INVESTIGATION OF THE INFLUENCE OF SOME PAINT SYSTEMS AND WATER DISPLACING CORROSION INHIBITORS ON ANODIC UNDERMINING CORROSION OF ALUMINIUM 2024 CLAD ALLOY

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ABSTRACT

The influence of two low-chromate paint systems and two water displacing corrosion inhibitors (WDCI) on the anodic undermining corrosion behaviour of aluminium 2024-T3 clad alloy is investigated. Test methods used were the salt spray test and the alternate immersion test. Test results indicated that the use of a top coat layer in a low-chromate paint system may enhance the anodic undermining corrosion. This is attributed to a lower oxygen concentration in the blisters due to the reduced diffusion of oxygen through the thick paint layer. The oxygen concentration is too low to repassivate the anode. The application of a WDCI offers only a good protection as long as a good WDCI-layer is maintained. A partly washed off WDCI layer will result in an increase of the number of blisters.

Keywords

organic coatings   salt spray test
corrosion         alternate immersion test
paint systems     anodic undermining
water displacing corrosion inhibitors   paint blisters
aluminium alloy
blanko blz. 2
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1. INTRODUCTION

The application of an organic coating is one of the most important means available for the protection against corrosion of aircraft structures. An organic coating is often applied over a non-organic protective coating, such as a clad-layer, a chemical conversion coating or a man-made oxide film, but it can be used on bare materials as well.

A typical organic coating is a paint system. A paint system generally consists of several layers of paint, where every layer of paint has its own special function. The general build-up of a paint system is given in figure 1.

An other type of organic coating is formed by the so-called water displacing corrosion inhibitors (WDCI). Often a WDCI is used over a paint system, as a first barrier against corrosion, but it can also be used to protect non-painted materials.

A typical property of a WDCI is that it is able to penetrate easily into faying surfaces, cracks and other crevices and expels the water (when present) from these crevices.

An extensive literature review of paint systems and WDCI's (and other forms of protective coatings) is given in ref. [1].

A typical form of corrosion of painted aluminium alloys is the anodic undermining corrosion. A thin layer of the substrate material is selectively dissolved, so that the paint coating becomes detached (figure 2). Clad aluminium alloys are more susceptible to this form of corrosion than bare aluminium alloys, because of the lower nobility of the clad layer as compared to the base material. The clad layer will act as the anode in the corrosion process and is dissolved.

Also the diffusion of Cu-atoms from the base metal into the cladlayer, as is sometimes observed in Al-Cu alloys (e.g. Al-2024) increases the susceptibility to anodic undermining (figure 3). Addition of leachable chromates to the paint system can prevent or reduce the undermining corrosion. A more detailed discussion of undermining corrosion is also presented in ref. [1].

In the investigation described in this report the primary objective was to study the influence of some WDCI's, applied over a paint system, on the anodic undermining corrosion behaviour. So low chromate paint systems are used in order to exclude any interfering effects from leachable chromates. These low chromate paints are still frequently encountered in service.
2. EXPERIMENTAL PROCEDURES

2.1. General

The anodic undermining corrosion of clad Al-2024 T3 sheet material (with a thickness of 2 mm) was investigated in two different ways:
- by salt spray testing
- by alternate immersion testing.

The salt spray test is selected because this test is often regarded as the standard corrosion test. The alternate immersion test is used because this test is often used to investigate the performance of paint systems.

Two low chromate paint system are used:

System A: - etch primer
- polyurethane primer

System B: - same as system A, plus
- polyurethane topcoat

The paint systems were applied to the specimens by the paint manufacturer.

The water displacing corrosion inhibitors used in this investigation are Boeshield T-9 and LPS-3. Both WDCI's do qualify to the Boeing BMS 3-23 specification.

2.2. Salt spray testing

The salt spray testing has been performed in accordance with the ASTM standard B117 (5% NaCl-solution, T = 35°C), ref. [2]. The specimens were degreased and sprayed with an etch primer and a polyurethane primer (paint system A). Six specimens were also sprayed with a polyurethane top coat (paint system B).

After painting two X-shaped 'scratches' (indicated as X1 and X2) were milled through the paint and the cladding layer on one side of the specimen. The scratches are 2 mm wide and 0.2 mm deep. The largest scratch (X2) was almost completely covered by a piece of perspex in order to simulate a crevice condition. The specimen dimensions and configuration is shown in figure 4a.

Boeshield T-9 was applied to three specimens each with paint system A and B before the scratches were milled and the perspex was attached. Two specimens with paint system A were treated with Boeshield T-9 after the scratches were milled and the piece of perspex was attached over scratch X2. LPS-3 was applied to three specimens with paint system A before the scratches were milled and the piece of perspex attached. Two non-painted specimens (with scratches and perspex) were also included in the test as a reference. Also no WDCI was applied to these specimens. A survey of the combinations tested is given in table 1. The exposure time was 3425 hours.

2.3. Alternate immersion testing

The alternate immersion testing was performed in accordance with the French standard AFNOR A91-411 (ref. [3]). The testing apparatus is shown in figure 5. The closed cabinet was partly filled with a solution of 30 g/l NaCl, 1.25 g/l
H$_3$BO$_3$ (boric acid) and 0.19 g/l Na$_2$HPO$_4$ in distilled water. The pH of the solution was adjusted with Na$_2$CO$_3$ to pH 8. The solution temperature and the temperature of the air within the cabinet were kept at 35 ± 2°C. The solution was air-circulated to guarantee an even temperature distribution. The relative humidity of the air was about 97% as a result of the salt concentration in the solution. The testing cycle consisted of 2 hours immersion in the solution, followed by 2 hours in the air above the solution. The solution was refreshed once every two days. This proved to be necessary because of the contamination of the solution by the excess of WDCI on the specimens. After the first week, the solution was refreshed every ten days.

The specimens used in the alternate immersion tests are smaller than those used in the salt spray tests: 100 x 50 x 2 mm. After degreasing paint system A was applied to six specimens and paint system B to four specimens. One X-shaped scratch (2 mm wide and 0.2 mm deep) was milled through the paint coating and the clad layer on one side of the specimen. The specimen configuration is shown in figure 4b. In the alternate immersion tests only the Bueskell T-9 WDCI was used. The T-9 WDCI was applied to two specimens with paint system A and two specimens with paint system B before the scratch was milled and two specimens with system A after milling of the scratches. Also in this test a non-painted specimen was used as a reference. A survey of the combinations tested is given in table 1. The exposure time was 1500 hours.

2.4. Assessment of the corrosion damage

The standard procedure for the evaluation of the performance of a coating system is to measure the maximum corrosion penetration perpendicular to both sides of the artificial scratch. This procedure is also used in this investigation. Besides this standard procedure two other methods are used in order to investigate the influence of the measuring method on the test results. These alternative methods are:

- the total number of blisters occurring along both sides of the scratches is counted. As an evaluation parameter the number of blisters per millimeter scratch length is used,
- the total length of the scratch that is affected by corrosion is measured and expressed as a percentage of the total of the scratch length (both right and left sides).

The underlying philosophy of these alternative evaluation methods is that not only the maximum blister size is an important criterion to express the effectiveness of a paint coating, but also the total extent (the number of blisters or area affected by corrosion) of the corrosion damage.

In order to make all corrosion visible, paint blisters were carefully removed with the aid of a surgical blade. Cross-sections of some paint blisters were examined by optical microscope.
3. RESULTS

3.1. Salt spray testing

The specimens were removed from the salt spray cabinet after an exposure time of 3425 hours. The non-painted reference specimens showed a relatively light uniform surface corrosion with a few small pits. The area which had been covered by the piece of perspex showed more severe (crevice) corrosion (figure 6). The results of the painted specimens are presented in table 2 and figure 7.

From these results can be seen that the use of a primer system only or a primer + top coat system (without WDCI) does not make any difference in the number of blisters occurring. The number of blisters on the free exposed surface (scratch X1) is about 2-3 times larger than the number of blisters on the surface covered by the piece of perspex (scratch X2). Application of a WDCI increases the number of blisters on the free exposed surface (X1). This increase is larger when the WDCI was applied to the specimens before the scratches were milled. Inside the crevices (X2) the number of blisters is influenced both by the type of WDCI and the moment of application. The number of blisters on the specimens with T-9 is smaller than on the specimens with LPS-3.

A large increase in the distance which the blisters penetrated from the scratches is found when the specimens with primer + top coat are compared to those with primer only. This can also be seen in figure 8 where both types of specimens are shown.

For the specimens with a primer system only there is no difference in the penetration distance on the free surface (X1) and within the crevice (X2). For the specimens with primer + top coat the penetration distance in the crevice area is smaller than on the free exposed surface, but still considerably larger than it is for the specimens with primer only. The use of a WDCI has no, or only a small influence in the case of the specimens with a primer system. If the WDCI is applied after the scratches were milled there is a small increase in penetration length.

In the case of the specimens painted with a primer + top coat system, the maximum blister penetration is decreased when a WDCI is used, especially inside the crevice.

The percentage of the scratch length affected by corrosion can to some extent be regarded as resulting from the combined effect of blister size and the number of blisters. From the results shown in table 2 and figure 7 it can be seen that the percentage affected scratch length increases as the result of using WDCI on the exposed surface (X1). Inside the crevice (X2) however, the use of WDCI does not seem to have any important effect. Some increase in the percentage affected scratch length was also found for the specimens with primer + top coat. Generally, the percentage affected scratch length seems to correlate stronger with the number of blisters occurring than with the maximum penetration distance.

3.2. Alternate immersion testing

The non-painted reference specimen showed severe pitting corrosion after 1500 hours of testing. Examination of the pits by optical microscopy revealed that in the initial stage of pitting only the clad layer is dissolved. Once an insoluble crest of corrosion products has formed over the pit, dissolution of the base metal will also occur (figure 9).
The results of the painted specimens are presented in table 3 and figure 10.

On some specimens, the blisters showed a strong tendency to grow preferentially in the rolling direction of the material. This preferentially growth will have influenced the results of those tests. Specimens suffering from this directionality have been indicated in table 3 and figure 9 (of the specimens in the salt spray testing only one showed preferentially blister growth; this is also indicated in table 2).

The results of the alternate immersion testing are generally the same as those found in the salt spray testing. However, the differences in coating performance were much smaller than those found for the salt spray testing, although from the corrosion of the non-painted reference specimens it can be seen that the alternate immersion test was more severe than the salt spray test.

3.3. Microscopic examination of the blisters

The large penetration distances found for the specimens painted with the primer + top coat system (both with and without a WDCI) are associated with a relatively small number of large blisters occurring on these specimens (especially in the salt spray testing).

Most of the metal surface underneath these blisters showed dissolution of a thin layer of the cladding only. At some locations within the blisters (especially the largest blisters) the corrosive attack extended into the base material. The same observation was made for the specimens in the alternate immersion tests, although in these tests the maximum blister size was smaller (figure 11). Blister growth on the salt spray test specimens coated with the primer + top coat system (with and without WDCI) was observed to be very rapid initially, but stopped almost completely after some time.

The size of the blisters on the specimens coated with the primer system only (both with and without a WDCI) was much smaller than on the specimens with also a topcoat. Microscopic examination of these blisters showed that in many cases not only the clad layer was dissolved, but that also the base material was seriously attacked by corrosion, sometimes in a form resembling pitting corrosion (figure 12).

The forming of blisters not originating from the artificial scratches occurred in only a very few instances.
4. DISCUSSION

In the anodic undermining corrosion process the anode is located in the crevice between the metal surface and the paint coating at the edge of the detached area. Because diffusion of oxygen into this crevice is difficult, oxide formation occurs to slow for the anode to become repassivated. The cathode will most likely be located in the region where the coating has already detached and the material is repassivated. The oxygen necessary for the cathodic reaction will be able to reach the cathode via a break or thin spot in the paint. It is also possible that the cathode is located in the area surrounding the anode, where the coating is still intact. In this case the oxygen has to diffuse through the coating. This reduces the rate of oxygen transport to such a low level that it is possible that the cathodic reaction becomes rate controlling. On the other hand, a larger area may be available as the cathode, so that the cathodic reaction does not necessarily becomes rate controlling (ref. [4]).

Charge compensation, which is necessary for every corrosion process, may be provided by transport of the cations formed at the anode (Al$^{3+}$) towards the cathode, and of cathodically formed OH$^-$ ions towards the anode when the cathode is located in the detached area. Charge compensation may also be provided by diffusion of other anions, such as Cl$^-$, to the anode and cations, such as Na$^+$ or K$^+$, to the cathode. This method of charge compensation is also possible when the cathode is located outside the detached area. In that case the cations will have to diffuse through the paint coating. Koehler has shown that this is possible, especially at thin spots in the coating. He also showed that these cations and the cathodically formed OH$^-$ ions can be transported via the interfacial water, which is always present, so that charge compensation is possible.

In many cases ionic transport to or from the anode will be the rate controlling step in the corrosion process. When either this, or the anodic dissolution process itself is rate controlling, dissolution of exposed metal not located at the edge of the blister may take place, often in the form of pitting corrosion (ref. [5]).

It is now possible to explain the results of the experiments. As is mentioned before, the corrosive attack at the large blisters on the specimens with a primer + top coat paint system has mainly taken place by the dissolution of only a part of the cladlayer. This preferential dissolution indicates that at the edge of the blister (the anode) strong crevice conditions exists, meaning a very low oxygen concentration. Due to this low oxygen concentration, repassivation of the metal at the edge of the blister is not possible and the blister continues to grow.

Blister size on the specimens painted with a primer system only was much smaller than on the specimens with a topcoat. This indicates that the metal at the edge of a blister on a specimen coated with primer only is better able to repassivate, which results in a lower dissolution rate and thereby reducing blister growth. However, this limited dissolution rate at the edge of the blisters makes corrosive attack of the base material possible, because the clad layer cannot dissolve at a rate sufficiently high to protect the base material.

This different behaviour of blisters on specimens coated with different paint systems can best be explained by a difference in the oxygen concentration at the edges of the blisters. In the first case (primer + top coat system) the oxygen concentration at the edge of a blister is too low to repassivate the metal; in the second case (primer system only) the oxygen concentration is sufficiently
high to repassivate the metal at the edge of the blister. Microscopic examination of the blisters showed that the shape of the crevices is almost the same in both cases, so this can be eliminated as a cause of the different oxygen concentration.

The difference in oxygen concentration can best be explained by the difference in oxygen permeability of the two paint systems. Due to the difference in coating thickness, less oxygen can diffuse through the relatively thick layer of the primer + top coat system than through the much thinner layer of the primer only system. This difference in layer thickness of the two paint systems can also be observed in figures 11 and 12.

The observed sudden decrease in the rate of growth of the large blisters on the specimens painted with a primer + top coat system, most likely coincided with the first corrosive attack of the base metal. It is likely that at that moment the ionic transport processes to and/or from the anode at the edge of the blister has become rate controlling. An other possible explanation is that due to the large blister size the oxygen diffusion through the paint layer into the blister became sufficiently high to repassivate the metal at the edge of the blister. In both cases the limited dissolution rate of the clad layer at the edge of the blister made dissolution of metal at other locations possible.

The influence of the water displacing corrosion inhibitors is more difficult to explain. The results are more or less disappointing and not in agreement with the generally good service experiences (ref. [6,7]). However, it must be noted that after some time of testing, both for the salt spray testing as well as for the alternate immersion testing hardly any T-9 could be detected on the free exposed surfaces (X1) of the specimens. Some LPS-3 had also washed off, but a visible film of LPS-3 still remained. These observations correspond with the fact that during WDCI application, it was noticed that the characteristics of T-9 were more 'oil-like' and those of LPS-3 more 'wax-like'. The exposed surface underneath the perspex plate (X2) was mostly still coated with a largely intact film of WDCI (note: for the specimens which had their scratches milled after the WDCI was applied, it was necessarily to 'repair' the WDCI-film at the back of the specimen after milling because of the damage to the WDCI-film caused by the milling process. Unfortunately, this caused some of the relatively thin T-9 to penetrate between the perspex cover and the scratch X2. Also this film was largely intact after testing).

If the results of the tests are analyzed it can be seen from figure 7 that in the salt spray testing for both paint systems, especially on the free exposed surface where the WDCI is partly washed off, the number of blisters is increased by the application of a WDCI. The size of the blisters is not significantly influenced by the WDCI in the case of the primer only paint system and is decreased in the case of the primer + top coat paint system.

Inside the crevice (X2) where the WDCI film remained largely intact there is no significant influence on the number of blisters (note: the increase of the number of blisters on the specimens with primer + top coat + LPS-3 is mainly due to the fact the piece of perspex did not cover the whole area of scratch X2 (figure 4a). A relatively large number of blisters occurred in this case in the not covered area). The influence on the blister size is about the same as it is on the free exposed surface.

It is possible that when the WDCI is washed off, some WDCI (or a component of the WDCI) attaches to the metal in the scratch or remains on the metal (depending on whether the WDCI is applied before or after milling the scratches). This however does not constitute a good protective layer, as some parts of the metal are not covered. Localized corrosion can therefore initiate at the unprotected parts of the metal.

Wilson and Devereux found that when they added the WDCI (they used T-9 in their
investigation) to the testing solution, instead of applying it directly to the specimens, the WDCI still was an effective inhibitor (ref. [8]). This does suggest that T-9 contains at least one water soluble component which attaches to the metal and is able to inhibit corrosion. If this soluble component is preferentially absorbed at anodic sites (i.e. an anodic inhibitor), incomplete coverage will indeed enhance corrosion at the sites which remain unprotected, as has been suggested above. However, further investigation is necessary.

As far as the usefulness of the two test methods is concerned the following remarks can be made. Although the alternate immersion test was thought to be more severe than the salt spray test (and indeed the results of the non-painted reference specimens proved it was more severe), this test method did not provide any information that did not also result from the salt spray test. In fact, the salt spray test was much better capable of showing differences in coating performance than the alternate immersion test.

Of the damage assessment criteria used in this investigation the 'number of blisters' criterion proved to be a useful extension of the number of criteria. Together with the normally used 'maximum penetration distance' criterion, it provided useful information about the coating performance. The 'percentage of scratch length affected' criterion, which was very labour intensive to obtain, did not provide any information that was not available from the two other criteria, which were both much easier to obtain.
5. CONCLUSIONS

- The use of a top coat in a low chromate paint system on clad aluminium alloy may enhance anodic undermining corrosion. The top coat reduces the amount of oxygen available at the anode so that repassivation cannot, or is more difficult, to occur.

- Although the use of a top coat in a low chromate paint system has a negative influence from the corrosion protection point of view, other considerations (such as appearance or resistance to aggressive chemicals like hydraulic fluids) may require the use of a topcoat. The thickness of the top coat should be as thin as possible.

- Application of a water displacing corrosion inhibitor (WDCI) will only offer good protection against corrosion forms such as anodic undermining as long as a good WDCI film is maintained. This means that in areas where the WDCI can be washed off, regular re-application of the WDCI is required.

- A washed off WDCI film results in an increase of the number of blisters.
6. ACKNOWLEDGEMENT

The assistance of Sikkens B.V., Aerospace Finishes Division in Sassenheim, Holland in preparing the specimens is gratefully acknowledged.
7. REFERENCES


### 8. TABLES AND FIGURES

<table>
<thead>
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<tr>
<td>none</td>
<td>S(2)</td>
<td>I(1)</td>
<td></td>
<td></td>
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<tr>
<td>Etch primer polyurethane primer (system A)</td>
<td>S(3)</td>
<td>S(3)</td>
<td>S(2)</td>
<td>S(3)</td>
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<tr>
<td>Etch primer polyurethane primer polyurethane top coat (system B)</td>
<td>S(3)</td>
<td>S(3)</td>
<td>I(2)</td>
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</table>

S = salt spray test  
I = alternate immersion test  
( ) = number of specimens

Table 1: Survey of the combinations of paint systems and WDCI's tested.
<table>
<thead>
<tr>
<th>Damage criterion</th>
<th>WCDI + paint system + scratch</th>
<th>none</th>
<th>T-9 applied before scratch</th>
<th>T-9 applied after scratching</th>
<th>LPS-3 applied before scratching</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>X1</td>
<td>X2</td>
<td>X1</td>
<td>X2</td>
</tr>
<tr>
<td>number of blisters per millimeter scratch length (mm)</td>
<td>etch primer/ primer (system A)</td>
<td>0.048 0.074 0.063</td>
<td>0.025 0.033 0.025</td>
<td>0.171 0.183 0.166</td>
<td>0.033 0.019 0.017</td>
</tr>
<tr>
<td></td>
<td>etch primer/ primer/ topcoat (system B)</td>
<td>0.048 0.072 0.076</td>
<td>0.013 0.020 0.047</td>
<td>0.097 0.146 0.160</td>
<td>0.030 0.030 0.033</td>
</tr>
<tr>
<td>Maximum blister penetration from scratch edge (millimeter)</td>
<td>system A</td>
<td>2.20 1.95 1.55</td>
<td>2.15 2.05 2.15</td>
<td>2.20 1.90 2.00</td>
<td>1.75 1.90 1.85</td>
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<td></td>
<td>system B</td>
<td>17.6 19.5 6.5</td>
<td>12.1 9.3 11.85</td>
<td>10.05 12.45 6.30</td>
<td>4.75 6.90 3.55</td>
</tr>
<tr>
<td>Percentage affected length of scratch edges (X)</td>
<td>system A</td>
<td>7 9 7</td>
<td>4 6 5</td>
<td>29 38 34</td>
<td>7 4 5</td>
</tr>
<tr>
<td></td>
<td>system B</td>
<td>11 16 20</td>
<td>6 7 16</td>
<td>29 43 45</td>
<td>11 9 8</td>
</tr>
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</table>

Table 2: Results of the salt spray testing.

*) Result may have been influenced by directionality of blister growth.
<table>
<thead>
<tr>
<th>Damage criterion</th>
<th>WDCI paint system</th>
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<th>T-9 applied before scratching</th>
<th>T-9 applied after scratching</th>
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<tr>
<td>number of blisters per per millimeter scratch length (mm²)</td>
<td>etch primer/ primer (system A)</td>
<td>0.107</td>
<td>0.134</td>
<td>0.123</td>
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<td></td>
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<td>0.080</td>
<td>0.118</td>
<td>0.102</td>
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<td></td>
<td>etch primer/ primer/ top coat (system B)</td>
<td>0.110</td>
<td>0.080</td>
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<td></td>
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<td>0.078</td>
<td>0.131</td>
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<tr>
<td>maximum blister penetration from scratch edge (millimeter)</td>
<td>system A</td>
<td>7.20*</td>
<td>3.95*</td>
<td>2.70*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.00</td>
<td>2.75*</td>
<td>4.20*</td>
</tr>
<tr>
<td></td>
<td>system B</td>
<td>5.30*</td>
<td>2.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.25</td>
<td>7.90*</td>
<td></td>
</tr>
<tr>
<td>percentage affected length of scratch edges (%)</td>
<td>system A</td>
<td>41</td>
<td>59</td>
<td>72</td>
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<tr>
<td></td>
<td></td>
<td>47</td>
<td>51</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>system B</td>
<td>51</td>
<td>71</td>
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<td></td>
<td></td>
<td>22</td>
<td>82</td>
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Table 3: Results of the alternate immersion testing.

* results may have been influenced by directionality of blister growth
<table>
<thead>
<tr>
<th>coating</th>
<th>function</th>
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</thead>
<tbody>
<tr>
<td>a - oxide film</td>
<td>pre-treatment</td>
</tr>
<tr>
<td></td>
<td>adhesion</td>
</tr>
<tr>
<td>- or chemical conversion coating</td>
<td></td>
</tr>
<tr>
<td>- or etch primer</td>
<td>durability, decorative</td>
</tr>
<tr>
<td></td>
<td>and other functional characteristics</td>
</tr>
<tr>
<td>b - primer</td>
<td></td>
</tr>
<tr>
<td>c - intermediate coat *)</td>
<td></td>
</tr>
<tr>
<td>d - topcoat or finishing coat</td>
<td></td>
</tr>
</tbody>
</table>

*) not often used

Figure 1: General build-up of a paint system. Ref. [1].

![Diagram of anodic undermining]

Figure 2: The principle of anodic undermining: a thin layer of metal is dissolved, leaving the paint detached; anode and cathode are separated. Ref. [1].
Figure 3: The influence of a clad layer on anodic undermining behaviour. Ref. [1].

Top: pure aluminium cladding: the clad layer is dissolved and the base metal is protected,
Bottom: cladding with copper gradient:
only part of the cladding is dissolved, thereby increasing the rate of blister growth.
Figure 4: Dimensions of the test specimens.

a: salt spray test specimen
b: alternate immersion test specimen.
Figure 5: The alternate immersion test equipment.

Figure 6: The appearance of a bare reference specimen after 3425 hours of salt spray testing.
Figure 7: Results of the salt spray testing
Figure 8: A comparison of blister formation on a specimen coated with etch primer/primer (top) and a specimen coated with etch primer/primer/top coat (bottom) after 3425 hours of salt spray testing.
Figure 9: The two stages of pitting corrosion:
   a) only the clad layer is dissolved,
   b) also the base metal is attacked
     (clear field, magn. 72x).
Figure 10: Results of the alternate immersion testing.

x): results influenced by directionality of blister growth.
Figure 11: Blister formation and corrosion underneath the blister on a specimen coated with a primer + top coat system. Magn. 72x. a) dark field - b) clear field.
Figure 12: Blister formation and corrosion underneath the blister on a specimen coated with primer system only. Magn. 72x.
a) dark field - b) clear field.