Surface Treatment Enabling Low Temperature Soldering to Aluminum

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Abstract

The majority of flexible circuits are made by patterning copper metal that is laminated to a flexible substrate, which is usually polyimide film of varying thickness. An increasingly popular method to meet the need for lower cost circuitry is the use of aluminum on Polyester (Al-PET) substrates. This material is gaining popularity and has found wide use in RFID tags, low-cost LED lighting and other single-layer circuits. However, both aluminum and PET have their own constraints and require special processing to make finished circuits. Aluminum is not easy to solder components to at low temperatures and PET cannot withstand high temperatures. Soldering to these materials requires either an additional surface treatment or the use of conductive epoxy to attach components. Surface treatment of aluminum includes the likes of Electroless Nickel Immersion Gold plating (ENIG), which is extensive wet-chemistry and cost-prohibitive for mass adoption. Conductive adhesives, including Anisotropic Conductive Paste (ACP), are another alternate to soldering components. These result in component-substrate interfaces that are inferior to conventional solders in terms of performance and reliability. An advanced surface treatment technology will be presented that addresses all these constraints. Once applied on Aluminum surfaces using conventional printing techniques such as screen, stencil, etc., it is cured thermally in a convection oven at low temperatures. This surface treatment is non-conductive. To attach a component, a solder bump on the component or solder printed on the treated pad is needed before placing the component. The Aluminum circuit will pass through a reflow oven, as is commonly done in PCB manufacturing. This allows for the formation of a true metal to metal bond between the solder and the aluminum on the pads. This process paves the way for large scale, low cost manufacturing of Al-PET circuits. We will also discuss details of the process used to make functional aluminum circuits, study the resultant solder-aluminum bond, shear results and SEM/ EDS analysis.

Introduction

Aluminum is the most abundant metal in the earth’s crust. Its alloys have found wide use as building material in the construction of automobiles, aircraft, bicycles, building-frames etc. Other uses range from electrical connectors, packaging cans and foils, and house-hold utensils. While it is a material of choice in the above fields, it is second to copper in the field of flexible circuits.

This is despite the various advantages that Aluminum has over copper. Aluminum is more than three times lighter than copper. Density of Aluminum is 2.7gm/cm3 while that of copper is 8.92gm/cm3.Its electrical resistivity is 26.5 nΩ·m (at 20 °C) while that of copper is 16.78 nΩ·m (at 20 °C). Also, its thermal conductivity is 237 W/(m·K) while that of copper is 401 W/(m·K)[i].Although it is not as good an electrical and thermal conductor as copper, it can radiate heat better than copper due to its lower density. Overall, aluminum has 68% of the conductivity of copper, but has only 30 % of the weight of copper. This means that a bare wire of aluminum weighs half as much as a bare wire of copper that has the same electrical resistance[ii].This will be similar for aluminum traces in the case of flexible circuits. Also, aluminum is generally less expensive when compared to copper conductors. A recent check indicated the price of aluminum was 35% less than that of copper[iii]. It is three times less expensive than Copper on an equal weight basis and six times less expensive on an actual usage basis. This is the biggest advantage that aluminum has over copper. Comparative properties of the two metals that are relevant to flexible circuits are listed in Table 1.

Table 1: Properties of Aluminum and Copper[iv]

Property	Aluminum	Copper
Density	2.702 gm/cm3	8.92 gm/cm3
Electrical resistivity	26.5 nΩ·m (at 20 °C)	16.78 nΩ·m (at 20 °C)
Thermal conductivity	237 W/(m·K)	401 W/(m·K)

Flexible circuits and Al-PET substrates

The majority of flexible circuits are made using copper on polyimide(Cu-PI) substrates. These consist of copper foil laminated onto polyimide film. Varying the thickness of copper and polyimide, gives rise to various combinations of thicknesses of Cu-PI to suit the conductivity and dielectric requirements of the end applications. Traces are formed using photolithography followed by a print and etch process. Components are soldered on to make the finished circuits. A reasonable selection of solders that can easily bond to copper traces without the need for any special surface treatments are available.

An increasingly popular method to make flexible circuits is by using Aluminum on PET (Polyethylene terephthalate) or Al-PET substrates. These are available in varying thickness of aluminum foil laminated onto PET film as shown in Figure 1.

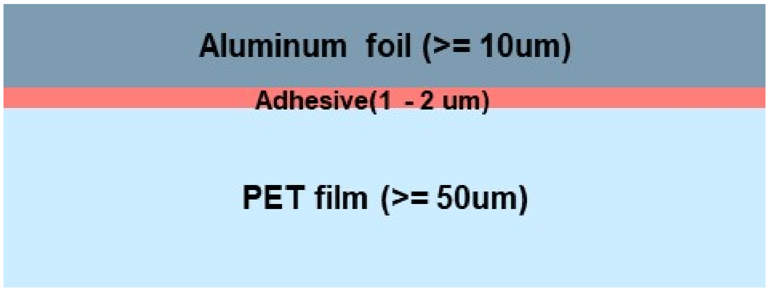

Figure 1 – Typical laminated construction of Al-PET substrates

While aluminum is less expensive than copper, PET is also significantly cheaper than polyimide film. Hence, lower material cost is a major driver for the increasing use of Al-PET substrates, but their use has been limited because of processing challenges.

The process to generate the traces on aluminum substrates is similar to that of copper. A dry-film or liquid resist is used for photo-lithography which is then followed by chemical print and etch to form aluminum traces. But attaching the components onto aluminum is a challenge. Unlike copper, it is not easy to solder to aluminum. Soldering to aluminum is difficult because of the presence of a thin layer of aluminum oxide. This layer forms naturally when the bare metal is exposed to air. Since most flexible circuit manufacturing is done under atmospheric conditions, all aluminum surfaces will have an oxide layer. While the formation of this natural oxide is self-limiting, its presence cannot be overcome by the flux used in existing solder pastes. If harsher fluxes are used within solder pastes to address the aluminum oxide problem, they will cause corrosion of the very thin aluminum layers and thus reliability problems.

There are two methods currently used to attach components to Al-PET substrates. One is the Zincate and plating process while the second is using conductive epoxy.

Al-PET circuits using Zincate and plating finish

Special processing can be done on the aluminum pads to remove and prevent the formation of aluminum oxide. These include Electroless Nickel Immersion Gold plating (ENIG), nickel-palladium or nickel-silver plating. These processes require a surface preparation process called the Zincate process[v]. The purpose of zincation is to clean the aluminum surface for plating of the nickel or other metal. An example of a zincate process is shown in Figure 2.

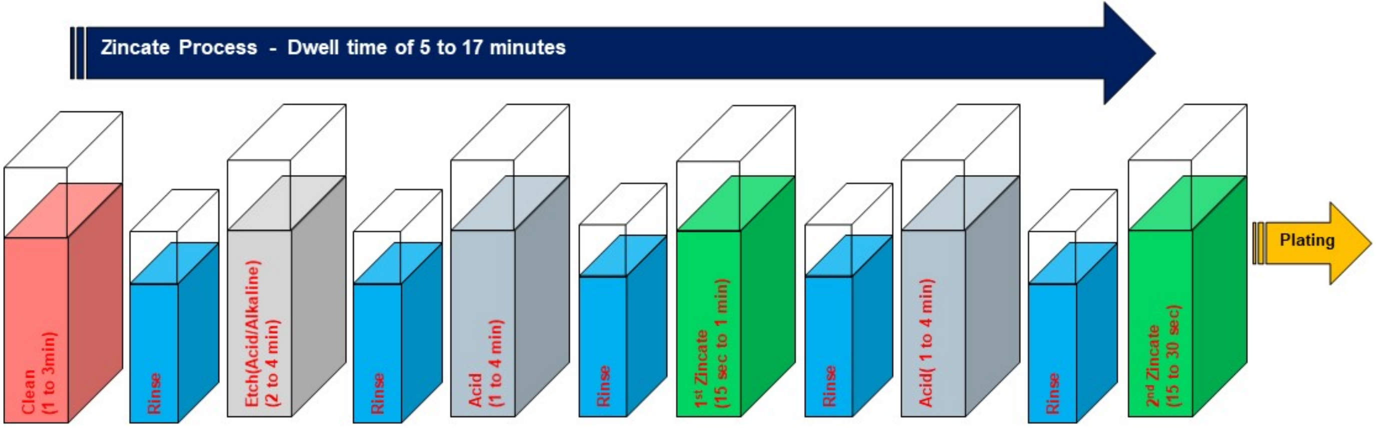

Figure 2 – Zincate process used to prepare aluminum surface for plating

As can be seen in Figure 2, the zincate process involves extensive wet chemistry. The dwell time, which can vary per the alloy of aluminum, ranges from 5 to 17 minutes. In addition, a plating finish must follow zincation before components can be attached. These add extra costs that make it difficult for large scale adoption of Al-PET substrates in the field of flexible circuits.

Al-PET circuits using Conductive Epoxies

Al-PET substrates are widely used in the manufacture of Radio-frequency Identification (RFID) tags, Smart-tags and low-end Light Emitting Diode (LED)lighting. These are patterned using a roll-to-roll process for print and etch. Components are attached roll-to-roll or in panels, using silver-based conductive epoxies, including Anisotropic Conductive Paste (ACP).The assembly process begins with the application of conductive epoxy on the pad or chip. The chip is then flipped onto or placed on the pad followed by heat and pressure. This cures the epoxy and the chip is attached. While they are used in very small amounts in regular RFID tags, they are a big part of the total expense in making Smart-tags. These tags are larger than RFID tags and have a lot more components that demand more conductive epoxy per Smart-tag.

Conductive epoxies have their own challenges. They are made of adhesive epoxy filled with conductive metal particles, usually silver. They are typically syringe applied, require longer cure times, have pot-life issues and electrically inferior to conventional solders. In addition, they must be stored at low temperatures in special freezers, to control the polymerization of the epoxy. Overall, they are very expensive and limit the use of Al-PET substrates[vi].

Al-PET circuits using Advanced Surface treatment

An advanced Surface Treatment chemistry has been developed as a new alternative. It enables soldering to aluminum without zincate and plating. It can be printed directly on the aluminum pads where components need to be assembled. The print thickness depends on the application. Any of the conventional printing techniques can be used including screen, stencil, etc. The aluminum surface does not need any surface cleaning or preparation. Once this treatment compound is printed, it must be cured thermally to leave the pad surface treated, active and ready to accept solder. Cured treatment compound is non-conductive and hence makes room for easy print registration. To attach a component, it needs solder on it via printing or plated bumps, placed on the activated pad, and then passed through a reflow oven. The compound overcomes the aluminum oxide layer and allows the formation of a true metal to metal bond between the solder and the aluminum on the pads. Thus, both the electrical properties and the bond strength are far superior to silver epoxies. In addition, it can be stored at room temperature, and reused multiple times[vii]. The overview of the process to use the surface treatment is shown in Figure 3.

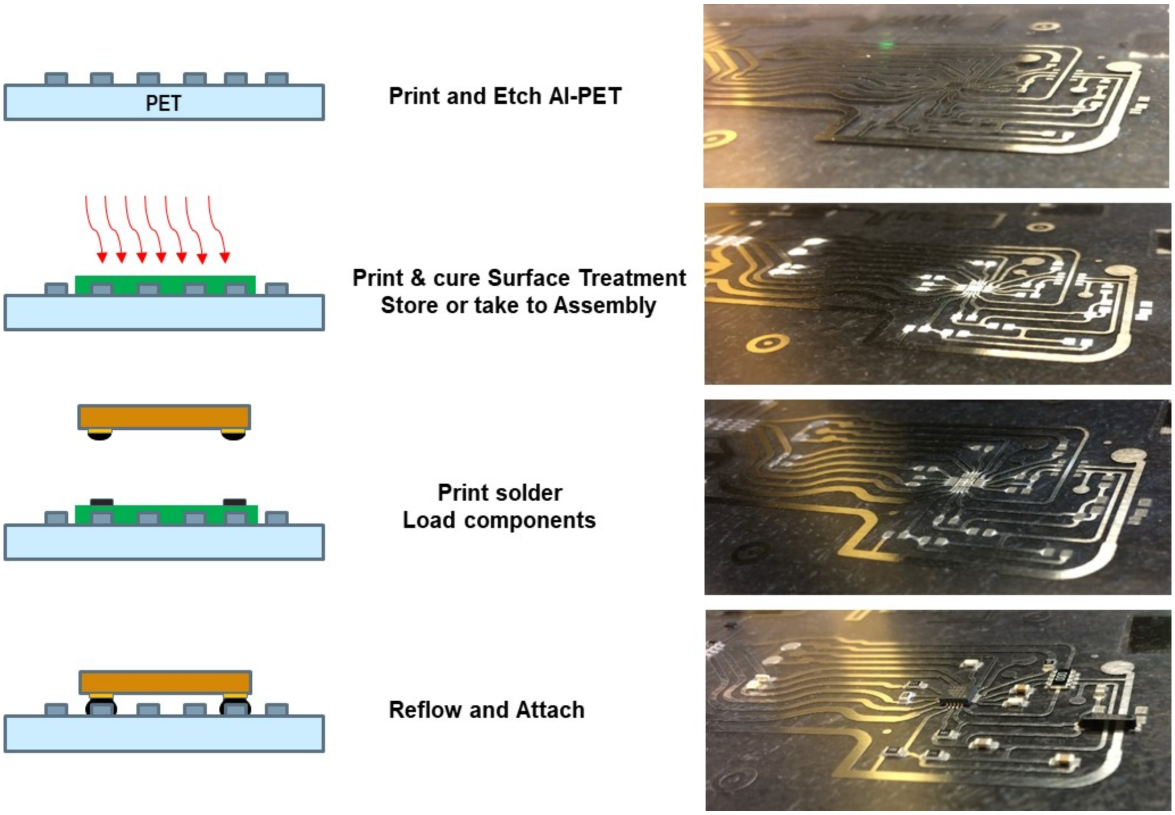

Figure 3 – Overview of process using Surface Treatment to solder to Aluminum

Surface Treatment Cure Temperature, PET constraints and Solders

The surface treatment requires a low temperature cure of less than 100°C. The required dwell time ranges from a few seconds to a minute depending on the oven type and air flow. Conveyor based reflow ovens in PCB assembly houses can cure the printed Surface Treatment. A variety of solders can be used to attach to aluminum using the Surface Treatment. However, the type of solders that can be used on Al-PET substrates in limited by the PET film. Key properties common to heat-stabilized PET films are listed below in Table 2.

Table 2: General properties of Heat-stabilized Polyethylene terephthalate film (PET film)[viii, ix]

Property	Value	Units
Glass Transition Temperature	78	°C
Thermal Contraction (150°C, 30 min)	<= 0.3 MD, <= 0.1 TD	%
Upper Temperature for Processing	150	°C
Melting point	250 – 260	°C
Dielectric constant	3.1	
Dielectric Strength	3000	Volts/25um

Per Table 2, the working temperature of PET films is limited to about 150°C.This is the temperature that they can be subjected to for an extended period and rules out the use of most solders that have a higher melting point. But PET films can withstand higher temperatures for a brief period. This opens the door for using a variety of low temperature solders for assembly of components to Al-PET substrates. Most of the solders are made up of Tin (41-42%), Bismuth(57 to 57.6%) and Silver (0.4 to 2%) in various flux systems, with a melting point of ~138°C. The highest temperature during reflow is about 185 °C but only for a very short time.

Assembly trials made using Surface Treatment and related observations

Boards were made with 10um thick aluminum foil laminated onto 125um thick film of PET. The etched design was a Smart-tag that had components including resistors, capacitors, LEDs, QFNs, battery holder and RFID chips. The surface finishes of these components were typically Ni/Pd/Au or Sn plated. Special fixtures were designed to hold the boards during processing. A partial view of the Smart-tag design used is shown below in Figure 4.

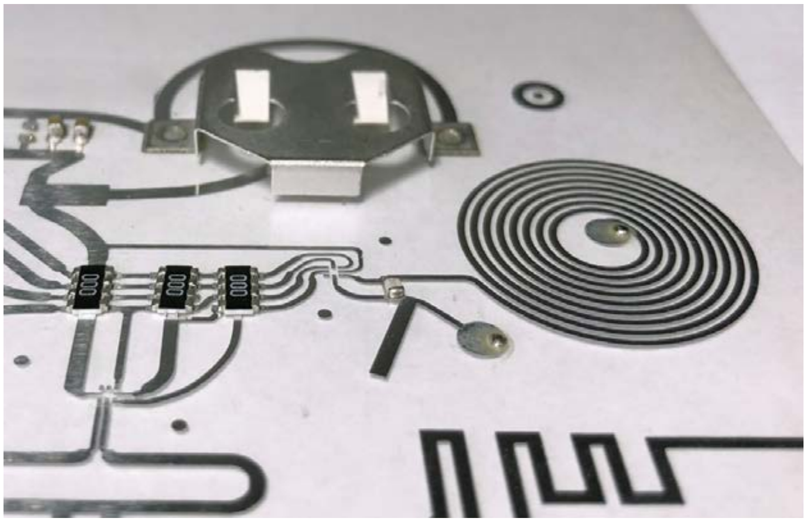

Figure 4 – Smart-tag design used to test Surface Treatment

The trials were done at a local Printed Circuit Board (PCB) assembly house and consisted of two steps. Step 1 was to mount etched aluminum panels on the fixture and print surface treatment compound using a stencil made of stainless steel,737x737mm,50um thick. A conveyor based reflow oven was used to cure the Surface Treatment Compound at 85°C. Step 2 was to use the same fixtures to hold the panels during stencil printing of solder, pick-and-place loading of components and reflow oven processing. The stencil used for the solder paste was stainless steel,737x737mm,100um thick. The solder used was commercially available Lead-free, Low-temperature, No-Clean Sn/Bi/Ag with a melting point of 138°C. The reflow cycle used was as recommended by the manufacturer of the solder paste.

The resultant bond was characterized by shear tests, X-rays and cross-sectional analysis of the intermetallic formed with the aluminum.

Shear tests were done to gauge the strength of the bond. They were also done on various components – resistors, capacitors and chips. The tests were done using a production force gauge. The shear test values were greater than 15 N/mm2. The Solder-Aluminum bond was so strong that failure was often between the Aluminum and PET. Such failures are depicted in Figure 5.

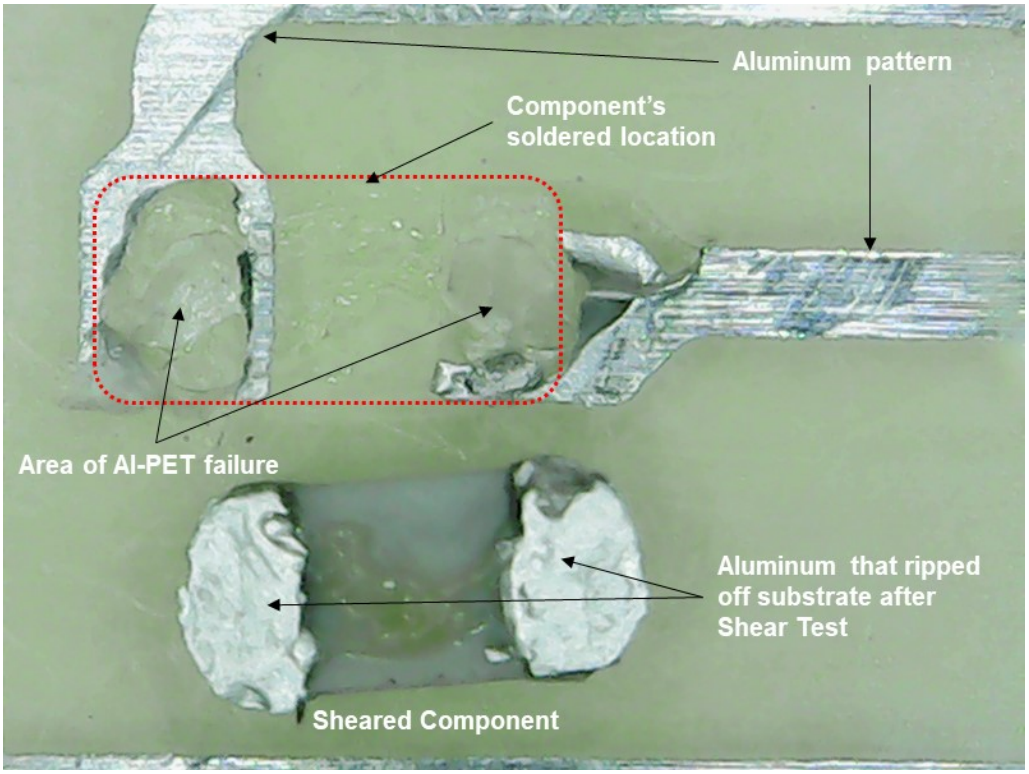

Figure 5 – Shear test results showing failure between Aluminum and PET substrate (Package - Capacitor 0805, Shear value - 22N/mm2)

The assembled boards were also inspected using X-ray. This was done to get a better understanding of the wetting of the solder. The components when examined under X-ray showed good solder joints and voids were within an acceptable limit of less than 30% of the solder joint area. The key process parameters were thickness of surface treatment, thickness of solder and reflow profile of the solder. X-ray images of the components are shown in Figure 6.

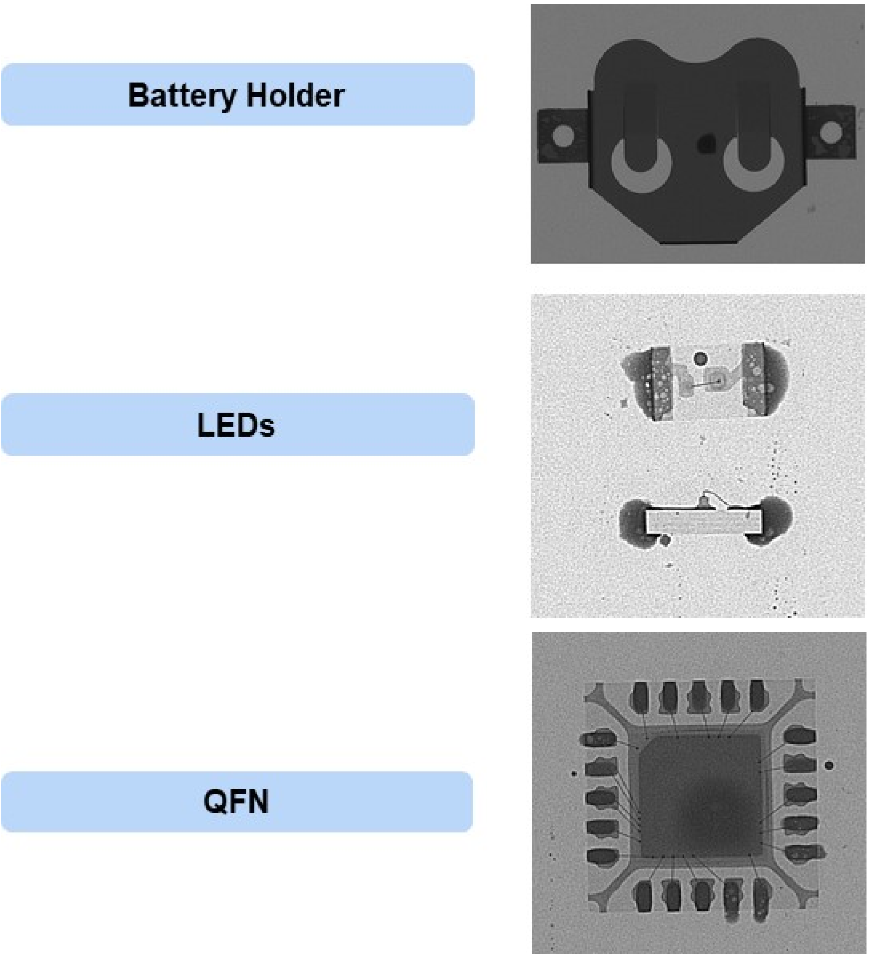

Figure 6 – X-ray images of components showed good solder joints

Cross sections were done on various components including capacitors, battery holder and QFN chips. These give a better view of the wetting of the solder and the intermetallic formed with the aluminum. Some cross sections are shown in Figure 7.

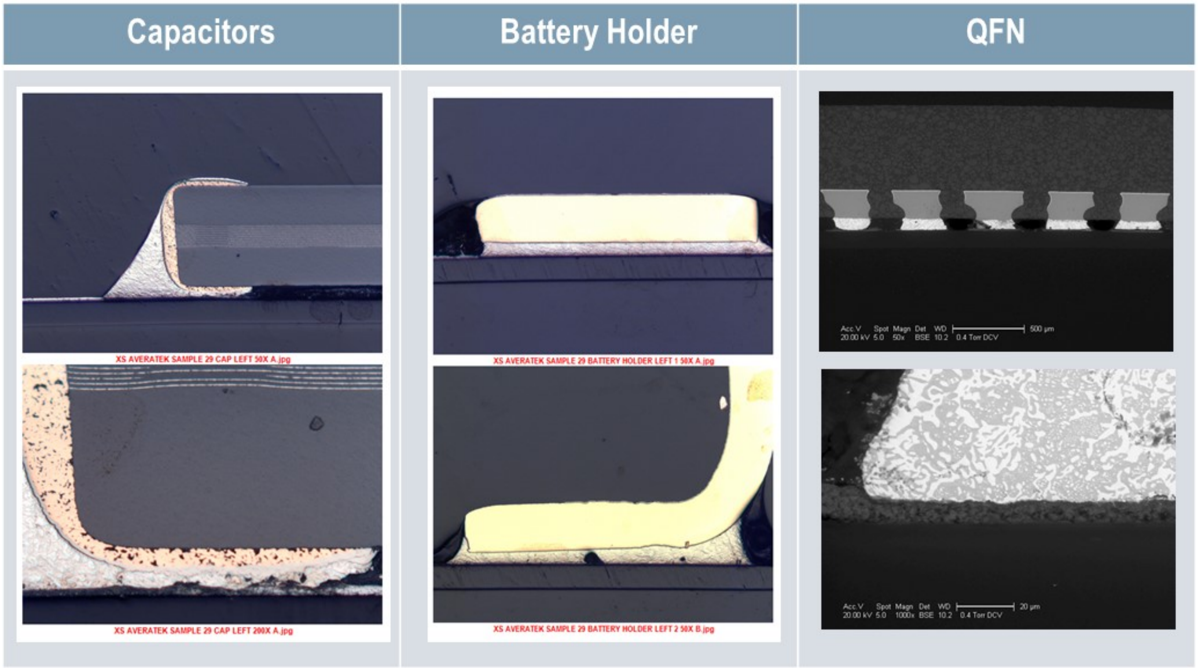

Figure 7- Cross sections of Capacitor, Battery holder and QFN/BTC soldered using Surface Treatment

As can be seen, while the solder wet and bonded well to the aluminum in most areas, voids were within the acceptable limit and are seen under the capacitor and battery holder's pad. These were further examined by doing an Energy Dispersive X-ray Spectroscopy (EDS). An EDS of one such resistor pad is shown in Figure 8.

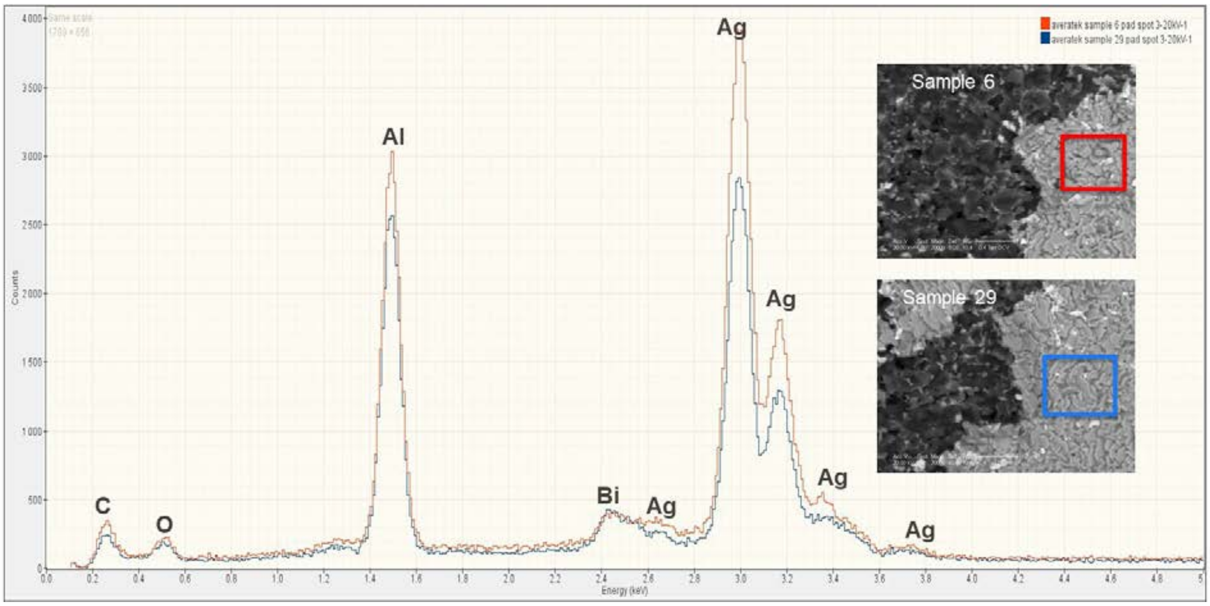

Figure 8 - EDS Spectra from pad side after pulling resistor from pad showing Ag-Al intermetallic

As can be seen in the EDS, there is evidence that the surface treatment results in the formation of a Silver-Aluminum (Ag-Al) intermetallic with some presence of Bismuth.

Conclusions

The surface treatment was shown to enable soldering to aluminum. Since solders vary in metal composition and flux, they each will have specific reflow profiles. Additional work may be needed to fine tune reflow parameters for specific applications to get consistent wetting and good solder joints. Most new soldering applications would require such process development. Overall, this surface treatment has the potential to open the path for large scale use of Al-PET substrates. This could revolutionize the manufacturing of Smart-tags, RFID and single layer aluminum circuits.

References

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