This value was developed when only the mechanical tester was available. Pull-off strength measurements are also used for failure analysis, where information about location of the break may be more important than the actual strength and where continuity of adhesion on the structure is being evaluated.

**Summary**

The two main types of adhesion tests are tape tests and pull-off tests. The tape test is easy to run, requires a minimum of equipment, gives immediate results, and is subjective. The pull-off test requires special equipment and time for the adhesive to cure, and it is objective, though there is a large variability among individual pulls and among the types of instruments used.

**Next month: Personal Hygiene and Skin Protection for Coating Applicators**