Equipment Impacts of Lead Free Wave Soldering

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Abstract

The popular tin (Sn) rich lead free solders are causing severe corrosion to many of the materials used in today's Wave Solder systems. Users are experiencing higher maintenance frequency and reduced life of wave solder machine components. This paper describes the effects of Sn rich solders in contact with various materials and discusses alternate methods to alleviate this problem.

In cooperation with the Metallurgy Department of the University of Missouri - Rolla, the Sn corrosion effects were studied for stainless steels, coated stainless steels, titanium, cast iron, and other materials. Corrosion effects and test results are presented for each of these materials. Optical and scanning electron microscopy and x-ray emission chemical analysis were the primary tools used in the evaluation of failed samples. Based upon this research and field trials, recommendations are given which address the expected field life, economic impacts, and materials selections for new or used Wave Solder equipment.

Introduction

The increasing popularity and use of lead free solders has uncovered weakness areas in the Wave Solder equipment in operation today. The primary weakness is visible corrosion and short life of the materials used in the solder module. Various equipment manufacturers have proposed a variety of solutions to combat this problem. Solutions range from doing nothing to entire pot and nozzle replacement using expensive alloys. This paper evaluates the materials used to construct the solder unit of Wave Soldering equipment.

With safety foremost in mind, failure of the solder pot or vat is the more serious concern over failure of the internal components used to pump and form the waves. A failure in the pot material can create a severe safety hazard and cause injury. Failure of the other components may cause downtime or lost production but will generally not create a safety hazard.

While it may be acceptable for some users to replace the internal components of the soldering unit on a regular basis due to corrosion, replacement of the solder pot on a regular basis may be an entirely different story.

History

Equipment manufactured prior to the popularity of lead free solders generally utilized welded 300 series stainless steel as the base pot material. Some manufacturers treated the stainless steel with a salt bath nitriding process and some manufacturers use cast iron for the pot components.

The majority of internal nozzle and pump components are manufactured from 300 series stainless steel, either treated with a nitriding process or left untreated. All of these materials have shown excellent life when used with tin-lead solders.

The installed base of Wave Soldering machines is quite large. It is important to understand the impact to the equipment before switching to lead free solder. Some machines may require very little change regarding materials while other machines may require replacement of the entire soldering unit.

Solutions to prevent the degradation and corrosion are varied and many. Some of the popular methods for the internal nozzle and ducting components are:

- All Titanium construction
- Nitrided Stainless Steel
- Melonite QPQ Coating
- Ceramic Coated Stainless Steel

For the solder pot the known alternatives being offered are:

- Cast Grey Iron
- Ceramic Coated Stainless Steel
- Nitrided Stainless Steel

In collaboration with the University of Missouri – Rolla Metallurgical Engineering Department, a variety of the common solder pot materials were tested and analyzed to determine the corrosion effects of high tin (Sn) exposure. Treated and untreated stainless steels were tested along with cast iron, titanium, and Melonite® coated plain carbon steel.

Utilizing the data presented, the person responsible for Wave Soldering operations should be able to make good decisions as to what will need to be replaced in his/her existing Wave Solder machine. The data can also be used as a guide to assist in the selection of the proper materials used in a new machine.

Field Observations:

Older equipment that has been drained and filled with lead free solder has brought to light the severe corrosion that occurs to the internal stainless steel components. Experience has shown that corrosion occurs after as little as six months of operation in high uptime environments.

Figure 1 shows a typical failure of an unprotected stainless steel solder flowduct used in a lead free application. Severe erosion and pitting of the metal has occurred and some areas have lost all structural integrity. The most vulnerable stainless steel components are those in contact with flowing solder (i.e. pump impeller, ducts, and nozzles).

Figure 1 – Failed Stainless Steel Solder Flow Duct

Stainless Steel Effects: Stainless steel is resistant to corrosion due to a thin chromium oxide compound layer that forms on the surface. This layer is impervious to most materials, including common electronics solders using lead, however, solders with high concentrations of molten tin (Sn) will attack and dissolve the natural protective coating on stainless steels. When this layer is gone, wetting occurs. Once wetted, it is only a matter of time before the underlying material dissolves into the molten solder bath.[1]

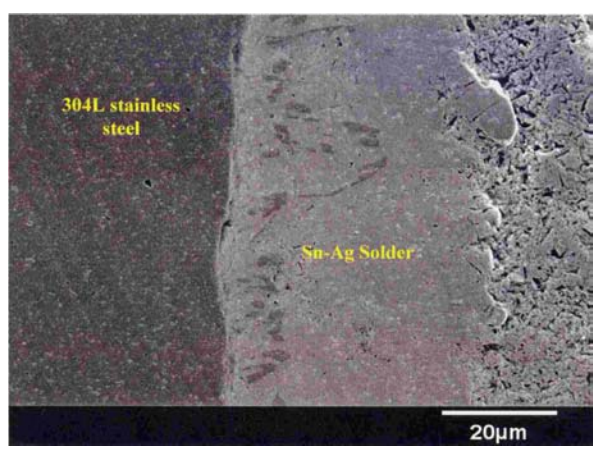

Figure 2 – SEM Image of Corrosion Pit

Figure 2 shows a scanning electron microscope (SEM) image of a sectioned sample of a corrosion crater from a stainless steel component operated with 97% Sn solder for approximately 1 year. Energy dispersive spectroscopy (EDS) compositional analysis was then performed in the SEM on the crater in 20µm increments, as shown in Table 1. Both indicate that a gradient of elements exist between the underlying stainless steel substrate and the external bulk Sn-Ag solder. This confirms that wetting to the stainless steel has occurred and that the underlying material is dissolving into the molten Sn bath of solder.[1]

Table 1 – EDS Analysis of Corrosion Pit

Element	Bulk 304L SS	20µm	40µm	60µm	Bulk Sn-Ag Solder
Nickel	8.76	0.00	0.00	0.25	0.00
Iron	71.25	18.19	16.97	0.59	0.00
Manganese	1.69	0.09	0.02	0.00	0.00
Chromium	17.31	2.36	0.80	0.05	0.00
Silicon	1.00	0.71	0.67	0.21	0.00
Tin	0.00	75.71	78.71	95.61	93.87
Silver	0.00	2.95	2.82	3.29	6.13

Cast Iron Effects: Solder pots made of cast iron that are currently being utilized in lead free applications show what appears to be a slight wetting. Severe pitting and corrosion has not been observed in field use as it is seen on the components made from stainless steel.

Other challenges not addressed by this paper that have been observed in the field are:

- More aggressive fluxes that reduce the long-term life of the wave solder machine.
- Preheat temperatures are generally higher.
- Higher solder pot operating temperatures.
- Solder pot mechanical devices that function by floating in the Sn/Pb solder may provide different feedback when used with the less dense lead free solders. Solder level controls and dross reduction "dams" may give unexpected results.

Materials Testing

Laboratory testing was conducted on representative samples exposed to 97%Sn solder at different temperatures and various exposure times. Material samples were fabricated into strips approximately 1 in. wide by 3 in. long. These strips were then immersed into a static bath of 97%Sn solder and examined at 2-week, 4-week, and 8-week intervals for signs of wetting (Figure 3). Baseline pictures were taken prior to running tests.[2]

Figure 3 – Solder Exposure Baths

Figure 4 – Typical Test Specimen with Scribed Mark

Some materials rely upon a coating to provide increased corrosion resistance. Since it is likely that components in the solder unit may be scratched during routing maintenance, a scribe mark was added to the samples to determine the effects in field use (See Figure 4).

Materials tested and test criteria are noted in Table 2.

Table 2 – Matrix for Testing[2]

Temperature (°C)	250	250	250	250	350	450
Time (weeks)	0	2	4	8	4	4
304 stainless	X	X	X	X		
Coated 304 **	X	X	X	X		
316 stainless	X	X	X	X		
Coated 316**	X	X	X	X	X	X
Plain Carbon	X	X	X	X		
Grey Cast Iron	X	X	X	X		
Titanium	X	X	X	X		
** Melonite® Treated						

Melonite®[3] coating is one form of treatment that is used on stainless steel and other materials to improve properties. It is a salt bath nitriding process used to improve the surface properties of ferrous metal parts. The specific process used is designated as Melonite® QPQ. The QPQ designation indicates that the part goes through a quenching process followed by a polishing operation and finally quenched again. This last quenching operation enhances the corrosion protection properties and sets this method apart from other common nitriding processes.[4]

The Melonite coating consists of two layers, a compound layer and a diffusion layer. The compound layer consists of ε-iron nitride (Fe_3N) that is a hard, chemically stable material and is primarily responsible for the improved corrosion resistance. The diffusion layer is γ-iron nitride (Fe_4N) and is responsible for improved material fatigue strength.[5]

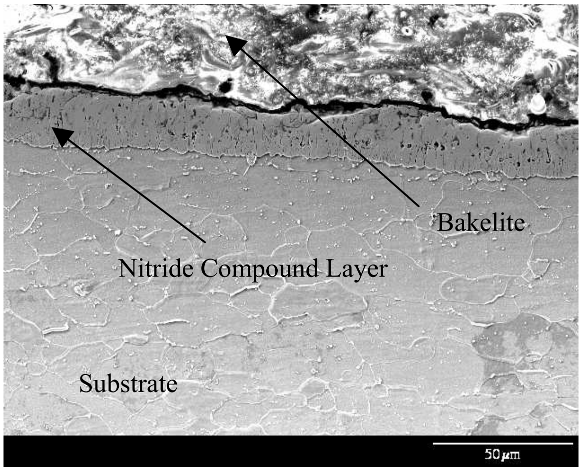

Figure 5 – SEM Image of Melonite® Coated Substrate

Test Data and Discussion

Macroscopic Images are given below for samples exposed to the Sn-Ag solder for the 2, 4, and 8-week exposure period at 250°C. Note: All photos are sequenced left to right according to exposure time with the 8-week sample shown on the right.

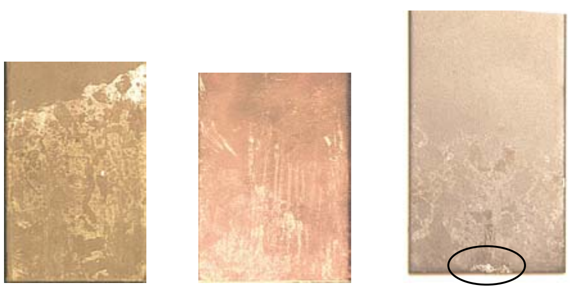

Figure 6
Melonite Coated Plain Carbon Steel
Wetting only on 8-week sample at scribe mark.

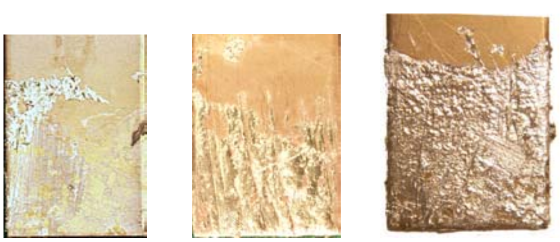

Figure 7
Uncoated 304 Stainless Steel Samples
Wetting Present on all samples.

Figure 8
Melonite Coated 304 SST Samples
Wetting only on 8-week sample at scribe mark.

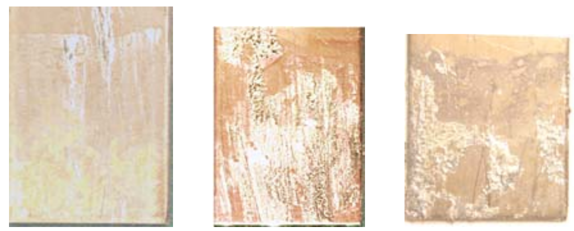

Figure 9
Uncoated 316 SST Samples
Wetting present on all samples.

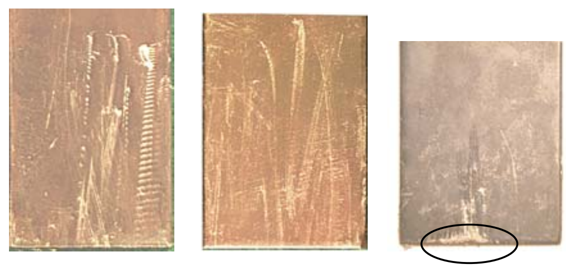

Figure 10
Melonite Coated 316 SST Samples
Wetting only on 8-week sample at scribe mark.

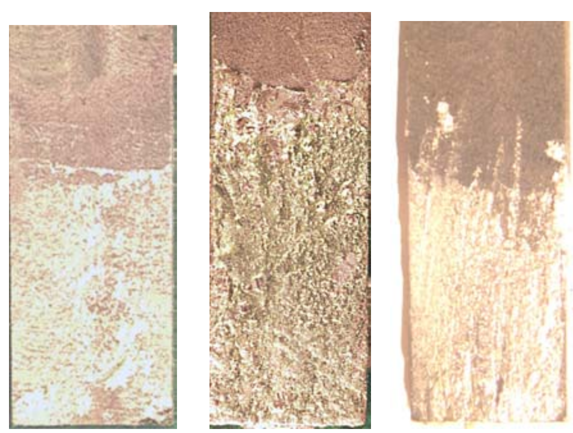

Figure 11
Grey Cast Iron Samples
Wetting on all samples.

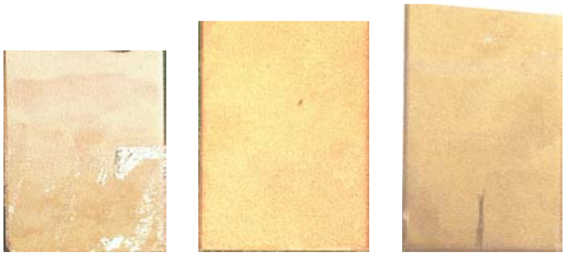

Figure 12
Titanium Samples
No evidence of wetting

Figures 6, 7, 8, 9, and 10 show the ability of the Melonite® QPQ Nitriding process to protect the underlying substrate of the stainless steel and carbon steel materials. Macroscopically, all coated samples showed very little wetting except in the area that was scratched. The unprotected 304 and 316 stainless steels had significant wetting on all samples. Plain carbon steel samples were tested as a possible "lower cost" material for solder unit internal components. Plain carbon steel exhibited good resistance to corrosion when protected by the Melonite coating. Results indicate that coated plain carbon steel will give equivalent corrosion protection to the stainless steel materials.

Samples were examined microscopically to determine if any corrosion effects could be found.

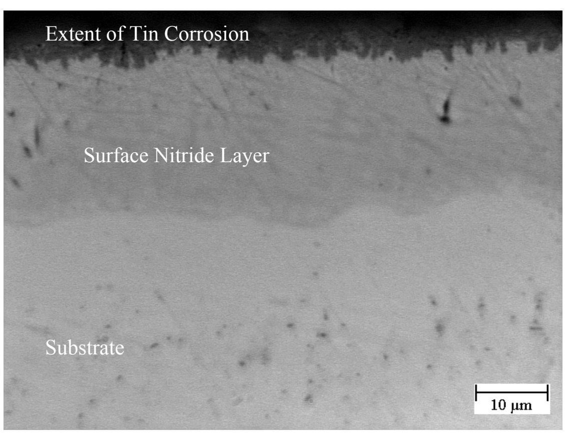

Figure 13
100X Light Microscope Image of Melonite Coated 304 SST

Under magnification, the coated 304 SST sample shows (Figure 13) that the nitride layer remained intact and continues to protect the underlying material. Some pitting was observed on the surface of the nitride layer.

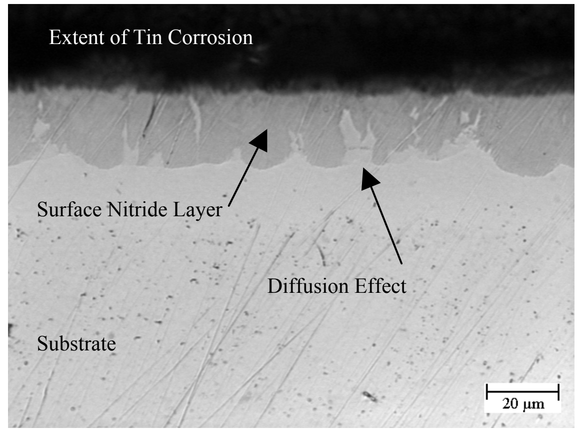

Figure 14
50X Light Microscope Image of Melonite Coated 316 SST

Figure 14 shows a close-up view of the 316 stainless steel sample after exposure to Sn-Ag solder. Visually, the samples did not show any signs of wetting or corrosion. Under magnification there appear to be "fingers" of material protruding into the nitride coating from the substrate side. These fingers do not appear on the baseline samples. It is suggested that the austenitic SST is diffusing nitrogen from the Melonite compound layer. Once extended to the surface, the Sn will attack and undercut the protective coating and eventually cause failure. [2]

It is interesting that the 304 SST samples did not show the presence of these fingers that cause degradation of the protective layer. Further investigation needs to be done to determine if this phenomenon is only applicable on the 316 alloy. Given the theory proposed, similar diffusion in the 304 alloy samples would be expected.

Higher temperature testing was conducted on the 316 stainless steel coated samples using temperatures of 250°C, 350°C, and 450°C. At the elevated temperatures none of the samples showed significant wetting [2]. Under microscopic examination the austenite diffusion phenomena was much more pronounced than the testing done at the lower temperature levels. Undercutting of the Melonite coating was observed for the 316 coated sample at 350°C (Figure 15)

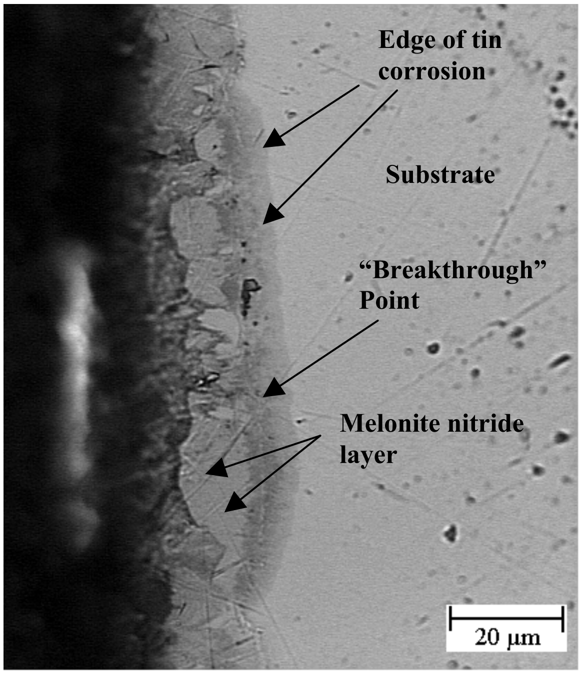

Figure 15
Image showing undercutting at 350°C exposure.

This testing indicates that the service life of coated SST components is finite. The coating significantly improves the corrosion protection compared to non-coated stainless steel but will eventually degrade at some point in time.

The Grey cast iron samples visually wet after two weeks of exposure. Light microscope images were taken of the 8-week exposed sample to determine the extent of the corrosion.

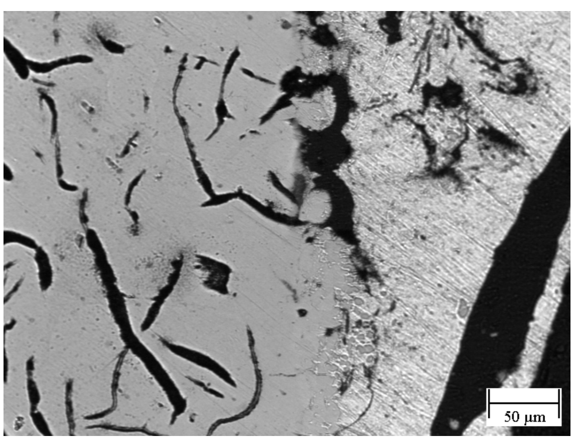

Figure 16
Grey Cast Iron showing graphite flakes and "damming" action

Microscopic images of the grey cast iron sample show a "damming" action created by the graphite flakes in the cast iron material (Figure 16). Since Tin will not dissolve the graphite flakes, less iron surface area is available for attack by the Sn-Ag solder thus slowing the rate of corrosion to a very low level.

Available corrosion data shows that cast iron will corrode at a rate of 0.25 mm/year when exposed to molten Sn at 300°C.[6] At this rate, we would expect many years of acceptable service life given the 10-12 mm thickness of these components.

Titanium samples exhibited no effects of corrosion or wetting after exposure. This is expected as titanium forms a passive oxide on its surface and the titanium-tin phase diagram indicates that titanium has no solubility in tin at the temperatures common to soldering [7]. Of all samples tested, titanium had the most resistance to corrosion attack.

Summary of Test Results

Based upon testing, field data, and experience better decisions can be made concerning the use of lead free solder in Wave Solder equipment. Up-front costs, maintenance costs, safety, and reliability must be considered when determining the best selection.

Based upon corrosion resistance alone, titanium is by far the best material. The likelihood of being able to afford an entire Wave Solder unit manufactured entirely out of titanium is very low. It is estimated that the purchase price of a new Wave Solder machine with an all titanium solder unit would be double the cost of a regular unit.

Unprotected stainless steel, either 304 or 316, is not suitable for long term use in tin-rich lead free solder. Samples of these materials are readily wet after a relatively short-term exposure to solder. On the other hand, when protected by the Melonite coating process the testing indicates that an extended life will result over the non-protected stainless steel. It is important to note that the nitriding coatings do not protect the stainless steel forever, they only delay the eventual corrosion. It is difficult to make predictions on the actual life, but from field experience, three to five years is not unreasonable when protected with a nitride type coating. For comparison, unprotected stainless steel has degraded to the point of failure after as little as 6 months of use. The key to a long life is to avoid scratching or damaging the Melonite protective coating. Once the coating is damaged, corrosion of the substrate will be accelerated. Though not evaluated in this examination, we would expect similar results when ceramic coated stainless steel is used.

Grey cast iron quickly wets with lead free solder but exhibits a damming action that slows the corrosion to a very low level.

Table 3 gives a summary of the recommended uses for the variety of materials under evaluation.

Table 3 - Summary of Material Recommendations

Material	Pro's	Con's	Recommended Uses	Inspection Frequency
Titanium	Extremely resistant to effects of Tin.	Very expensive. Impractical to manufacture many solder unit components.	Areas subject to frequent maintenance or cleaning. Nozzle plates. Safety critical components.	Every two years.
304 Stainless Steel	Inexpensive.	Little to no corrosion resistance to lead free solders.	Exterior Hardware. Interior Hardware if corrosion resistant hardware in unavailable. Not recommended for safety critical components.	Inspect monthly.
316 Stainless Steel	Inexpensive.	Little to no corrosion resistance to lead free solders.	Exterior Hardware. Interior Hardware if corrosion resistant hardware in unavailable. Not recommended for safety critical components.	Inspect monthly.
304 Stainless Steel Melonite/Nitrided	Inexpensive. Good Resistance to Tin-rich solder.	Will degrade if scratched.	Internal Solder module components. Nozzles, ducts, impellers, pumps, etc. Not recommended for safety critical components.	Inspect every 6 months.
316 Stainless Steel Melonite/Nitrided	Inexpensive. Good Resistance to Tin-rich solder.	Will degrade if scratched.	Internal Solder module components. Nozzles, ducts, impellers, pumps, etc. Not recommended for safety critical components.	Inspect every 3 months*.
Grey Cast Iron	Inexpensive. Good Resistance to Tin-rich solder. Can be scratched.	Difficult to form for nozzle components.	Internal components in contact with non-flowing solder. Safety critical components (Main Solder pot).	Inspect thickness annually.

* Due to the undercutting shown on the 316 samples tested a more frequent inspection is recommended.

Conclusion

Tin-rich, lead free solder can be used in pre-existing and new wave solder machines if appropriate materials are used in the construction of the soldering unit. Older machines utilizing unprotected 304 or 316 stainless steel solder pots should not be used with lead free solder. Melonite or other nitride coated stainless steel is a cost effective material to use for the internal solder module components but care must be taken to not damage the surface coatings during maintenance. Melonite or other coated stainless steel is only recommended in safety critical areas when frequent inspections are made to identify degradation of the material. Due to the difficulty of such inspections, safety critical components such as the solder pot should be produced from titanium or grey cast iron but not stainless steel.

Acknowledgements

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