

Resistance of Common PWB Surface Finishes Against Corrosion in Harsh Environments

Mustafa Özkök , Atotech Deutschland GmbH
Mario Gensicke, Atotech Deutschland GmbH.
Hugh Roberts, Atotech USA Inc
Joe McGurran, Atotech USA Inc
Guenter Heinz, Atotech Deutschland GmbH

ABSTRACT

Corrosion resistance is becoming one of the most important topics in the electronics industry. Corrosion results in field failures and huge losses, which annually total several billion U.S. dollars. The actual extent of losses caused by corrosion is not well documented in the industry. As such, corrosion is currently one of the most challenging topics and is acquiring more attention as a result of increased product warranties, new materials and process changes caused by recent legislation impacting the electronics industry.

Depending on the final application and the environment to which the product is exposed, the requirements for corrosion resistance can be significantly different. Products used in military, automotive and medical applications typically demand higher corrosion resistance than products for lower performance or lifetime expectations, such as consumer electronics or similar products used in non-aggressive environments. As a result, to avoid corrosion on electronic products each industry sector has essentially adopted its own reliability testing procedures and standards. These facts all lead to the question, "What is the right corrosion resistance level of the surface finish for a particular product?"

One key function of surface finishes on printed wiring boards (PWB) is the protection of the underlying metal surface from environmental influences until assembly operations, such as soldering or wire-bonding, are performed. Also, after assembly there are areas on the PWB that are not covered by solder, including contact pads, test pads, heat seal and heat sink areas and the inside of through holes and vias. These areas are covered only by the surface finish and must still be resistant against any corrosive environment in the field. When corrosion occurs on a surface finish the metal decays and undefined corrosion products are created. The result of this process could be either an "open", caused by attack of the underlying copper or a "short", caused by creep from undefined corrosion products.

This paper investigates the performance of eight primary types of surface finishes using four different corrosion tests. The compiled data, findings and recommendations are offered as a guide to selecting the most suitable surface finish based on the end use application and required level of corrosion resistance.

INTRODUCTION

In particular, for the automotive and handheld electronic device industries the PWB requirements concerning reliability and lifetime are steadily growing. In addition, the highly competitive automotive industry offers extended warranties for cars (now three to five years), making the reliability of an electronic device a decisive product and cost advantage. Corrosion damages to the PWB surface are often the main reasons for a reduced reliability and product lifetime.

One function of the surface finish on PWBs is to withstand corrosive impacts until assembly operations are completed. However, areas not covered by solder after assembly, such as heat sinks and the inside of through holes and vias, must be protected in the field against harsh corrosive conditions. Therefore, it is imperative to choose the appropriate surface finish based on all final influences and specific product requirements for the end-use environment.

This paper discusses the corrosion resistance of seven common surface finishes. In the course of the investigations the performance of the surface finishes was determined via four standard industry corrosion tests. The results are finally presented as a guide, which should help in the selection of the most suitable surface finish based on the end-use requirements.

BACKGROUND

In general, corrosion is an interaction process between a material, adjacent materials and the environment. From a physiochemical point of view corrosion is the reaction of a system, which leads to a change of the material properties. It can cause defects by damaging the adjacent devices of the system, thus impairing the material function. In the final stage the corrosion can result in the total loss of the system functionality.

It is important to understand which conditions promote corrosion and what types of failure that corrosion products can generate. High humidity combined with a strong airflow and a saliferous environment can generate a harsh, corrosive atmosphere. Also, the presence of environmental gases (NO₂, SO₂, Cl₂) in conjunction with a certain level of humidity can have strong detrimental effects on the PWB surface finish. Many possibilities for corrosion-triggering errors exist within the PWB fabrication sequence, which can also be cumulative. For example, this path can begin with

an unfavorable circuit design, followed by poorly controlled plating conditions and solder mask application. Improper storage and packing of the boards before assembly can further contribute to corrosion susceptibility. Storage is also critical following arrival of the PWBs at the assembly operation, when the boards are unpacked and cleanliness prior to soldering is decisive.

Another reason for corrosion is a significant difference in galvanic potential between precious metals and underlying base metals. A greater difference in electrochemical potential between two materials results in a stronger corrosive effect.

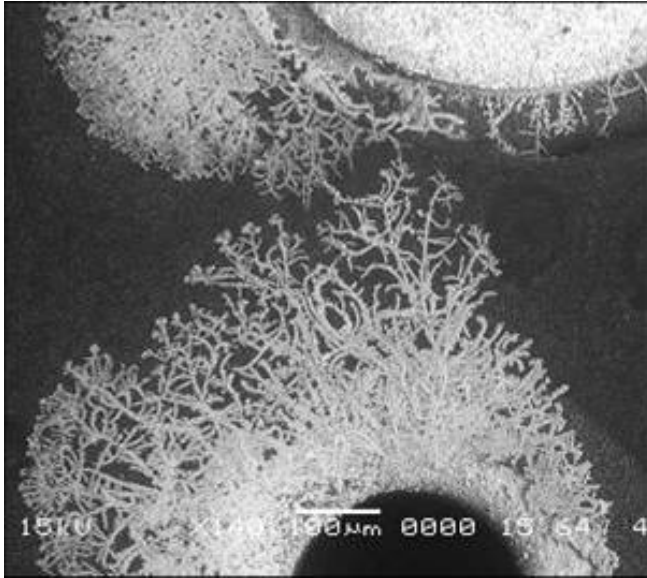


Fig. 1 Device with immersion silver surface finish. Cu_2S precipitates out of solution in a dendritic structure [2]

The corrosion products are various oxide compounds with different physical characteristics. These multi-colored oxide mixtures can cause a variety of electronic failures, ranging from interruptions to shorts. Also, such corrosion can cause damaged switch contact areas and contact losses in electronic devices.

Corrosion Mechanism

In general, the corrosion mechanism can be divided into two simple steps. In the first step, commonly known as tarnishing, oxygen from the air is adsorbed on the metal surface. Via a chemical oxidation reaction, a thin metal oxide layer is formed between the metal surface and the absorbed oxygen. In the second step, known as scaling, the metal electrons and cations are typically migrating to the outer surface (rarely does oxygen diffuse inside the metal layer). Ultimately, different oxides form on the metal surface as its porosity increases and the functionality of the PWB is damaged or possibly destroyed.

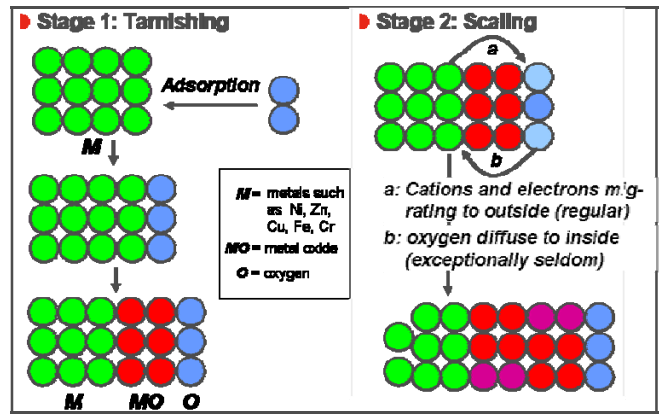


Fig. 2 Overview of the corrosion mechanism

DESCRIPTION OF TESTING

To evaluate the corrosion resistance of common PWB surface finishes four different tests were designed, simulating a reasonable range of corrosion influences. The selected tests differ with respect to corrosion atmosphere and corrosion medium. The following Tests were used for this investigation:

- SO₂-Gas-Test
- Kesternich Test
- Salt-Spray Test
- Surface Insulation Resistance Test

Table 2 presents an overview of the selected surface finishes.

To obtain comprehensive results about the surface changes every test is conducted for up to 6 cycles. In the industry standards like DIN 50021/ ISO 9227 corrosion testing is usually done for one or two cycle.

In the following sections the corrosion tests and the surface finishes are described in more detail.

Test Vehicles

For the SO₂-Gas Test, Kesternich Test and Salt-Spray Test an Atotech corrosion test vehicle was used, as shown in Figure 3. For the SIR Test a standard IPC Multi-Purpose test board was employed, shown in Figure 4. In the analysis only the test vehicle designs identified in the figures as “detail” were used to evaluate the corrosion resistance of the surface finishes.

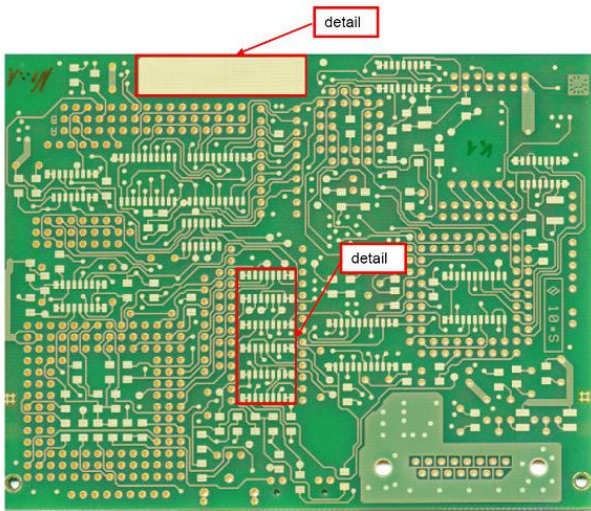


Fig. 3 Atotech corrosion test vehicle

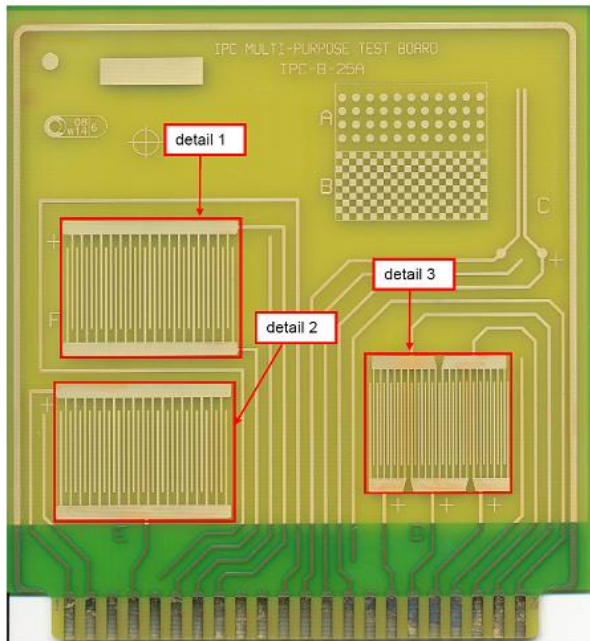


Fig. 4 IPC Multi-Purpose Test Board (IPC-B-25A)

Surface finishes

The test vehicles were fabricated with five different surface finishes:

- Electroless nickel/immersion gold (ENIG)
- Electroless nickel/electroless palladium/immersion gold (ENEPIG)
- Immersion silver
- Immersion tin
- OSP (organic solderability preservative)

Table 2 presents a summary of the surface finishes included in the investigations. As shown, two versions of ENIG and ENEPIG surface finish were examined, differing primarily in terms of the presences of phosphorus in the palladium layer.

Table 2: Summary of Surface Finish Specifications	
Surface Finish	Thickness
ENIG (7 - 9.5w%P) Med P	Ni 5µm / Au 0.07µm
ENIG (10-13w%P) High P	Ni 5µm / Au 0.07µm
ENEPIG (Ni-P / Pd / Au)	Ni 5µm / Pd 0.1µm / Au 0.03 µm
ENEPIG (Ni-P / Pd-P / Au)	Ni-P 5µm / Pd-P 0.1µm / Au 0.03µm
Immersion Sn	Sn 0.8-0.9 µm
Immersion Ag	Ag 0.3-0.5 µm
OSP	Organic surface

SO₂-Gas Test

The SO₂-Gas test simulates a high humidity environment containing sulfur dioxide. The test is a standard corrosion test in the mobile phone industry. The Atotech corrosion test board, described in the previous section, was used for this test. According to DIN 50018:1997 and ISO 6988:1985, the SO₂-Gas Test is performed under the following conditions:

- Number of cycles: 6 consecutive
- Cycle duration: 24h
- SO₂ content: 10 ppm
- Temperature: 42°C
- Heating of desiccator in oven

Following all cycles, an optical inspection of a 5x5 mm area at a 10x magnification is used for evaluation. Pass/ fail criteria are based on the total counts of pores and corroded products generated. To illustrate, an example of the pass/ fail criterion is shown in the figure 5.

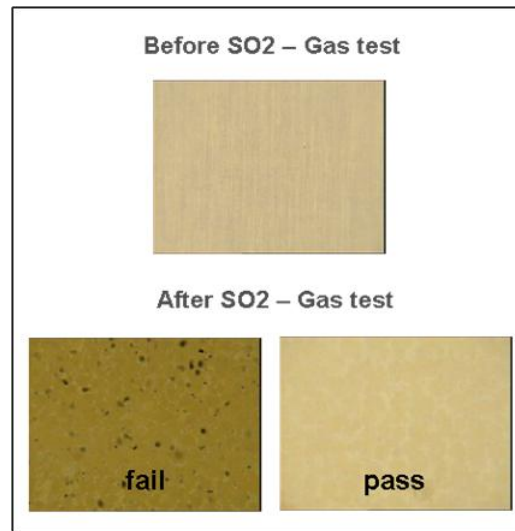


Fig. 5 Example of pass-fail criteria for the SO₂ Gas Test

Kesternich Test

The Kesternich Test is a standard, highly reproducible industrial test for protective coatings, particularly for evaluating the detrimental effects of acid rain. The test is

based on DIN EN ISO 6988 and is conducted under the following conditions.

- Number of cycles: 6 (consecutive)
- Cycle duration: 24h
- Heating: 8h / 40°C / 100% rel. humidity
- Ventilation: 16h / RT / <75% rel. humidity
- SO₂ content: 200 ml / 300 l chamber

Equipment used for Kesternich testing is shown in Figure 6. The chamber design allows the testing of any test sample layout. After all test cycles are complete an optical inspection at 50x magnification is used for evaluation.



Fig. 6 Kesternich-test chamber

Salt-Spray Test

The Salt-Spray Test is an accelerated corrosion test, which simulates a corrosive attack in a harsh marine climate. The procedure is also a standard test in the electronic industry, based on the DIN 50021/ ISO 9227. According to this standard, the test was performed under the following conditions:

- Test solution NaCl*: 50 g/l
 - Test solution pH*: 6.0-7.5
 - Temperature: 35°C
 - Spray volume:: 1.5 ml/h (16h average)
- *makeup; no adjustment

Figure 7 shows typical equipment used for this testing.



Fig. 7 Salt-Spray Test Chamber

Because of the multivariable layout of the chamber, testing of any sample layout is possible. After exposure in the test chamber, the samples were optically inspected at 50x magnification.

Surface Insulation Resistance (SIR) Test

The SIR Test is a common investigation measuring the electrical resistance between two conductors. The objective of the test is to assess the potential failure of PWB assemblies through corrosion and other processes associated with ionic contamination. In a case of electrical voltage between the conductive lines the contamination (salts, humidity) functions as an electrolyte and is, therefore, conductive. The electrical resistance is reduced and short-circuiting is eventually possible.

For the SIR Test an IPC-B-24-380 test vehicle with 520-µm lines and spaces was used. The samples were evaluated based on two pass/fail criteria: (1) the dendrite growth must be less than 25-percent of spacing and (2) the resistance must be greater than 10⁸ Ohms. The test conditions were as follows:

- Temperature: 85°C
- Relative Humidity: 85%
- Duration: 7 days
- Bias: 50V

TESTING RESULTS

Every corrosion test was performed for every single surface finishing for multiple cycles. The guidelines for qualifying the corrosion effects on the surface were as follows:

- **No surface tarnish**
- **Minor surface tarnish**
- **Major surface tarnish**
- **Minor surface corrosion**
- **Major surface corrosion**

Testing Results – SO₂ Gas Test

The samples from the SO₂ Gas Test were analyzed in the following exposure conditions:

- As received (AsR) without SO₂ exposure
- After one reflow without SO₂ exposure
- As received (AsR) with SO₂ exposure
- After one reflow with SO₂ exposure

Figure 8 shows the results for the two ENIG and two ENEPIG surface finishes. After one reflow the finishes show no corrosive changes. Only the ENEPIG (Pd-Phosphor) surface is slightly tarnished. Also in the states, “AsR SO₂” and “One Reflow SO₂”, the corrosion resistance of the layers remains largely unchanged. Only the ENIG (medium P) and ENEPIG (Pd-P) finishes exhibit slight corrosion.

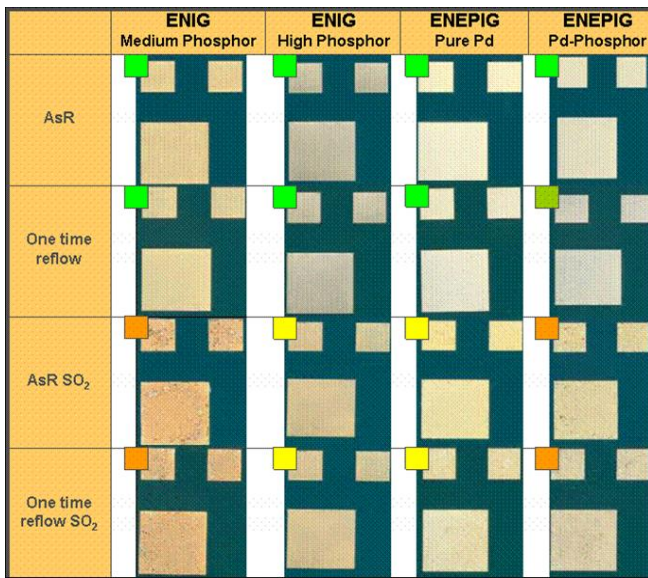


Fig. 8 SO₂ Gas Test results for ENIG and ENEPIG

In Figure 9 the SO₂ Gas Test results for immersion silver, immersion tin and OSP finishes are presented. As shown, a single reflow exposure did not pose a problem for any of the three finishes. However, it is apparent that the corrosion resistance of immersion silver was fully destroyed in the presence of small amounts of SO₂. The OSP surface also exhibits unsatisfactory results under SO₂ gas influence. By comparison, the immersion tin surface finish passed the test with relatively good results. After one reflow with SO₂ exposure the immersion tin surface was significantly tarnished, but the corrosion resistance was still maintained.

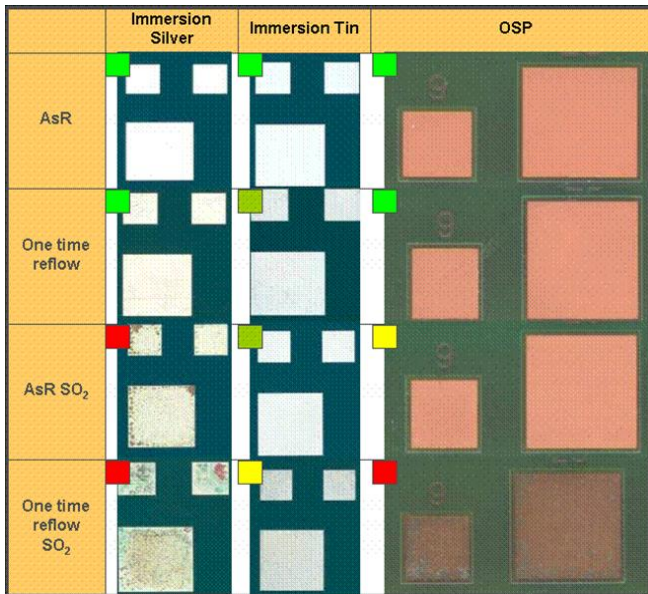


Fig. 9: SO₂ Gas Test results for immersion silver, immersion tin and OSP

Testing Results – Kesternich Test

In the Kesternich Test the performance of the selected surface finishes was evaluated over six cycles. Figure 10 summarizes the results for the ENIG and ENEPIG surface finishes.

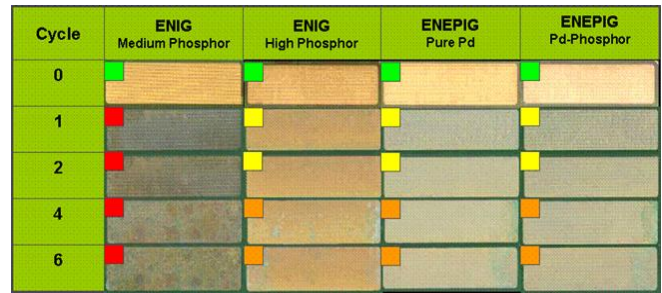


Fig. 10 Appearance of coupons after the Kesternich Test for ENIG and ENEPIG finishes

In general, the ENEPIG surface exhibited good corrosion resistance in this simulated harsh industry environment. Through the sixth cycle the ENEPIG surface displayed only slight corrosion. However, the two ENIG finishes performed quite differently under the applied conditions. The ENIG surface with medium phosphorus was totally corroded after only one cycle. By comparison, the ENIG surface with the high phosphorus content was only slightly corroded, even after the last test cycle. This result supports the theory that higher phosphorus content in the nickel deposit plays a critical role in maintaining the overall corrosion resistance.

The Kesternich Test results for the immersion silver, immersion tin and OSP finishes are presented in Figure 11.

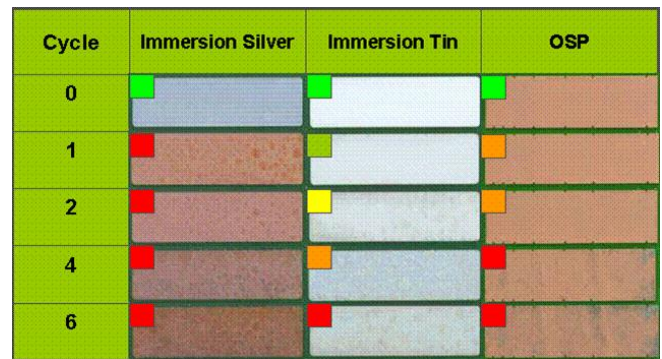


Fig. 11 Appearance of immersion silver, immersion tin and OSP coupons after the Kesternich Test

As shown in the figure, immersion silver achieved only a very limited level of corrosion resistance. After only one cycle (day) the original surface was already degenerated. By comparison, both OSP and immersion tin showed significantly less deterioration with increasing number of cycles. The immersion tin finish, in particular, exhibited excellent corrosion resistance in this test.

Testing Results – Salt Spray Test

The Salt Spray Test was performed over six cycles to simulate the worst possible exposure identified in the test protocol. Figure 12 summarizes the results of the Salt Spray Test for the ENIG and ENEPIG surface finishes.

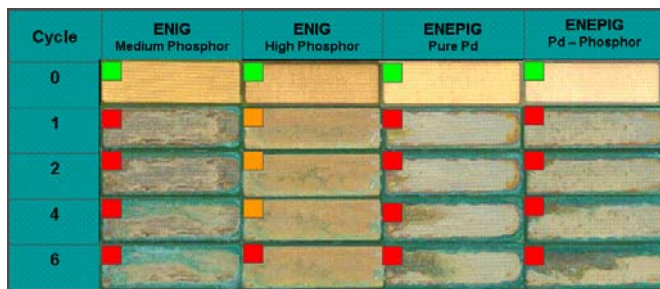


Fig. 12 Appearance of coupons after the Salt Spray Test for ENIG and ENEPIG finishes

Because the Salt Spray Test simulates a very harsh marine environment, the corrosion on the surfaces can be significant, as clearly shown on the ENIG (Medium P) and on both ENEPIG surfaces. However, by comparison, the ENIG finish with high phosphorus content showed only slight evidence of corrosion through the fourth cycle. This finding again supports the highly positive influence of the higher phosphorus content in the nickel layer for the corrosion resistance of ENIG.

Figure 13 presents the results of the Salt Spray Test for the immersion silver, immersion tin and OSP surface finishes.

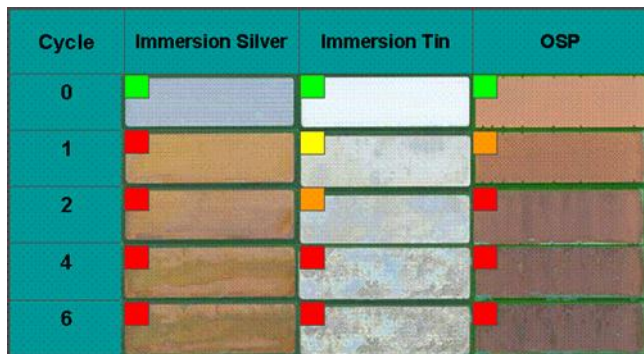


Fig. 13 Appearance of immersion silver, immersion tin and OSP coupons after the Salt Spray Test

Similar to the performance of the ENIG finish with high phosphorus content, the immersion tin surface offers some corrosion resistance through the second test cycle. However, under the harsh conditions of the Salt Spray Test the immersion silver and OSP finishes provide inadequate corrosion protection.

Test Results – Surface Insulation Resistance (SIR) Test

As previously mentioned, results from the SIR test indicate the presence of ionic contamination. In addition to measuring the SIR, an optical inspection (50x magnification) was performed to observe any dendritic growth. Because OSP is a non-metallic layer (i.e. insulator) SIR investigations of this surface finish are not meaningful.

Figure 14 shows the visible results of SIR testing for the following conditions:

- As received (AsR)
- After three days and 3x reflows
- After seven days and 3x reflows

As shown in the figure, dendritic growth was not visible for any tested samples.

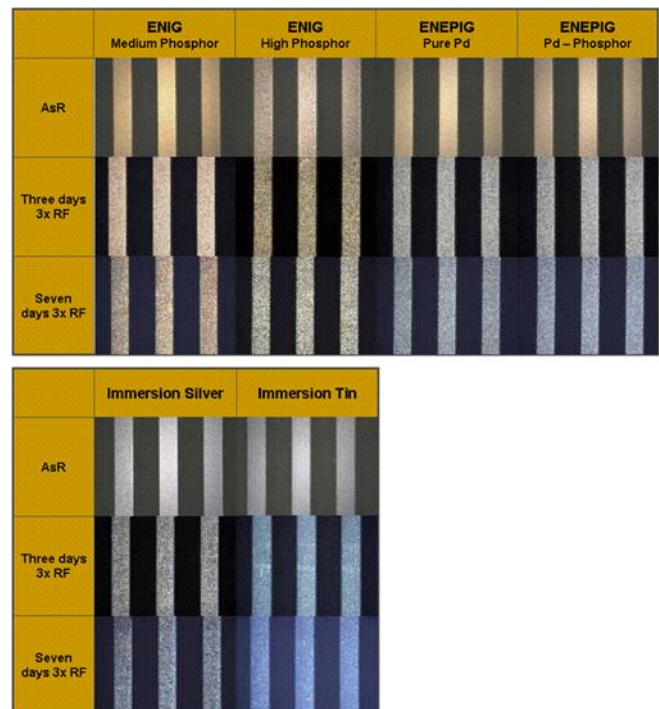


Fig. 14 Detail view of the SIR test results for ENIG and ENEPIG (above) and for immersion silver and immersion tin (below)

Figure 15 shows the measured insulation resistance for each surface finish sample for the following conditions:

- As received plus four days
- As received plus four days, followed by 3x reflow, followed by four hours at 155°C.

As shown in the figure, both the automotive OEM specification (500 MOhm) and the IPC specification (100 MOhm) were passed by all tested surface finishes.

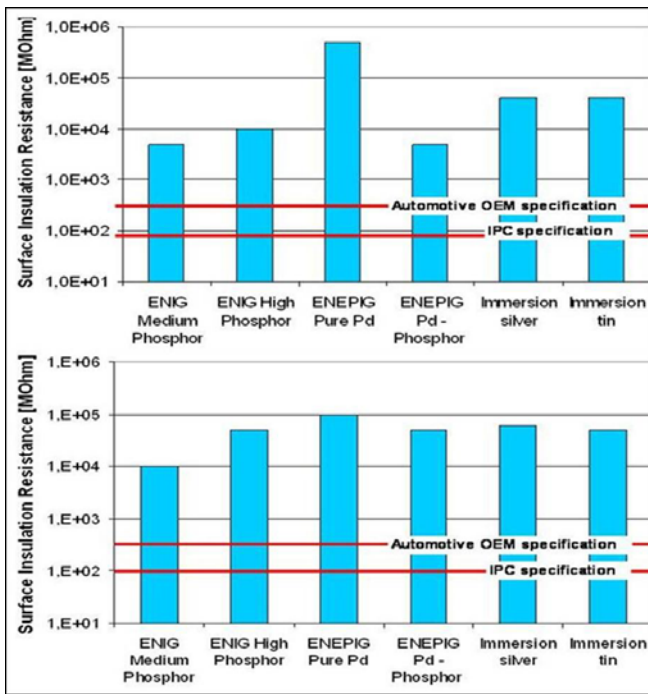


Fig. 15 Summary of the measured SIR as received plus four days (above) and after four days followed by 3x reflow, followed by four hours at 155°C (below)

DISCUSSION

Four different test methodologies were employed in this investigation to examine the susceptibility of surface finishes to corrosion. In this section the results for the seven different common surface finishes are summarized and discussed.

ENIG (Medium Phosphorus)

The tests performed in this study have shown that, as a surface finish, ENIG with medium phosphorus content in the electroless nickel deposit has limited corrosion resistance. As such, an additional protection of the surface against harsh environmental influences would be necessary. The following diagram summarizes the corrosion test results.

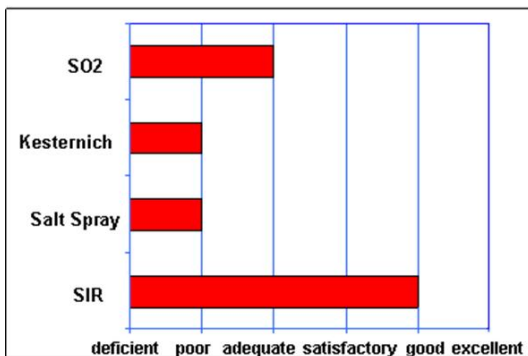


Fig. 16 Corrosion test results for ENIG (Medium P)

Because of its good contact resistance characteristics ENIG (Medium P) is commonly used for mobile phone keypads and for heat seal applications. Because of its Al-wire bonding capability and multiple Pb-free solderability, this finish is widely accepted, especially in the automotive and consumer electronics segments.

ENIG (High P)

The ENIG surface finish with increased phosphorus content in the nickel layer clearly achieved better corrosion resistance results, as summarized in Figure 17.

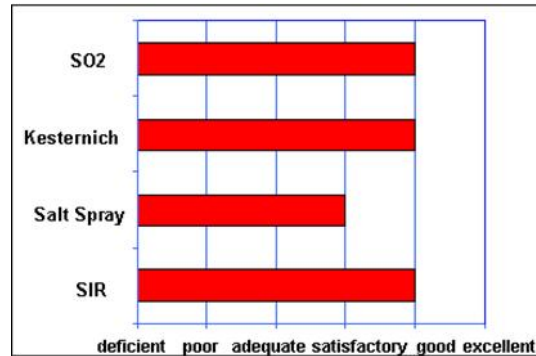


Fig. 17 Corrosion test results for ENIG (High P)

As shown, ENIG (High P) performed well in all corrosion tests. Therefore, it has found applications on mobile phone keypads that require a higher degree of corrosion protection. The primary assembly procedures are very similar to those for ENIG (Medium P). The Al-wire bondability and multiple Pb-free solderability are the main characteristics of this finish. Its suitability in heat seal and key pad (mobile phone) applications is an added benefit of ENIG (High P).

ENEPIG (Pure Pd)

Analysis of the test results has shown that ENEPIG with a pure palladium deposit performed comparably to ENIG (High P) in terms of its corrosion resistance. As shown in Figure 18, its performance in the Salt Spray Test was slightly lower, compared to ENIG (High P). In a direct comparison to ENIG (Medium P), the ENEPIG (Pure Pd) performed much better in both the SO₂-Gas Test and the Kesternich Test.

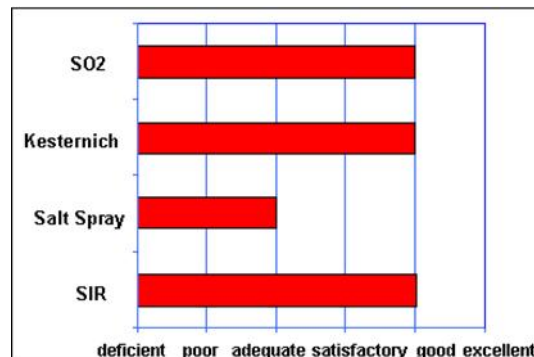


Fig. 18 Corrosion test results for ENEPIG (Pure Pd)

ENEPIG (Pd-Phosphorus)

The ENEPIG (Pd-P) finish did not perform as well in the SO₂ Test as the ENEPIG with the pure palladium layer. Otherwise, the two finishes performed similarly in terms of corrosion resistance. A summary of the test results is given in figure 19.

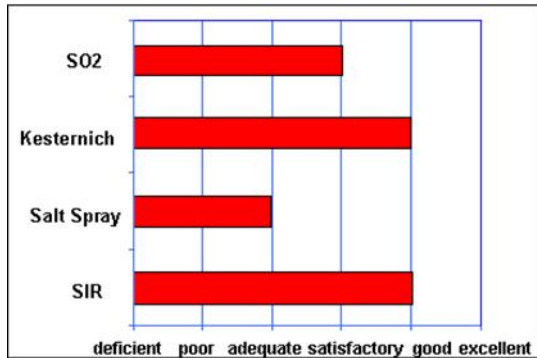


Fig. 19 Corrosion test results for ENEPIG (Pd-P)

Immersion Silver

Based on the testing performed, immersion silver provided the lowest level of corrosion resistance of the surface finishes tested. As such, an additional corrosion protection against environmental influences would be necessary. Figure 20 summarizes the corrosion test results for the immersion silver finish.

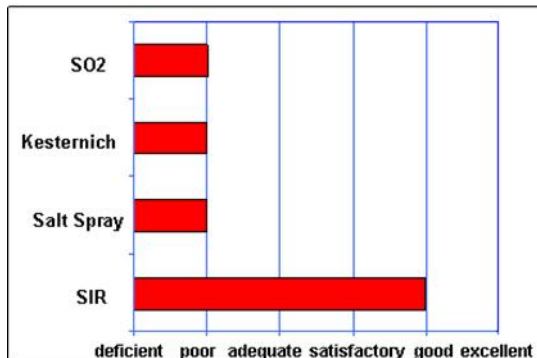


Fig. 20: Corrosion test results for immersion silver

Immersion Tin

Because of its suitability for both eutectic and Pb-free soldering, as well as compliant pin assembly applications, immersion tin satisfies a wide range of performance requirements for PWBs in the automotive industry. One important reason for its widespread use in the automotive sector is the excellent corrosion resistance of the surface. Overall, no finish in the test series delivered better results. Figure 21 shows a summary of the test results for the immersion tin finish.

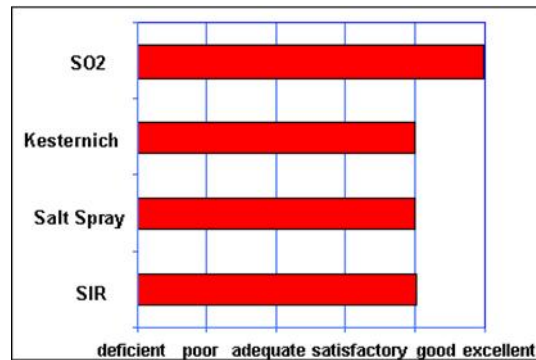


Fig. 21 Corrosion test results for immersion tin

Three primary mechanisms protect the immersion tin surface against harsh environmental influences. The first one mechanism is called passivation and is illustrated in Figure 22.

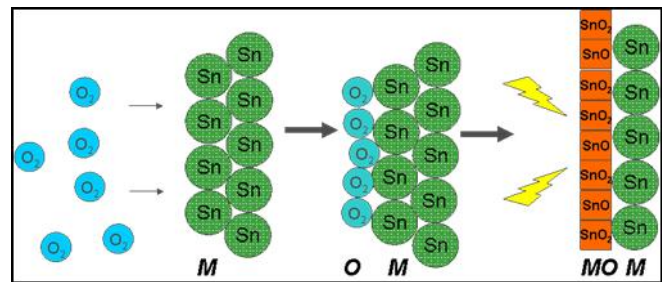


Fig. 22 Passivation of the immersion tin surface [1]

In the first step, oxygen molecules from the air are adsorbed onto the tin surface. In a second step, the oxygen molecules react with the tin atoms and create a thin, pore-free tin-oxide layer (SnO/SnO₂), providing the tin surface with a high degree of corrosion resistance.

The second mechanism is the build up of a high hydrogen overvoltage by the tin oxide formation. This avoids the reaction with water molecules in a humid environment. This “hydrogen overvoltage” provides the immersion tin surface with a high resistance against acidic environmental influences. [1]

The third step is the formation of the copper tin IMC this copper tin alloy (bronze) is known as very corrosion resistant.

OSP

As the only non-metallic finish examined, OSP was found to provide limited corrosion resistance. The tests have shown that the corrosion protection breaks down if the OSP surface becomes damaged. Therefore an additional corrosion protection after assembly such as sealing with lacquer, capsulation or a close package of the electronic system is advisable. Figure 23 shows a summary of all corrosion test results for the OSP surface.

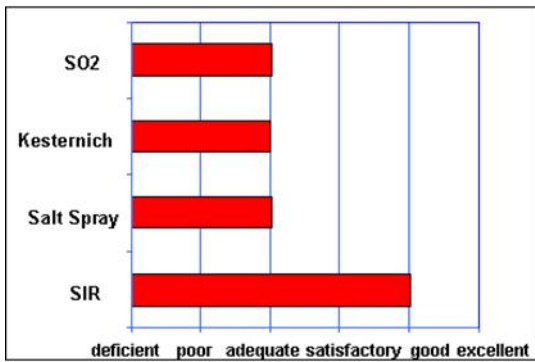


Fig. 23 Corrosion test results for OSP

CONCLUSIONS

As shown in this evaluation, each surface finish exhibits different corrosion protection characteristics in the various harsh environments. Typically, products used in military, automotive and medical applications have higher corrosion resistance requirements than products with lower lifetime or performance expectations, such as consumer or office products. In nearly all segments of the electronics industry, the increasing variety of raw materials, manufacturing processes and performance specifications pose a wide range of factors influencing the requirements for corrosion resistance.

Figure 24 gives a comprehensive assessment of the corrosion protection performance of all tested final finishes.

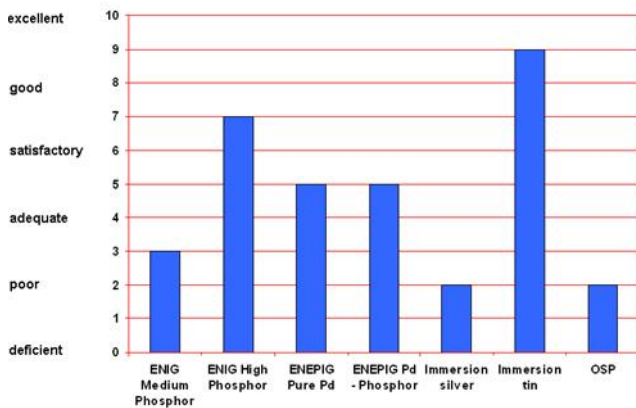


Fig. 24 Summary of corrosion test results for tested finishes

As shown in the figure, immersion tin, ENIG (High P) and ENEPIG provide a higher level of corrosion protection. By comparison, OSP, ENIG (Medium P) and immersion silver deliver only limited corrosion resistance. For protection against corrosion, selection of the appropriate surface finish must include consideration of all product-specific aspects. Therefore, a close cooperation with all segments of the supply chain is essential.

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