CONNECTOR DESIGN FOR WEARABLES

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ABSTRACT
As electronics continue to shrink and their performance capabilities grow, these electronics are becoming more and more integrated into our daily lives. The next step is the internet of everything and wearable electronics. Communication between devices and providing power through the use of connectors is critical; connector sales are a $50 billion/year industry. As critical as they are, separable connectors are often times the first item to fail in electronics. This problem is only expected to worsen as electronics are used in increasingly challenging environments. This paper will discuss contact physics, contact plating options, normal force requirements and general tradeoffs that frequently occur when designing or selecting a connector for an application. Physics of failure along with a number of connector failure examples will be presented as well.

INTRODUCTION
Electronics are being used in increasingly harsh environments. In the past, most electronic products were used in home/office or controlled data center environments. As we progress towards the internet of everything and wearable electronics, these products become exposed to moisture, particulate contaminants, hot and cold temperatures, sweat, and mechanical shock and vibration. In the first 5 years of the iPhone customers reportedly lost $5.9 billion on damaged phones. 33% of the damaged phones were due to water damage while 40% were due to being dropped.[1] There are about a dozen connectors in a phone and loss of function due to water damage largely occurs due to corrosion or dendrite formation under these connectors.

Of course smartphones are just one example of what we might call wearable electronics. Google Glass was introduced in 2014 with a lot of fanfare, however it was removed from the market in 2015 and is currently being redesigned to be made more acceptable to users from an appearance standpoint.[2] Meanwhile, there have been an abundance of other wearable electronics recently released for use in the workplace and home. For example, Tesco, a supermarket company in Europe, is using armbands that automatically track goods that workers are transporting to stock shelves. Previously pen and paper were used to record all such product movement. Of course, such tracking also enables employers to gauge the efficiency of employees.

Wearables are also finding use in health and wellness programs. Bracelets can track an employee's or patient's heart rate, breathing, and other vital signs. There is an EEG headband that helps understand your cognitive patterns thereby giving you insights on when you are most creative and productive. Samsung recently released a product called Simband (Figure 1) that is worn on the wrist and is full of sensors that can track a number of bodily functions for health monitoring. It is open for application developers to produce various creative apps for a multitude of uses.

Figure 1. Example of a Simband health monitor device.

A company called Lifebeam has come out with wearable products such as a bike helmet that monitors heart rate, counts your calories, tracks your location and speed and gives an accurate analysis of your performance. Figure 2 shows an example of a similar product with video. This tracks speed, mileage, altitude, location, etc. GoPro is a pioneer in this space as well and their products are designed to withstand very challenging environments, including underwater.

Figure 2. Video gathered by a bicycle helmet camera with live location and speed data.

And of course, last but not least, Fitbit must be mentioned due to their recent IPO on June 18, 2015 (ticker: FIT). This company makes and assortment of wrist bands that track various health metrics.

With electronics becoming more ubiquitous in our lives and they are being built with more aggressive design rules. At the same time, customers seemingly have a higher level of expectation for reliability. Reliability is the measure of a product's ability to perform the specified function over the desired lifetime. Loss of contact between conductors is often times the first item to fail with electronics in harsh environments. Product designers and connector manufacturers need to work together to avoid failures. This paper is meant to educate designers on the physics of failure of connectors and how to implement best practices to minimize the chance of failure in challenging environments.

CONNECTORS

Connectors can sometimes be overlooked as a critical component because they are not as sophisticated as integrated circuits and the complex technologies used to package them. However, a standard server may have over 80 connectors while a notebook computer might have 60 or more. So many electronics have thousands of opportunities for contact failure, any one of which can shut the system down. A wearable product may have connectors used in: antennas, sensors, power/grounding, battery connections, board-to-board, flexible printed circuit connection, wire-to-board, removable memory cards, etc.

There are dozens of companies producing electrical connectors and all of these feel constant pressure to reduce costs. A connector engineer has to have a good grasp of the contact physics to ensure adequate reliability is achieved in this challenging environment.

CONTACT PHYSICS

When two contacts meet, actual electrical connection is made through contact points called asperities (see Figure 3). There may be as little as three asperities per connection (often less than 1% of the apparent contact area). It is at these points where actual metal to metal contact is made. Cold welding of metal often occurs at these locations. Metallic bonding takes place through the sharing of electrons, so if all oxides and contaminates are removed, such cold welding is allowed to take place. Other asperities may just be points of very close contact where current can jump the gap (or tunnel through the oxide).

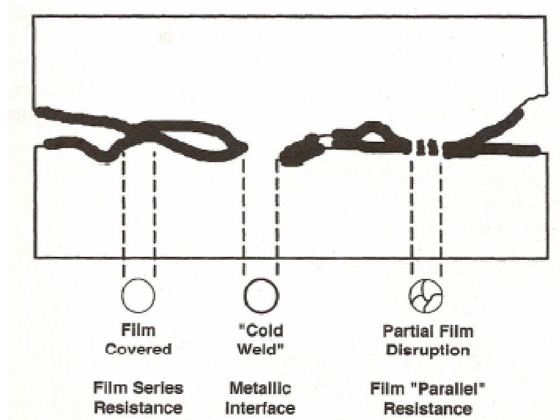

Figure 3. Asperities are the small peaks, observed at a microscopic level, where actual contact is made.

Constriction resistance occurs when current flows across these small asperities (resistance increases due to the small area in which current is allowed to flow – see Figure 4). So the fewer the asperities the higher the constriction resistance. When the number of asperities decreases to a critical amount then constriction resistance can cause localized heating. This heating can cause accelerated oxidation which can further increase the resistance. This runaway effect is what leads to loss of contact.

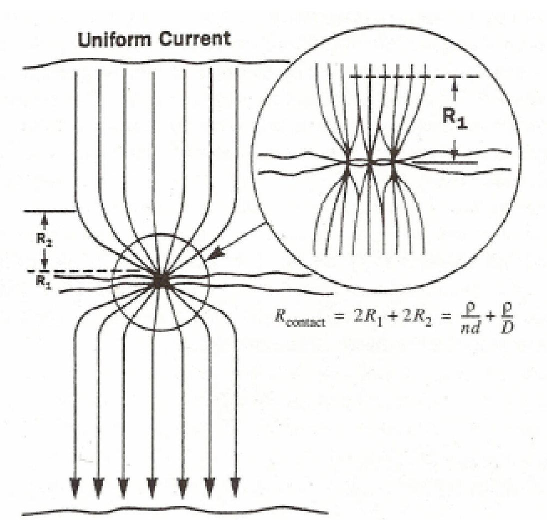

Figure 4. Constriction resistance occurs when current is forced through small asperities.

The objective in achieving a reliable connection is to maintain sufficient number of asperities to allow current flow at low resistance. The number of asperities is affected by factors such as the contact force, the hardness of the metal finish, the oxide layer, any absorbed gasses, and physical contaminants. The constriction resistance vs normal force of a contact system is shown in Figure 5. This simply illustrates that a critical number of asperities is needed to cause a significant reduction in resistance, at which point added force only reduces the resistance marginally.

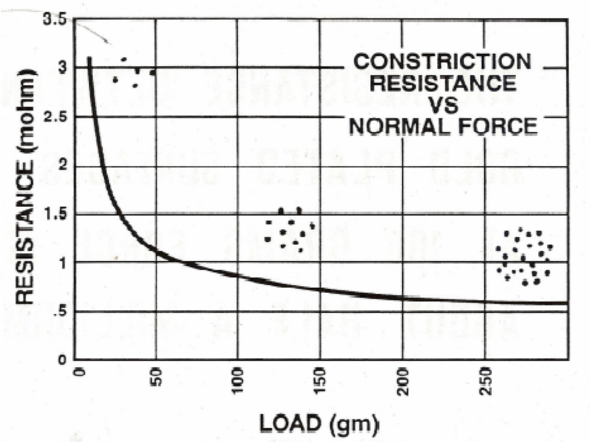

Figure 5. Constriction resistance vs normal force for a gold-to-gold connection (the small dots represent number of asperities).

All surfaces have a layer of absorbed moisture and OH groups. Contaminant gases that contain sulfur or chlorine, for example, can also attack the metal and leave a reactive film that must be broken through. Therefore, normal force requirements are higher in less controlled environments. Mixed flowing gas testing is often used to determine the susceptibility of the contact metal to contaminant gasses. For example, Figure 6 shows contact resistance vs. load after various periods of time in a class 3 mixed flowing gas environment. As one would expect, the load required to achieve 10 mohm resistance varies by exposure level.

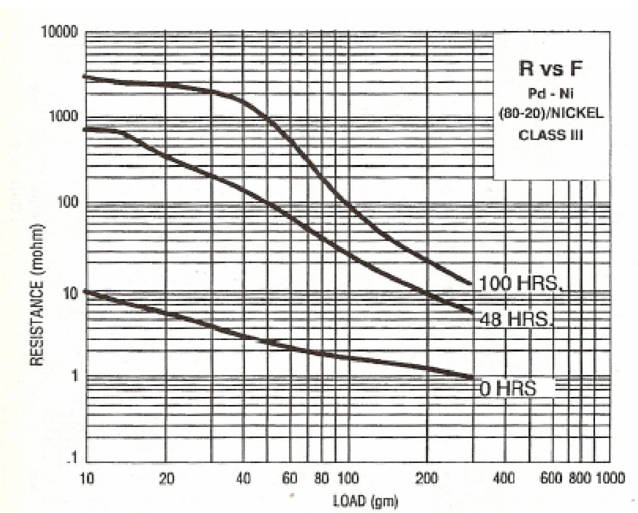

Figure 6. Contact resistance vs normal force after exposure to mixed flowing gas.

CONTACT METALS

By far, the best metal for making contact is gold. This is because gold does not have a native oxide and does not react with other common contaminant gases. For this reason, gold can form a reliable contact with very low normal force (as little as 20 grams). If gold was cheap, this would be the end of the discussion on contact metals, but due to its expense other metals are often used as plating materials.

Gold

When using gold, it is common practice to first plate a layer of nickel over the base copper. This nickel layer prevents copper from diffusion through the gold and creating a copper oxide on the surface. This Ni layer should be at least 1.27 µm thick to ensure low porosity. Soft gold (pure gold) is most often used because it allows the highest density of asperities with low contact force. However, in applications in which wear is a concern (many insertions withdrawal cycles) then sometimes hard gold is used (alloyed with cobalt or nickel). For contact applications, electrolytic gold is most often used. Contacts are plated after stamping in bandolier form so electrical conduction is easily attained. Gold is most efficiently used by selective plating in only the region where actual contact will be made.

The thickness of gold should be based on the application requirements and the reliability demands. Military or certain medical applications may use 50 µ" of gold (or in applications with a high number of insertion cycles). A moderate number of connection cycles (perhaps 10 – 30) may use 30 µ" of gold. Most common connectors use closer to 10 µ" of gold and are intended for up to 10 insertion cycles. Flash gold (1-5 µ") is being used more frequently to reduce cost but one should not expect high reliability or more than a cycle or two before wearing off the gold. Keep in mind that there are other contributing factors that can influence the appropriate gold thickness as well, factors such as normal force, contact area, amount of wipe, environment, etc.

Tin

Tin is often used on lower cost connectors. It is an adequate contact metal for certain controlled environments but one must be cautious. Tin is a soft metal that grows a hard and brittle oxide. At a microscopic level it can be thought of as ice on mud. Upon contact, the oxide is easily broken and fresh tin oozes through to make contact (Figure 7). Once contact is broken the exposed tin reoxidizes and must be broken through again.

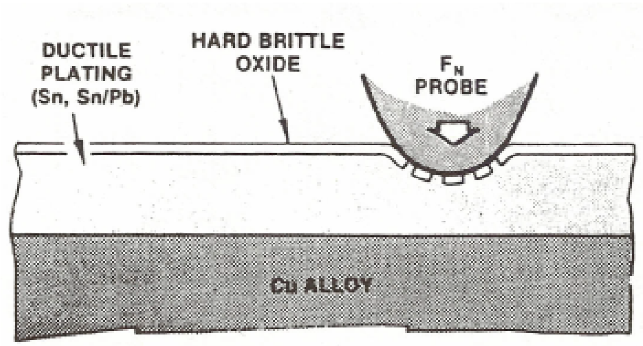

Figure 7. Tin is soft but forms a thin and brittle oxide which is broken through to make contact.

If a new contact location is frequently made due to displacement of the contact, then the tin oxide can build up and eventually create a debris field that inhibits adequate contact (see Figure 8). This process is called fretting and often occurs on tin plated contact that are used in a vibrating environment or an application with many insertion withdrawal cycles. It can also occur with frequent temperature cycles that can also cause micromotion of the contacts.

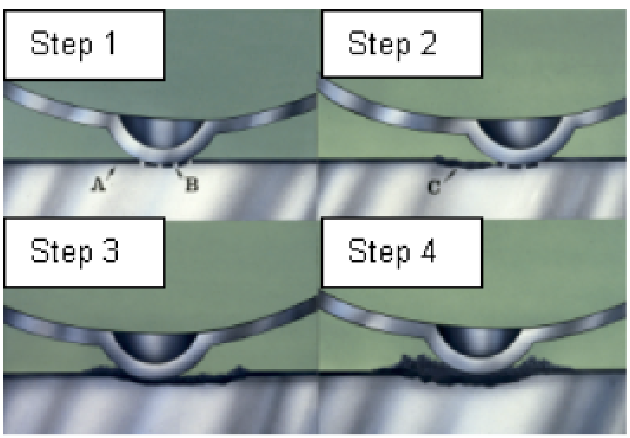

Figure 8. The fretting process for tin plated contact.[3]

When using tin plated contacts, one should be familiar with the Tin Commandments which are a list of guidelines (not hard and fast rules shown in Figure 9). These were created by J Whitney in 1981 and still hold true today.[4] Perhaps the most controversial is #3 that suggests the use of contact lubrication. Lubrication may be desired in a situation where tin is used in a non-mechanically stable condition. In such a situation the lubrication provides a gas tight environment that reduces the rate of tin oxidation. In electronics application, tin is most frequently used on pin headers held firmly in place that will likely only see a few cycles.

TIN COMMANDMENTS

TIN OR TIN ALLOY COATINGS ARE COST EFFECTIVE AND RELIABLE ALTERNATIVES TO GOLD IF USED ACCORDING TO THE FOLLOWING GUIDELINES:

1. Tin coated contacts should be mechanically stable in the mated condition
2. Tin coated contacts need at least 100 grams contact normal force
3. Tin coated contacts need lubrication
4. Tin coating is not recommended for continuous service at high temperatures
5. The choice of plated, reflowed, hot air leveled, or hot tin dipped coatings does not strongly affect the electrical performance of tin or tin alloy coated contacts
6. Electroplated tin coatings should be at least 100 microinches thick
7. Mating tin coated contacts to gold coated contacts is not recommended
8. Sliding or wiping action during contact engagement is recommended with tin coated contacts
9. Tin coated contacts should not be used to make or break current
10. Tin coated contacts can be used under dry circuit or low level conditions

Figure 9. The tin commandments put together by J. Whitney in 1981.

Nickel, Steel, Palladium

Other metals and combinations of them are also occasionally used for contacts. Nickel and steel (usually stainless steel) can be used in special situations but require high normal force to break through the tough oxides on these metals. The oxide on stainless steel is actually chrome oxide (basically ceramic) so at least 300 grams of force is recommended. Palladium and palladium nickel alloys were introduced some time back as contact materials due to the high cost of gold. Palladium is often used as a catalyst in chemical reactions and therefore some found that organics could build up on Pd contacts and create a waxy buildup. For this reason, a thin flash gold was used over the Pd. But it wasn't long before most realized that this was little better than flash gold on nickel, so Pd has not been highly used.

NORMAL FORCE REQIREMENTS

Newer materials are being created for contacts in the continuous drive for lower cost while maintaining reliability. For any material one needs to understand the minimum contact force required to break through the oxide layer and achieve sufficient contact sites. For common materials discussed here these are:

- Gold: 20-30 grams
- Pd: 30-50 grams
- Tin: 100 grams
- Nickel: 200 grams
- Stainless Steel: 300 grams

CONTACT WIPING

When contacts are used in an environment with high levels of moisture, gaseous contaminants, or physical contaminants (a common situation with wearable electronics), one needs to further increase the normal force or, better yet, design in some amount of contact wiping. Wiping effectively pushes debris off the contact surface to allow a metal-to-metal interface. Ideally, the wipe would be 50 µm or more with a small amount of reversal. The reversal prevents the contact from sitting on the pile of debris that may have been plowed up.

BASE METAL OPTIONS

The base metal used for contacts is extremely important because the material used along with the contact design will determine the normal force of the contact. The higher the yield strength of the material the thinner the contact can be to achieve the spring properties required. When the yield strength is exceeded the contact becomes permanently deformed and the normal force is reduced. Beryllium Copper alloy was commonly used prior to the 1980s due to its high strength. However, the high cost and concerns with working with Be has reduced this alloy to only special applications. Phosphor Bronze is most commonly used today because the cost is less than BeCu yet has fairly high yield strength. This alloy comes in many different tempers with the tradeoff being the higher the yield strength the lower the ductility. Brass is being increasingly used for further cost reduction. However, one should be cautious with using brass as it has lower strength and higher stress relaxation. Consequently, spring force can be lost over time.

Under a constant load all materials will creep (deform) over time due to atoms within the material diffusing from regions of high stress to regions of lower stress. Since the diffusion rate is highly dependent on temperature, elevated temperature naturally results in much faster creep. In a deflected contact the creep results in a reduction in stress over time (stress relaxation). So a material with high stress relaxation will lose its contact force much faster that one less prone to relaxation. BeCu is very resistant to stress relaxation, phosphor bronze is intermediate, and brass is lowest. So wearable electronics that could be left in a hot vehicle might do best to use a phosphor bronze contact material.

USEABILITY

Another attribute that deserves attention is the force required to insert or extract the connector. If the forces required are too high full mating may not be achieved or users may pull on cables to get the connectors apart. Too loose and the connectors may separate on their own. Some will design in latching features on a connector that prevents it from coming apart on its own. It is also wise to design a "key" into a connector so it only mates in one orientation. This prevents a user from forcing a connection and perhaps damaging the connector body.

COMMON FAILURE MECHANISMS

An increase in contact resistance can eventually result in loss of function (or an intermittent failure). The most common cause of failure is likely due to contamination of contact surfaces. This can be due to particulates or fibers that can get under the contacts (sometimes during vibration). Another cause could be corrosion or the growth of corrosion products from pores through the gold layer. Excessive oxidation, such as fretting, is another area of concern.

Loss of normal force can also lead to contact failure. Contacts can become physically bent or jammed, or contacts can become caught on the plastic body of the connector restricting their movement. Stress relaxation of contacts over time could also be a source of reduced normal force. Wear off of the gold can also become a problem. The normal force may have been sufficient for a gold-to-gold contact, but if the gold is worn away the normal force may no longer be sufficient for a nickel-nickel contact.

CASE STUDY

As an example I'll go through a contact failure situation that actually occurred to illustrate a number of these failure mechanisms. This example involves a simple CR2032 battery socket. I was brought into a meeting and asked to find the best contact lubrication so our field technicians could use it when repairing failures in these battery sockets. After finding them a good lubricant, I then asked to get some failures into our lab for analysis. Fretting corrosion was found on the tin pated contacts (likely due to vibration from a nearby fan). The company had recently changed the battery socket contact from gold plating to tin plating, so it made sense why the failure rate suddenly increased. When investigating the field failure rates it was also noticed that there was another increase in field failures even prior to the contact finish change. Discussions with the battery supplier revealed that the battery shell had been previously changed from nickel to stainless steel as a cost reduction (but the internal part number had not changed).

So it was determined that with a gold contact to a nickel plated battery there were no failure issues. Changing the battery shell to stainless steel resulted in an uptick in field failures since stainless steel has a tougher oxide and requires more normal force (see Figure 10). Battery socket normal force is typically 100-200 grams. However, trouble really arose when the contact interface became tin to stainless steel. Initial contact was sufficient, but even small amounts of vibration were enough to cause failures (since only modest amounts of fretting impeded contact).

The correction was to change back to a gold plated contact (5 µ" gold) and to change back to a nickel shelled battery. When this was done the field failures were eliminated. This example illustrates that much can be learned from deep diving into the issue and really understanding the contact materials being used in the system.

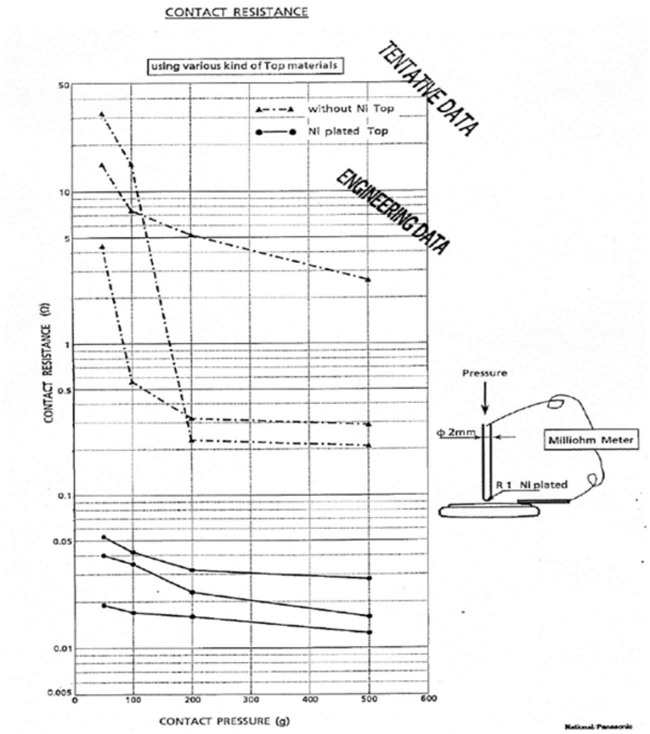

Figure 10. Contact resistance vs contact normal force for nickel and stainless steel (battery contact normal force was 100-200 grams).

LUBRICATION

Contact lubrication was brought up in the previous case study and was also mentioned earlier in the Tin Commandments. The primary purpose of contact lubrication is to protect the interface from oxidation and contamination. The lubricant (mostly oil based) fills all the space between the asperities thus protecting them from the environment (illustrated in Figure 11). This is especially beneficial for an application where fretting may occur since it prevents reoxidation of the tin. Another benefit of lubrication is a reduction in sliding friction and wear of the contact metallurgy.

The downside of lubricants is that they are generally messy to work with (since they are oil based). They are typically sprayed on and require drying. Some lubricants can also degrade the plastic body of the connector. Also, if the contact is left in the unmated state, debris can accumulate on the lubricant and can actually degrade contact. For these reasons contact lubrication is rarely used in personal electronic applications, therefore, is not a good fit with wearable devices.

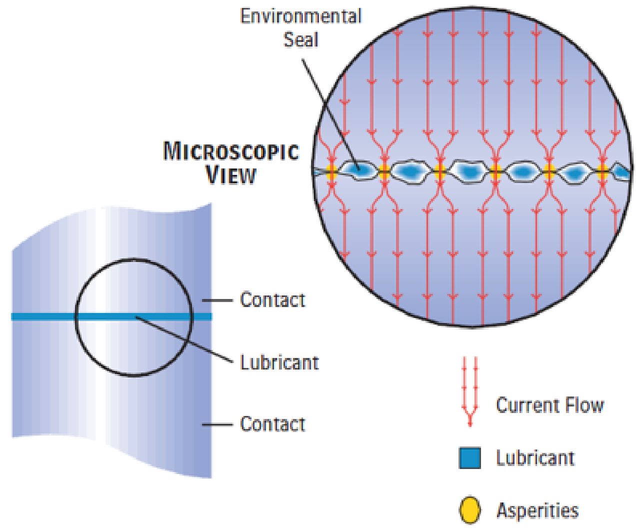

Figure 11. The purpose of lubrication is to protect the interface from oxidation/contamination.[5]

TIN WHISKERS

Another area to address with tin plating is the possibility of tin whisker growth. This will only be briefly discussed here since other papers can provide much more dedicated material to this important topic. The primary concern is that a whisker will grow from the surface of the tin coating and cause an electrical short.

The primary cause of whisker growth is an increase in compressive stress in the tin layer most commonly caused by growth of a copper-tin intermetallic. For this reason, most contact suppliers will plate a layer of nickel under the tin to prevent this intermetallic growth. It is also important to know that there are two types of tin, matte and bright. When organics are added to the plating bath the grain size becomes smaller and provides a bright (shiny) tin layer. This type of tin will grow whisker much faster due to an increase in grain boundary diffusion and stress from the organic additives. Matte tin has larger grains and is less prone to whisker growth. For this reason bright tin should not be used in close proximity to other conductors. As an example, the D-sub connector in Figure 12 caused a major failure when a whisker grew from the bright tin shell to a pin.

Another proven area of concern is on flexible printed circuit (FPC) connectors. In an FPC the conductors are on a soft polymer backing material (usually polyimide). When contact normal force is applied, the polymer conforms, and pressure is exerted over a large area of the conductor. If the conductor is tin plated, compressive stress over the large area can feed growth of long whiskers that can cause an electrical short between conductors. An example is shown in Figure 13. It has been found that a nickel underplate does not reduce this type of whisker growth. This is obviously a concern for wearable devices where closely spaced conductors on FPC are frequently used. The solution is to gold plate the FPC conductors and contacts on the mating connector.

The primary actions to take to reduce whisker risk can be summarized as follows:

- Forbid bright tin when it is close to conductors
- Ensure nickel is plated under the tin (50µ" min)
- Use gold plate on IPC mated with a connector
- Don't use tin plating on iron or brass (whiskers can grow very long due to thermal cycle stress)

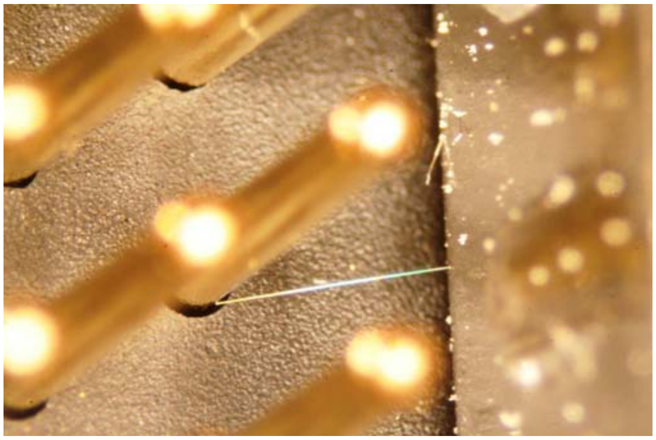

Figure 12. Tin whisker shorting between the bright tin shell and the pin (courtesy of Emerson).

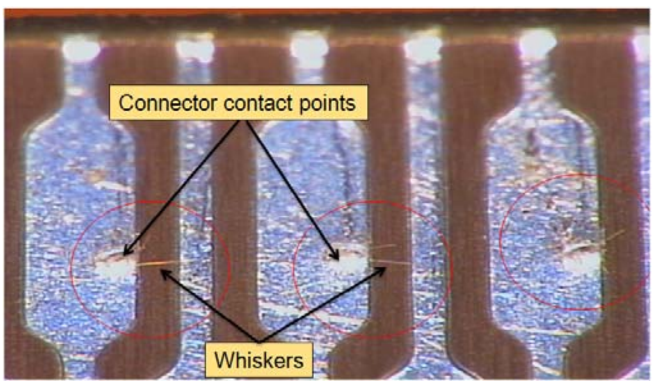

Figure 13. Tin whiskers growing from contact points on a flexible printed circuit.

CONNECTOR DESIGN STRATEGY

Often times as engineers we design our product from the outside in. That is, we design the case, list all the functional requirements, and attempt to fit all the critical electronics inside. When space is limited (and it always is), we start designing special connectors to fit into just this or that space. If you are a multibillion dollar company named after a fruit, then you can successfully do this because you have an army of engineers and suppliers who will design special connectors to fit the application. However, for most companies it is probably wiser to select a proven connector technology with years of data behind it and design the product around it (and other critical components).

This approach is sometimes called TEST and DESIGN as opposed to DESIGN and TEST. Toyota is known for designing their vehicles in this manner to achieve the highest reliability. So the advice is to do this whenever possible to avoid unnecessary expense and reliability risk.

SPECIFICATIONS

A connector specification will consist of an electrical section and a mechanical section. The electrical section will address requirements such as maximum current per contact, insulation resistance between contacts, dielectric withstand voltage (arc protection), maximum contact resistance and maximum ground shell resistance. If live mating is allowed then sometimes the ground pins are longer and will mate first. Make sure that none of these specifications are exceeded for the application.

The mechanical section will cover items such as insertion and withdrawal force, retention strength to the PCB, durability (max insertion cycles), any keyed feature, any blind mating feature, max temperature allowable, and so forth. Again, make sure these meet requirements of the application.

CONNECTOR QUALIFICATION

Qualification of connectors can be a lengthy topic to discuss so only the basics will be addressed here. All good connector suppliers should be performing reliability testing on their connector/contact systems. The mated connectors would be subjected to various environmental tests and the contact resistance measured with 4-point probe before and after the testing. No test should result in a contact resistance increase of more than 10 milliohms. EIA-364-23 5.4.1 addresses this procedure.

There are various EIA standards that specify environmental conditions and durability preconditioning (usually insertion withdrawal cycles). For example, EIA-364-17 addresses high temperature life (usually at 105ºC). EIA-364-31 addresses cyclic temperature and humidity. Vibration is covered by EIA-364-28 and mixed flowing gas by EIA-364-65. There is even a dust test covered by EIA-364-91. The important thing is to become familiar with these standards and determine which conditions apply best to the environment that your product will be exposed. Make sure the supplier has performed such testing and ask to see the data.

SUPPLIER MANAGEMENT

An electronic connector requires mastery of many disciplines. These include stamping and forming of contacts, plating of contacts, injection molding, insertion of contacts, not to mention material control, reliability testing, packing/shipping, etc. A deep dive is recommended into each of these areas to ensure all are running with good data driven statistical process control.

SUMMARY

Connectors are one of the most critical components in an electronic product and this is anticipated to be especially true with wearable products that will have to endure sweat, high humidity, elevated temperature, corrosive gasses, and various types of debris. In addition, those charged with a power connector should experience a high number of insertion withdrawal cycles. Whenever possible, select connector systems with a long history of success. Use gold plated contacts when possible and be aware of the appropriate thickness of gold. There are a wide range of connector suppliers and it usually pays off to use those with a proven reputation. Be aware of the primary failure mechanisms and design to avoid them. Understand the environment that the connector will be placed in and make sure that sufficient reliability testing has been performed.

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