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P E Tomlins, J Nottay &
L Zou

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National Physical Laboratory
Queens Road, Teddington, Middlesex, TW11 0LW

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P E Tomlins, J Nottay and L. Zou
Centre for Materials Measurement and Technology
National Physical laboratory
Teddington, Middlesex
United Kingdom, TW11 OLW

SUMMARY

In service failures of conformal coatings usually occur as a result of delamination due to repeated thermal cycling of the board due to differences in the coefficients of thermal expansion. The quality of the adhesive joint between the coating and substrate can be assessed by scratch testing (BS3960 pt 6) after a period of thermal cycling to simulate ‘in service’ use. This technique which is commonly used within the electronics industry only provides qualitative data that are often operator dependent. During the scratch test the coating is subjected to a complex mixture of tensile, compressive and shear stresses that are quite different to the predominantly shear stress imposed by repeated thermal expansion and contraction. These limitations can be overcome by using the butt tension test which measures the tensile properties of the entire coating/substrate assembly. The test generates quantitative data and provides valuable information regarding the point of failure of the coating/substrate assembly. However it does not provide a measure of the shear properties that are important for in service performance.

CONTENTS

1 INTRODUCTION

The adhesion of thin polymer coatings to circuit boards has always been considered an important factor in determining their long-term ability to protect printed circuit assemblies from corrosion in aggressive environments. Delamination of the coating can occur as a result of thermal cycling during the service life of the product. The driving force for delamination is usually attributed to a mismatch in thermal expansion coefficients between the coating and substrate, tracking or any of the components mounted on the board. Visible signs of decoupling of the coating to the substrate although a cause for concern may or may not affect its ability to protect it from corrosion.

A scratch test method is commonly used to measure adhesion of coatings in the electronics industry. This technique which is described in more detail below (Section 2.2) involves cutting a cross hatch pattern into the coating. The quality of the adhesive bond between the coating and the substrate is then assessed by studying the pattern of cuts. The interpretation of the results is subjective and hence prone to inaccuracy. The aim of this investigation is to investigate other mechanical tests that could replace or complement the scratch test method.

2 MEASUREMENT OF ADHESION

The adhesion of thin coatings (< 50 μm) to substrates can be measured using a range of different mechanical tests that monitor the force required to delaminate the coating by either pulling or shearing it. There are practical difficulties involved in trying to shear thin films away from the underlying substrate particularly in ensuring that the path of the delaminating tool accurately follows the interface between the coating and the substrate. Failure to control the shearing path will result in measurements of the cohesive strength of either the adhesive itself or the substrate. To some extent these difficulties can be overcome by using a peel test[1] whereby the coating is peeled away from the substrate at a prescribed rate. However there are a number of practical problems associated with this test i.e.:

- The success of the test is very dependent on the ductility of the adhesive i.e. improves with increasing adhesive flexibility.
- The coating and substrate are subjected to a mixture of shear and tensile stresses.
- The rate of peel can be difficult to control due to the stick-slip behaviour of some adhesives.
- Controlling the direction of crack growth is difficult i.e. the failure mode can easily switch from adhesive to cohesive.

We have therefore chosen to use a butt tension test (Section 2.1) which measures the force required to pull the film off the substrate to compare with the scratch test method (Section 2.2) that is commonly used by the industry for ranking the ‘adhesive’ properties of different coatings.

2.1 BUTT-TENSION TEST

The butt-tension test configuration is shown in Figure 1. The pull stud attached to the coating and board is then coupled to an Elcometer (110 Patti) as shown in Figure 2. Inflation of the Elcometer collar by compressed air applies a tensile force to the pull stud. The rate at which this tensile force is applied is controlled by the rate at which the air bladder inflates. The ultimate tensile force required to detach the pull stud from the circuit board is recorded by the instrument. The results obtained by this method were consistent with those determined using a calibrated materials testing machine (Instron 4505).

2.2 SCRATCH TESTING

The procedure used for scratch testing is described in detail[2] in BS3960 pt 6. The principle of the test is shown in Figure 3. A cutting tool is drawn over the surface of a specimen at an angle of 90^o such that the cutting edge of the knife edges penetrates through the film to the underlying substrate. The cutting action is done at a relatively slow rate and at relatively constant pressure although these factors are obviously operator dependent. The procedure is repeated after rotating the specimen through 90^o. A piece of adhesive tape is then applied to the cut cross hatched region of the coating and subsequently peeled off. This process is designed to remove small fragments of coating material that have become delaminated during scoring. The standard gives guidance on interpreting the resultant grid pattern of cuts in terms of ranking the adhesion of the coating to the substrate.

During the scoring process the coatings are subjected to local shear stresses. These forces can initiate crack growth either within the coating or substrate or more likely at the interface between the coating and substrate. Growth of such cracks results can ultimately result in film delamination although this does depend on the ductility of the coating material. More ductile coatings absorb more stress through deformation than brittle coatings and therefore are less prone to significant delamination[3,4].

3 EXPERIMENTAL

3.1 BOARD DESIGNS AND MATERIALS

The test coupon (NPL TB15) shown in Figure 4 consists of a square board of length 100 mm manufactured from FR-4 laminate or ceramic. Each board contains three double comb patterns of dimensions 25 mm x 25 mm that can be used for surface insulation resistance measurements. The 25mm square metallised pad is used to compare the adhesion of different coatings to it and the bare board by cross-hatch or similar measurement techniques.

3.1.1 Selection of finishes and resist

FR-4 boards were finished with gold whilst ceramic boards were finished with either silver or gold plated over nickel.

3.1.2 Selection of coatings

Twelve coatings were selected for this investigation representing acrylics, polyurethanes, silicones and paraxylene. A number of examples from each generic type were chosen including water and solvent based materials and those cured by heat and UV light. The paraxylene was deposited by vacuum deposition. The application method and curing route for these materials are listed in Table 1. Most boards were coated on both sides i.e. dipped as is apparent from the final column of Table 1 with the coating covering approximately 92.5 % of the board. (The products have been classified only according to material type as the manufacturers supplied them under a confidential agreement.)

Resin Type	Code	Method of application	Method of Cure	Coated on one or both sides
Acrylic	AC1	Dip/Spray	Solvent	Double
	AC2	Dip/Spray	Ambient/Heat	Double
	AC3	Dip/Spray	Ambient/Heat	Double
	AC4	Dip/Spray	UV	Single
	AC5	Dip/Spray	Solvent	Double
Paraxylene	XY	Vacuum Deposition	None	Double
Urethane	UR1	Dip/Spray	Water/Heat	Double
	UR2	Dip/Spray	Solvent	Double
	UR3	Dip/Spray	Solvent	Double
Silicone	SR1	Dip/Spray	Water	Double
	SR2	Dip/Spray	Heat	Double
	SR3	Dip/Spray	Heat	Double
	SR4	Spray	UV/Water	Single

Table 1: Conformal coating materials.

3.1.3 Pre- and post-coating treatments

Prior to coating the boards were cleaned with an isopropyl alcohol/water mixture, baked at 125 ^{o}C for 1 hour and then subjected to a typical reflow oven profile for eutectic SnPb solders. After cleaning, the boards were handled by their edges by operators wearing latex gloves to avoid contamination prior to coating. After coating and curing the boards were packaged into moisture-proof bags containing desiccant material. Sheets of paper were used to prevent the boards from coming into contact with each other.

3.1.4 Curing procedure

The coatings were cured following the manufacturers recommended procedures.

3.1.5 Environmental conditioning

In-service thermal fatigue of the coatings was simulated by exposing the test boards to 10 cycles of –40°C to 125°C in an environmental chamber. The cycle time was 35 minutes and specimens were allowed to equilibrate for a period of 5 minutes at both ends of the cycle.

3.1.6 Preparation of butt tension test specimens

A pull stud of diameter 12.5 mm was attached to the surface of the coatings using a 2-part epoxy adhesive (Araldite, Ciba Specialty Chemicals). Coatings were cleaned using isopropyl alcohol (IPA) prior to bonding. The surface of the pull stud has a keyed surface to improve bond strength. The epoxy was cured at room temperature for a period of at least 18 hours before testing.

The fillet of adhesive that can form around the base of the pull stud during the bonding process can have a significant effect on the mechanical properties of adhesive joints. The results of mechanical test such as single lap shear are particularly affected by the size and shape of the fillet[5]. To assess the importance of the fillet, the butt tension test data specimens were prepared with and without fillets.

4 RESULTS

4.1 VISUAL INSPECTION

Optical microscope examination of the boards after thermal cycling showed no evidence of delamination of the coatings.

4.2 BUTT TENSION TEST DATA

4.2.1 Gold finished FR-4

Figures 5a and 5b show the butt tension tests results for conformally coated FR-4. These data clearly show that the force required to detach the pull stud from the substrate is markedly increased in the presence of an adhesive fillet. This is presumably due to the effective increase in the cross-sectional area of the pull stud when surrounded by a ring of adhesive – the calculations of detachment force are based on the diameter of the pull stud. Removing the fillet from the pull stud appears to have a beneficial influence on the variability within the data. This is presumably due to the consistency in the effective area of the un-filleted pull stud in comparison with a filleted stud. These butt tension tests data show that the forces required to uncouple the pull studs from differently coated substrates are essentially independent of the type of coating. The value of this information can be significantly enhanced if the point of failure is established.

The location of coating failures for conformally coated FR-4 boards is schematically shown in Figures 6a and 6b. From these figures it is apparent that some coatings fail close to or at the interface of the coating and the substrate e.g. AC2, SR1, SR2 and XY as shown, for example, in Figure 7. The substrate surface in these cases does not appear to be significantly damaged suggesting that the coating has cleanly separated from the substrate. Other coatings consistently fail cohesively i.e. within the coating or the substrate i.e. AC1, UR1 or AC4. Figures 8 and 9 show examples of cohesive failures within the conformal coating and within the substrate respectively. Detachment of the pull studs in some conformally coated boards e.g. SR3 and AC3 occurred either cohesively within the coating or the substrate but not adhesively at the interface between the two. This finding suggests that the adhesive bond between the coating and substrate is particularly good.

Combining the fracture surface information with measurements of the force required to detach the pull stud suggest that less energy is required to break the adhesive bond between the coatings and FR-4 than to cause cohesive failure either within the coating or substrate. (The evidence to support this claim is more apparent in the fillet free tests.)

4.2.2 Gold and silver finished ceramic boards

Figures 10a and 10b show the butt tension test data for a limited number of gold and silver finished ceramic boards. From these figures it is apparent that the relative strengths of each coating are similar irrespective of the finish applied to the substrate. The forces required to detach the pull stud are, not surprisingly, similar to those measured for FR-4. Figure 11 schematically shows where the pull stud/coating/substrate assemblies failed for both gold and silver finished ceramic. Failure occurred either cohesively within the board or adhesively at the interface between the stud and the conformal coating. Only one example of cohesive failure in the adhesive layer was observed. These results are quite different to those obtained for FR-4 where no failures of the pull stud - coating interface were observed. Figure 12 shows an example of cohesive failure within the ceramic substrate.

The quality of the adhesive joint between the coatings and pull studs appears to be satisfactory for the ceramic boards since the force required to detach them from the coatings is in excess of that required to cause cohesive failure within FR-4 boards. This suggests that the coating is more strongly coupled to the ceramic substrate than to FR-4. There is an indication in both sets of data that more force is required to cause actual failure of the board or cohesive failure within it than that required to cause adhesive failure at the interface of the pull stud and coating. Note also that in two cases the board itself catastrophically failed during the test.

4.3 SCRATCH TESTS

4.3.1 Gold finished FR-4

Figures A1, A2 and A3 (Appendix 1) show examples of scratch test results for ‘excellent’, ‘good’ and ‘poor’ adhesion of coatings to gold finished FR-4 boards following the guidelines stated in BS3900 pt 6. The rankings for each coating system are shown in Figure 13 for conformally coated FR-4 boards, most of the coatings show excellent adhesion (0 ranking) to the substrate with very little delamination of the film. Excellent adhesion of the coating to the substrate is associated with cohesive failure as measured by the butt tension test within either the coating itself or the substrate. Ranking coefficients in excess of zero appear to be associated with adhesive failure of the coating to the substrate as indicated by the butt tension test. This association does not appear to be valid for coatings SR1 or AC4.

4.3.2 Gold and silver finished ceramic boards

Figures 14a and 14b show the rankings for both silver and gold finished ceramic boards. There are no obvious links between these data and the results from the butt tension test, for example, the poor ranking of 4 for coating SR2 on gold finished ceramic is associated with adhesive failure at the junction of the pull stud with the substrate. Excellent adhesion rankings of zero are linked with both catastrophic board failure or cohesive failure within the board as well as adhesive failure at the junction of the pull stud and coating.

5 DISCUSSION

5.1 ADHESION OF COATINGS TO DIFFERENT SUBSTRATES

Table 3 summarizes the butt tension data and results from scratch testing for all of the coating/ substrate combinations.

	FR-4				Ceramic					
Coating	Filleted	Non-filleted			Silver finish			Gold finish		
	Type of failure	Type of failure	Pull-off force	Scratch test rank	Type of failure	Pull-off force	Scratch test rank	Type of failure	Pull-off force	Scratch test rank
AC1	CC	CC	M	0	SI	H	0	SI	H	0
AC2	AI	AI	M	1	SI	M	1	CB	M	0
AC3	CC	CB	M	0	CB	H	0	CB	H	0
AC4	CB	CB	M	2						
SR1	AI	AI	M	0	SI	L	0	SI	L	0
SR2	AI	AI	L	5	SI	L	4			
SR3	CB	CC	M	0	CB	H	0	CB	H	0
SR4	AI	CB	M	2	SI	M	2	SI	M	2
UR1	CC	CC	L	0	CB	H	0			
UR2	CB	CC	M	0	CB	H	0	CB	H	0
UR3	CB	CB	H	0	CB	H	0	CC	H	0
XY	AI	AI	L	2.5	CB	M	3			

Table 3: Summary of the type of failure, pull strength force and BS3960 rating for each coating/ substrate combination.
Key: CC – cohesive failure within a coating.
CB - cohesive failure within a substrate.
AI – adhesive failure at the interface between the coating and substrate.
SI – adhesive failure at the interface between the pull stud and a coating.
Pull-off forces have been classified as low (0-1.99 Nmm^{-2}), medium (2- 3.99 Nmm^{-2}) and high (>4 Nmm^{-2}).

From Table 3 the following conclusions can be drawn:

- Cohesive failure within the coating and substrate is associated with non zero ranking values of the scratch test.

- Cohesive failure within the coating or substrate are associated with zero ranking values of the scratch test.
- There is no obvious link between failure at the stud/coating interface and scratch test rating.
- The polyurethane coatings fail cohesively within the coating or substrate irrespective of the type of substrate.
- Coatings AC3 and SR3 fail cohesively within the coating or substrate irrespective of the type of substrate.
- With the exception of coating UR3 none of the coatings fail cohesively in the ceramic.

5.2 COMMENTS ON ADHESION TESTING

Table 4 shows a comparison between the butt tension and scratch tests. From this table it is apparent that more reliable data can be obtained using the butt tension method. However this technique does predominantly determine the adhesive properties of the pull stud/coating/substrate system in tension although in service the coatings will be subjected to predominantly shear stresses due to mismatched thermal expansion coefficients. This suggests that these data can only serve as a guide to in-service performance.

Butt tension test		Scratch test	
Strengths	Weaknesses	Strengths	Weaknesses
- Low cost. - Quantitative data generated. - Point of failure during decoupling of pull stud easily established. - Requires less area than scratch test.	- Requires attachment of pull studs to coatings. - Measures adhesive properties of the coating/ substrate in tension (CTE mismatch results in the coating being exposed to shear stresses) - Fillets on the base of the pull stud need to be removed before testing.	- Low cost - Requires no preparation	- Results operator dependent. - Coating subjected to complex stress field. - Results subjective. - No details of failure location available. - Requires large flat area for testing.

Table 4: The strengths and weaknesses of butt tension and scratch test techniques.

5.3 THE INFLUENCE OF THERMAL CYCLING ON ADHESION

The butt tension test data coupled with fractographic analysis shows that the adhesive properties of all the conformal coatings used in this study are not adversely affected by 10 thermal cycles of $-40^{o}C$ to $125^{o}C$.

5.4 ADHESION AND SIR PERFORMANCE

It has been suggested that the ability of different conformal coatings to protect the underlying circuitry from exposure to a hazardous environment could be related to the quality of the bond formed between the coating and the substrate. In a previous study[6] we assessed the performance of the conformal coatings listed in Table 1 during exposure to a range of different combinations of temperature and humidity by monitoring the surface insulation resistance (SIR) of double comb patterns. The environmental conditioning in these tests consist of superimposing a cyclic change in humidity (ranging from 10%RH - 90%RH) on to a stepped increase in temperature (40^{o}C - 80^{o}C). The period of the humidity cycle is two hours and the temperature at each 10^{o}C step remains constant for four hours.

The log SIR data for each coating are ranked in Table 5 according to a predicted value at 50^{o}C and a measured temperature dependence. Table 5 also contains the pull strength forces and rankings according to BS3960 for the thermally cycled conformally coated boards used in the present study. From Table 5 it is apparent that there is no link between the strength of the adhesive bond formed between the coating and the substrate and the SIR performance subject to that caveat that the FR-4 boards have been exposed to different environmental conditioning.

Generic coating type	Log SIR ranking of bare board and specific coatings (shown in bold)	Temperature dependence of log SIR as function of different coatings (shown in bold)
Acrylic	**AC1 > Bare > AC3 > AC4 > AC2** M > Bare >M > M > M 0 > NA > 1 > 0 >2	**Bare ≡ AC1 ≡ AC2 ≡ AC3 > AC4** Bare ≡ M ≡ M ≡ M > M Bare ≡ 0 ≡ 1 ≡ 0 > 2
Urethane	**Bare > UR2 > UR3 ≡ UR1** Bare > M > H ≡ L Bare > 0 > 0 ≡ 0	**Bare > UR1 ≡ UR2 ≡ UR3** Bare > L ≡ M ≡ H Bare > 0 ≡ 0 ≡ 0
Silicone	**SR2 > Bare ≡ SR3 > SR1 > SR4** L > Bare ≡ M > M > M 5 > Bare ≡ 0 > 0 > 2	**Bare ≡ SR2 ≡ SR3 > SR1 ≡ SR4** Bare ≡ L ≡ M > M ≡ M Bare ≡ 5 ≡ 0 > 0 ≡ 2
Paraxylene	**Bare ≡ XY** Bare ≡ L Bare ≡ 2.5	**Bare ≡ XY** Bare ≡ L Bare ≡ 2.5

Table 5: A comparison of the predicted log SIR values at 50 ^{o}C for gold finished FR-4 boards and the temperature dependence of log SIR measured under ***damp*** conditions[6]. The equivalent pull strength force and BS3960 ratings from table 3 are also shown for each coating.

Similarly there is no link between the surface insulation resistance of both conformally coated FR-4 and ceramic boards and the measures of the strength of the adhesive bond formed between the two (Table A1 of appendix 2).

6 CONCLUSIONS

The butt tension test is a viable destructive test for measuring the adhesion of conformal coatings to different types and finishes of substrate. Measurements of the force required to cause cohesive failure either within the coating or the substrate or at the interface between the two should be taken as an indication of performance rather than a criteria for a pass or fail. It is more instructive to examine the point at which failure occurs. A disadvantage with this particular test is that it measures the adhesive performance of the coatings in tension rather than in shear. Despite this limitation the test can still be used to assess the quality of adhesion of a coating to a substrate after it has been exposed to a period of thermal cycling. The scratch test is flawed as a measurement method because of its subjective nature and because of the complex stress field that it imposes on the coating. Some coatings particularly those based on silicones showed poor adhesion using this technique which was not confirmed by butt tension measurements or fractography. This may be attributed to the complex stress field imposed by cross hatching compared with butt tension.

With respect to the performance of coatings on different substrates the following conclusions can be drawn:

- Failure at the interface of the coating and substrate is associated with non zero ranking values of the scratch test.
- Cohesive failure within the coating or substrate are associated with zero ranking values of the scratch test.
- There is no obvious link between failure at the stud/coating interface and scratch test rating.
- The polyurethane coatings fail cohesively within the coating or substrate irrespective of the nature of the substrate (ceramic or FR-4).
- Coatings AC3 and SR3 fail cohesively within the coating or substrate irrespective of the nature of the substrate (ceramic or FR-4).
- With the exception of coating UR3 none of the coatings fail cohesively in the ceramic.

The butt tension test data coupled with fractographic analysis shows that the adhesive properties of all the conformal coatings used in this study are not adversely affected by 10 thermal cycles of $-40^{o}C$ to $125^{o}C$.

The performance of conformal coatings can be assessed by measuring the surface insulation resistance of coated double comb patterns during exposure to a range of different combinations of temperature and humidity. These data when compared of the pull strength force and BS3960 ratings for the same batch of conformally coated FR-4 and ceramic boards subjected to a different and more severe thermal cycling regime suggest that the level of adhesion is not related to SIR performance.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

1) ASTM/D/1876: ‘Standard test method for peel resistance of adhesives’, November 1995.
2) BS 3900 Part E6: Cross-cut test, 1974
3) M.G. Kruger, ‘ Elastomeric conformal coatings improve reliability of integrated circuits’, Proc. Nepcon West ’96, **1**, 479, 1996.
4) B. Brox and P. E. Tegehall, ‘Reliability of electronics in harsh environments’, Soldering and Surface Mount Technology, **21**, 13, 1995.
5) ASTM/D/1002: ‘Test methods for shear strengths of single lap joints’, 1994.
6) P.E. Tomlins and L. Zou, ‘Surface insulation resistance and the properties of conformal coatings’, National Physical Laboratory Report CMMT (A)267, May 2000.

APPENDIX 1: CLASSIFICATION SCHEME FOR CROSS HATCH TESTING (ACCORDING TO BS3960 PT6)

FIGURE CAPTIONS

Figure 1. A schematic representation of the butt tension test. The test method gives a measure of the force required to detach the pull stud from the coated board. This can happen through cohesive failure within the coating or substrate or at the interface between the two.

Figure 2. Inflation of the collar applies a tensile force to the coating and substrate via the pull stud until the point of failure.

Figure 3. The scratch test technique involves cutting a cross hatch pattern in a conformal coating with a cutting tool as shown in the photograph.

Figure 5. The force required to detach the pull studs from conformally coated FR-4 boards appears to be linked to the mode of failure. Not surprisingly larger forces are required to detach filleted pull studs from conformally coated boards in comparison with un-filleted studs as shown in A and B respectively. Note also that there is less variation in the force required to cause failure of the stud/coating/board system in the un-filleted studs.

Figure 6. Detachment of the pull stud from the substrate can occur cohesively within the coating or substrate or adhesively at the interface between the two. Figure 6a shows the location of failure points for filleted studs and figure 6b for un-filleted studs respectively for coatings adhered to FR-4.

Figure 7. An example of adhesive failure at the interface of the coating and FR-4 substrate (SR1 on FR-4, mag. X20).

Figure 8. Photomicrograph of cohesive failure within a conformal coating (AC3 on FR-4, mag. X22).

Figure 9. Photomicrograph of cohesive failure within FR-4 substrate (UR2 on FR-4, mag. X23).

Figure 10. The force required to detach the pull studs (un-filleted) from conformally coated gold (A) and silver (B) finished ceramic boards.

Figure 11. The location of failure points the pull studs (un-filleted) from conformally coated gold (A) and silver (B) finished ceramic boards.

Figure 12. Cohesive failure within a ceramic substrate (on mag. X20)

Figure 13. Rankings according to BS3960 pt 6 for different coatings applied to FR-4. Note that the scale begins at –1 so that 0 ranking adhesives are clearly seen.

Figure 14. Rankings according to BS3960 pt 6 for different coatings applied to gold (A) and silver (B) finished ceramic. Note that the scale begins at –1 so that 0 ranking adhesives are clearly seen.

Figure A1. An example of ‘excellent’ adhesion (Class 0 ranking) between a coating and FR-4 substrate (coating AC3 applied to FR-4).

Figure A2. An example of ‘average’ adhesion (Class 2 ranking) between a coating and FR-4 substrate (coating XY applied to FR-4).

Figure A3. An example of ‘poor’ adhesion (Class 5 ranking) between a coating and FR-4 substrate (coating SR2 applied to FR-4).

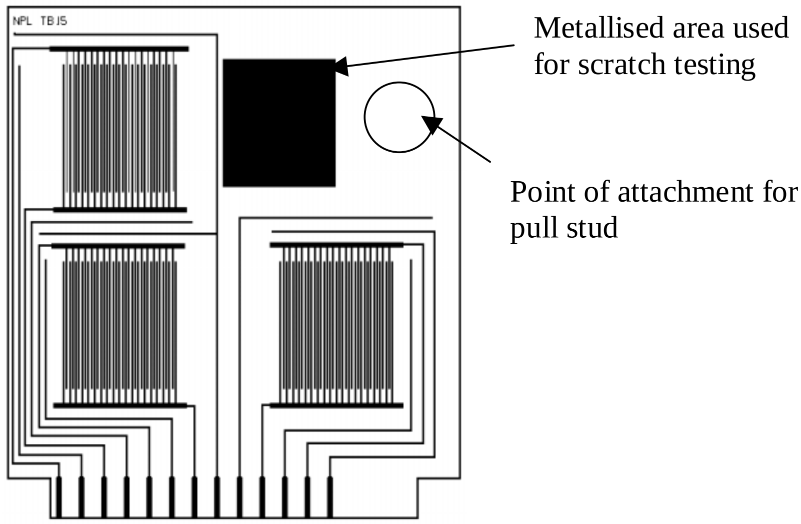
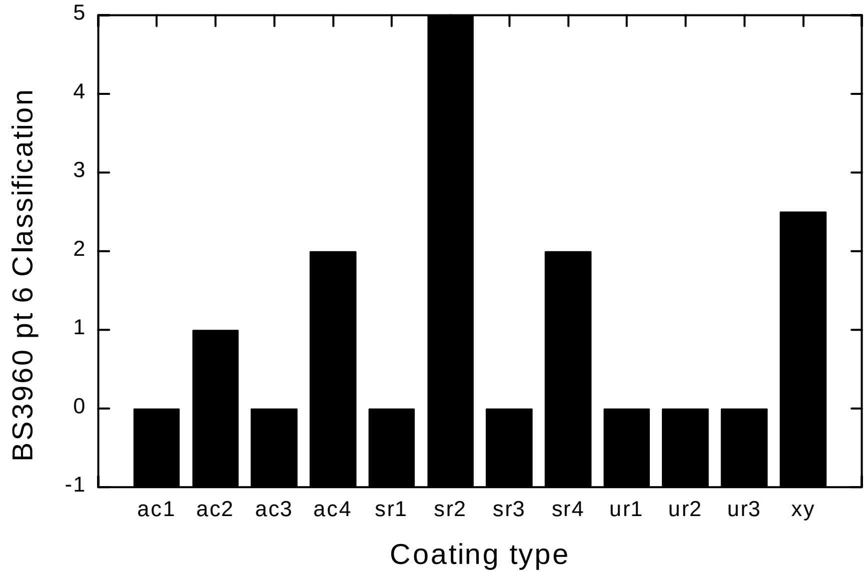


Figure 4: Test board showing the SIR double comb patterns and the areas used for butt tension testing and scratch testing.



BS3960 pt 6 Classification
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4
3
2
1
0
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ac2
ac3
ac4
sr1
sr2
sr3
sr4
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ur2
ur3
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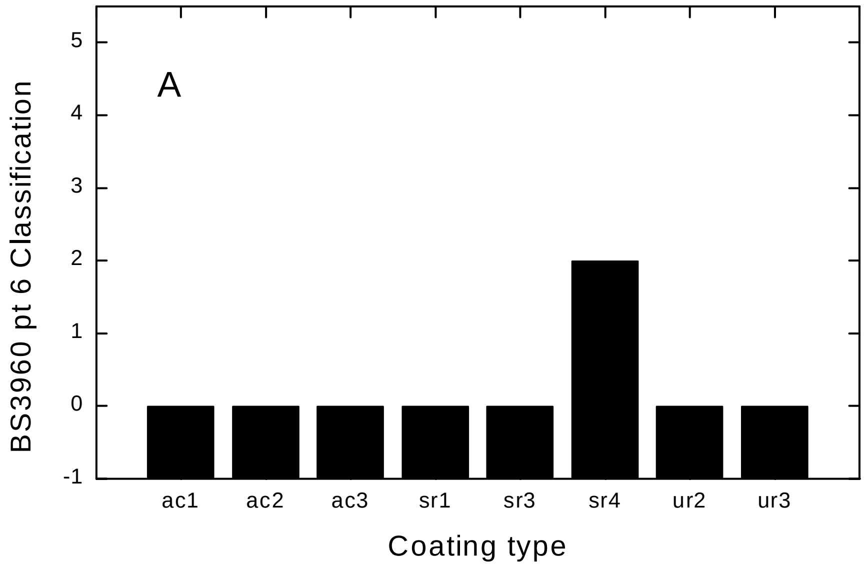
Coating type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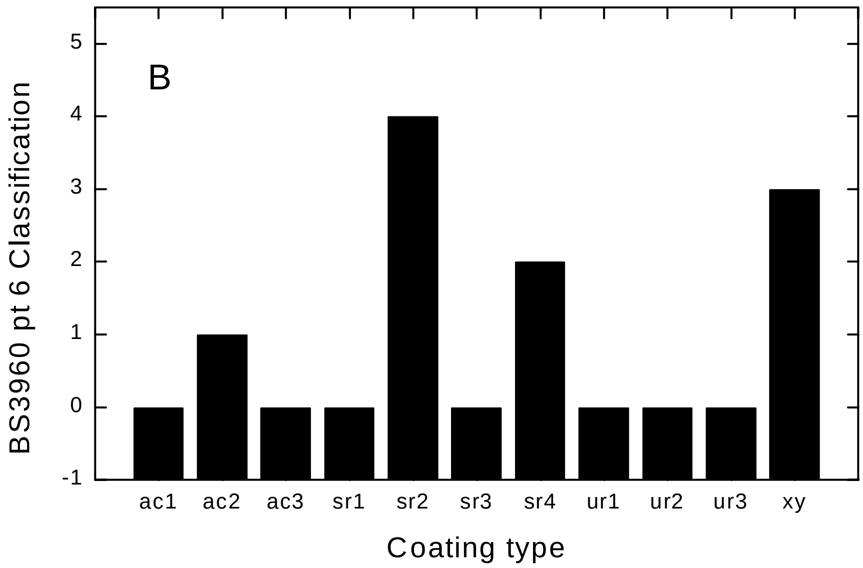
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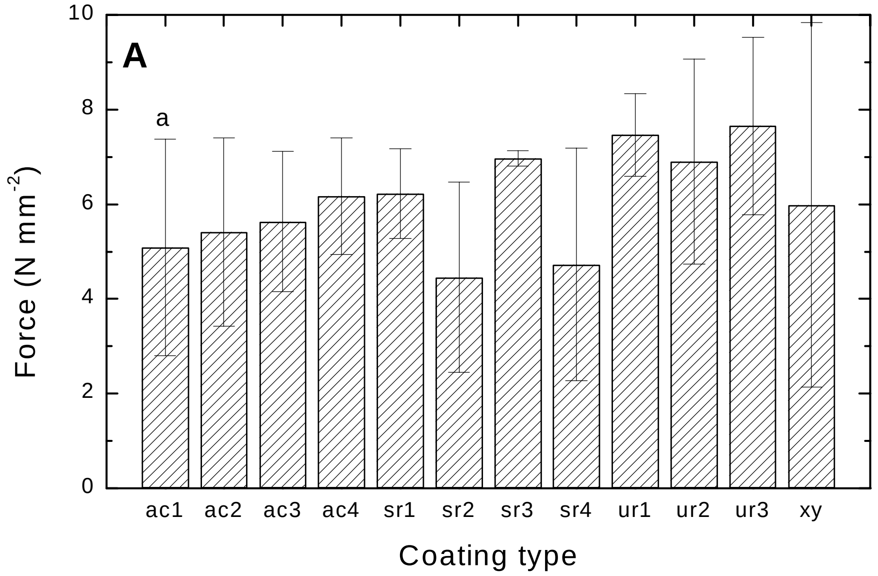
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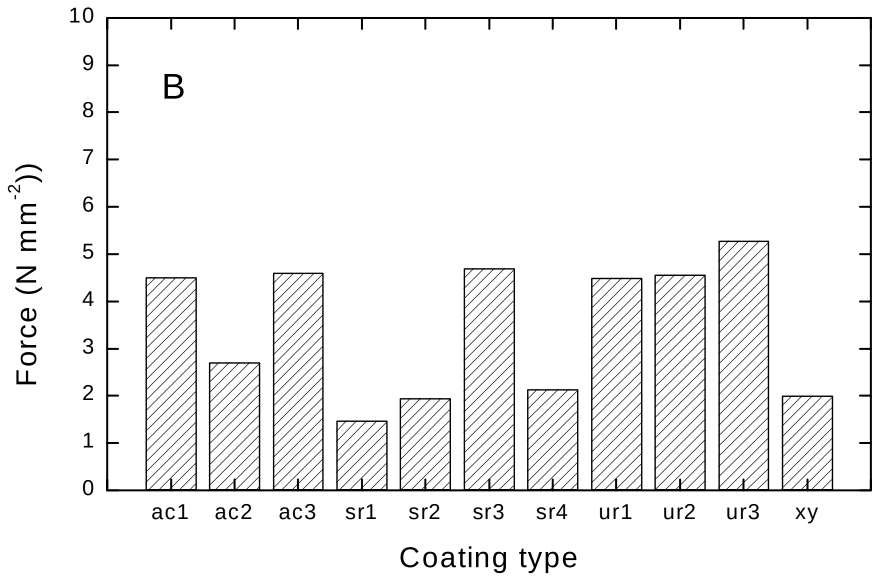
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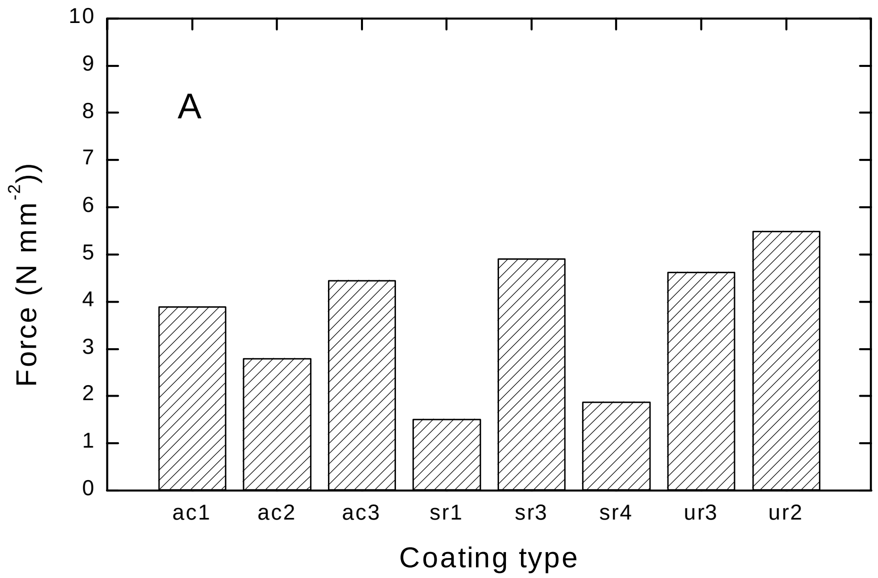
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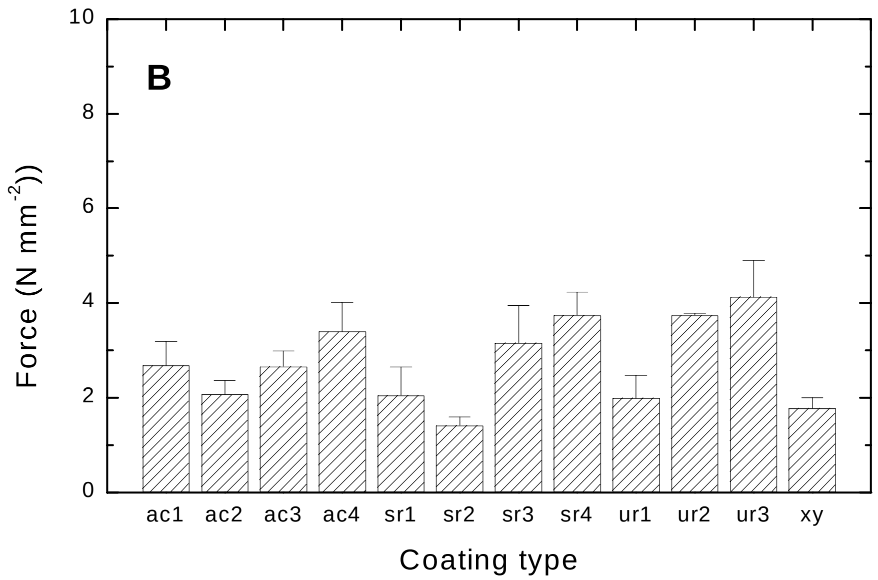
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Coating type