

**Review of Test Methods
for Coating Adhesion**

A S Maxwell

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A.S. Maxwell
NPL Materials Centre
National Physical Laboratory
Teddington
Middlesex
TW11 0LW

ABSTRACT

The following report summarises the results of a literature search and a series of industrial surveys that have been conducted to determine the current status of test methods for the measurement of coating adhesion. The review consists of: a list of test methods that have been identified from current scientific literature; a short description of the methodologies used in industry; a review of applicable standards; a summary of recent scientific reviews; and the results from two recent industrial surveys conducted by the National Physical Laboratory (NPL) and the National Institute of Standards and Technology (NIST) into current industrial practice.

Acknowledgements

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National Physical Laboratory
Teddington, Middlesex, TW11 0LW, UK

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Approved on behalf of Managing Director, NPL by Dr C Lea,
Head of the NPL Materials Centre

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1 Introduction

Surface coatings offer engineers the opportunity to modify the surface properties of a component, independently of the bulk properties. The development of a wide range of cost effective coating techniques [physical vapour deposition (PVD), chemical vapour deposition (CVD), thermal spray and electro-deposition] has opened up the use of coatings in a wide range of different industries. Indeed, today coatings are used in applications as diverse as machine tools, biomedical components, food processing equipment and optical systems. However, the over-riding criteria for all these applications is the same, the coating must adhere to the substrate. It is therefore clear that, in order to fully exploit the advantages that coatings can offer, it is essential to have suitable adhesion test methods to guarantee the quality users expect.

The following report is a summary of a series of literature searches and industrial surveys that have been conducted to determine the test methods that are currently available for measuring coating adhesion. The review includes the following:

- a list of adhesion test methods identified in the scientific literature (Section 2),
- descriptions of the methodologies used in industry (Section 3),
- review of applicable test standards (Section 4),
- summary of recent scientific reviews (Section 5),
- results from two recent surveys examining current industrial practice in the UK and USA coatings sector (Section 6).

2 Adhesion Test Methods

The following table lists the test methods that have been identified during a literature search and an industrial survey for measuring the fracture properties of coatings. Scientific literature was reviewed back to 1980 using the Metadex database. The industrial survey used to identify current test methods used in industry was conducted as part of a larger survey into current industrial practices in the coatings industry, details of which are given in Section 7 of this report.

Table 2.1 Adhesion Test Methods Identified in the Literature and their Current use in Industry (References are given in Section 8).

Adhesion Test Method	Literature Reference	Test used in industry
Abrasion test	38	
Acoustic emission scratch test	5	
Acoustic emission	1	
Acoustic microscopy	2	
Ball test	46	
Bend test	26, 38	Yes
Blister test	27, 51	
Buckled elastic film test	17	
Capacity test	38	

Cathodic Treatment	51	
Cavitation test	2	
Conical-head tensile test	56	
Continuous Microscratch test	19	
Double cantilever beam test	17	
Electrochemical impedance testing	3, 6, 25	
Electrochemical method	51	
Electron-beam technique	51	
Flyer Plate Techniques	52, 58	
Four point bending test	2	Yes
Hydraulic Adhesion Tester	31	
I-beam tests	58	
Impact test	2	
Indentation including Rockwell	2, 9, 10, 12, 23, 26, 37, 38, 53, 54	Yes
Knife and scribing tests	51	
Knife test	51	Yes
Laser shock wave technique	35	
Laser-acoustics	2	
Laser spallation test	38	
Laser ultrasound	46, 51	
Microindentation	47	
Modified peel test for thermally sprayed coatings	13	
Moment test	1	
Nanoindentation	55	
Nucleation test	38	
N-Methyl Pyrrolidone paint retention test	22	
Ollard Method	51	
Peel test	11, 21, 30, 33, 40, 51	Yes
Pressure-sensitive tape test	38	Yes
Pull method	21, 38, 40, 57	Yes
Ring Shear test	56	
Rutherford backscatter spectrometer	20	
Scratch test	2, 14, 16, 18, 21, 24, 26, 36, 37, 38, 39, 40, 41, 51	Yes
Shear test	1, 26, 51	
Stylus method	50, 51	
Tensile adhesion tests	18, 34, 42, 51	Yes
Tensile delamination using a bonded stud	26	
Thermal method	38	Yes
Torsion technique	45	
Ultracentrifuge test	38, 51	
Ultrasonic surface echo	6, 29	
X-ray diffraction	28, 38	

3 Description of Test Methods Used in Industry

This section of the report summarises the methodologies of the adhesion test methods obtained during a series of interviews conducted with technical staff in the coatings industry. It should be noted that these methodologies represent the current industrial practice of the interviewees and a not necessarily best practice.

3.1 Bend tests

Principle of technique

This technique involves bending the coated specimens and visually monitoring the damage caused to the coating (Figure 3.1). The extent to which the specimen is distorted depends upon the nature and thickness of the substrate and the coating. The test method is described in BS 5411: Part 10

Specimen type and preparation

The specimens should be machined into a form suitable for bending, these can be up to 3 meters long. No special preparation of the coating is required and the test can be performed on most types of coating.

Apparatus and Method

The specimen to be tested is bent over a mandrel, bending the specimens as sharply as possible from one side to the other until the coating fractures. This may be conducted manually using pliers or at a constant rate using automated machinery. Any sign of peeling, chipping or flaking is taken as indicating that the coating has failed due to poor adhesion. Visual inspection of the coating is normally undertaken when the coating is under tension with the coated layer on the outside of the bend. It is useful to record the rate and radius of curvature, the thickness of the specimen and coating, and any observed damage.

Application of the test

The bend test only gives qualitative results and is normally used for quality control purposes. The advantage of this test over similar techniques is that it is quick and simple and can be used by non-technical staff within a manufacturing environment.

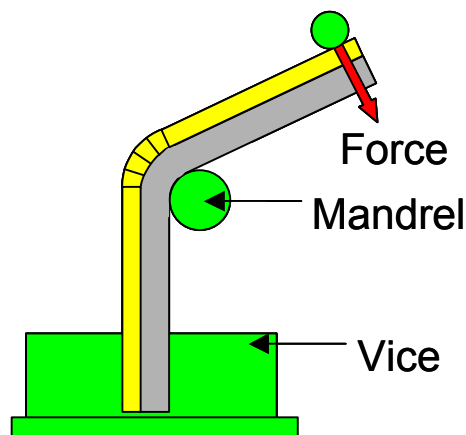


Figure 3.1 Schematic diagram of a simple bend test for coating adhesion.

3.2 Ball Cratering

Principles of the technique

A ball typically made of steel is rotated against the coated specimen with an abrasive slurry present in the contact area (Figure 3.2). This produces a wear scar in the shape of a spherical cap that can be used to gain information on interface sharpness, layer thickness and coating adhesion. Delamination of the coating around the crater indicates low adhesion. Samples can be flat, cylindrical or spherical. A British standard (DD ENV 1071-2:1994, Advanced technical ceramics, Determination of coating thickness by the cap grinding method) exists with a methodology for producing the wear scar.

Specimen type and preparation

Witness coupons, characteristically 25 × 15 mm, are used in this test. These are samples deliberately included in the coating process to provide samples for testing that have coatings representative of the actual deposited coating. These coupons are subsequently tested for quality control (QA) to avoid damage to actual parts. No special preparation or storage of the witness coupons is required.

Apparatus and method

Commercially available ball crater equipment is used. A 30 mm diameter steel ball, spun by contact with a drive shaft, is rotated against the clamped sample with a 0.25 µm diamond slurry abrasive dripped into the contact area. Loading is provided by the dead weight of the ball. Testing will typically take between 2 and 10 minutes depending on coating hardness and thickness. A different apparatus is available where the ball is fixed in the drive shaft and the sample loaded against it on a pivot. This has the advantage that load can be easily adjusted and, if instrumented, friction and wear rates recorded.

Applications of test

The ball crater test is primarily used to determine coating thickness. However, delamination around the crater is generally indicative of a low adhesion or brittle coating and will lead to further testing.

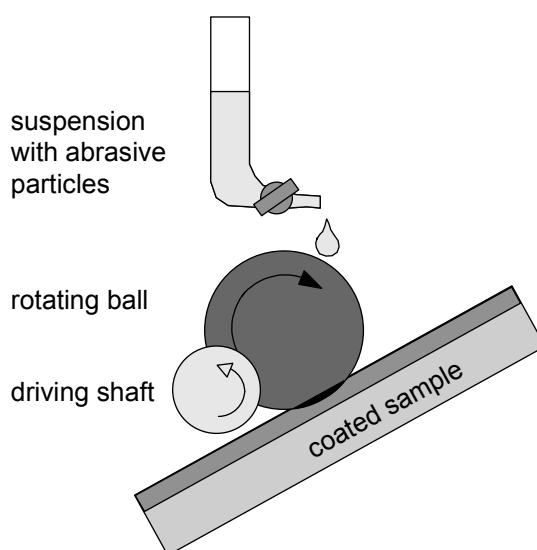


Figure 3.2 Schematic diagram of typical ball cratering apparatus.

3.3 Four-point bend

Principle of technique

This technique involves inducing a tensile strain in the coating using four-point bend and detecting damage caused to the coating using acoustic emissions monitoring (Figure 3.3).

Specimen type and preparation

Specimens are taken from a bulk component are machined to suitable dimensions to fit into the four-point bend jig, typically 100 mm long, 10 mm wide and 2 mm thick.

Apparatus and Method

Four-point bend jigs normally use rollers to provide the four points of contact, two rollers on top of the specimen typically 20 mm apart and two rollers underneath the specimen usually 40 or 60 mm apart. The rollers used on the jig should be covered with a smooth, low friction material to minimise acoustic emissions. The specimen must be correctly aligned within the jig so that it lies perpendicularly to the two sets of rollers, with the specimen positioned so that the tensile stresses are generated on the coated side of the specimen. Strain in the specimen is increased at a constant rate while acoustic emissions are monitored to detect failure events in the specimen. The strain should be increased up to a specified level or until a failure event is detected. At least three repeat tests should be conducted and the critical strain at failure determined.

Application of the test

The four-point bend test can give highly accurate quantitative values of adhesion strength. However, the technique does require skilled staff to correctly set-up the acoustic monitoring equipment. Furthermore, the technique will not detect failure events in materials where the acoustic emissions produced are too weak to be monitored.

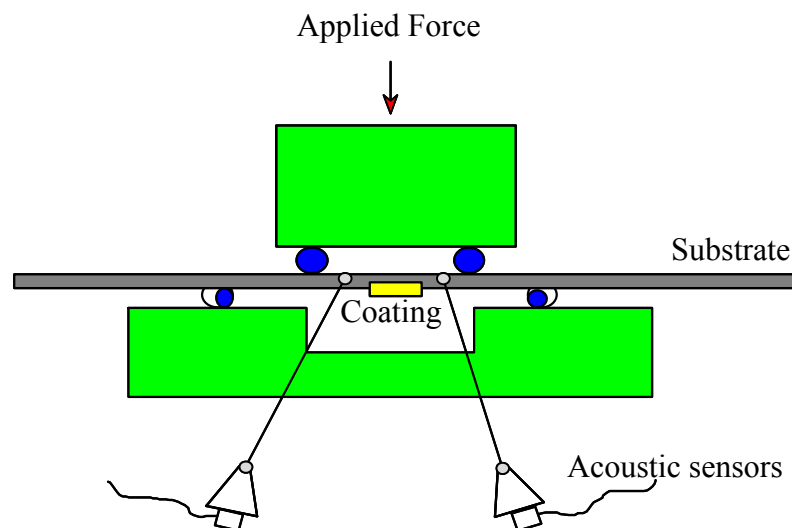


Figure 3.3 4-point-bend apparatus using acoustic sensors to detect the onset of damage in coatings.

3.4 Indentation (Rockwell)

Principle of technique

A Rockwell C indent is made on the coated sample (Figure 3.4). The fracture and delamination pattern around the indent can be used to rate the sample adhesion (Figure 3.5).

Specimen type and preparation

Witness coupons, typically 25×15 mm, are coated with the batch products. These coupons are subsequently tested for QA to avoid damage to actual parts. No special preparation or storage of the witness coupons is required.

Apparatus and method

A hardness tester using a Rockwell C diamond stylus with a 150 kg load is used to indent the sample. Light optical microscopy is used to qualitatively rate the indent with comparison to a wall chart on a scale of 1 (high adhesion) to 6 (low adhesion). Repeat tests are conducted only if required.

Application of the test

The Rockwell test is a quick and simple test for quality assurance. The sample fails if the fracture pattern is rated greater than 4.

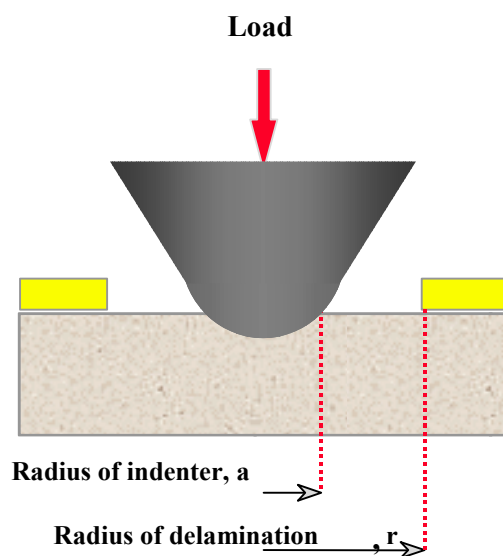


Figure 3.4 Schematic diagram of a Rockwell C indenter.

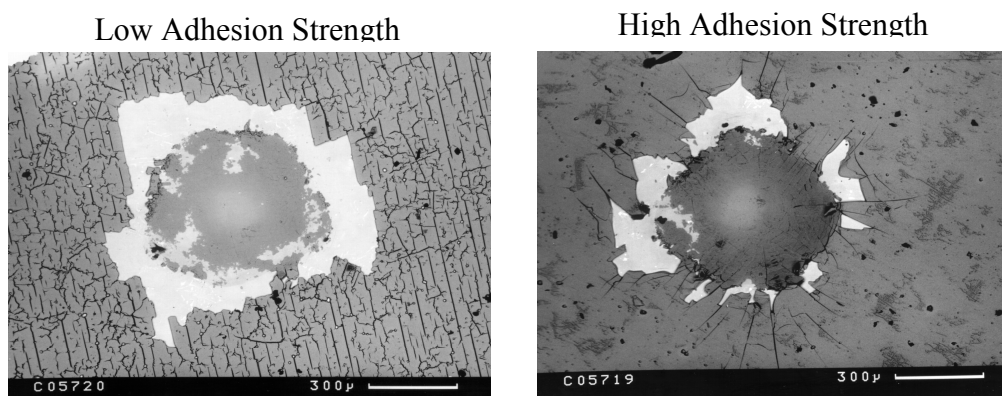


Figure 3.5 Rockwell indentations into MCrAlY coatings.

3.5 Knife test

Principle of technique

This technique involves measuring the force that is required to detach a coating from a substrate by drawing a loaded knife across the coating (Figure 3.6). This is similar to the scratch test, but is generally used for thicker softer coatings.

Specimen type and preparation

The specimens used are normally flat, although slightly curved surfaces can be used. This technique is most commonly used to examine thicker organic coatings (<1mm). Sampling should be conducted in accordance with BS 6001.

Apparatus and Method

The apparatus consists of a motorised plate on to which the specimen is clamped. The plate is then driven at a constant speed beneath a weighted knife to allow a defined width of the coating to be removed. The exact conditions depend upon the coating and its application and should be agreed with the customer prior to testing. The operator should record the speed, weight and rake angle of the knife and the width and depth of material removed. It is recommended that the test is repeated at least twice to obtain repeatable results. Commercial apparatus is available for carrying out these tests.

Application of the test

The results obtained from this technique are normally used simply for comparative purposes for the selection of new coatings and quality control. The knife test is quick and cheap but not suitable for in-situ applications.

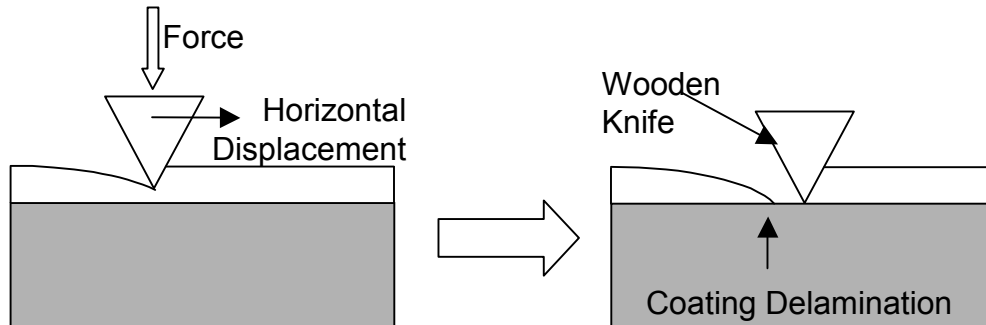


Figure 3.6 Illustration of the procedure used in the Knife test to assess coating adhesion.

3.6 Peel tests

Principle of technique

The peel test involves attaching a grip to the coating and peeling the coating away from the substrate. If a corner of the coating can be detached from the substrate the grip can be attached directly to the coating. However, a more common method of conducting this test is to attach a metal strip to the surface of the coating and to peel the coating off with the metal strip (Figure 3.7). A brief description of this test method is given in BS 5411: Part 10: 1981.

Specimen type and preparation

This test is suitable for coatings of less than 0.125 mm thick on substantially flat surfaces.

Apparatus and Method

A strip of mild steel or brass approximately $75 \times 10 \times 0.5$ mm is bent at right angles 10 mm from one end of the strip. The shorter limb of this strip is attached to the surface of the coating, either using adhesive or solder. A load is gradually applied to the free limb of the metal strip, normal to the surface of the coating. If the adhesion strength of the coating is weaker than the adhesive/solder the coating will detach. If the adhesion strength of the coating is greater the adhesive/solder will fail.

Application of the test

The peel test is a simple, reliable method of quantifying the adhesion of poorly adherent thin coatings. This test method will only establish whether the adhesion of a coating is adequate and does not provide quantitative values of adhesion suitable for design purposes.

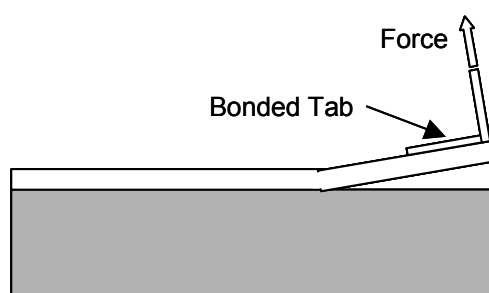


Figure 3.7 Illustration of the type of apparatus used in Peel tests.

3.7 Pressure-sensitive tape test

Principle of technique

A cross-hatch pattern is scored into the coating and a strip of pressure-sensitive tape applied to the scored area (Figure 3.8). The specimen is deemed to have passed if no coating is removed as the tape is peeled off the specimen. This test has recently been standardised in ASTM D3359-97.

Specimen type and preparation

Principally used for examining thin organic/polymeric coatings. The type of specimen that can be examined is limited as the adhesive strength of the tape must be greater than that of the coating. The test is not considered to be suitable for films thicker than 0.125 mm.

Apparatus and Method

A sharp knife, a cutting guide and pressure-sensitive tape are required for this test. The surface of the coating is scored with the knife to form a cross with two parallel lines approximately 40 mm long and 15 mm apart in one direction and two identical lines scored at 90° to the first two. The adhesive tape is pressed on to the scored surface and rub down firmly with a pencil rubber. The tape is then removed as quickly as possible from the surface and visually examined to determine whether any of the coating is present on the tape. If any coating remains on the tape the coating is deemed to have failed the test. The ASTM standard contains a table to grade the type of damage observed. Two repeat test should be conducted to ensure repeatability.

Application of the test

This is a simple and cheap test used mainly by non-technical staff for quality control purposes. This test method will only establish whether the adhesion of a coating is adequate and does not provide quantitative values of adhesion strength. A more sophisticated form of this test is suggested in the ASTM standard for use in laboratories. However, from our survey it would appear that this alternative method is not in common use.

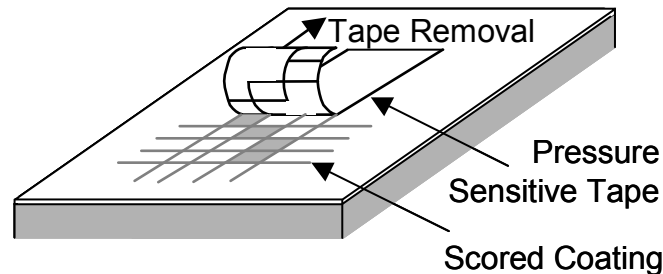


Figure 3.8 Schematic diagram of tape removal during the pressure-sensitive tape test.

3.8 Pull test method

Principle of technique

An aluminium dolly is attached to the coated surface using an epoxy adhesive. Tensile stresses are gradually applied to the dolly until the coating debonds from the substrate (Figure 3.9).

Specimen type and preparation

The coating to be examined is abraded with a medium grit paper. It is then cleaned with acetone and an aluminium dolly adhered to the surface using an epoxy adhesive. The dolly must be left in place for at least 8 hours prior to testing to allow the epoxy adhesive to dry. This method is unsuitable for curved surfaces or coatings that may react with the epoxy adhesive.

Apparatus

The apparatus for the pull test method consists of a main screw, which applies the tensile load to the dolly, a typical commercial instrument is the “Elcometer”. By gradually turning the screw it is possible to increase the loads that are applied to the dolly and hence the coating. A spring loaded balance in the instrument enables the loads applied to the coating to be measured. The whole apparatus is approximately 1 meter tall, which may prevent its use in restricted areas.

Method

The loading apparatus is attached to the dolly and the load increased at a constant rate. This is continued until the coating fails. One repeat test is sufficient to ensure that a coating has passed. One issue of concern with this test is whether lateral forces influence the results that are obtained. Some operators cut through the coating around the dolly before they conduct the tests to eliminate lateral forces. It is, however, unclear as to whether this procedure induces further damage.

Application of the test

The results from this test method are essentially quantitative. The technique is cheap and simple to use and may be used in-situ.

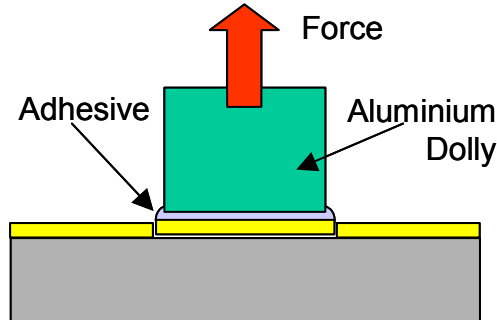


Figure 3.9 Schematic diagram of the pull-off test method using an aluminium dolly.

3.9 Scratch test

Principle of technique

A diamond stylus is loaded against the sample and then drawn across the surface to cause a scratch (Figure 3.10). The load applied to the stylus is either held constant or linearly increased. Scratches can be single or multipass. Damage patterns on the surface (Figure 3.11) are correlated with acoustic emission and friction forces to derive the critical loads at which various failure mechanisms occur.

Specimen type and preparation

Witness coupons, typically 25×15 mm, are coated with the batch products. These coupons are subsequently tested for quality assurance to avoid damage to actual parts. No special preparation or storage of the witness coupons is required.

Apparatus and Method

Commercially available scratch testing equipment is used. The stylus is cleaned in acetone before the test starts. A pre-load of 10 N is applied to the stylus before the scratching starts. The scratch covers a load range from 10 to 60 N, with load increasing at 100 Nmin^{-1} , and a horizontal displacement of 10 mm.min^{-1} . Load, displacement, acoustic emission and friction forces are recorded. The scratch is observed with light optical microscopy and values of critical load determined. There has been recent work in collaboration with NPL to provide a scratch test calibration procedure, draft standards and reference materials.

Application of the test

The scratch test is used for quality control and research. For quality control levels of friction and coating damage are set above which the coating will fail. The scratch test is relatively quick and simple to undertake, however care is needed when defining the damage type that is used to determine the critical load values.

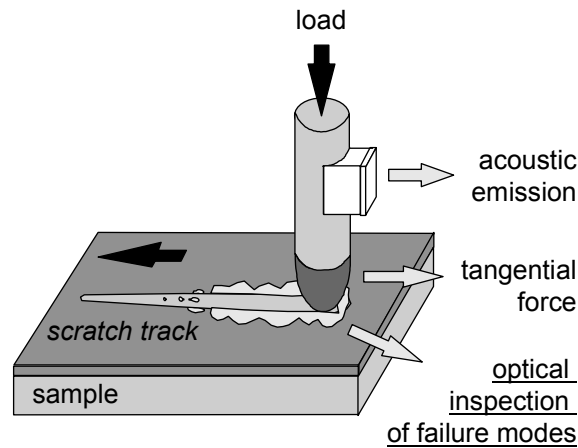


Figure 3.10 Illustration of the scratch technique for assessing the adhesion strength of coatings.

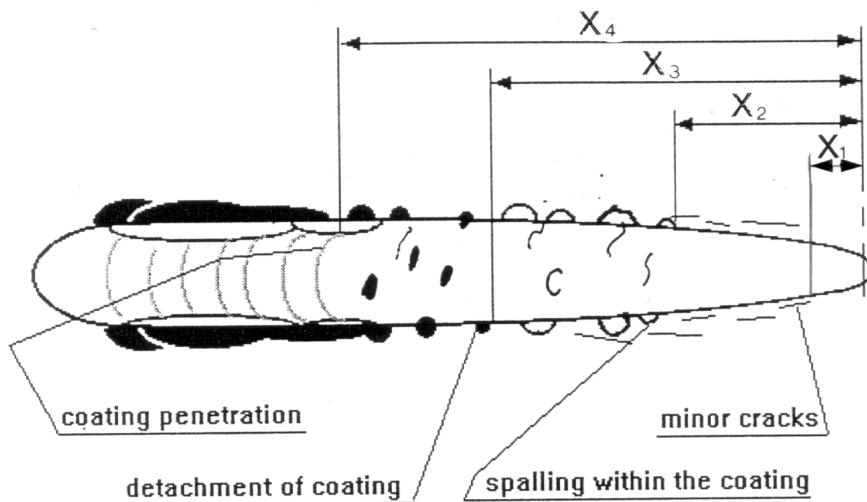


Figure 3.11 Diagram illustrating the different types of damage that may be observed in a scratch test and how this is related to the acoustic emissions observed at positions $X_{(1 \text{ to } 4)}$.

3.10 Shot peening

Principle of technique

Steel shot, typically ~0.75 mm diameter, is accelerated with compressed air and impacted against the coated samples (Figure 3.12). This is often used as a simple adhesion test for chrome plating, etc, to replace the pull-off test where the coating/substrate interfacial strength is greater the adhesive/coating strength (see standard BS 2829).

Specimen type and preparation

Witness coupons are coated with the batch products. These are subsequently tested for quality control purposes to avoid damage to actual parts. Specimen size is limited to the size of the shot peening cabinet.

Apparatus and Method

Coupons are masked to leave a 12.5 mm² area free which is tested in a commercial shot peening cabinet. A hand held tool blasts the shot at the specimen for 30-45 seconds. A visual inspection of the damage is made and a pass/fail awarded.

Application of the test

Shot peening is a simple quality control test, and is inexpensive to operate after initial relatively high equipment expenses. However, the technique is destructive and requires a representative coating to be tested.

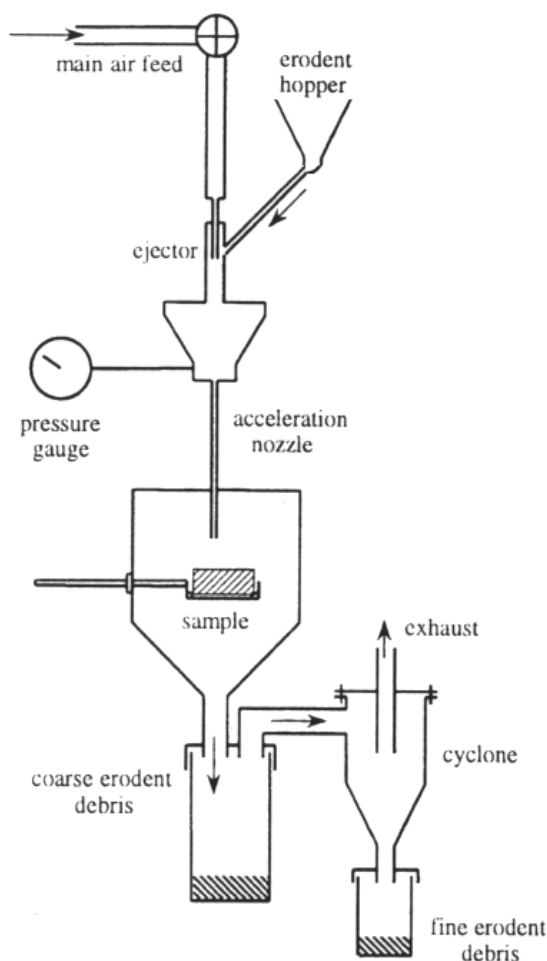


Figure 3.12 Typical experimental apparatus used to assess adhesion strength of coatings using the shot peening technique.

3.11 Standard ASTM tensile adhesion test

Principle of technique

This standard test method involves fixing a coated specimen into the lower grips of a tensile testing machine and bonding the coated surface of the specimen to the loading fixture at the other end of the machine. A tensile load is applied to the specimen normal to the surface of the coating (Figure 3.13). The test method has been standardised by ASTM (C633), details of which are given in Section 4 of this review.

Specimen type and preparation

The specimens consist of two circular blocks approximately 24 mm in diameter and 23 mm long. One end of each block is adapted so that it may be attached to a self-aligning tensile testing machine. The other end of each block is machined so that the end faces are parallel to each other and normal to the loading axis. One of these blocks is held in the upper grips for loading, the other is first coated and then fixed into the lower grips. These two parallel faces are then joined together using an adhesive bonding agent and allowed to completely cure prior to testing.

Apparatus and Method

A tensile load is applied to the test pieces at a constant rate of between 0.013 and 0.021 mm/s until rupture occurs. The maximum load that has been applied to the specimen is recorded. The adhesive strength of the coating is determined by dividing the maximum load by the cross-sectional area of the specimen. The adhesive strength should only be quoted if the rupture occurs entirely along the coating-substrate interface. If failure occurs in the coating the value should be quoted as the cohesive strength. The location of failure can be determined visually using a low-power microscope with a magnification range up to approximately $\times 100$.

Application of the test

This technique is limited by the strength of the adhesive, as the adhesive must be stronger than the coating/substrate interface. The use of high strength adhesives is not recommended as these usually require high temperature cures that may influence the properties of the coating. The method is useful for comparing the adhesion strength of coatings. The results should not be used for design data.

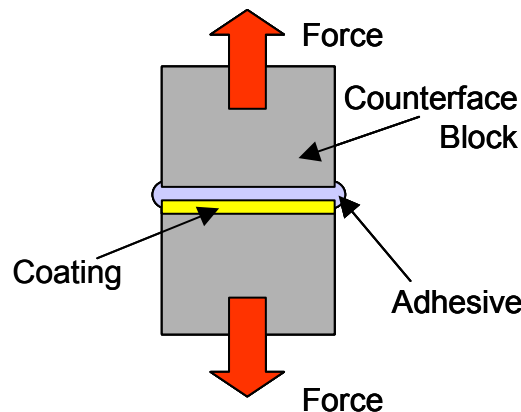


Figure 3.13 Schematic illustration of the test pieces used in the Standard ASTM tensile adhesion test.

3.12 Thermal shock

Principle of technique

Coating adhesion is tested by heating the sample and then rapidly cooling in water (Figure 3.14). This utilises the differences in thermal expansion coefficients between the coating and substrate. British standard [BS 1224:1996] specifies a suitable experimental procedure.

Specimen type and preparation

The technique is mainly used to test nickel and chromium coatings on brass substrates.

Apparatus and Method

A standard convection oven is used to heat the samples to 250 °C, which are held at that temperature for an hour. Samples are then quenched in ambient temperature water for 30 minutes, then air dried for another 30 minutes. A visual inspection is made for any signs of delamination or blistering of the coatings. The samples may also be abraded with a scraper to find areas with low adhesion.

Application of the test

The thermal shock test is used as a simple quality assurance test on each batch production. It shows good results with a minimum of equipment.

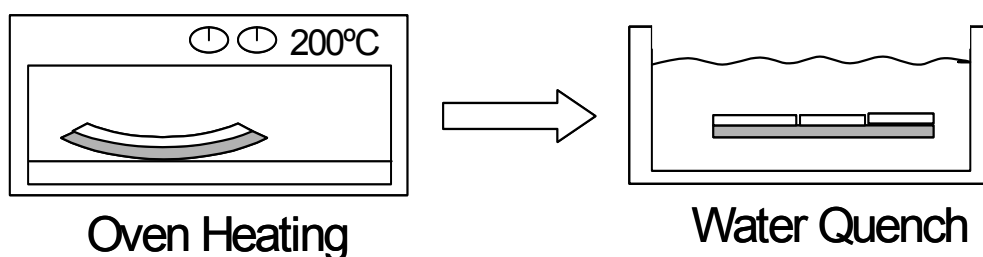


Figure 3.14 Schematic diagram illustrating the procedure used to determine coating adhesion with the thermal shock technique.

4 **Applicable Standards**

4.1 **Standards Review**

A search has been conducted using the Technical Index (Courtesy of TRW). First stage evaluation concerned British Standards of which the following were assessed:

4.1.1 **British Standards**

4.1.1.1 BS EN ISO 2819: 1985 - Metallic coatings on metallic substrates- Electrodeposited and chemically deposited coatings - Review of methods available for testing adhesion.

The standard is limited to describing tests of a qualitative nature, which are also destructive. Essentially, the standard is designed for general quality control testing and in the *Scope* it is stated that if more specific international standards for individual coatings are available then they should be used in preference.

“Table 2” in the standard indicates the applicability of individual test methodologies for different categories of coating. The tests reviewed are as follows:

- Ball Burnishing
- Chisel
- Bending and Twisting
- Grinding and Sawing
- Thermal Shock
- Extrusion (Erichsen)
- Extrusion (Flanged Cap)
- Cathodic Treatment

4.1.1.1.1 Ball Burnishing

Ball burnishing uses a barrel or vibratory burnisher with steel balls about 3 mm in diameter and a soap lubricant to produce blisters when the adhesion is poor. This test is, however, limited to thin coatings (approx. 40 µm) maximum.

4.1.1.1.2 Chisel

The test which is used on thick coatings (> 125 µm), is extremely qualitative. The technique uses a chisel or other sharp object to attempt to prise the coating away from the substrate. This may be either by means of a coating overhang or after sawing the coating to reveal the interface.

4.1.1.1.3 Bending and Twisting

The test consists of bending or flexing the coated products, usually by hand or with pliers. A mandrel can be used to control the extent of bending. The test result will

depend upon the ductility of the coating and in the case of a hard brittle coating fracture of the coating is likely to occur. The fracture can subsequently be examined to determine whether the coating peeled or can be removed with a knife or chisel. Any sign of peeling, chipping or flaking is taken as indication of poor adhesion.

4.1.1.1.4 Grinding and Sawing

An edge of the coated specimen is ground with a grinding wheel with the direction of cutting from the substrate to the deposit. If adhesion is poor, the deposit is torn from the base. A hacksaw can be substituted for the grinding wheel but the forces involved are likely to be reduced. *"Grinding and sawing tests are especially effective on harder coatings such as nickel and chromium."*

4.1.1.1.5 Thermal Shock

The effectiveness of this test is dependent upon there being a difference in coefficient of expansion between the coating and the substrate. Sudden expansion and contraction of the part will therefore lead to high stresses being developed at the interface which will highlight poor adhesion.

To comply with the Standard, the test is performed by heating the specimen in a furnace for a set time until a suitable temperature is reached. The specimen is then quenched in water at room temperature. For a specimen to pass, no separation, for example by blistering, flaking or exfoliation, of the coating from the substrate shall occur.

It should be mentioned that heating can improve the bond strength of deposits so that any test method which requires heating of the test piece may not give a correct indication of the bond strength. Conversely, in some cases, the diffusion of the coating into the base metal can create a brittle layer so that peeling of the coating is caused by fracture rather than non-adhesion.

4.1.1.1.6 Extrusion (Small punch test)

These techniques produce a deformation of the deposit and substrate into a cup or flanged depression by some sort of plunger. The plunger is pushed into the specimen at a set speed to a predetermined distance. Poorly adherent deposits will peel or flake from the substrate after a few millimetres distortion, while adherent deposits will exhibit no peeling, even when the substrate has been cracked by the penetrating mandrel. The microstructure of the drawn section can be examined to see how the deposit has been affected.

This technique is fairly easy to perform and gives good insight into the relative bond strength of the deposit. A quantitative measure relating to the amount of plunger displacement recorded prior to the coating cracking may be obtained. This will relate to coating ductility.

4.1.1.1.7 Cathodic Treatment

This test involves the coated part being made cathodic in a solution from which only

hydrogen is evolved. Blistering of the coating may take place due to pressure of gaseous hydrogen, which diffuses through certain coatings and accumulates at the site of any discontinuities between the coating and the substrate. The test is limited in application to coatings that are permeable to cathodically discharged hydrogen.

4.1.1.2 BS EN 2830 - Adhesion test for metallic coatings by shearing action.

The scope of the document defines that it is only applicable to coatings up to 700 Hv.

The test is qualitative and can only be used as a pass/fail test. The procedure involves cutting the sample normal to the coating and then applying force using a file, in a direction which forces the coating away from the substrate. The acceptance criteria is purely that no flaking is permissible after visual inspection with the naked eye.

4.1.1.3 BS EN 2829 - Adhesion test for metallic coatings by shot peening.

The scope of this standard specifies that the test method is applicable for ductile metal coatings such as cadmium, silver or copper.

The method involves peening the coated sample with steel balls of approximately 0.5 mm in diameter. The intensity of the blast will induce compressive stresses in the surface of the component and cause it to deflect. The acceptance criteria is such that neither blistering or peeling are permissible after peening by visual inspection at six times magnification.

In essence, the test is a controlled form of erosion test and therefore may be useful in showing the adhesion of the coating. As in other such tests, the acceptance criteria are subjective and qualitative.

4.1.1.4 BS EN 2828 - Adhesion test for metallic coatings by burnishing

The scope of the document states that it is only applicable to coatings of ductile metals such as cadmium, copper or silver with a hardness less than 250 Hv. The burnishing method and acceptance criteria are similar to those already described for BS EN ISO 2819.

4.1.1.5 BS 6669 Part 2 1986 - Electroplated silver and silver alloy coatings (adhesion tests)

The methods covered by this standard included such techniques as burnishing, bending, shear, shot peening and thermal shock, which have already been examined in BS EN 2819.

4.1.1.6 BS 6670 Part 5 1986 - Electroplated gold and gold alloy coatings (adhesion tests)

Three of the methods stated in this standard are identical to those already assessed, namely burnishing, thermal shock and bend test. The fourth uses an adhesive tape tear off test.

4.1.2 British Defence Standards

The following Defence standard relating to hard chromium plating has been reviewed.

4.1.2.1 Defence Standard 03-14: Electrodeposition of Chromium for Engineering Purposes

The specification states that adhesion testing of plated deposits is generally qualitative and subjective to interpretation. Guidance to the behaviour is generally given by the grinding performance. It states that displacement of the deposited metal indicates poor adhesion, although some plucking-out of cone shaped particles is to be expected.

A further method which gives guidance as to the adhesion of the coating is given. A carbide tipped tool having an included angle of 90° is placed vertically on the coated surface. It is then given a sharp hammer blow and if adhesion is satisfactory, then flaking is limited to the area local to the indent. If flakes of deposit are removed remotely from this indentation point, then this indicates unsatisfactory adhesion.

4.1.3 ASTM Standards

Other International standards were also assessed and, in the main, the European Standards were identical to the British Standards and were covered by the appropriate ISO number. Other tests tended to refer to specific industries e.g. optical coatings.

It was found that the only other national standard body that issued relevant standards for coating adhesion was ASTM.

4.1.3.1 ASTM B571

This document is essentially the American equivalent of BS EN ISO 2819 and describes qualitative methods for testing of adhesion of coatings which require only simple tools and moderate skill. Examples of tests covered which have already been discussed are bend, burnishing, chisel, file, grinding and heat quench. Additional tests which could potentially be used for testing of adhesion are:

1. Impact testing using a drop weight tester
2. Push test. A blind hole (0.75 mm diameter) is drilled on the underside of the coating until the point of the drill tip becomes within approximately 1.5 mm of the interface. The material is then supported on a ring about 2.5 mm in diameter and a steady force is applied in the hole using a steel punch until a button sample is pushed out. Exfoliation or peeling of the coating in the button or crater areas is evidence of inadequate adhesion.

Review of Section 2 of ASTM B571 is particularly enlightening in giving an overall view of the adhesion testing of coatings.

"2.2 Interpreting the results of qualitative methods for determining the adhesion of metallic coatings is often a controversial subject. If more than one test is used, failure to pass any one test is considered unsatisfactory. In many instances, the end use of the coated article or its method of fabrication will suggest the

technique that best represents functional requirements. For example, an article that is to be subsequently formed would suggest a draw or bend test; an article to be soldered or otherwise exposed would suggest a heat quench test."

"2.4 'Perfect' adhesion exists if the bonding between the coating and the substrate is greater than the cohesive strength of either. Such adhesion is usually obtained if good electroplating practices are followed.

2.5 For many purposes, the adhesion test has the objective of detecting any adhesion less than 'perfect'. For such a test, one uses any means available to attempt to separate the coating from the substrate. This may be prying, hammering, bending, beating, heating, sawing, grinding, pulling, scribing, chiselling or a combination of such treatments. If the coating peels, flakes or lifts from the substrate the adhesion is less than perfect.

2.6 If evaluation of adhesion is required, it may be desirable to use one or more of the following tests. These tests have varying degrees of severity; and one might serve to distinguish between satisfactory and unsatisfactory adhesion in a specific application. The choice for each situation must be determined.

2.7 When this guideline is used for acceptance inspection, the methods to be used must be specified. Because the results of tests in cases of marginal adhesion are subject to interpretation, agreement shall be reached on what is acceptable."

4.1.3.2 ASTM C633 - Standard test method for adhesion or cohesive strength of flame sprayed coatings

Although the test method is targeted at flame sprayed coatings, the technique out of all those examined is probably one of the most suitable for obtaining quantitative values for bond strength. The test consists of coating one face of a substrate fixture, bonding this coating to the face of a loading fixture and subjecting this assembly of coating and fixtures to a tensile load normal to the plane of the coating.

The test is limited to ambient temperature due to restrictions concerning the strength of the adhesive bonding agents. This will normally be an epoxy with a maximum bond strength of 12,000 psi. The adhesion strength of the bonding agent shall be determined each time the test is performed, which will ensure that no degradation of the adhesive has occurred. This is done by using the bonding agent to attach a loading fixture to a second loading fixture. To be used as an acceptance test, C633 requires that at least five specimens of each type be used.

The adhesion strength of the coating is given if failure is entirely at the coating-substrate interface. The cohesive strength of the coating is given if rupture is only within the coating. Failure in the bonding agent may be a satisfactory result for a quality assurance test, or for a qualification test, if the strength of the bonding agent is greater than the maximum required adhesion or cohesive strength of the coating. If failure occurs in a combination of these locations in one specimen, generally no interpretation of the initial cause can be provided. No justification statements can be made regarding the precision and accuracy of this method because it evaluates coatings that exhibit unpredictable brittle fracture.

4.2 BSI and ISO Standards

BS 6669-2:1986, ISO 4522/2-1985

Methods of test for electroplated silver and silver alloy coatings. Adhesion tests

BS 6670-5:1986, ISO 4524/5-1985

Methods of test for electroplated gold and gold alloy coatings. Adhesion tests

BS AU 148-3:1969

Methods of test for motor vehicle paints. Flexibility and adhesion

BS EN ISO 1461:1999

Hot dip galvanized coatings on fabricated iron and steel articles. Specifications and test methods

BS EN ISO 3613:1995

Chromate conversion coatings on zinc and cadmium. Test methods

BS ISO 9211-4:1996

Optics and optical instruments. Optical coatings. Specific test methods

BS ISO 13805:1999

Vitreous and porcelain enamels for aluminium. Determination of the adhesion of enamels on aluminium under the action of electrolytic solution (spall test)

DD ENV 1071-3:1994

Advanced technical ceramics. Methods of test for ceramic coatings. Determination of adhesion by a scratch test

BS EN 2828:1993

Adhesion test for metallic coatings by burnishing

BS EN 2829:1995

Adhesion test for metallic coatings by shot peening

BS EN 2830:1993

Adhesion test for metallic coatings by shearing action

BS EN ISO 2819:1995

Metallic coatings on metallic substrates. Electrodeposited and chemically deposited coatings. Review of methods available for testing adhesion

98/120106 DC

Metallic and other inorganic coatings. Method for quantitative measurement of adhesion by tensile test

00/120603 DC BS EN 13523-6

Coil coated metals. Methods of test. Part 6. Adhesion after indentation (cupping test)

4.3 ASTM Standards

D4541-95

Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers

D2197-98

Standard Test Method for Adhesion of Organic Coatings by Scrape Adhesion

D5179-98

Standard Test Method for Measuring Adhesion of Organic Coatings to Plastic Substrates by Direct Tensile Testing

C633-79(1999)

Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings

F1147-99

Standard Test Method for Tension Testing of Calcium Phosphate and Metal Coatings

B571-97

Standard Practice for Qualitative Adhesion Testing of Metallic Coatings

F692-97

Standard Test Method for Measuring Adhesion Strength of Solderable Films to Substrates

B905-00

Standard Test Methods for Assessing the Adhesion of Metallic and Inorganic Coatings by the Mechanized Tape Test

F1842-97

Standard Test Method for Determining Ink or Coating Adhesion on Plastic Substrates for Membrane Switch Applications

D3359-97

Standard Test Methods for Measuring Adhesion by Tape Test

4.3 Other National Standards

National Tensile Adhesion Standards:

- DIN 50160-A (Germany)
- AFNOR NF A91-202-79 (France)
- JIS H8666-80 (Japan)

These test methods are equivalent to ASTM C633 but differ in specimen geometry and test methodology.

5 *Adhesion Test Method Reviews*

METHODS OF TESTING THE ADHESION OF METAL COATINGS TO METALS

D. Davies and J.A. Whittaker, Metallurgical Reviews, vol.12, pages 15-26, 1967.

Test Methods

- Tensile tests
- Ollard test
- Shear tests
- Peel test
- Knife and scribing tests
- Ultracentrifuge technique
- Bullet test
- Blister test
- Electrochemical method

Conclusions

This is an early review of adhesion test methods that covers many of the basic techniques. The review suggests that although the techniques reviewed are useful for simulating service behaviour they are not quantitative making it difficult to compare the properties of different types of coating. It concludes that there is a growing demand for a reliable quantitative adhesion test method that would ideally:

- Permit interpretation of results without dependence on operator experience.
- Measure bond strength independently of the composition and properties of the substrate and coating.
- Determine bond strength over small as well as large areas.
- Determine bond strength independently of coating thickness.
- Give adhesion checks independently of cathode geometry.

ACRITICAL APPRAISAL OF THE METHODS FOR MEASURING ADHESION OF ELECTRODEPOSITED COATINGS

K.L.Mittal, in Properties of Electrodeposits: Their measurements and significance, edited by R. Sard, H. Leidheiser and F. Ogburn (Electrochemical Society, Princeton, NJ, 1975), Chapter 17, pages 273-306.

Test Methods

- Tensile test
- Shear test
- Peel test
- Knife test
- Scratch test
- Ultracentrifuge technique
- Ultrasonic method
- Blister test

- Electrochemical method
- Cathodic treatment method
- Pulsed laser or electron-beam techniques

Conclusions

It is evident from this survey that a plethora of qualitative techniques are available for measuring adhesion, but there is no single technique which processes all the virtues of an ideal test, as specified by Davies and Whittaker. The conclusions that were drawn from this review are as follows:

- There are no quantitative tests which can be recommended for quality control, product development and for customer needs.
- Qualitative adhesion tests are useful in simulating the service conditions.
- If the absolute numerical values of adhesion are not required then practically any of the test methods can be used to follow the effects of process variables aging, environment, etc.
- Scratch and ultracentrifugal test methods appear to offer the greatest potential and with further development may evolve as practical adhesion tests.
- Adhesion strength measurement techniques are not directly comparable and care should be taken when comparing data obtained from different techniques.

TECHNIQUES FOR QUANTITATIVELY MEASURING ADHESION OF COATINGS - PART 1 & 2

J.W.Dini and H.R.Johnson, Metal finishing, vol 75, part 4, pages 42-46, March 1977.

J.W.Dini and H.R.Johnson, Metal finishing, vol 75, part 4, pages 48-51, April 1977.

Test Methods

- Ring shear test
- Conical-head tensile techniques
- I-beam test
- Flyer plate test

Conclusions

These papers examine the measurement of adhesion strength from a practical point of view assessing the time required to conduct qualitative tensile adhesion test methods (Table 5.1). The authors conclude that the ring shear, conical-head, Ollard and I-beam test methods were all straightforward, rapid tests requiring simple test equipment. By contrast, the flyer-plate technique was found to be difficult to perform, time consuming but could be used for measuring the adhesion of thinner coating.

Table 5.1 Assessment of the Time Required to Conduct Qualitative Adhesion Tests

Test method	Specimen Dimensions	Minimum thickness of coating	Time to prepare a specimen	Time to test a specimen
	(mm)	(mm)	(mins.)	(mins.)
Ring shear test	12.7 mm diameter rod	1.52	20	5
Conical-head tensile technique	3.2 x 6.4 plate	5.1	120	10
Ollard tensile technique	12.7 x 152 plate	1.27	15	10
I-beam	12.7 x 152 plate	2.54	180	5
Flyer plate	3.2 x 63.5 x 127 plate	0.25	240	60

A REVIEW OF THE METHODS FOR THE MEASUREMENT OF COATING-SUBSTRATE ADHESION

D.S.Rickerby, Surface and Coating Technology, 36, 541-557, 1988.

Test Methods

- Pull-off test
- Ultracentrifugal test
- Ultrasonic method
- Indentation
- Laser spallation
- Scratch test

Conclusions

Rickerby concluded that few, if any, of the test methods available for the measurement of coating-substrate adhesion give a value for the true adhesion of the system, all measure an experimental adhesion value. The author noted that the simplest of these tests is the pull-off test. This, however, suffers from the need to attach a device to the coating that will transmit forces across the interface from which measurements can be made. Two techniques that overcome this problem are the ultracentrifugal and ultrasonic methods. However, these methods are not suitable for measuring the adhesion properties of engineering components. Of the methods reviewed it was concluded that the indentation, laser and scratch test methods offer the best prospects of relating adhesion results to the performance of real engineering components. The main advantage of the indentation and laser techniques is that the adhesion parameters are relatively insensitive to the substrate hardness compared to the scratch test. It was therefore concluded that there is still a need to develop a more general equation for scratch testing to take into account the properties of the coating and substrate.

MEASUREMENT OF ADHESION FOR THERMALLY SPRAYED MATERIALS

C.C.Berndt and C.K.Lin, J.Adhesion Sci. Technol. Vol.7, pages1235-1264, 1993.

Also published in:

Adhesion Measurement of Films and Coatings, pages 41-70, Ed. K.L.Mittal, 1995.

Test Methods

- Double cantilever beam test
- Acoustic emission
- Indentation
- Scratch test

Conclusions

The measurement of adhesion is at least on the conceptual level a routine operation. The tensile adhesion method as detailed in ASTM C633 is simple and often used in industry for ranking different coatings. The main shortcoming of this test is that it does not allow for any understanding of coating performance. Many theories or mechanisms for coating adhesion have been proposed, however, none of these fully explains each situation and there is no adhesion test available which satisfies all requirements. Therefore the most suitable test method to choose is often the one that best simulates the stress conditions. Standardisation of measurements, which may be achieved by improving existing experimental techniques or by the combination of two or more techniques, will aid future coating development.

A COMPARATIVE STUDY OF ADHESION TEST METHODS FOR HARD COATINGS

H.Ollendorf and D.Schneider, Surface and Coating Technology, 113, 86-102, 1999.

Test Methods

- Scratch test
- Four point bending
- Rockwell
- Cavitation technique
- Impact test
- Laser- acoustic
- Acoustic microscopy

Conclusions

This paper is a comparative study of seven different adhesion tests methods. The study was performed on TiN coatings (thickness 1.2-2.45 μm) that were deposited on annealed steel. Coatings with a range of different adhesion properties were obtained by varying the length of time the steel substrate was pre-sputtered with argon ions prior to coating. The longer the steel was pre-sputtered the better the adhesion. The results that were obtained from this study are shown in the Table 5.2. The paper makes the following conclusions:

- The test methods used in this study did not provide any corresponding coherent results.
- Some of the test methods in particular those examining local rather than global adhesion actually indicated a reduction in coating adhesion rather than an increase.
- Tests that showed the expected increase in adhesion quality with sputtering time are indicated in Table 5.2 by “+”, those showing behaviour opposite to that expected are indicated by “-“, where no correlation was found the tests are indicated by “0”.
- It is therefore concluded that extreme care must be taken when selecting adhesion test methods as different techniques may give completely different and unexpected results.

Table 5.2 Evaluation of Results from Adhesion Test Methods.

Test method	Test Parameter	Correlation with sputtering time
Scratch test	Microscopic evaluation of the scratch trace	0
	Friction work	+
	Total number of acoustic emission signals	+
	Critical load, from first acoustic emission event of 20 tests	-
	Critical load, from first acoustic emission in single scratch test	-
Four-point bend	Crack density	+
	Critical strain from acoustic emissions	-
Cavitation test	Proportional area of damage	+
Impact test	Critical number of cycles	-
Laser-acoustics	Young’s modulus	+
Scanning acoustic microscopy	Imaging of the defects	0
Rockwell test	Classification of damage patterns	0

0: no significant correlation with pre-sputtering

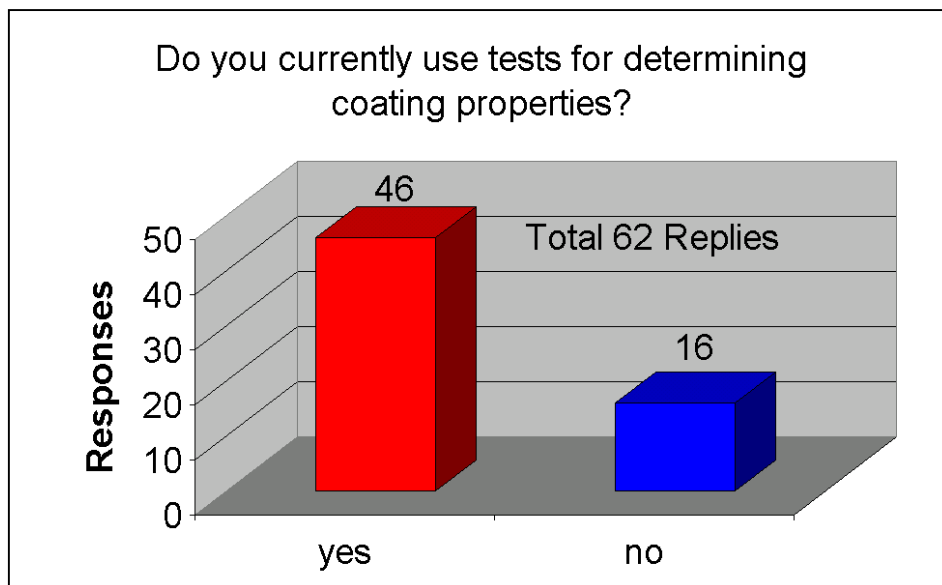
+: significant correlation with pre-sputtering time: the parameter indicates an improvement in adhesion.

-: significant correlation with pre-sputtering time: the parameter indicates a reduction in adhesion.

6 Industrial Surveys

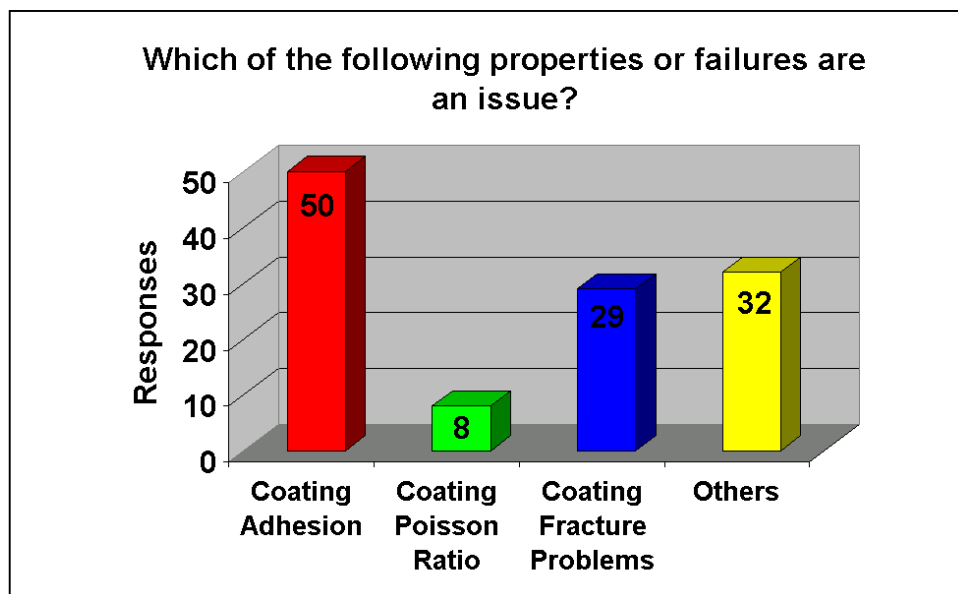
6.1 NPL Survey

- 1) Do you currently use tests for coating properties or for thin film or coated component performance?



UK Industrial Responses	International Responses	UK University Responses
51	8	3

- 2) Which of the following properties or failures are an issue within your organisation?

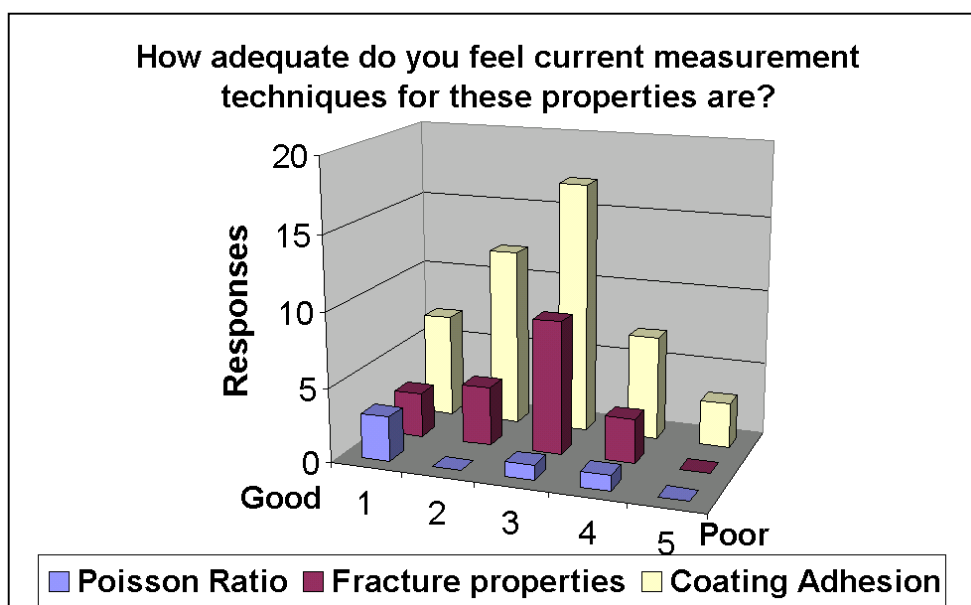


Other Properties Included:

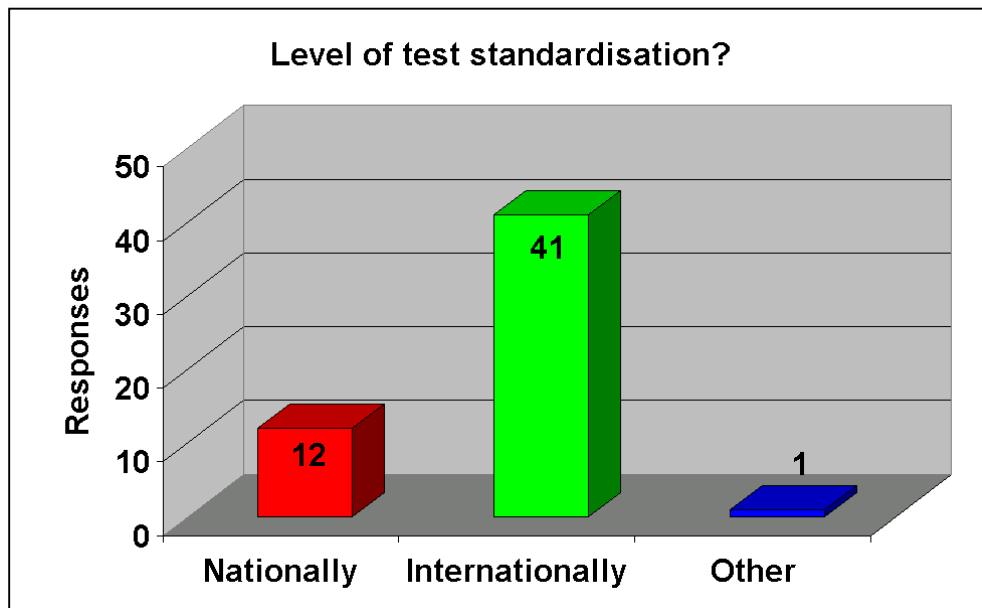
- Abrasion resistance;
- Accelerated weathering colour;
- Cathode disbondment;
- Chemical composition of coatings;
- Coating defects;
- Coating deformation;
- Corrosion performance / protection / resistance;
- Damping;
- Durability;
- Electrical;
- E-Modulus;
- Environmental attack;
- Fatigue;
- Friction;
- Gloss;
- Impact;
- Inadequate surface preparation;
- Inadequate mixing of coating constituents;
- Influence of contact with polymers;
- MBK rub test for cure;
- Microhardness;
- Opacity;
- Orange peel;
- Paintability;
- Roughness;
- Scratch resistance;
- Slip resistance;
- Stiction properties;
- Thickness;
- Transparency to CP currents;
- Wear;
- Weathering.

3) In general, how adequate do you feel current measurement techniques of these properties are?

1 = adequate and 5 = inadequate

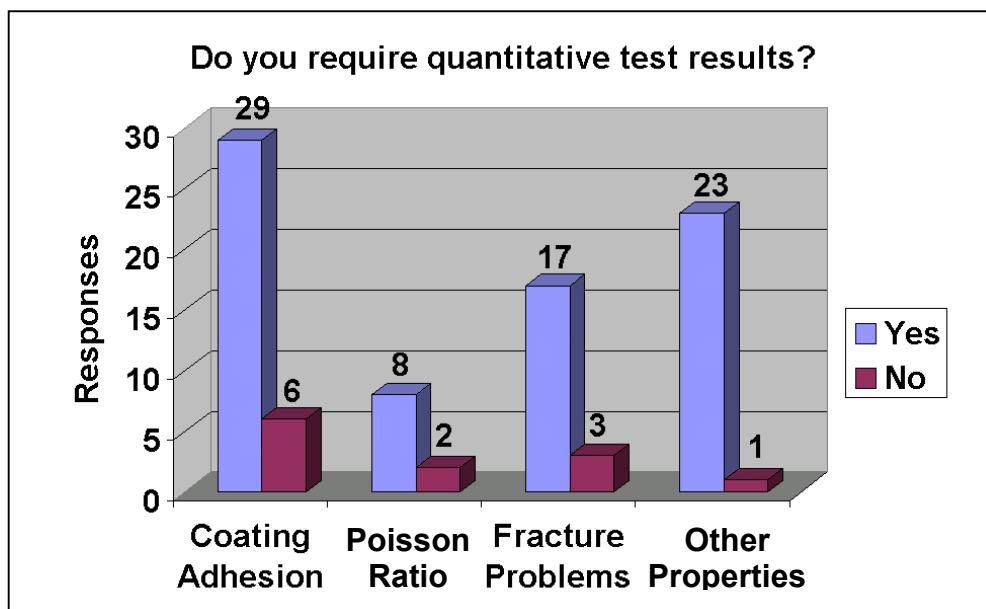


- 4) At which level would you like the tests to be standardised?



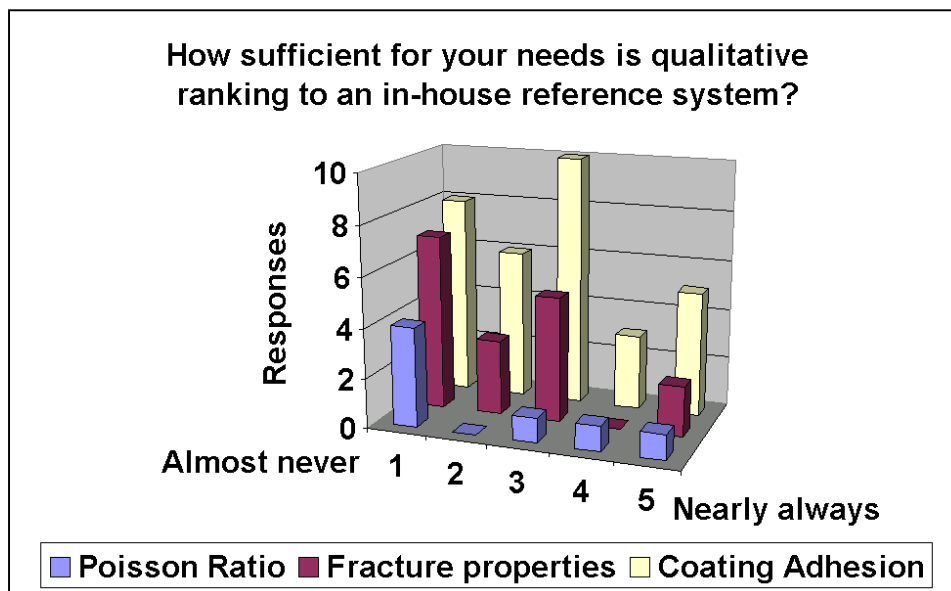
The other response suggested that a good industry or laboratory derived standard is a good start to international standardisation.

- 5) Do you require quantitative results from these tests?

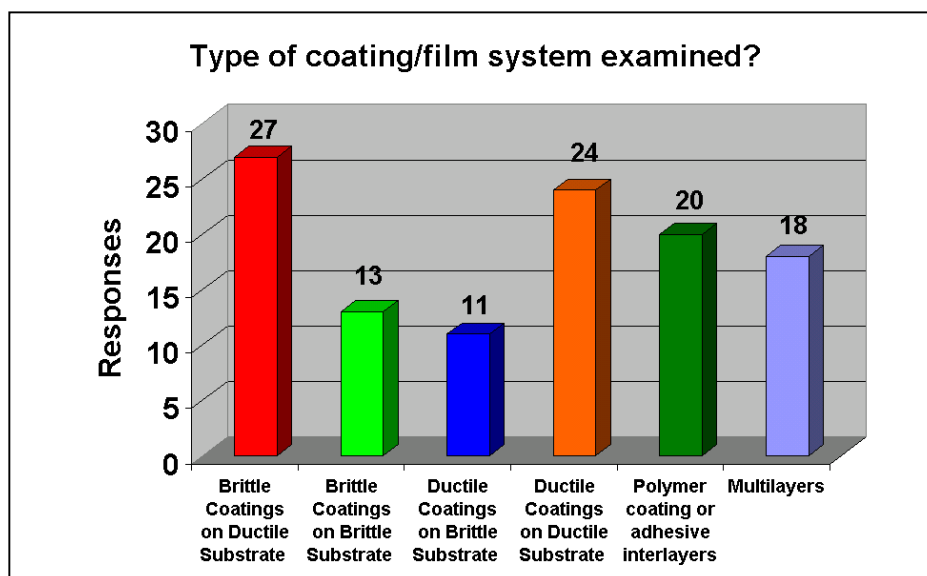


- 6) How sufficient for your needs is qualitative ranking or comparison to an in-house reference system?

1 = *almost never* and 5 = *nearly always*



- 7) With what basic types of coating/film systems do you work:

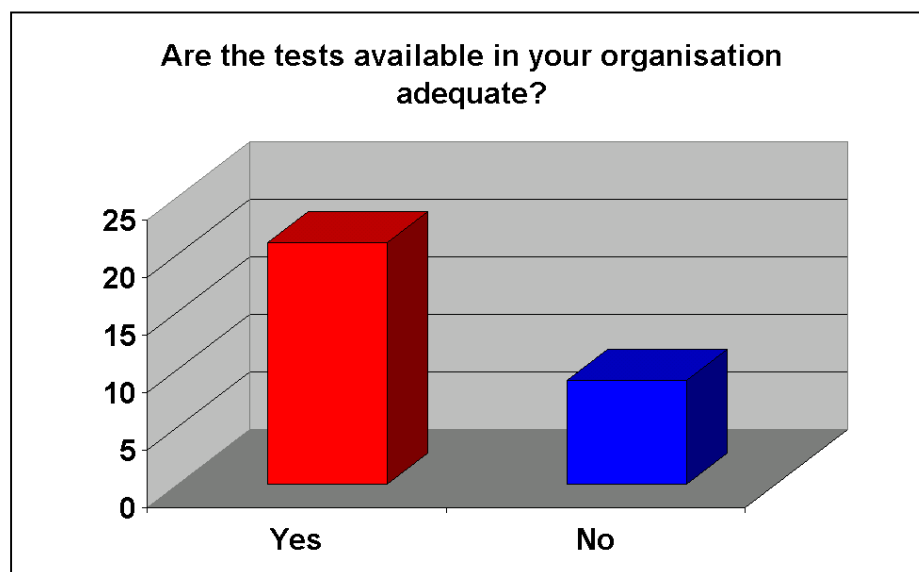


- 8) What adhesion tests do you currently use? (Please be specific if possible, otherwise generic test types will do).

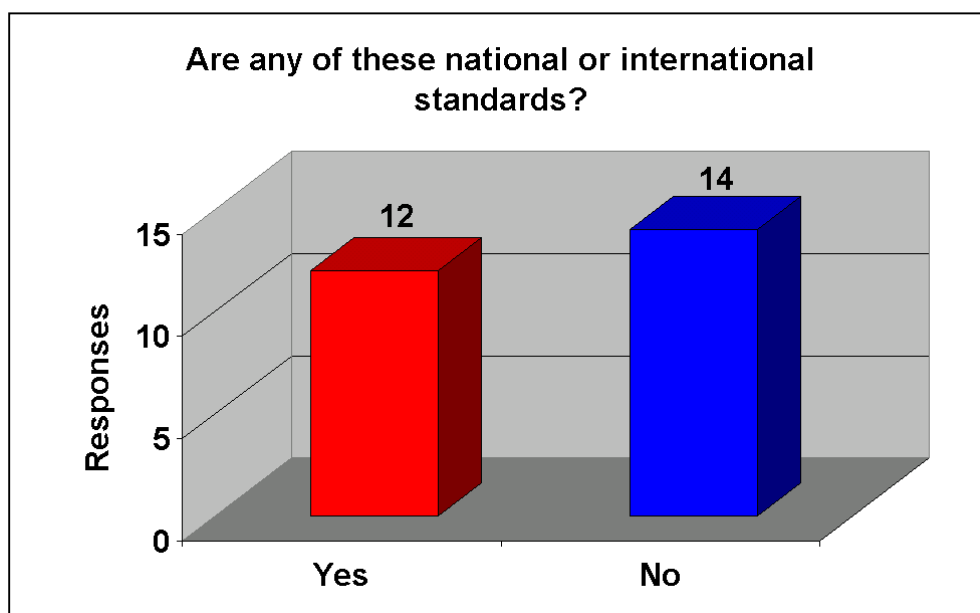
Adhesive tape test;
 ASTM C633;
 Bend test;
 Cross-cut tests,
 Cross-hatch test;
 Heat and quench;
 Indentation,
 Initial abrasion method using X-hatch;
 Peel test;
 Plastic deformation until rupture of coating during bend test,
 Pull-off (hydraulic),
 Pull-off tests,

Rockwell C
 Rockwell C with SEM;
 Rockwell C (Mercedes Benz test);
 SEM inspection after scratch;
 Scrape coating with sharp edge;
 Scratch test;
 Sellotape adhesion;
 Shot peening exposure;
 Slow bending testing,
 Strip bending test,
 Tape tests,
 Thermal cycling under vacuum.
 Thermal shock.

- 9) Are there tests available within your organisation adequate for your needs?



10) Are any of these national or international test methods?



Standards specified:

ASTM C633
 ASTM D3359,
 ASTM D4541,
 BS 6670 1986.
 BS 3900 / E6 ISO 2409 (Test method for paints),

BS Product specifications quoted:

BS 1224 1996,
 BS 3712,
 BS 4254,
 BS 5889.

11) If a national measurement laboratory like NPL were to work on developing, quantifying or standardising a small number of adhesion test methods, what kinds of tests or films/substrates do you feel would be most valuable to you?

Test methods

Bend (4-point-bend)
 Indentation
 Laser-ultrasound
 Nano-scale measurements
 Scratch
 Tensile
 Thermal

Coatings/substrate

Ceramic coatings on metal
 Electroplated coatings on metal
 PVD hard coatings on steel
 Multi-layer coatings
 Organic/polymeric coatings
 Thermal spray coatings
 Thin metallic and amorphous coatings
 Optical coatings

6.2 NIST Survey

Summary of Survey Responses:

Received: 38 responses received from the following organisations

Industries	19
Universities	13
National Laboratories	12

Survey Questions, with Responses:

1. Do you currently work with adhesion testing, or with film or coating systems where adhesion measurement or failure is an issue?

[Yes/No]:.....

Yes	36
No	2

2. How adequate do you feel current thin film or coating adhesion measurement techniques within your field of research are?

[1=inadequate; 3=barely adequate; 5= completely adequate]

	Average	1-sigma
Qualitatively	3.2	1.2
Quantitatively	2.1	1.3

3. If adequate tests are available within your organization, please specify the tests:

People who listed tested here put down essentially the same tests that they said they used in response to Question 8. However, 11 of the 33 people responding to this question said that they had no adequate test available.

4. Would you like to see the tests nationally or internationally standardized?
[please check one -]

Nationally	Internationally	Neither
1	29	0

5. Do you require quantitative results from an adhesion test?
[Yes/No]:

Yes	No	Sometimes
25	1	5

6. How sufficient is qualitative ranking or comparison to an in-house reference system?
[1= almost never; 3=sometimes; 5=nearly always]:

Almost Never	Sometimes	Nearly Always
4	16	7

7. With what basic types of coating/film systems do you work:
[check those that apply]

Type of Coating System	Responses
Brittle coatings on Ductile substrates	24
Brittle coatings on brittle substrates	18
Ductile coatings on brittle substrates	13
Ductile coatings on Ductile substrates	14
Polymer coatings or adhesive interlayers	18
Multilayers: all ductile; all brittle; mixed components.	18
Others (please specify)	Inorganics on polymers; Paints on steel; Elastomers on stiff substrates.

8. What adhesion tests do you currently use (be specific if possible, otherwise generic test types will do)? If any of these are national or international test methods, please identify the tests (e.g. N=National, I=International).

Adhesion Test Used:

Abrasion (in house) Mercedes (VDI 3198)
 Bend (typically 4-point) Microtensile
 Bulge/pressure Modified edge lift off
 Cavitation Peel
 Cross-hatch (ASTM 3359) Pull
 Cyclic fatigue (bend or tensile) Push
 DCB sandwich layer Optical observation of debond
 Double Vickers Scotch tape
 Grit blast Scratch (usually ball stylus)
 Indentation: Shear
 Normal, interface, Rockwell Tensile strain
 Indentation fatigue

9. If a national measurement laboratory like NIST in the US or NPL in the UK were to work on developing, quantifying or standardizing a small number of adhesion test methods, what kinds of tests or film/substrate systems do you feel would be of the most value to you? [Please specify]:

Specific Tests:

Scratch
 Tensile
 4-point bend
 Peel
 Normal indentation (using low to intermediate load)
 Indentation at interface (e.g., in cross section)
 Rockwell Indentation (high load)
 Thermal

Properties of a desirable test:

Proof test
 Tests for real components
 Tests that give quantitative results
 Tests for free surface films
 Tests for well-adhered films
 Optical observation of debond

10. If an international round robin test were to be conducted, either to compare several test methods or to work toward quantifying specific test methods, would you be willing to participate, with the assumption that the test is one that you can perform? [Yes/No]:

Yes	Maybe	No
27	6	3

7 Conclusions

- There is a plethora of qualitative test methods for measuring the adhesion strength of coatings.
- Few of these test methods are quantitative and only a limited number are used by industry.
- Simple standardised test methods are most frequently used in the UK, whereas a wider range of techniques are used in North America.
- The development of international standards for quantitative test methods is considered important by industry both in the UK and internationally.
- The test methods industry is most interested in developing are: ***Four-point bend, Indentation, Scratch, Tensile and Thermal.***

8 **References**

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Author(s): Schrooten, J. ; Van Oosterwyck, H. ; Sloten, J.V; Helsen, J.A.
Source: Society for Biomaterials 25th Annual Meeting; 31stInternational Biomaterials Symposium (1999), 423,Society for Biomaterials. 6518 Walker Street, Suite 150,Minneapolis, MN 55426-4215, USA Conference: Transactions of the Society for Biomaterials. Vol. XXII, Providence, RI, USA, 28 Apr.-2 May 1999
- 2 A comparative study of adhesion test methods for hard coatings.
Author(s): Schneider, D.; Ollendorf, H.
Source: Surface and Coatings Technology (1999) 113, (1-2), 86-102.
- 3 Determination of the adhesion properties of an alkyd pigmented coating by electrochemical impedance spectroscopy.
Author(s): Gonzalez, J.E.G.; Rosca, J.C.M.
Source: Journal of Adhesion Science and Technology (1999) 13, (3), 379-391.
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Author(s): Manika I. ; Muktepavela, F.; Jensen, H; Sobota, J.; Sorensen, G.
Source: Surface and Coatings Technology (1998) 100-101, (1-3), 333-337, Graphs, Numerical Data, Photomicrographs, 12 ref. . Switzerland Conference: 1997 ICAM / E-MRS Conference, Symposium K: Coatings and Surface Modifications for Surface Protection and Tribological Applications, Strasbourg, France, 16-20 June 1997
- 6 Evaluation of adhesion and properties of sprayed coating by ultrasonic testing method.
Author(s): Suga, Y.; Lian, D.
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