Corrosion Failure in Electronic Devices for Aerospace Application

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Corrosion Failure in Electronic Devices for Aerospace Application

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Abstract

Corrosion of complex electronic systems is a growing and expensive concern. New materials and technology are constantly being introduced to increase performance of devices. There are many factors that can induce a corrosive environment during the various stages of manufacturing, processing, transport, and storage of these devices. The scope of this paper was to identify potential causes for the corrosion failure of optocoupler batches being used in launch applications. Optical microscope with surface profile measurements, scanning electron microscopy (SEM), energy-dispersive X-ray spectrometry (EDS), and X-ray photoelectron spectroscopy (XPS) were used to identify and analyze the source of these failure. These studies revealed that the loss of adhesion between the electrolytic plated gold and nickel layers is the critical area that traps impurity ions into the chip allowing for blisters to form along the pins of the optocoupler.

I. Introduction

It is essential for researchers and engineers to understand corrosion's mechanism and prevention. In the study, "Corrosion Costs and Preventive Strategies in the United States," showed the annual cost of corrosion in the U.S. is \$276 billion[1]. The electrochemical process in corrosion leads to failure of critical infrastructures and industries such as oil and gas, aviation, building, chemical plants, water treatment, and aerospace. This amount does not accurately include the cost of failure and decreased reliability of electronic components due to corrosion since most non-functioning electronic parts are replaced and not investigated. Due to the large cost of corrosion processes in so many industries, the best way to combat corrosion is identification and prevention. As the miniaturization of circuits and electronic components increase factors such as component spacing, lower voltages in electrical contacts, and use of dissimilar materials have resulted in failures that are often times overlooked. Due to the size and complexity of the problem it is usually easier to replace the part than to consider the root cause. However, as size decreases so does the tolerance for corrosion. The less material used to make a device, the greater the effect of corrosion on the part. The tolerance for corrosion loss is in the order of pico-grams (10^{-12} g)[2].

While material selection and size of the device play integral parts in the cause of corrosion, process and service environment related contaminations cannot be dismissed. Process contaminations are impurities on the electronic device from production such as etching agents, plating residues or additives[3]. Service environment contaminants are the aggressive ions found in the environment where the device is being used. These ions include chlorides, nitrates, sulfates and dust particles that can trap moisture. Due to the miniaturized size of the electronic device, even a tiny water droplet can bridge two dissimilar metals to form a voltaic (galvanic) cell thus allowing for electrochemical corrosion.

Optocouplers are ideal devices used in space electronics due to their dual role in transferring signals using infra-red light generated by light-emitting diode (LED) and that is then absorbed by a photodetector receiver. This is accomplished by providing electrical isolation between microelectronic circuit sectors using an optically transparent but electrically isolating medium. The electrical isolation is very important for space electronics. In this case, the input power can be very high and may bring a lot of noise. The electrical isolation helps to reduce the noise and protects the receiver from potential power surges[4]. The LED component and the photo-sensitive device are enclosed in a light free package with metal pins extending outward to make the necessary electrical connections. As seen in

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Figure 1, power is given to the anode (A) and cathode (C), pins 1 and 2 respectively, to turn on the LED light. The light is a beam of infrared that triggers the phototransistor, pins 9 and 10 respectively. The phototransistor conducts across the pins from collector (C) to emitter (E) and then can reduce any noise level in the signal or power any load connected to the output[4].

Optocouplers from space flight missions were received from four batches for investigation as to (1) cause of electrical failure, (2) corrosion formation along the pins, (3) pin breakage.

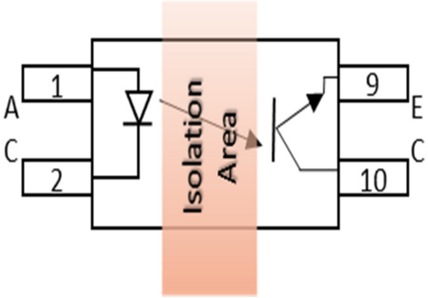


Figure 1. Basic circuit design of an optocoupler providing isolation between two circuits.

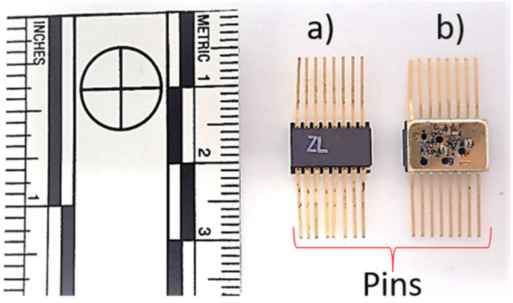


Figure 2. Sample Optocoupler received (a) front side ceramic coated (b) back side gold coated.

II. Experimental

Optocoupler Batches 1-4 were received in static shielding sealed bags (two samples per batch). The optocoupler leads are comprised of Alloy 42, which is a work-hardened based metal made primarily of both nickel (41 percent) and iron (the balance minus some minor alloying elements that occur at ~1 percent). Both nickel and gold are electrolytically plated onto the leads at thicknesses of a minimum of 80u for the nickel and 60u for the gold. The optocouplers are handled under controlled conditions during processing, but they were stored in several conditions where contaminations and corrosion could have resulted. The conditions of most concern are when 1) the packaging was unsealed during long term storage, 2) the relative humidity reached greater than 60% and the temperature was elevated for brief periods intermittently, and 3) when they were stored in PVC tubing that is known to outgas chlorides.

A. Characterization Methods

The surface and cross-sectional morphologies of the samples were observed using scanning electron microscopy (SEM JEOL 6390) coupled with energy-dispersive X-ray spectrometry (EDS) and Al-K-Alpha source X-ray Photoelectron Spectrometer (XPS Thermo Scientific). The acceleration voltage was set at 15 kV for SEM and 3000 eV for XPS. Optical microscopy (Keyence VHX-5000 digital microscope and VK-X200 Laser 3D Profile Measurement microscope) were used to map out cracks, blisters and pitting of interest on the samples as well as the 3D topography of the surface. The pins on the optocoupler are identified as seen in Figure 2. Additionally, visual inspections are based on the corrosion forms seen in Figure 3[10]. The most prevalent forms of corrosion found on the samples were: no corrosion, pitting, and cracking.

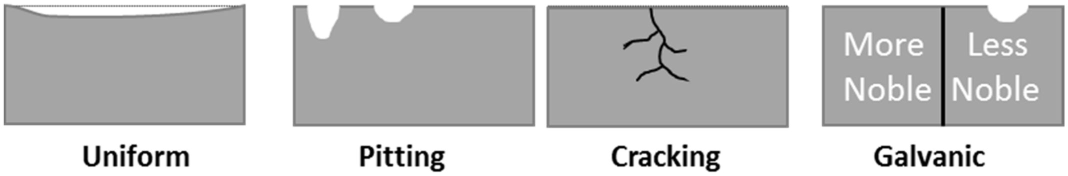


Figure 3. Various forms of Corrosion

B. Optical Microscopy

Optical microscopy was used to help identify and plot fundamental areas of failure on the pins of the optocoupler batches. A significant amount of damage were observed on each of the pins of the samples received as seen in Figure 4. Corrosion was not localized to just one area of the pins but rather randomly along the sides, surfaces, and tips of the pins. The gold top coating was prevalent with cracks, pitting, discoloration, and blistering. Additionally, symmetrical scratching marks from some type of mechanical device handling (Figure 4, Batch 1, a) were observed in all the batches. Additionally, various forms of blisters were observed in all the batches. For example, blisters erupted with corrosion product were the most common form that were found, but there were areas with intact blisters with no visual evidence of cracking or eruption, and blisters surrounded by cracks and/or pits. Figure 5 depicts 1000x magnification of the typical blistering found on the pins and is a clear example of blisters that erupted from the gold coating with corrosion product.

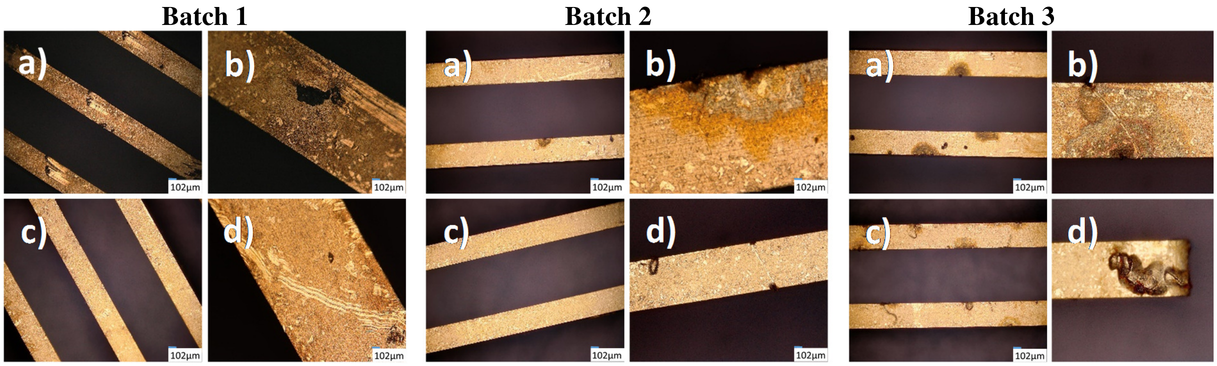


Figure 4. Optical Microscope images of pins from Batches 1-3 showing various failures such as cracking, pitting, corrosion discoloration and unknown scratching marks.

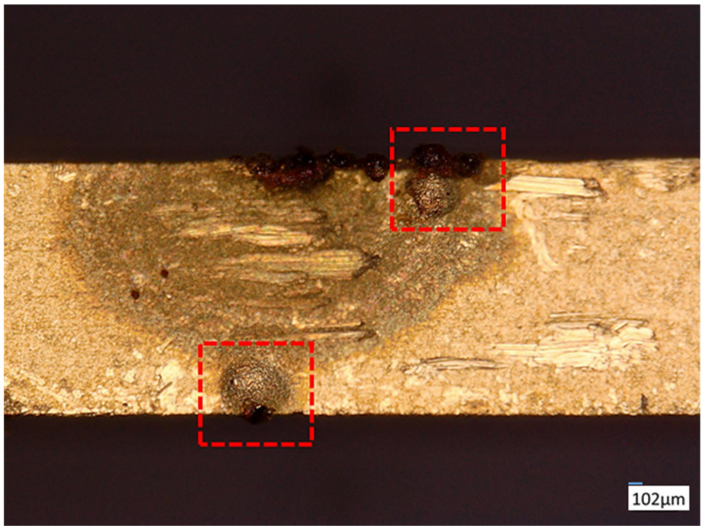


Figure 5. Optical Microscope image of a pin from Batch 3 showing blisters impregnated with corrosion products outlined in red.

Laser microscopy of the three-dimensional surface of a typical blister found on the optocouplers are depicted in Figure 6. Profiles of various forms of: (a) blisters along the edge of the pin, (b) blisters with scratches and discoloration, and (c) blisters on the surface of the pin. The volume of the blisters varies presumably with time and continued exposure to the contaminant. The blisters tend to have a depth between 80-120 µm.

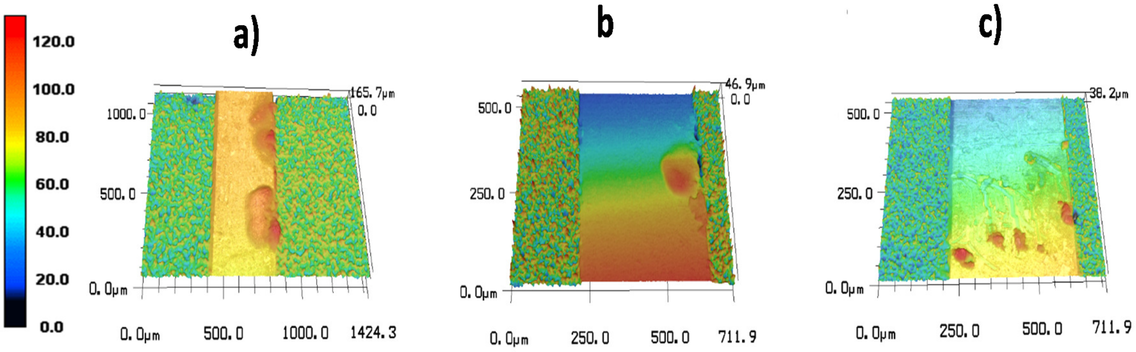


Figure 6. Three-dimensional images of various blisters: (a) blisters along the edge of the pin, (b) blister with scratches and discoloration, and (c) blisters on the surface of the pin.

C. SEM observation and EDS analysis of various defect features

The overall EDS mapping seen in Figure identifies clearly the area of top coated gold and the interior layers under the top coat with contamination-related elements O, Sn, and Cl (Figure 7) [5]. The base metal is made from an alloy of Fe and Ni, and the strike plate is Ni. The soldering contains Co and Cu in small quantities. These elements can be accounted for although they should not be exposed above the Au plating when in service. Figure 8 shows the different surface morphologies found on the samples: (a) area of pin with no surface defect or discoloration thus corrosion product should not be present, (b) area directly on top of the pin with an erupted blister surrounded by corrosion product, and (c) an erupted blister on edge of the pin. Figures 9 – 13 show the SEM data and EDS analysis for optocoupler batches received and the major systematic corrosion failures are identified along with the chemical components found in the corrosion products. Figure 9 depicts pins from sample Batch 1. Spectrums (1) is a sample area on the pin that shows no mechanical or corrosion defects and is considered a control area, (2) is a typical pitting hole, and (3) larger pitting area on the side of the pin. The EDS chemical analysis indicates that Spectrum 1 has no elemental detection of corrosion products while spectrums 2 and 3 have several contaminants identified as Cl, Fe and Sn. The amount of Au in the pitting areas is significantly less than seen in spectrum 1. Spectrum 1, the control area, is composed of primarily of Au and minor contributions of N, and O.

Figure 10 is from Batch 1 from areas with severe discoloration and pitting. Spectrums (1) is taken from an area of the pin with a large pit, (2) has minor defects (3) shows no visual indication of having any defects, and (4) pitting area. EDS analysis of Spectrums 2 and 3 shows no elemental detection of typical corrosion products while spectrums 1 and 4 have several contaminants such as Cl, Fe, and Sn. The amount of Au in the pitting areas is significantly less than the other spectrums. Spectrum 2 had both Ag and Cl elemental contaminants probably due to corrosion diffusion however the source of the Ag is unknown. Figure 11 depicts pins from sample Batch 2 that showed visual signs of discoloration. Spectrums 1, and, 3 have various pitting while spectra 2 and 4 are taken in an area with little defect. EDS analysis of Spectrum 2 shows no elemental detection of typical corrosion products while spectrums 1, and 3 have contaminants such as Cl, Fe, Ni, and Co. The amount of Au in the pitting areas is significantly less than the other spectrums. Figure 12 is the analysis of Batch 3. The sample area used is taken from an area on the edge of the pin that was severely damaged and showed signs of cracking. Spectrums from areas 1, 2 and 3 were all taken in cracked areas that shows detection of Al, Cl, Cu, and Ag elemental contaminants. Figure 13 is from Batch 3 and the area of interest is erupted blister with severe discoloration. Spectrums from area (1) has no visual defect but is on top portion of the blister that didn't erupt, (2) is an area on top of the blister with a minor crack, and (3) is the area where the blister has erupted. EDS analysis of Spectrums 1, 2 and 3 shows detection of several contaminants. However, Cl was only identified in spectrum 3 which has the lowest amount of Au detection.

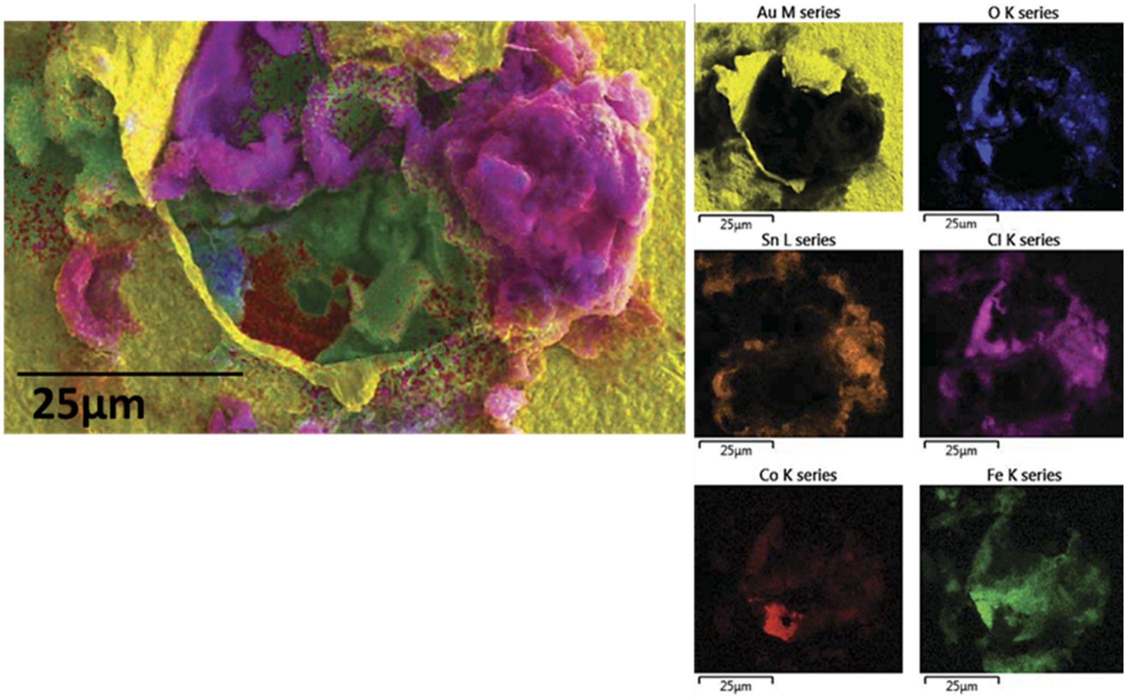


Figure 7. Combined EDS Mapping of an erupted blister.[5]

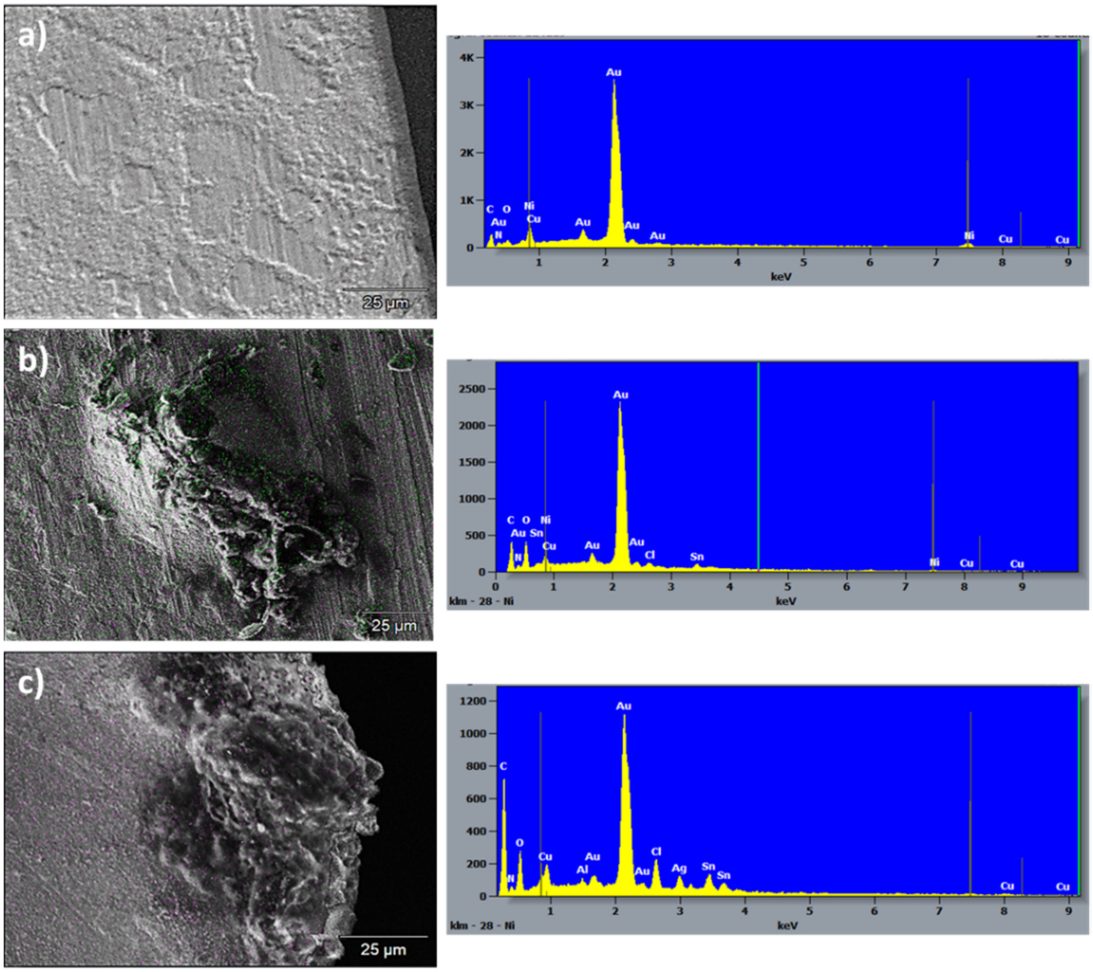
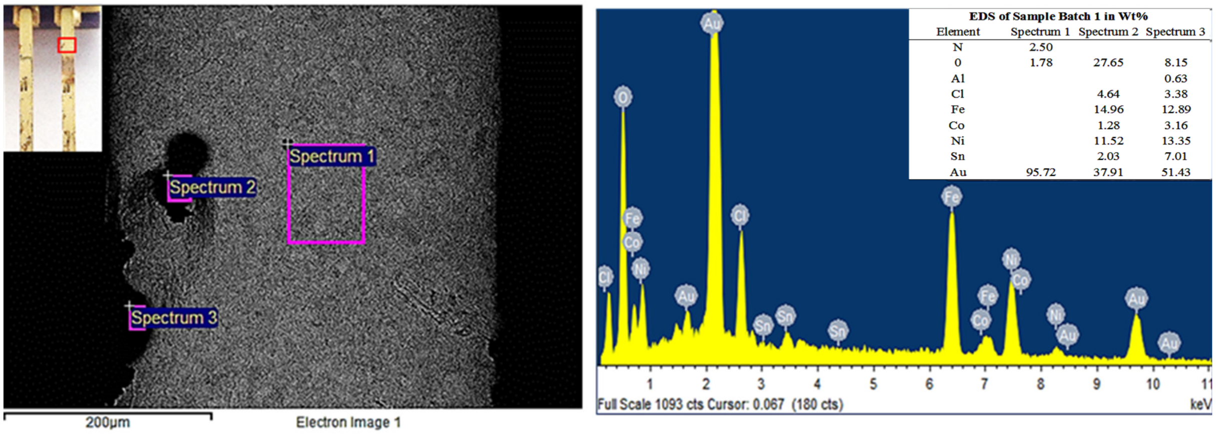


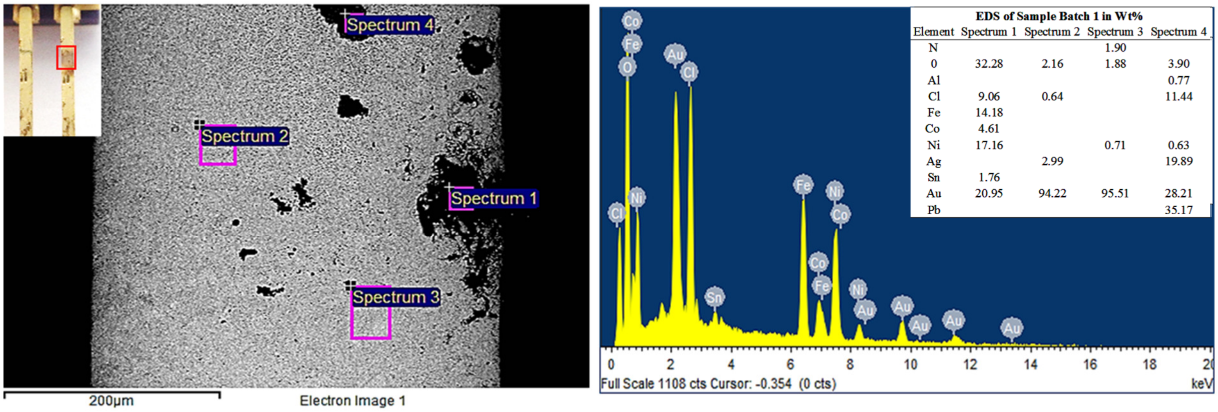
Figure 8. SEM images (left) and EDS analysis (right): (a) defect free surface area, (b) blistering with corrosion eruption on the surface of the pin and (c) blistering on edge of the pin.



EDS of Sample Batch 1 in Wt%

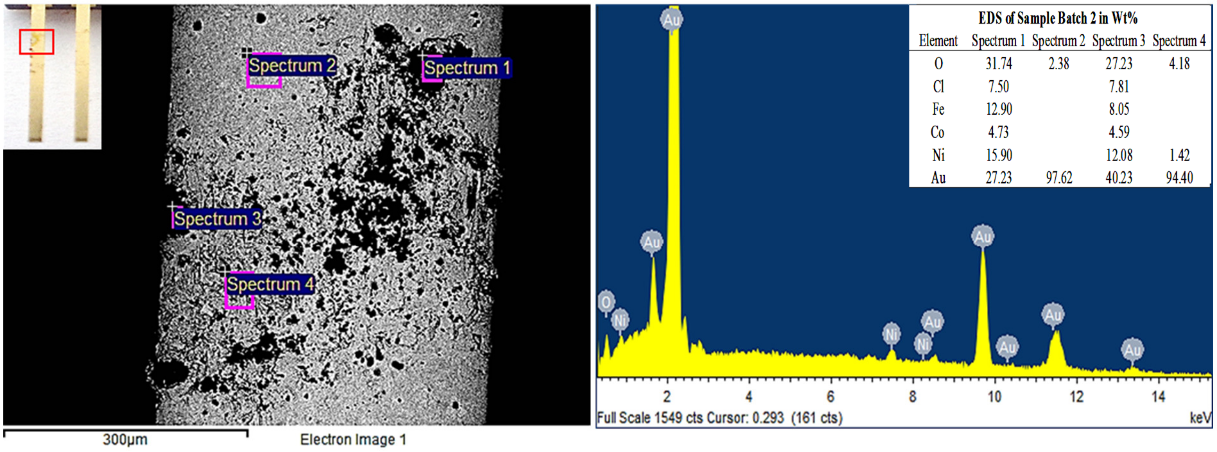
Element	Spectrum 1	Spectrum 2	Spectrum 3
N	2.50		
0	1.78	27.65	8.15
Al			0.63
Cl		4.64	3.38
Fe		14.96	12.89
Co		1.28	3.16
Ni		11.52	13.35
Sn		2.03	7.01
Au	95.72	37.91	51.43

Figure 9. SEM and EDS analysis of optocoupler batch Batch 1.



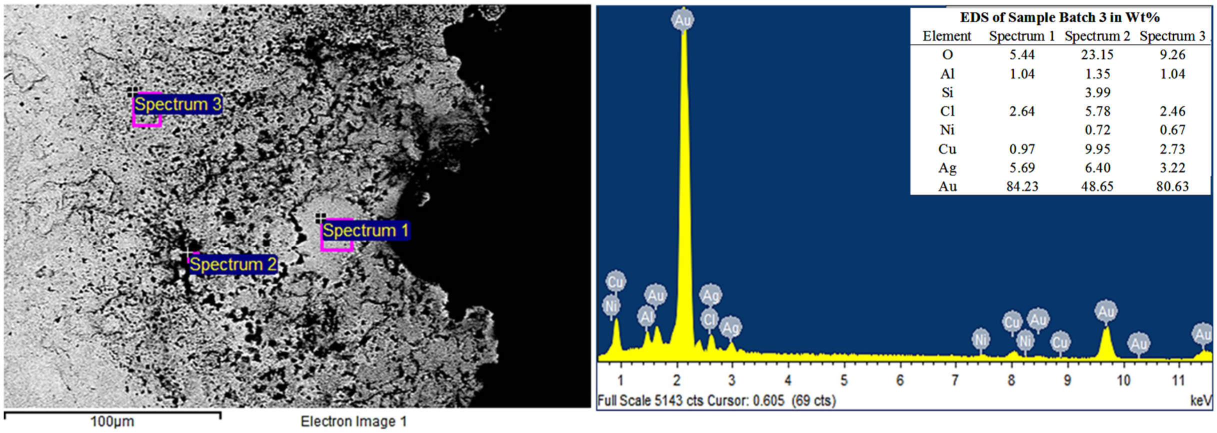
EDS of Sample Batch 1 in Wt%				
Element	Spectrum 1	Spectrum 2	Spectrum 3	Spectrum 4
N			1.90	
0	32.28	2.16	1.88	3.90
Al				0.77
Cl	9.06	0.64		11.44
Fe	14.18			
Co	4.61			
Ni	17.16		0.71	0.63
Ag		2.99		19.89
Sn	1.76			
Au	20.95	94.22	95.51	28.21
Pb				35.17

Figure 10. SEM and EDS analysis of optocoupler Batch 1 taken in an area that is visually discolored and without discoloration.



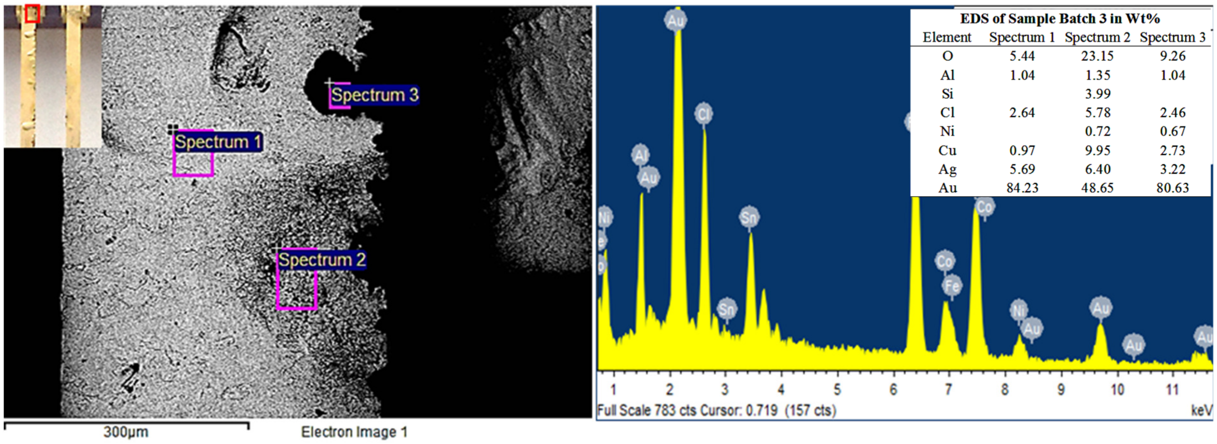
EDS of Sample Batch 2 in Wt%				
Element	Spectrum 1	Spectrum 2	Spectrum 3	Spectrum 4
O	31.74	2.38	27.23	4.18
Cl	7.50		7.81	
Fe	12.90		8.05	
Co	4.73		4.59	
Ni	15.90		12.08	1.42
Au	27.23	97.62	40.23	94.40

Figure 11. SEM and EDS analysis of optocoupler Batch 2 taken in an area that is visually discolored.



EDS of Sample Batch 3 in Wt%			
Element	Spectrum 1	Spectrum 2	Spectrum 3
O	5.44	23.15	9.26
Al	1.04	1.35	1.04
Si		3.99	
Cl	2.64	5.78	2.46
Ni		0.72	0.67
Cu	0.97	9.95	2.73
Ag	5.69	6.40	3.22
Au	84.23	48.65	80.63

Figure 12. SEM and EDS analysis of optocoupler Batch 3 taken in an area that is severely damaged with cracking and flaking.



EDS of Sample Batch 3 in Wt%

Element	Spectrum 1	Spectrum 2	Spectrum 3
O	5.44	23.15	9.26
Al	1.04	1.35	1.04
Si		3.99	
Cl	2.64	5.78	2.46
Ni		0.72	0.67
Cu	0.97	9.95	2.73
Ag	5.69	6.40	3.22
Au	84.23	48.65	80.63

Figure 13. SEM and EDS analysis of optocoupler Batch 3 taken in an area that is visually discolored and blistered.

D. XPS analysis of surface

X-ray photoelectron spectroscopy (XPS) was used to analyze the surface chemistry of the material. XPS can measure the elemental composition, empirical formula, chemical state and electronic state of the elements on the surface of the material however, depth penetration greater than ~1 – 5 nm is a challenge. The surface of a material is representation of a discontinuity between each phase in the material. This makes identification of the physical and chemical properties of the surface area different from that of the bulk material[6].

Figure 14 shows the XPS spectra for Batch 1, Batch 2, and two places on Batch 3. The typical spectrums show components of Au, C, O and minor Sn was found in Batches 2 and 3. There is no clear indication of corrosion contaminants on the surface. This analysis was limited by the size of the pins on the optocoupler and the size of the blisters were around 10-30 µm thus making it challenging to focus the x-ray beam directly on the corrosion products identified in the optical microscopy and SEM.

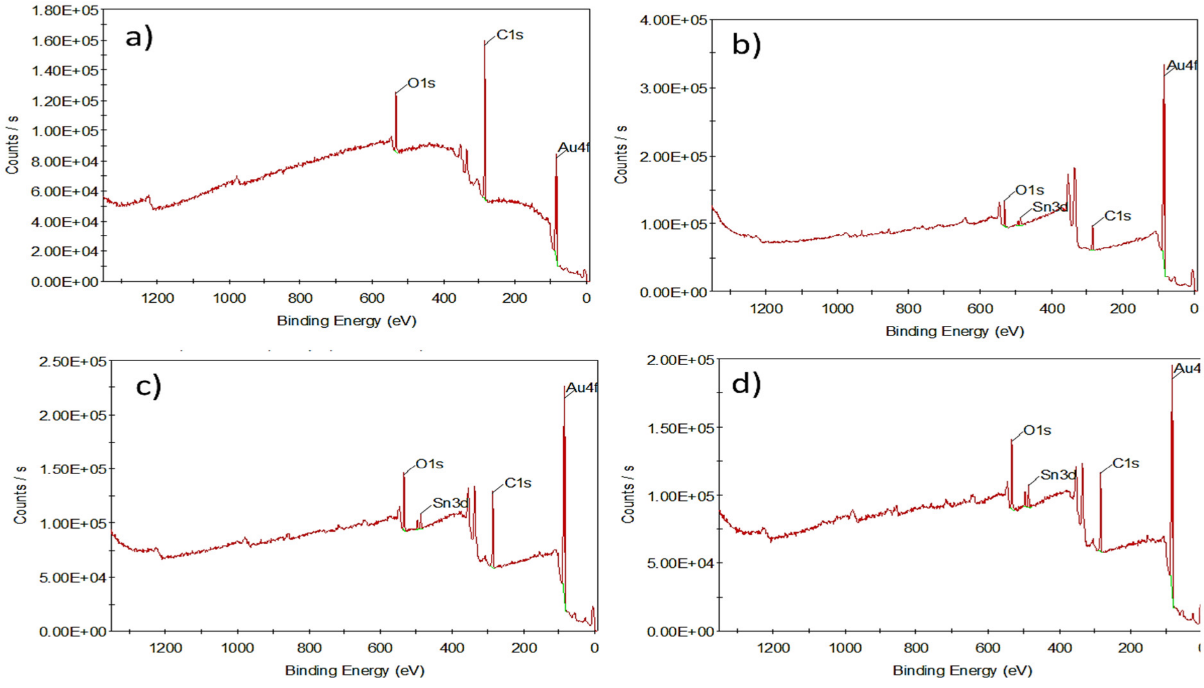


Figure 14. XPS Analysis of Optocouplers from (a) Batch 1 , (b) Batch 2, and two locations in Batch 3 (c) and (d).

III. Discussion

Adhesive failure is common in electronic devices. This can occur through high storage temperatures[7], degradation of the binder agent[8], dissimilar materials being used[2], curing, and contaminants from the environment and processing[9]. In the samples of optocouplers received, blistering is associated with interface contamination. The life of the blister on the optocouplers is hypothesized to begin with some sort of contaminant that occurred during processing. The adhesion layer is disrupted by an unknown source and creates pockets of contaminants under the Au layer. The contaminant causes galvanic corrosion between the plating layers and the corrosion products form primarily as a shallow pit. Eventually as the corrosion progresses the blister erupts. As shown in the SEM/EDS analysis, the concentration of corrosion products and contaminants are confined to areas of blistering, cracking, and pitting. SEM and EDS links contaminants to areas under the blisters (below the Au top layer). Contaminants were not found on areas without defects or cracks. This is a clear indicator that the environment under the Au top layer contained the contaminants prior to visual confirmation of corrosion products. Areas that are intact show no traces of chlorides. In SEM, the morphology of erupted blisters consists of cracks in the plating and dark and bright phases. Whereas, the morphology of the areas with no visual defects are more uniform and without blemishes. Clusters of corrosion products are found near and around erupted blisters found along the surface of the pins, edges of the pins and at the tips of the pins. Cracks are found in the areas where a blister or pitting is formed. For example, in Figure 4 Batch 1d, Batch 2d and Batch 3b all shows a crack line that spans between two pits. The main elements in the corrosion products identified by EDS are O and Cl along with Fe, Ni and Co along the corrosion areas only. In areas that are severely corroded the Au content is greatly reduced in comparison to the intact areas. At the time of this report, the source(s) for contamination remained unknown. Electrical output will be interrupted due to cracking, pitting and breaking of the pins, and major corrosion collection on the pins will all interfere with signal transmission.

IV. Conclusion

Electronic components consist of variety of metallic materials which increases the likelihood that an improper combination of these metals can form a galvanic cell. Added to the problem is the miniaturized size where a minor accumulation of dust particles, atmospheric contaminants along with slight moisture on the components can cause severe damage to the device. It is important to demonstrate reliability of electronic components during every stage of manufacturing, processing, handling, and storage. Manufacturers of the most safety critical products have to provide evidence that reliability has not been negatively affected by using new materials or new technological concepts. This is particularly important in aerospace or defense devices. Optocouplers used in space electronics were investigated for corrosion failure using Microscopy, SEM, EDS, and XPS. The source of the contaminants is thought to be the PVC tubing outgassing, but the source of the intrusion points for the chlorides to breach the outer gold plating is unknown. However, due to the lack of corrosion product on the surface of the pins while, corrosion products are significant in the blisters, the defects in adhesion of Au to the substrate should be further investigated for proper processing and handling.

Acknowledgments

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