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FEBRUARY 2015

Risk and Mitigation for Tin Whiskers and Tin Pest

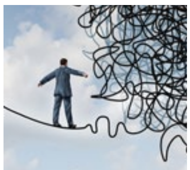
by Dr. Ronald C. Lasky, page 18

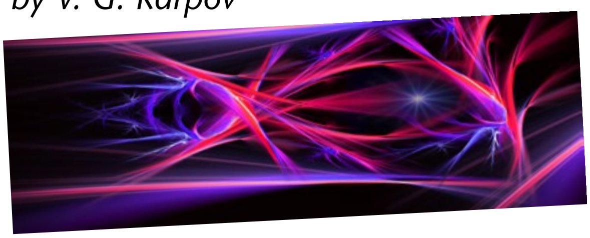
February 2015

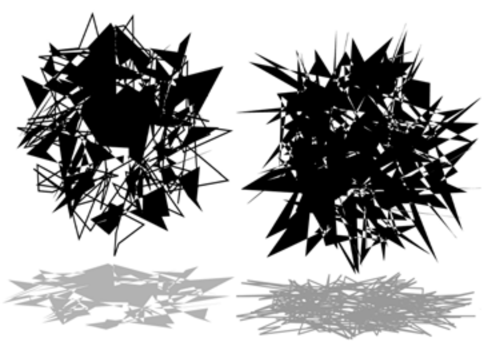
Featured Content

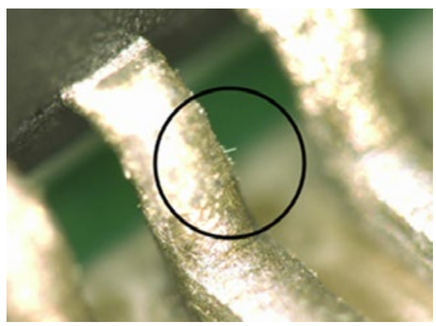
Tin Whiskers

Technologists have studied tin whiskers for decades, but the proliferation of lead-free electronics has pushed these microscopic fibers to the forefront of assembly challenges. This month, we focus on the mitigation of tin whiskers with articles by V. G. Karpov, Dr. Jennie Hwang, Michael Osterman, Andrzej Czerwinski, Scott Sentz, and Dave Hillman.









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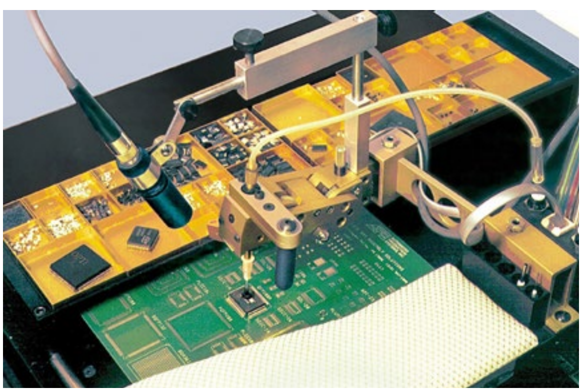

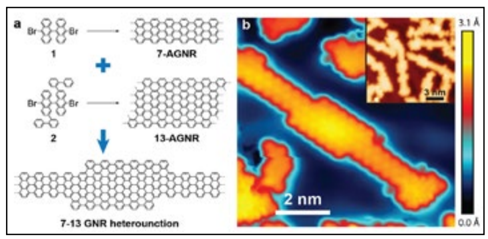

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Bits and Pieces

by Ray Rasmussen
PUBLISHER, I-CONNECT007

Something New at I-Connect007

Probably the biggest news from our team is our very soon to be launched new website. Using all the latest and greatest web technology, we've developed the site to make it really easy for our readers to find what they're looking for and we've integrated the latest advertising tools to help sellers and buyers quickly find each other. This fast and user-friendly site, with over 80,000 news items, articles and columns, is the industry's most significant information resource. Let us know how you like it.

2015 also bodes well for the industry. With just about every leading indicator pointing north, it looks like we're in for a nice ride. Markets that we've only dreamed about in the past are beginning to emerge. Moving past the hype, shows like CES and the North American International Auto Show have laid out the path forward with a plethora of new technologies and requirements for technology. Electronics are everywhere!

Another boon for the economy is the price of energy, in particular, oil. I read an article recently that said the low gas prices could save the U.S. economy up to $300 billion this year. That's not bad. Lower fuel prices mean lower energy and shipping costs and less pressure on wages as consumers keep more of what they earn. The bad news is that many believe one reason for the low prices is an attempt by OPEC to crush higher-cost producers in the U.S. and Canada. Even so, I'm hopeful that lower energy costs will ultimately help stimulate the global economy, increasing growth, overall. Once the global economy kicks into gear, demand will increase and oil prices will rise again, incentivizing domestic producers.

I can't wait until we're all electric. Nuclear, hydro, wind and solar, and someday, fusion: that's the way forward. That's what frees us from so many of the problems associated with petroleum. This is not a political statement, it's just common sense. Domestically produced clean energy just makes sense.

CES

I don't know if you've paid attention to what was going on at CES last month, but for me, it was the most interesting show I've ever seen. The products and the implications of those products were astounding!

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This was the year of the wearables. With Apples's iWatch coming out soon, everyone was trying to get a jump on them with their own watch or wearable device. We've posted some of the broader announcements about markets, technologies and such but shied away from the plethora of product introductions. There was just too much stuff.

Dan Feinberg, our techno-geek editor at large, really got into it at this year's show, providing a solid flow of information for our readers. We only asked Dan to take a look at one product for us,: the Voxel8 3D printer for electronics. And if you read our January issues of both *The PCB Magazine* and *SMT Magazine*, you would have seen our coverage of structural electronics. The exciting thing about this segment is that it allows electronics to be built into everything. We just have to figure out how to become part of this revolution and not a casualty of it.

Voxel8

As I mentioned, Voxel8 introduced a 3D electronics printer at CES. The important part of this story isn't just the printer and its implications for the electronics industry as we know it, but rather, who's behind it. These are serious folks with serious money. Voxel8 isn't destined for the hobbyist market like most 3D printers. Instead, they've developed a product which will likely be a foundational piece of the coming revolution in structural electronics.

The company is a Harvard University spinoff and has some serious backing. Here is something from a recent posting on our website; you'll see what I mean.

...Voxel8 is collaborating with Autodesk on Project Wire, a Spark powered design tool for 3D printed electronics. Project Wire is a new design tool under active development at Autodesk that provides electronics and 3D printing enthusiasts with the ability to place components and route 3D wires.

Foxconn in Mexico

A couple of years ago, I mentioned Foxconn's consolidation of its Mexican operations in Ciudad Juarez. An article published by Open Democracy, *On the Border: Foxconn in Mexico*, talks about this new operation with a focus on the workforce. The article is slanted toward the workers and the conditions they face. It's certainly another side of the story that we in the trade press rarely cover. I found it interesting, and based on what I've been reading about the factory conditions in Asia, Mexico is just more of the same. Of course, it has to be said that not all companies are bad actors. And even in this case, we don't know the entire story. Most of them likely do a good job of caring for their workers. And most OEMs these days are under constant pressure from NGOs to improve conditions in the factories of their suppliers. The article only tells one side of the story, but it is interesting.

IPC APEX EXPO

Right around the corner, the IPC show and conference looks to be an exceptional event this year, with the show floor sold out and conference attendance up. As usual, we will be there in force with the I-Connect007 team conducting interviews, covering events and supporting our customers. IPC has listed over 300 new products from show exhibitors, so there's plenty to see. Please stop by our booth and say hello.

The Future

Barring some unforeseen political event or act of God, all signs point to a very good 2015 here in the U.S. Once Europe and Asia get back on track, and if energy prices remain relatively low, 2016 and beyond should bode well for the industry. The Internet of Things, printed electronics and 3D printing will certainly keep us all on our toes as we work to build the products of today while keeping an eye on the products of tomorrow. We have a lot to be thankful for in 2015.

See you at IPC APEX EXPO! **SMT**

Ray Rasmussen is the publisher and chief editor for I-Connect007 publications. He has worked in the industry since 1978 and is the former publisher and chief editor of *CircuiTree Magazine*. To read past columns, or to contact Rasmussen, click here.

SMT PROSPECTS & PERSPECTIVES

New Year Outlook: What Can We Expect in 2015?

by Dr. Jennie S, Hwang
CEO, H-TECHNOLOGIES GROUP

Once again, it is the time to look at the year ahead. This is a relished tradition as I am on the spot to think more intensely about the next 12 months and then have the opportunity to cross-check my predictions 12 months later. My 2014 outlook was, by and large, on or close to target (*Year-in-Review*, December 2014). In this column, I will take a long view on market thrusts in the anticipated global economic landscape, as well as mega-technological trends in selected areas deemed timely and relevant to the industry and tailored to the audience of this magazine, specifically: macro-economy, oil dynamics, China factor, cybersecurity, and grand challenges in technology and the path forward. Each of these areas will be highlighted, but more detailed discussions will be addressed in my future publications and speeches.

Global Economic Outlook

It is certainly not an easy time to look into the economic crystal ball, especially from a non-economist's perspective. Geopolitical risks have risen and show no signs of abating. On top of the continuing low commodity prices, additional market trends—dropping oil prices and the rising dollar—are setting in, which may have ripple effects on the global economy. China's slowdown relative to the last 25 years of fast-track growth manifests the power of a basic

Source: Osram

Source: Audi

principle that dictates the global market—the interplay of supply, demand, price and economics.

For the last several years, the U.S. economy was marked by consumer spending that's stuck in the ditch and growth, albeit tepid, being powered by non-import-dependent sectors, such as capital investment in oil and gas exploration. 2015 appears to be a year of change in main driving forces for the U.S. economy by falling energy prices and a stronger dollar. It is also entering into an uncharted territory that unemployment has dropped to around 5.5%, yet the inflation rate stays low (below the Federal Reserve's 2% target). And considering the slower growth in emerging markets, strengthening dollar, anticipated low commodity prices, not to mention the new force of low oil prices, the inflation outlook is expected to remain low.

The Eurozone's recovery continues to be sluggish, facing the danger of deflation. Japan's Abenomics, combining both monetary and fiscal stimulus programs, is yet to show its muscle, but, as an oil importer, the precipitous oil price plunge may benefit Japan's GDP (reportedly, Japan spends more than 3% of its GDP to pay for imported oil). Overall debt level in developed markets remains high, and the low growth and low inflation will not help reduce debt.

"The respective stock prices fluctuate far more than logic can justify. Going into 2015, as corporate austerity cost-cutting has been and should have been done, a new effort to garner top line growth is becoming prevalent, justifiably so—better products, better services, organic growth and critically thought-out acquisitions."

On both sides of Atlantic, central banks face tough decisions. Both U.S. and U.K. debate on monetary policy in terms of interest rate (i.e., when to raise, how much and how fast). With low inflation and low growth, a baby step could be most likely.

In emerging markets, the lower demand and lower prices of commodities are hurting the countries that produce minerals and metals. The economies of Russia and the Middle East depend on energy prices. Africa, a commodity producer, lives and dies on the swings in prices of raw materials. Some of the BRICS countries, such as Brazil and Russia, will look to meager GDPs compared to recent years. As the BRICS countries constitute 40% of the world's population, 20% world GDP and 17% world trade, a slow growth in the BRICS does not send good news to the world economy. However, in terms of growth, a couple of brighter spots may start to shine. Indonesia, with more stable political climate and infrastructure, and India, with the pragmatic and flamboyant new prime minister, may make better than historically typical contributions to the global growth rate.

In corporate America, the several years' rising tide (stimulus and low interest rates) has raised all boats in the equity market. S&P is trading at a multiple of 16, above the 10-year average of 14. The respective stock prices fluctuate far more than logic can justify. Going into 2015, as corporate austerity cost-cutting has been and should have been done, a new effort to garner top line growth is becoming prevalent, justifiably so—better products, better services, organic growth and critically thought-out acquisitions. For the companies that have not adroitly carried out the necessary cost cutting measures, 2015 will be a much more challenging year. Outside the oil and gas sector, cheap energy prices do not necessarily translate into corporate earnings. The stronger dollar and slower emerging market growth will make corporations face a heightened competitive global market and drive harder-to-get earnings.

Facing the triple whammy, there are all kinds of potential downside risks, and prudence is important. To mitigate controllable risks, I follow my "5-3 rule" of investments— stay with countries offering the macro-economic and market condition of less than 5% inflation and higher than 3% GDP (not a hard number). Needless to say, political stability is crucial.

If we bet on this dynamic, the 2015 global economy is not felt as robust as desired. The U.S. economy perhaps will be the brightest spot on the globe (above 3% GDP). The impact of oil prices, more complicated and elusive than is obvious, is yet to evolve.

Oil Dynamics

No one can make a precise call of the oil prices for next month or at the end of 2015. But we do know what are in play. The decision made by OPEC last November to keep up their production output sent the crude oil prices tumbling. This decision appears to be a substantive deviation from OPEC's historical mandate—to keep price high by limiting global oil production. Another new force is the booming U.S. shale oil output during the last five years as the result of increased efficiency and ample financial capitals. According to the International Energy Agency (IEA) report, the new U.S. shale fields have made the U.S. the top oil producer in 2014, generating 12.4 million barrels/day (Russia 11.0 million barrels/day, Saudi Arabia 9.5 million barrels/day, Canada 4.2 million barrels/day, China 4.1 million barrels/day).

Advanced technology and smart engineering deployment make lower cost and higher output shale oil possible. Lower cost and sustained output could push the price down further. Most OPEC countries' economies need to sell oil above $100/barrel to balance their budgets[1]. Yet Saudi Arabia officials indicated their economy can survive for at least two years with low prices partly to its huge energy reserve[2]. Canadian oil sands producers have not indicated their willingness to reduce production from the existing established operations. At this point, it seems that everyone looks to others to cut production. And the oil continues to pile up.

> "The declining oil price indeed is picking its winners and losers. Losers include major oil exporters, oil producers, and oil fields service providers. Countries heavily relying on oil exports, such as Russia, Iran, Nigeria, Venezuela, as well as, aspiring oil exporters, such as Brazil, are facing severe economic challenges."

The declining oil price indeed is picking its winners and losers. Losers include major oil exporters, oil producers, and oil fields service providers. Countries heavily relying on oil exports, such as Russia, Iran, Nigeria, Venezuela, as well as, aspiring oil exporters, such as Brazil, are facing severe economic challenges. On the other side of the spectrum, lower oil prices benefit consumers, transportation sector and manufacturing costs, as well as the oil importing countries (e.g., Japan, Germany).

As to individual companies, this is a shake-up process. Many less efficient companies will be driven out of the market. The extent of impact, simply put, varies with the industry sector that is directly or indirectly linked to the oil industry. Within oil industry, the prominent among the variables include where the business is positioned in the food chain—upstream to downstream, the efficiency of core engineering/technology associated with the business, the level of the balance sheet, and the market duration of low oil prices. The shakeout would be largely linked to the operation efficiency, thus the break-even cost is $35 or $55 or $70.

How long the low prices market will last is a billion-dollar question. Although oil prices constitute a small fraction of the global economy, its trickle-down impact and underlying implications can be profound.

How will the evolving oil price play out? Is this low oil price a transitory passing or a longer-term trend? How long will it take to reach the stabilized price and what is the stabilized price? More importantly, is this a transient supply glut or a sustained declining demand or both? It is anyone's guess. Nonetheless, here is my take: Barring substantial geopolitical events and other shocks, oil price would likely stay at the trough in the range of $45–$60 (plus/minus $10) until the market is stabilized and the equilibrium price will not return to over $100 for awhile (unlikely in 2015). And it seems reasonable to position oneself by assuming that the stabilizing process would continue throughout 2015.

China Factor

Again, China continues to be a factor!

Contributing to 38% global growth, China plays a significant role in global economic growth. However, China's economy with the double-digit growth rate as demonstrated over the last two decades is the way of the past.

Working on its next 5-year Strategic Plan (2016–2020), China deliberates on the specific technologies to own. The country wants to move from investment to consumption, while retaining its market share and its position as the low-priced exporter. The country is catching up its investment in R&D, hovering around annual 20+% increase in R&D spending. The rise of China's innovation is in sight, building up a critical mass of expertise and financial firepower that could potentially realign the power structure of the technology industry going forward.

While the country's stability is at the top of the new leaders' list of wants and needs, the central government leadership has set a new national theme—"rejuvenation," aimed at establishing global wealth, power, and respect.

Following its 5-Year-Strategic-Plan (2011–2015), major structural overhauls are being implemented. In short, in the coming year(s), China's mega priorities go to the following overhauls:

1. Government: implementing anticorruption measures
2. Economy: converting from investment-led economy to consumption-driven; refreshing state-owned enterprises; shifting to high technology sector
3. Market: aligning with the market, moving toward free market
4. Technology : growing investment in R&D; urging innovations
5. Environment: making deliberate efforts to fight pollution
6. Social: creating enough jobs
7. Business: reducing the reliance on imported components/parts that are strategically important

Although its efficiency and financial systems rank lower than desired, China continues to play an important role in manufacturing prowess. However, the focus areas in hardcore manufacturing are shifting. The strategically important industries range from infrastructure-related sectors to semiconductor to software. E-commerce and social network-related technologies are of interest. China's broadband project intends to give 95% of the country's urban population access to high-speed broadband networks.

Despite the fact that all businesses entities are concerned about the "China slowdown," China still stands as an important trading partner and a formidable marketplace. Going into the new year, its GDP at 7.0% plus/minus 0.2% is expected.

Cybersecuity

In this cyber age, stable, resilient and safe cyberspace is crucial to doing business and running our daily lives. As cyber intruders are increasing in number and intensity, 2015 is the year that cybersecurity takes the front and center seat.

Cybersecurity requires 360-degree attention and effort from the front office to the middle-office to the back office, or from the factory floor to the CEO suite to the boardroom[3].

As much as needed and desired, there is no panacea to totally prevent cyber attacks. Nonetheless, exercising the best practices is the way to mitigate the risks of attack and its consequences through several key areas:

1. Recognize the risk
2. Embrace the risk
3. Carry out a cyber-risk assessment
4. Plan and prioritize protective measures
5. Implement state-of-the-art technologies
6. Treat it as an on-going, company-wide effort (not just an IT department's function)

Grand Challenges in Technology—Path Forward

Advanced materials that offer unique properties, be it a polymer, a metal or a ceramic, to deliver revolutionary performance, will be one grand technological challenge. A class of new materials using layer-by-layer assembly as a versatile bottom-up nanofabrication technique is being pursed. Resorting to tuning the materials at the atomic scale in conjunction with multiscale modeling enables the design of the target materials properties, opening breakthrough and rewarding application and business opportunities.

Advanced manufacturing including 3D printing cannot go unnoticed. In 2015, further technology development will materialize. And increasing number of products/components/parts manufactured by using 3D printing will be rolling out across industries.

In last year's "Outlook" column, I stated five words that cover the essence of electronics hardware: smart; mobility; connectivity; wearability; and innovation.

Wearability is one of the main thrusts within electronics and beyond. The fruits of the collaboration between Google and Intel, to thrust themselves into wearable devices (e.g., Google Glass), will materialize in 2015 as it offers cooler products to consumers as well as to businesses, propelling from mobility to wearable mobility. The level of coolness has a lot to do with the extent of wearability (e.g., the wearable time before recharging the battery). The ability to synchronize the battery technology with the semiconductor technology will be another rewarding path forward.

IBM pledged to spend $3 billion over five years on semiconductor research toward two major tasks: tackling technical obstacles to the miniaturization of circuitry on conventional silicon chips, and developing alternative materials and technology to keep boosting computing speed while consuming less energy, e.g., replacing silicon with graphene (a thin film of pure carbon or structure called nanotubes). Other research includes neurosynaptic computing—a departure from the conventional computer designs that is expected to work more like a human brain.

The Internet of Things (IoT) will dictate the innovation and growth of the cool gadgets, and striking new products are expected to be introduced. **SMT**

References

1. International Monetary Fund.
2. The Wall Street Journal, December 22, 2014.
3. "Cybersecurity—From Factory Floor to Boardroom," July 2013.

Appearances

Dr. Hwang will present a lecture on "Preventing Manufacturing Defects and Product Failures" at IPC APEX EXPO, February 22, 2015 in San Diego, CA.

Dr. Hwang, an international businesswoman and speaker, and business and technology advisor, is a pioneer and longstanding contributor to SMT manufacturing since its inception, as well as to the lead-free electronics implementation. Among her many awards and honors, she is inducted to the WIT International Hall of Fame, elected to the National Academy of Engineering, and named an R&D-Stars-to-Watch. Having held senior executive positions with Lockheed Martin Corp., Sherwin Williams Co., SCM Corp, and IEM Corp., she is currently CEO of H-Technologies Group, providing business, technology and manufacturing solutions. She serves as Chairman of Assessment Board of DoD Army Research Laboratory, Commerce Department's Export Council, various national panels/committees, international leadership positions, and the board of Fortune 500 NYSE companies and civic and university boards. She is the author of 450+ publications and several textbooks, and an international speaker and author on trade, business, education, and social issues. Her formal education includes four academic degrees as well as Harvard Business School Executive Program and Columbia University Corporate Governance Program. For further info, visit JennieHwang.com. To read past columns, click here.

FEATURE

Risk and Mitigation for Tin Whiskers and Tin Pest

by Dr. Ronald C. Lasky
INDIUM

Abstract

There is considerable and justifiable concern over the risks of tin whiskers. However, the same concern is not apparent regarding the dangers of tin pest. This paper will present an overview of both of these reliability concerns by reviewing what is known about the mechanisms and the occurrence of both phenomena.

Mitigation techniques will be discussed, and for tin whiskers, the discussion will focus on barriers between the tin and copper base metal, additions of bismuth to the tin, annealing of the tin, designs that minimize tin whisker failure risk, and over-coatings of the tin. For tin pest, the mitigation technique will be primarily adding bismuth or antimony to the tin.

The article will close with a semi-quantitative analysis of the effect of these mitigation strategies on tin pest and tin whisker risk.

Introduction

Tin Whiskers

The existence of tin whiskers has been known since the early days of radio. Typically, tin whiskers form in tin plating on component leads, not bulk solder. Numerous, very expensive failures have been caused by tin whiskers; many of these failures were in satellites. NASA has a website[1] devoted to tin whisker failures.

The website is the home of many iconic tin whisker photographs, one of which is shown in Figure 1. This website is frequently and justifiably referenced when the topic of the risk of tin whiskers is mentioned. But what is the true risk of tin whiskers in today's products, and what are the mitigation strategies and their effectiveness in handling this threat?

What are Tin Whiskers?

Tin whiskers are hair-like metal filaments that erupt from tin metal surfaces and are most prominently observed in tin platings. They are typically 1/10 to 1/100 the diameter of a human hair or from 1–10 micrometers (Figure 2[2]). Their length can range from 10 to more than 10,000 micrometers, the longer whiskers being in the one centimeter range. However, more typical lengths are less than one millimeter (1,000 micrometers). A 1 mm tin whisker is certainly a concern in electronics, when one considers that typical distances between conductors are in the 10 mils or 0.25 millimeter range.

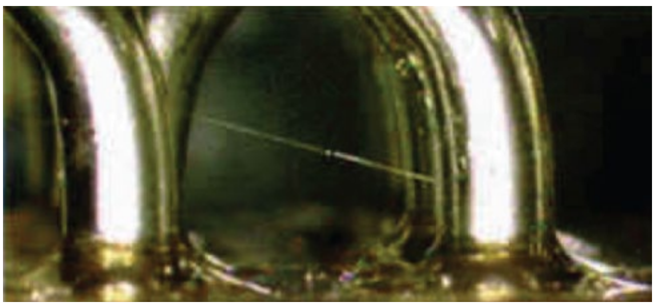

Figure 1: Photograph of tin whiskers on NASA Goddard tin whisker website.

The Mechanism of Tin Whisker Formation

It has been shown that long range diffusion supplies the atoms that form the whiskers[3]. Since the atoms diffuse at a distance, there is no depletion of atoms at the base of the whisker. At room temperature, the atoms diffuse most readily along grain boundaries. In a series of papers[4,5,6,7] Xu, Fan, and Abys, et al., reinforced the understanding that the driving force for tin whisker formation is compressive stresses in the tin. These compressive stresses drive the diffusion, hence, any mechanism that increases compressive stresses will make tin whisker formation worse, and any mechanism that decreases compressive stresses will mitigate tin whisker formation. Their work also verified that if tin plating is placed over a copper substrate, preferential diffusion of the copper into the tin will increase the compressive stresses in the tin, resulting in worse tin whiskering (Figure 3).

These researchers also noted that tin plating over nickel has a mitigating effect. The nickel diffuses into the tin much less aggressively, minimizing compressive stresses and mitigating tin whisker formation.

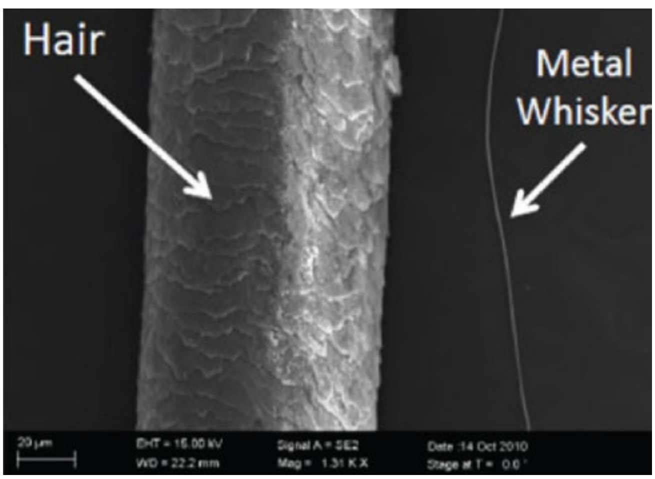

Figure 2: A tin whisker compared to a human hair.

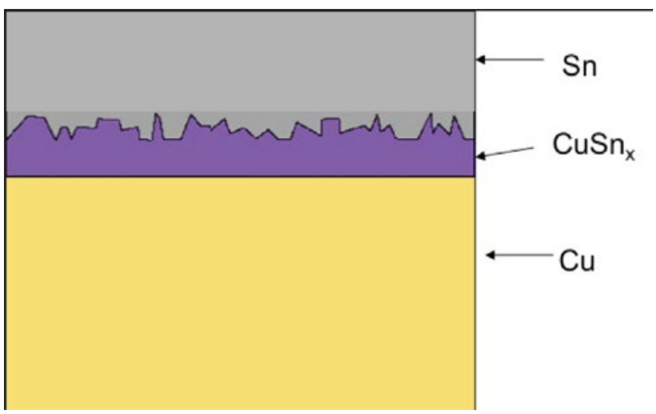

Figure 3: As the new copper-tin intermetallic grows mostly into the space previously occupied by the tin, stresses are relieved by the formation of tin whiskers.

Tin plating on alloy 42 can result in tin whiskers due to a mismatch in coefficient of thermal expansion in environmental conditions, which increase compressive stresses in the tin, as shown by Oberndorff, et al.[8]. In the same paper, Oberndorff and his colleagues showed that corrosion of the tin-enhanced tin whiskering, supporting a consensus on this topic. It also appears that the presence of some rare earth elements in the tin will enhance tin whiskering[9].

The Occurrence of Tin Whiskers

People who are concerned about tin whiskers often have the sense that tin whiskers are ubiquitous and are an unmanageable threat to the reliability of all electronics products. Their perceived ubiquity is likely linked to a few prominent iconic photographs, such as seen in Figure 4. Supporting this belief is the following story. At a workshop in 2008, a speaker was addressing reliability concerns related to tin whiskers. A senior technical leader from a major mobile phone manufacturer asked the speaker a few questions. The speaker finally asked the technical leader, “Does your company have a tin whisker mitigation strategy for mobile phones?” The response was, “We will, as soon as I get back to the office.” I will readily agree that this response is the right one, but the technical leader’s company had manufactured hundreds of millions of lead-free mobile phones starting in 2001, with a failure rate statistically equal to or less than phones manufactured with tin-lead solder. Clearly, for over seven years, this company did not have significant issues with tin whiskers, even without a plan. This good fortune may be because the component manufacturers had taken some effort to mitigate tin whisker risk.

The perception of the omnipresence of tin whiskers is also enhanced by the NASA Goddard Tin Whisker website[10]. However, almost all of the examples of tin whisker failures are dated before 2006, when RoHS was enacted. In addition, the total number of fails recounted is about 50. Few of the fails appear to be from devices where tin whisker mitigation was performed. It is difficult to study the details of the fails listed on the website, as many of the links do not work.

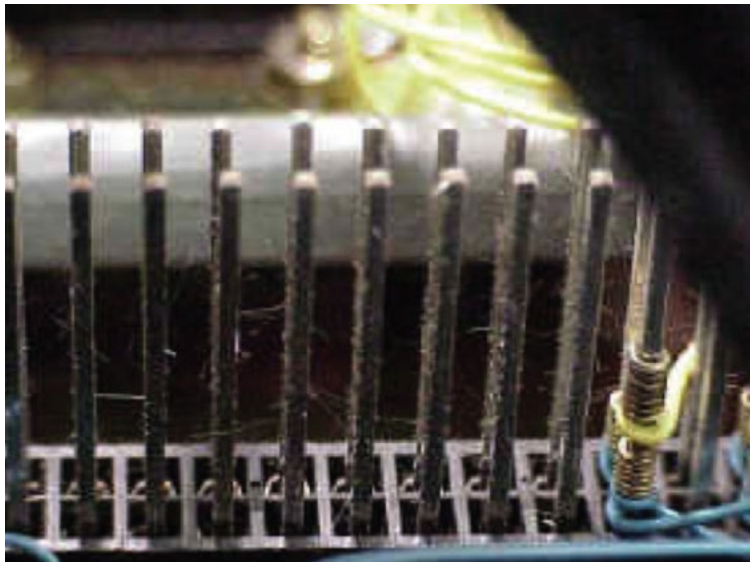

Figure 4: An iconic photograph of tin whiskers found on the NASA website.

Thousands of tin whiskers can be formed by creating the conditions that enhance tin whisker formation, such as developing compressive stresses in the tin plating with perhaps a bright tin finish, and plating the tin on a substrate that promotes tin whisker growth such as copper. It is relatively easy to make tin whiskers, and conversely, to minimize them, by avoiding compressive stresses and other factors that promote tin whisker growth.

However, it is critical to understand that it is impossible to totally eliminate tin whiskers if tin is used.

It should be understood that in mission-critical applications, a tin whisker mitigation strategy is essential. Such a strategy is essential because it is impossible to ensure that the risk of tin whiskers can be eliminated. This situation is especially true for long-service-life electronics, such as those found in many military applications.

Tin Whisker Mitigation

Xu, Zhang, Fan, Abys, et al.[11] use a whisker index (WI), defined as:

$$\mathbf{WI = Sn*d*L*f(L)}$$

to measure the propensity to produce whiskers in the WI, whereas S is the area; n is the number of whiskers per unit area; d is whisker diameter; L is the whisker length; and f(L) is a non-linear function of length, that being 1 for a whisker length of 1 micrometer and 500 for a whisker length of 50 micrometers. Using this metric, they demonstrated quantitatively that compressive stresses are a major driving force in tin whisker formation. Consistent with the compressive stress driving force theory, the researchers showed that bright tin platings tend to have WIs in the 100,000 range, whereas simply changing to satin bright plating reduces the WI to less than 10. Large grains in the tin plating are associated with low stresses, as is a matte finish, so large grains are another positive indicator for mitigating tin whiskers.

Xu, et al., also showed that reflowing the tin will minimize compressive stresses. In addition, reflowing can form a CuSn intermetallic that will minimize copper diffusion into the tin. These researchers also suggest that a thick tin layer is better because the diffusion of the copper in the tin will take longer to reach the surface, where the copper will cause compressive stresses in the tin that will exacerbate whiskering.

The addition of a nickel layer between the copper and tin resulted in WIs close to 0, even when bright tin plating was used (Figure 5). The nickel diffuses more evenly and does not diffuse as aggressively into the tin as does copper, hence, minimizing compressive stresses. It is not as widely known that over time this beneficial effect of nickel may diminish. So, for long service life applications, the nickel layer approach may not be adequate. Dimitrovska[12] demonstrated that pulsed composite plating with multiple NiSn layers provided improved performance over a standard nickel layer.

It has been shown that alloying the tin plating with small amounts of some metals, especially 2–4% bismuth[13], significantly reduces the growth of tin whiskers. It has been suggested that bismuth and other alloying metals, including lead, alter the structure of the tin so that cooper intermetallic growth is more even and reduced, minimizing compressive stress generation in the tin, hence subduing tin whisker growth. The tremendous benefit of alloying tin with lead can be seen in Figure 6. Similar results would be expected with 2% bismuth.

Coatings have shown some effectiveness in tin whisker mitigation. Osterman[14] investigated tin whisker mitigation effects of machine-sprayed acrylic and silicone, hand-sprayed urethane, and vapor-deposited parylene and ALD-Cap 05TA200. At the end of his studies, he found that only the parylene coating did not have any penetrating whiskers. He also stressed the importance of full and thick coverage of the coating and emphasized that past work on flat

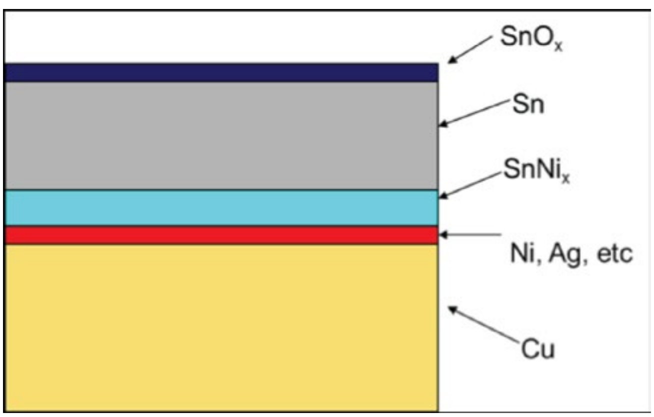

Figure 5: The addition of a nickel layer between the copper and tin dramatically reduces the WI.

Figure 6: The dramatic reduction in tin whisker growth as a result of a tin-lead solder dip. Similar results would be expected with 2% bismuth in the tin plating. The image is from the NASA Tin Whisker website.

test coupons did not represent the coating challenges of the contoured surfaces of typical electronic packages.

One aspect seldom discussed in coating studies is that the whiskers must penetrate two coating layers in order to cause havoc. Many studies show whisker penetration through the coating on the surface that the whisker is growing out of. However, it is not common for researchers to discuss whisker penetration of a coating that protects another surface. One might expect the whisker to bend as it tries to penetrate the second coating surface. Considering this point and the promising results of some coatings, such as parylene, it would appear that the judicious application of the best coatings would significantly aid in tin whisker mitigation.

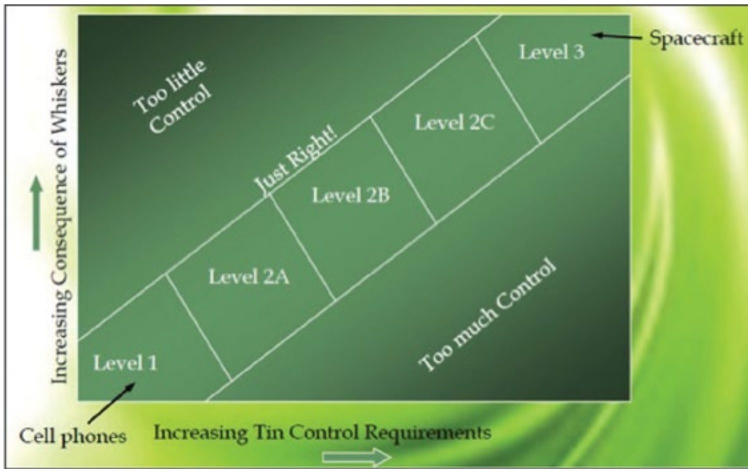

Figure 7: PERM's approach to control tin whisker risk.

Tin Whisker Risk Assessment

Failure modes and effects analysis (FMEA) is a good strategy to use to manage tin whisker risk. The central part of FMEA is the risk priority number (RPN). For tin whiskers, the RPN is equal to the product of three metrics: (1) the probability of tin whiskers (P); (2) the severity, if a tin whisker exists (S); and (3) how hard it is to detect a tin whisker (D). In equation form:

$$\mathbf{RPN = P*S*D}$$

As a first example, consider a consumer product like a mobile phone with a life of five years. With mitigation, on a scale of 1–10, P might be 2. For S, we might rate at 3, as a failure in the device would not cause bodily harm to anyone. Detection (D) is a problem because the tin whiskers that form later cannot be detected during manufacturing; hence, we would have to rate D as a 10. So, the RPN is: 2*3*10 = 60, which is not too high. Therefore, a tin whisker mitigation strategy would likely be successful for a consumer product. It should be pointed out that determining the RPNs would almost certainly require supporting data, brainstorming sessions, and a buy-in from the entire product team.

Now consider a mission critical product, such as some types of military equipment. If we assume that the electronics have a service life of 40 years and that a failure could cause bodily harm or death, we could likely end up with a consensus that RPN = 10*10*10 = 1000, the highest RPN possible. This situation would demand that special tactics be used to address the tin whisker risk.

Woody[15] presented strategies developed by PERM (Pb-Free Electronics Risk Management). PERM is a consortium of companies that develop and manufacture mission critical electronics for the military and aerospace industries. In her presentation, Woody shared PERM's "Three Bears" approach to managing tin whisker risk, as shown in Figure 7. Level 1 shows no control, while Level 3 shows tin avoidance.

CALCE has developed a tin whisker risk assessment calculation software tool.[16] This tool would appear to be a vital aid for those with mission critical applications with the risk of tin whiskers.

Tin Pest

As stated earlier, it is easy to process tin plating so that tin whiskers will result, and it is not difficult to minimize tin whisker occurrence with appropriate mitigation. Tin pest, on the other hand, is very difficult to produce, even in the lab. There have been numerous cases where researchers could not produce a virgin tin pest, even under ideal conditions.

Tin pest is an allotropic transformation of white beta phase tin to grey alpha phase tin that can occur at temperatures below13°C.

Figure 8: Plumbridge's photo of tin pest forming on a tensile specimen stored at 18°C for 1.5 years.

Since white tin has a density of 7.31g/cm3 and grey tin has a density of 5.77g/cm3, the tin pest transformation requires a significant volume expansion. This volume expansion will typically destroy any solder joint composed of white tin. Figure 8 shows a photo of tin pest forming on a tin tensile specimen. The author has published a review paper[17] on tin pest that discusses much of what is known about the transformation, occurrence, and mitigation of tin pest.

If tin pest is so hard to produce, why worry about it? The main concern should be that with trillions of solder joints in automobile, military equipment, remote electronics, etc. exposed to cold environments, some tin pest could form and cause a critical failure. The fix is relatively easy—using about 0.5% antimony or bismuth in the solder.

Conclusion

Tin whiskers should be taken seriously for long life, mission critical products due to the extremely high risk priority number that they present in these applications. In these applications, tin avoidance or multiple tin whisker mitigation techniques should be employed. A tin whisker mitigation strategy should also be employed for consumer products with lives of less than five years. However, it appears that tin whiskers are not common and the mitigation techniques discussed in this paper should be adequate for these applications.

The most common and effective tin whisker mitigation technique is to ensure that the tin coating on component leads has low compressive stresses. This can be accomplished by using a satin bright type of tin plating. The addition of a nickel layer between the copper lead substrate metal has also been shown to have a significant effect in tin whisker mitigation. The addition of 2–4% bismuth in tin is a strong further mitigation. Parylene polymer coating has been shown to be effective in containing tin whisker penetration. The combination of all of these mitigation techniques may not eliminate tin whiskers, but surely they would reduce their numbers in a striking way.

Tin pest has generated almost no concern in the community that is responsible for mission-critical products. This lack of concern seems surprising. Tin pest is admittedly much rarer than tin whiskers, but with no tin pest mitigation, tin pest failures in the 40-year service life of some mission critical products would seem inevitable. The tragedy of this situation is that the fix is so easy—simply adding 0.5% bismuth or antimony to the solder. SMT

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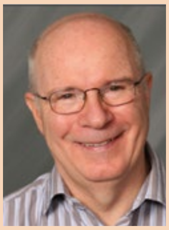

Ronald C. Lasky, PhD, PE, Senior Technologist, Indium Corporation, holder of the prestigious SMTA Founder's Award, is a world-renown process expert and an Instructional Professor at Dartmouth College. He has over 25 years of experience in electronics and optoelectronic packaging and assembly. He has authored or edited five books and numerous technical papers and holds several patent disclosures.

Electrostatic Mechanism of Nucleation and Growth of Metal Whiskers

by V. G. Karpov
DEPARTMENT OF PHYSICS AND ASTRONOMY,
UNIVERSITY OF TOLEDO

Abstract

Metal whiskers can grow across leads of electric equipment causing short circuits, arcing, and raising significant reliability issues. The nature of metal whiskers remains a mystery after several decades of research. Here, their existence is attributed to the energy gain due to electrostatic polarization of metal filaments in the electric field induced by a metal surface. The field is induced by surface imperfections: contaminations, oxide states, grain boundaries, etc. This theory provides closed form expressions and quantitative estimates for the whisker nucleation and growth rates, explains whisker parameters and predicts statistical distribution of their lengths. The details of the underlying mathematical treatments have been presented in a recent publication[1] . Here, the emphasis is on a more intuitive level, and the references are omitted.

Metal whiskers are hair-like protrusions observed at surfaces of some metals; tin and zinc examples are illustrated in Figure 1. In spite of being omnipresent and leading to multiple failure modes in the electronics industry, the mechanism behind metal whiskers remains unknown after more than 60 years of research. While not formally proclaimed, some consensus, at a rather qualitative level, is that whiskers can represent a stress relief phenomenon. However, that never led to any quantitative description including order-of-magnitude estimates of whisker parameters.

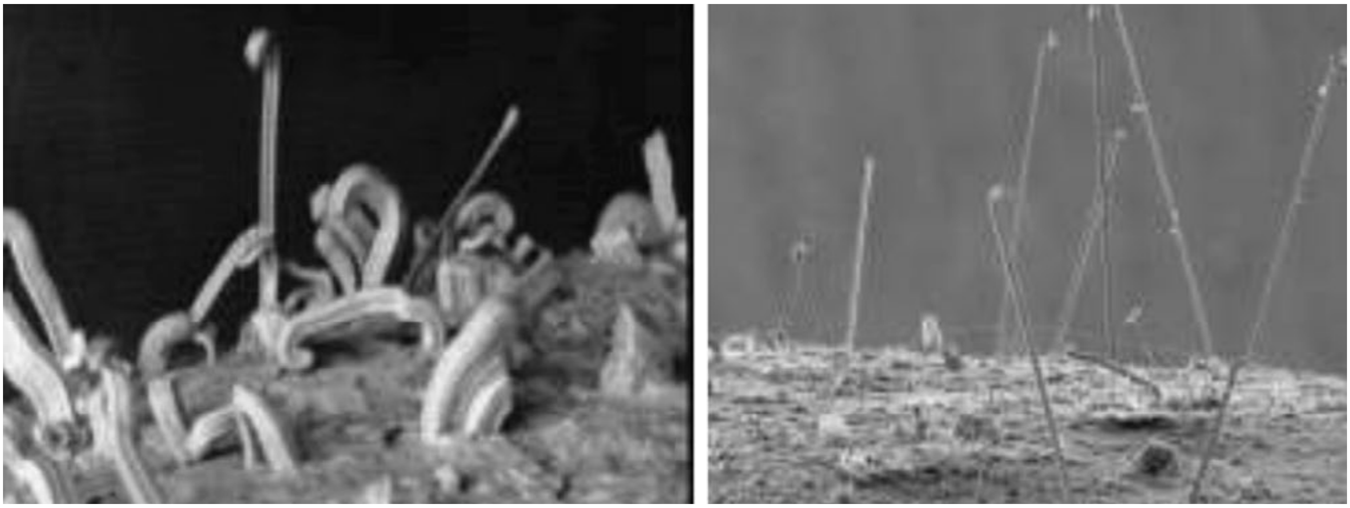

Figure 1: SEM pictures of tin (left) and zinc (right) whiskers (courtesy of the NASA Electronic Parts and Packaging [NEPP] Program).

As a brief survey of relevant data, it should be noted that whiskers grow up to ~1–10 mm in length and vary from ~100 nm to ~30 µm in thickness. Their parameters are characterized by broad statistical distributions: side by side with fast-growing whiskers there can be others, on the same surface, whose growth is much slower or completely stalled. The metal surface conditions play a significant role. In particular, oxide structure and various contaminations are important factors determining whisker concentration, growth rate and dimensions. The metal grain size appears to be less significant for small grains (nanometers to few microns), while whiskers are unlikely for very large grains, recrystallization can be of importance. Various additives can have significant effects on whisker growth, such as Pb strongly suppressing tin whiskering. Electric bias was reported to exponentially increase whisker growth rate, which was attributed to the effects of electric current, although other publications reported no bias effect on whisker growth and even the negative effect of bias suppressed whiskering. A common observation is that whiskers grow from the root rather than from the tip, and the material required for their growth is supplied from large distances through long range surface diffusion rather than from a narrow neighboring proximity; there is no surrounding dent formed in the course of whisker growth.

More appealing is an informal list of observations given below with the permission of its author, Dr. Gordon Davy[2]. It reflects the perspectives and the spirit of the live whisker research, shared by many in the community of Tin Whisker Group teleconferences. It has proved extremely useful for the author of this paper allowing multiple comparisons between the theory and the experiment.

- There are no "tin whisker experts." Workers in the field differ only in their degree of perplexity in the face of so many inconsistencies.
- Nominally identical specimens may demonstrate drastically different densities and growth rates.
- Density may differ greatly from one region of a specimen to another; on a finer scale, there is a whisker growing here, but not there.
- Growth is at the base (i.e., the film), not the tip.
- Growth may be from the tin-substrate interface or from near the tin surface.
- Growth rate is often not constant. A whisker may stop growing for a while, then start growing again.
- Growth rate is zero at low and high temperatures, and seems to peak at about 25–50°C.

- Growth can be promoted by thermal cycling.
- Growth rate is zero below a threshold film thickness and approaches zero for high film thickness. It appears to be zero for bulk tin.
- For sputtered films, the growth rate appears to be a minimum for near-zero residual stress, and greater for tensile as well as compressive stress.
- Growth rate is somewhat higher at high humidity.
- Growth rate seems to be higher from fine-grained microstructure.
- Growth rate can be increased by some kinds of residues on the surface.
- Most metals dissolved in tin appear to increase growth rate. The one exception is Pb. The mechanism may have to do with altering the grain structure to equiaxed (from columnar).
- I do not recall hearing of the effect of small amounts of Pb (~1%) in Sn for vapor-deposited films, or even for very thin electroplated films.
- Distribution of thickness and length are log-normal.
- There appears to be no correlation between thickness and length.
- Median thickness is about 3 µm.
- Longest whisker reported: ~25 mm.
- Thinnest and thickest whiskers reported: ~100 nm, ~20 µm.
- Various growth morphologies: needle-like, odd-shaped eruptions, occasional branches, and there may longitudinal or circumferential striations. Acicular (needle-like) whiskers may be bent or kinked, and may not have the same thickness along the entire length.
- Long whiskers are in constant motion in air—can be compared to Brownian motion.
- Whiskers have an oxide coating ~1–3 nm thick, even in vacuum. (Growth rate is logarithmic.)
- A whisker that melts exits the skin, leaving it behind.
- Whiskers penetrate even a thick oxide film (grown by prolonged exposure to steam).
- Whiskers eventually penetrate polymer (including Parylene) coatings, with the apparent exception of "whisker-tough."
- Whiskers appear to not penetrate thin caps of certain metals, and readily penetrate thicker caps of other metals.
- Whiskers appear to not penetrate thin films of tailored ceramics produced by chemical vapor deposition if the substrate has been properly prepped.

To emphasize the most challenging questions, here is the author's short list:

- A mystery of high aspect ratios, height/diameter up to ~10,000 not seen in other physics. Why wouldn't metal whiskers collapse into spheres, as other droplets do to minimize surface energy?
- Is their relation to metals of essence? In other words, why are metal whiskers metal?
- What is behind the metal whiskers randomness? Why do they grow here but not there, why are their parameters so dispersed, and what makes it so difficult to controllably grow or predict their appearance?
- What does Pb do in suppressing whiskers?

Multiple attempts to understand the mechanisms of whiskers growth revolved around the role of surface stresses relived by whisker production, dislocation effects, oxygen reactions, and recrystallization. It was shown stress gradients along with certain assumptions about system parameters can explain tin whisker growth rates but not their existence, shapes and statistics. Overall, these attempts have not led to verifiable quantitative predictions.

The 60-year old whisker challenge thus remains outstanding against the background of other historical developments in natural sciences. As an example, the fundamentally new phenomenon of superconductivity was discovered in 1911 and explained in 1957, taking a shorter time to understand than metal whiskers, in spite of being the first encounter of the macroscopic quantum phenomena physics. This remarkable elusiveness of the metal whisker problem warrants new theoretical approaches. They need to be made quantitative in order to allow experimental verifications and satisfy the standard scientific criteria.

This paper discusses one such approach based on the electrostatics of metal surfaces. It may appear rather contradictory in the light of a common perception (taught in the undergraduate physics) that neutral metal surfaces cannot have electric charges or fields. We will see however that the latter is true only for ideal metal surfaces (containing no imperfections, such as grain boundaries, contamination, dislocations, etc.), and that real metal surfaces can present rich electrostatics including strong electric fields significantly varying across the surface. A theory of metal whiskers presented here is consistent with many published observations and provides some quantitative analytical results. The appearance of whiskers is described as the electric field induced nucleation of needle-shaped particles. It is triggered by the energy gain $F_E=-p\cdot E$ due to the induced whisker dipole $p=\alpha E$ in the electric field E, where α is the polarizability. The latter is anomalously strong for the needle geometry. The nucleated whiskers continue growing to further decrease their energies in the electric field.

1. More specifically, the theory is based on the concept of strong electric fields, $E\leq 0.01$-1 MV/cm, in the sub-micron proximity of metal surfaces. Such fields can be generated by surface imperfections including “wrong” grain orientations, deformations, oxides, dislocations, or contamination. The importance of this concept is that it offers a unique pattern consistent with the observed wide variety of factors, in the first glance unrelated to each other, all having strong effects on whisker growth: stresses of mechanical and electric nature, material morphology and composition, surface contaminations, including the effects of humidity. According to that concept, all these factors are responsible for significant electric fields in the near surface region of a metal. The surface electric field becomes a common denominator of whisker driving forces. This new hypothesis remains to be carefully tested against all the available data and focused experiments including purposely created electric fields.

2. Being overall neutral these metal surfaces are composed of oppositely charged patches formed as a result of electron redistribution minimizing the system free energy. The patches are characterized by certain surface charge density and dimensions L~1–10 μm, maybe even shorter, ~0.1 mm, for fine crystalline grain structure. These patches form a sort of random chess board as shown in the right display of Figure 2.

3. The phenomenon of whisker nucleation and growth is attributed to the electrostatic energy gain due to strong polarization of the newly created needle-shaped metal particles. The conception of whiskers is described based on the (earlier developed) theory of field induced nucleation that predicts needle-shaped embryos h≤100 nm in length and d~1–10 nm in diameter. The mechanism is quite similar to that explaining the fact that amber or plastic comb attract small pieces of paper: The electric field polarized small particles making them electric

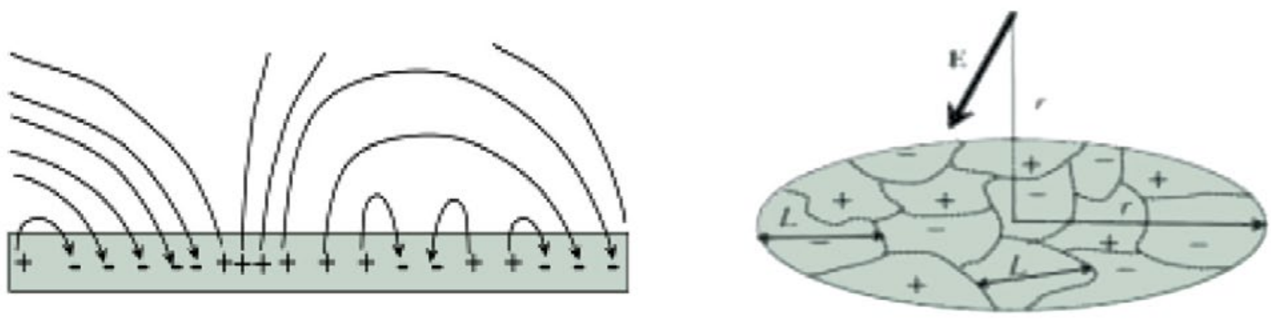

Figure 2: A sketch of the electric field E near a metal surface, cross-sectional (left) and 3D (right) views.

dipoles with energy –pE in the driving them in the region of stronger field E. It is important that the energy gain due to formation of a polarized metal needle does not depend on the field sign as illustrated in Figure 3. The dipole vector p is parallel to the field vector E, so the product –pE is negative. Another wording would be to say that like charges repel producing an outward stress. It is relieved by expelling some of these charges outward via creating a metal whisker with the expelled charge sitting at its far end. These nucleation events take place most easily where the metal surface is locally weak.

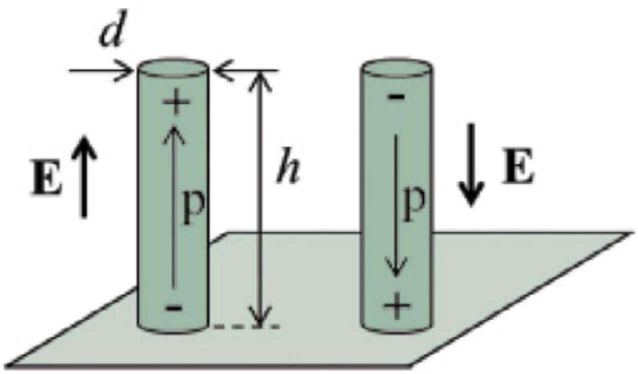

Figure 3: Sketch of two whiskers of length h and diameter d on a metal surface with local electric fields E (of opposite directions) inducing the dipole moments p. Like charges repel producing an outward stress. Where the material is weak enough, whiskers can grow. They provide polarization electrostatic energy gain –pE.

It is worth mentioning that the existence of strongly anisotropic stretched (needle-shaped) metallic particles is due to their strong polarization gain in the external electric field. In turn, that gain is a consequence of their large dipole moments due to considerable dipole length. As a result, long enough particles become energetically favorable in the external field in spite of the fact that their surfaces are much greater than that of an equivalent volume sphere. The needle-shaped metallic particles dominate when the field is greater than a certain critical value as illustrated in Figure 4. This consideration provides a physical mechanism of the very existence of extremely high aspect ratio metal whiskers not collapsing into spherical shapes of equivalent volumes. Their energetically favorable shapes are dictated by the existing electric fields. According to this understanding, whiskers would inevitably collapse into spherical-like shapes in the absence of external electric fields.

4. Following the nucleation is the growth stage where whiskers increase their length by accretion of material at their bases. The growth kinetics are different for whisker lengths below and above the characteristic charge patch dimension L. In particular, growth rates turn out to be extremely low for short (h<<L) whiskers. This dormant time period t_0 can be empirically identified as "no whisker present." However, whisker growth rates abruptly increase when they approach and overgrow the patch dimen-

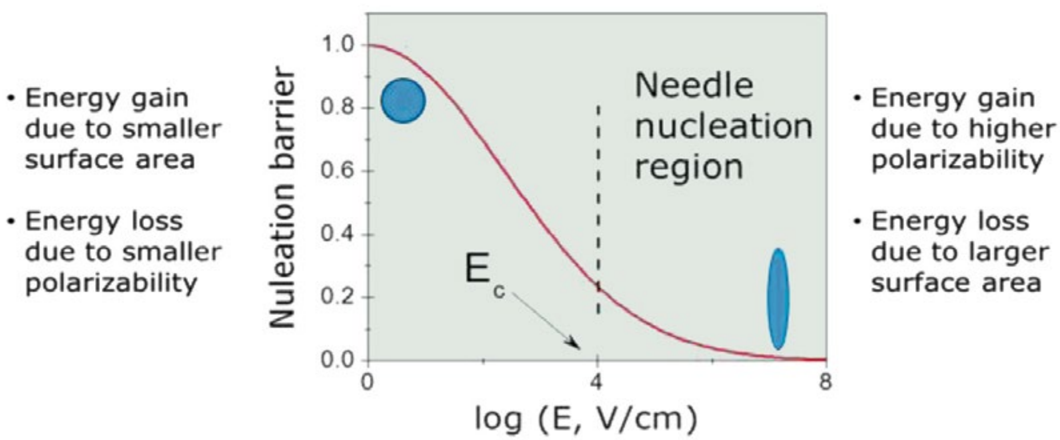

Figure 4: Competition between the surface tension and the electrostatic polarization.

sion L, after which the growth rate remains on average constant. The physical reason of that acceleration is that the longer the whisker the stronger the electrostatic energy gain and its corresponding thermodynamic force pulling the whisker. This process can be explosive (positive feedback) in nature: The stronger the force, the faster the growth, the greater the length, and the stronger the force, etc., as long as the force increases with length (for h<L when the field is more or less uniform). However, in the range of h>>L, the field appears strongly fluctuating (Figure 2) which significantly suppresses the pulling force. As a result, the pulling force becomes independent of whisker length (Figure 5). That distant independent average force results in constant average growth rates.

The predicted time dependent growth rate is sketched in Figure 6. The dormant time t_0 corresponds to whisker development over short distances h<L. As explained in the preceding paragraph, growth accelerates as h–>L. For the overgrown whiskers with h>>L, the growth rate becomes time independent on average.

5. The latter statement of constant growth rate for whisker lengths h>>L holds true on average. In reality, a whisker encounters a random distribution of fields in the course of its growth as can be realized from Figure 4. A whisker head passes through multiple regions of various directions and strengths. Correspondingly, the whisker length growth rate fluctuates between low and high values. It can be shown that the most significant electrostatic energy gain is achieved via the increase of whisker length rather than the diameter. Therefore, when the material supply is limited, the energy gain will dictate that whiskers grow in length as much as possible. However, when the length growth is suppressed

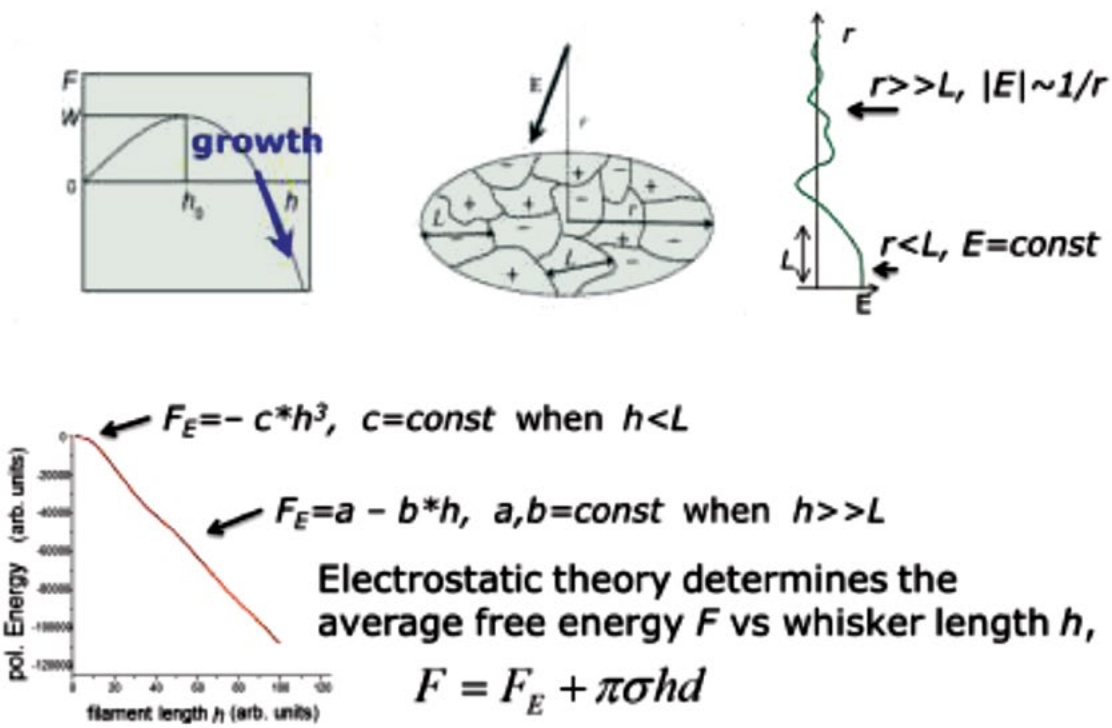

Figure 5: Top left: free energy vs. whisker length h where the downhill slope corresponds to the growth stage of whiskers; W is the nucleation barrier, h0 is the critical nucleation dimension of the needle-shaped embryo. The shape of that slope is determined by the charged patch model shown to the right of the free energy plot where r is the distance from a metal surface and L is the characteristic patch dimension. Bottom: the free energy vs. whisker length with the marked regions of qualitatively different dependencies.

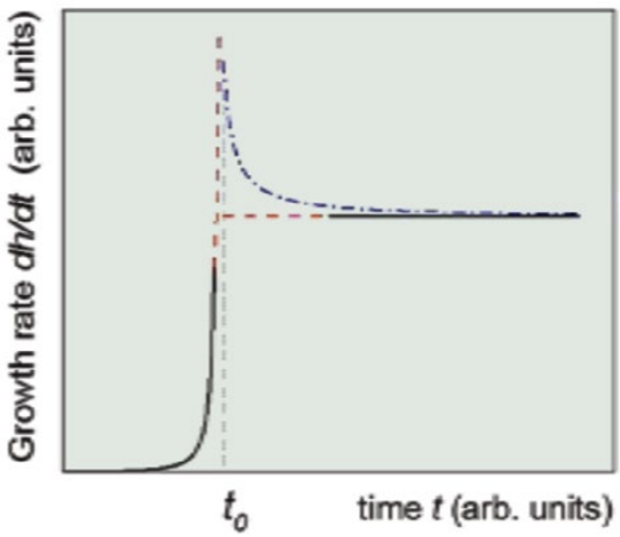

Figure 6: Sketch of the whisker growth rates vs. time. Solid lines represent the two limiting cases within the domains of their applicability (h<<L and h>>L, respectively). The dashed curves are formal solutions presented by the first and the second equations in the formula displayed above. The dash-dotted line shows a hypothetical sewing.

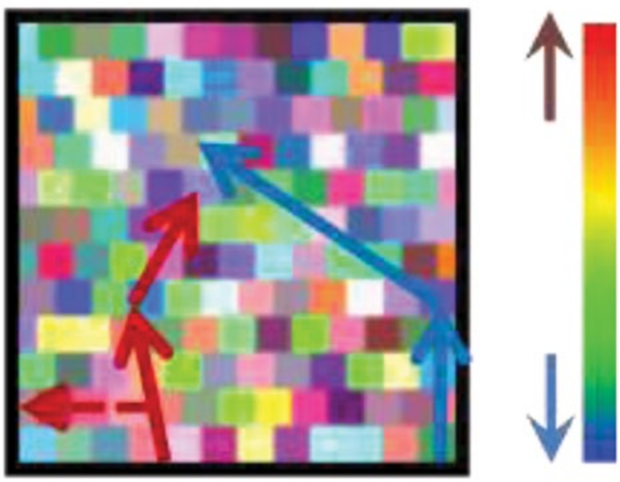

Figure 7: A sketch of whisker growth through a space of a fluctuating electric field:
- Rapid growth while either + or – fields dominate along the length.
- For large lengths, + and – fields start balancing each other.
- Whiskers *stop growing* at certain random lengths, which explains whisker statistics.
- Can resume growth after a while.

in some local regions, the further energy gain can be achieved via the diameter increase (i.e., whiskers get thicker intermittently with the periods of faster length increase). A snapshot of many such whisker lengths and diameters will therefore show broad statistical distributions that are mutually uncorrelated.

Figure 7 illustrates the process of whisker growth in a 2D fashion where the color coding is such that upward and downward local electric field directions are shown in respectively red and blue. The sign fluctuations of the field at large distances shown in Figure 5 do not eliminate the polarization energy gain. Indeed, consider a long metal whisker as a succession of many small metal rods, each occupying a small range of more or less constant field. They have local dipole moments p=aE, and partial electrostatic energies pE=aE2 that are quadratic in field and do not cancel each other. Taking into account the explanation in Figures 3 and 5, it is intuitively clear that the maximum polarization and electrostatic energy gain are achieved for the "color-matched" whiskers (all in blue or all in red). The corresponding pathways for whisker growth can be kinked in order to collect as many as possible color matched regions. This explains how whiskers can be kinked. It should be noted however that each kink entails certain deformation energy loss, so the whisker geometry will optimize between the gain in electrostatic energy and loss in deformation energy due to kinking. (These subtle features remain unaccounted quantitatively in the current electrostatic whisker theory.) Furthermore, some configurations of color-matched regions present pathways parallel or partially parallel to the surface; this explains the observed longitudinal or circumferential striations shown in dash in Figure 7.

6. In the course of growing at h>>L, whiskers encounter rare local regions of abnormally low electric fields where its further growth is blocked. The blockage is due to the fact that further growth in these low field regions cannot overweigh the energy loss due to increase in surface area: the latter increase presents a signifi-

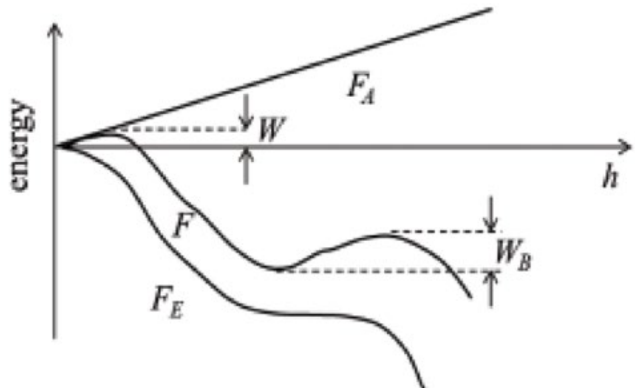

Figure 8: In the flat portion of the electrostatic free energy F_E, the whisker surface energy F_A forms a barrier W_B in the total whisker energy $F=F_A+F_E$. In this diagram, W is the whisker nucleation barrier.

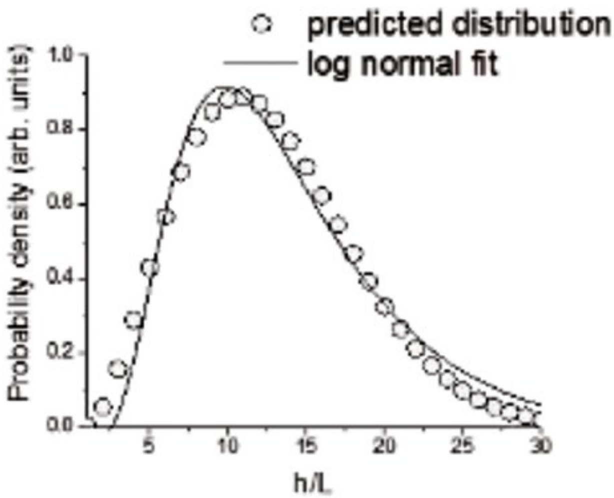

Figure 9: An example of the predicted probabilistic distribution of whisker lengths vs. its best fit approximation by the log-normal distribution. Note that the best fit (least square) approximation provides good fit in the middle part of the distribution, while it is less successful in the regions of both very long and very short whiskers.

cant energy barrier. The statistics of these blocking regions (barriers) determines the whisker length statistics. It is derived to be close to log-normal in the proximity of the most likely sizes, while decaying much faster for sizes well above the average. It should be emphasized however that such blocking energy barriers have finite heights WB. Therefore, they can be overcome after significant waiting times $t_W = t_0 \exp(W_B / kT)$ allowing for sufficient number of attempt-to-escape events, each taking time t_0 where kT is the thermal energy. This explains the observation of whiskers resuming growth after a considerable time (approaching a year) of lethargy. Based on this reasoning and using the standard techniques of the physics of random systems, it is possible to derive the probabilistic distribution of whisker length. Its explicit mathematical form turns out to be cumbersome; however, the qualitative features are quite simple and are illustrated in Figure 9.

7. The concept of field induced nucleation and growth of metal filaments is neither unique nor very new; in a quantitative form it was put forward in the recently developed field induced nucleation theory. Here we would like to mention some applications of that concept concerning objects that may be related to metal whiskers in their underlying physics.

Our first example is represented by the shunting entities observed in various electronic elements (mostly in semiconductor and insulator films) that are conductive filaments developed in the host of relatively insulating materials subject to electric bias. There is a considerable R&D activity, often in industrial settings, including different technologies, such as microelectronics, thin film photovoltaics, light emitting diodes, etc., in the course of which the problem is considered from different points of view, often ignoring a possibility of common mechanism based on the field induced electrostatic energy gain.

Side by side with the detrimental effects of shunting, there is a strong research effort to understand possible beneficial effects of formation of conductive filaments under electric bias. They include, first of all, the technologies of phase change and resistive memories, where the structure states with and without the conductive filament are used as the two logic states of the memory element. Some illustrations are given in Figure 10.

Shown in Figure 11 are needle-like structures that appear on the surface of a liquid metal in a strong perpendicular electric field. The nature

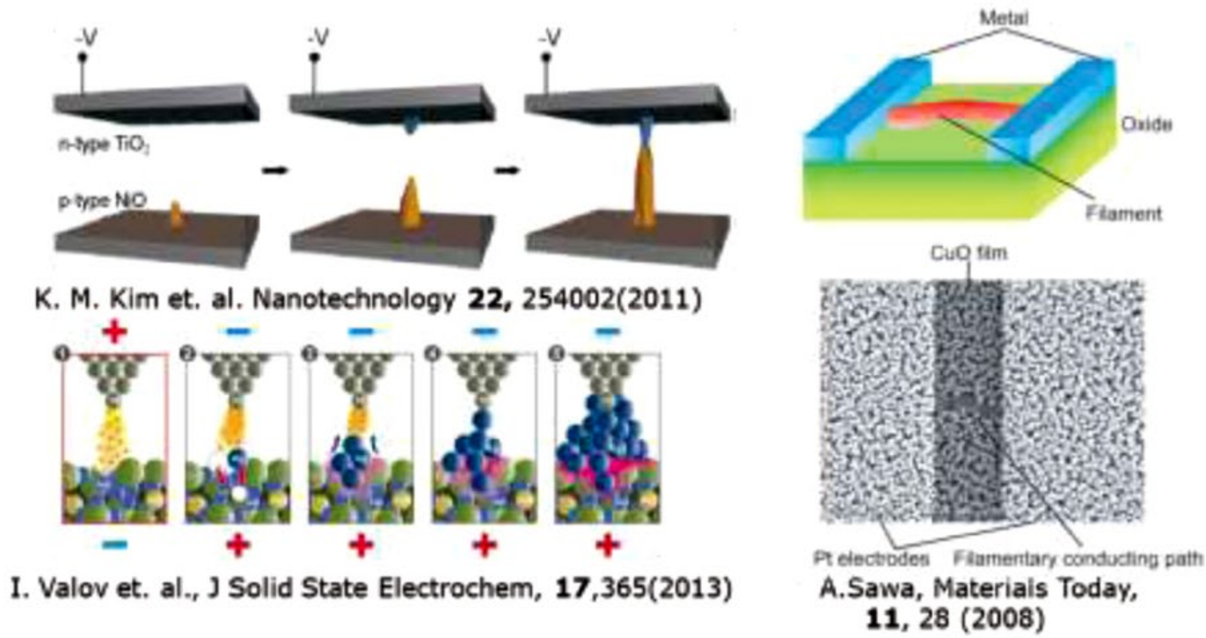

Figure 10: Illustrations of the electric field induced conductive filaments in resistive memory devices.

of such needles remains obscure, although the shape of their pedestals is explained as the so-called Taylor cones representing an equilibrium (between the electrostatic polarization and the surface tension) geometry of a metal surface. From the perspectives of this paper's philosophy, these needles, metal whiskers, and those responsible for shunting and solid state memory features are all mutually related due to the electrostatic energy gain.

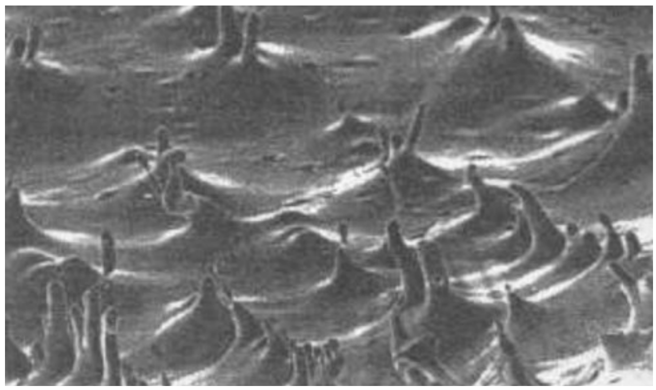

Figure 11: Structures pulled up by a strong electric field on the surface of a molten metal[3].

8. Because of its counterintuitive nature, the discussion about strong electric fields in the near surface regions of real metals may require further comment. These fields can arise from spatial variations of the work function depending on multiple imperfections in structure and composition. At the first glance, the existence of such fields may appear contradictory. Indeed, free electrons in metals have a tendency to screen electric charge fluctuations, thereby suppressing electric fields. However, as explained in the next section, the role of free electrons is exact opposite. Their ability to move underlies the electric charge variations.

To avoid any misunderstanding, it is not the condition of local electroneutrality, but rather that of minimum free energy that determines the electric charge (and other parameters) distributions. The electrons will always move to minimize the system free energy; this leads to non-uniform charge distributions in non-homogeneous systems. In other words, not only the existence of surface electric fields and their corresponding electric charge variations are fully consistent with the concept of free electrons, but it is due to free electrons that different local regions of a metal can exchange electric charges minimizing the system free energy. It is widely known in the physics of semiconductors (but has not been applied to metals often) that it is not the electric potential j, but rather the elec-

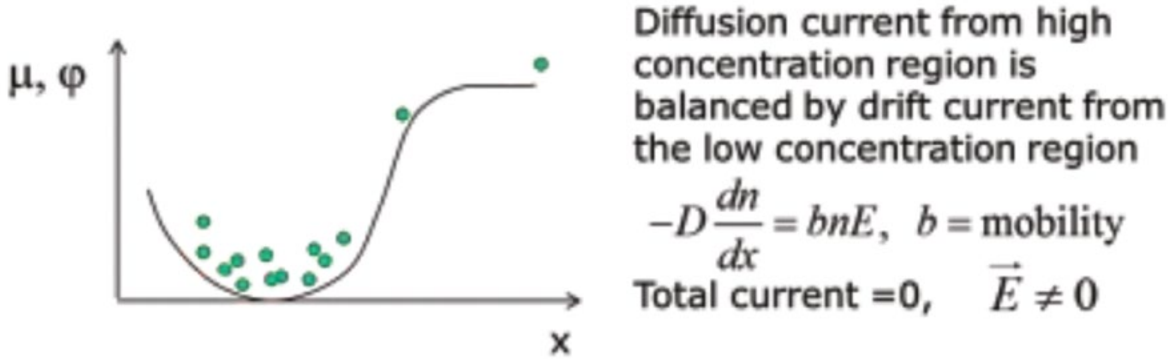

Figure 12: A sketch of a spatial distribution of the electric potential including two regions with the relatively low (left) and relatively high (right) chemical potential m. To utilize that difference in chemical potentials, the electrons partially moved from right to left creating non-uniform electric charge distribution and its corresponding non-uniform electric potential j and electric field E. The quantity that remains constant throughout the region is the electro-chemical potential $\Phi = \mu + \varepsilon\varphi$ where e is the electron charge.

trochemical potential F = m + ej that needs to be constant in space in order to minimize the system free energy. Here, m is the chemical potential (change in the system energy in response to the change of number of particles in it by one; the difference in chemical potentials between two substances equals minus that of the corresponding work functions). The chemical potential is sensitive to all kind of chemical features, deformations, defects, etc. Figure 12 shows how the concentrations of particles n are significantly different in the two regions with different chemical potentials. As a result, the particles move to the region of lower chemical potential. Because of the accumulated electric charge, there is now electric field E in the system. However, its corresponding drift current nEb (b is the mobility) is totally balanced by the diffusion current Ddn/dx, where D is the diffusion coefficient and x is the coordinate in the direction of concentration gradient. The important conclusion is that it is a metal where there is no current while the electric field is not vanishing.

It follows from the latter that some structural or compositional inhomogeneities are needed for the electric charge redistribution triggering whisker growth. Grain structure can be one (but not the only) example of such inhomogeneities. This is consistent with the general observation that whiskers are unlikely on metal surfaces built of very large grains, and that the presence of grain boundaries can be essential. Before pointing at more specific factors behind electric field variations, the following general examples (i–iii) are aimed at illustrating the underlying physics.

i. Consider local stresses (due to grain boundaries, dislocations, or external loads) modulating interatomic distances in a metal, thus making some local regions denser than the others.

Because of these local variations, some regions will present deeper potential wells for the electrons (a phenomenon known as the deformation potential D = dm / du 1 eV where u is the dilation). Should these regions be mutually independent, the Fermi level positions would vary between them. However, because they are connected, the free electrons will move to level out the Fermi level across the entire system thus minimizing the system free energy. As a result, the above regions become electrically charged.

ii. Spatial variations in chemical composition of alloys would similarly result in modulations of work function, which will be leveled out in the course of electron redistribution creating local electric fields similar to the previous example.

iii. The extreme case of the latter is presented by a contact of different metals with unequal

work functions. The free electrons will move between these metals to equalize their Fermi levels. This makes the metals electrically charged. The same phenomenon underlies the existence of Schottky barriers and p-n junctions in semiconductors. In the case of metal couples, it is known as the source of the galvanic action that occurs when two electrochemically dissimilar metals are in contact and a conductive path occurs for electrons and ions to move from one metal to the other. Furthermore, one can imagine a binary mixture of chemically different metal grains where the balance of Fermi energy makes the grains of two types charged oppositely.

The above cases (i) and (ii) are schematically illustrated in Figure 13.

More specifically, the regions of different surface potential (patches) may be due to the polycrystallinity of a metal. The work function will vary between regions of specific grain orientations (Figure 14) by typically a few tenths of a volt; these different grain orientations will be qualitatively similar to the above example (iii) of binary metal mixtures. Patch structure may also arise from the presence of adsorbed elements and compounds; that contamination is qualitatively similar to the above mentioned example (ii) of the chemical composition variations. Certain features of surface morphology, particularly, its roughness, may result in the electron redistribution caused by the corresponding modulations of microscopic structure parameters similar to the above example (i). They can be caused by dislocations, stress-induced spots of different structure phases, or general electric deformation coupling in combination with stress-induced buckling.

Local charges due to stress-induced oxide cracking or ion trapping under the whisker growing layer (say, Sn on Cu substrate) are conceivable sources of the above considered surface electric fields as well. Therefore, a surface, that is ideally electrically uniform, may acquire electric surface structure. Here we assume a simple model of uncorrelated charge patches on a metal surface characterized by two parameters: characteristic electron surface charge density ne (electrons per cm^2), and the linear dimension L. In reality, the charge distribution in patches can be nonuniform, possibly concentrating along grain boundaries or other structural imperfections. However, these conceivable complications fall beyond the present scope. The charged patch model is illustrated in Figures 2, 5, and 15.

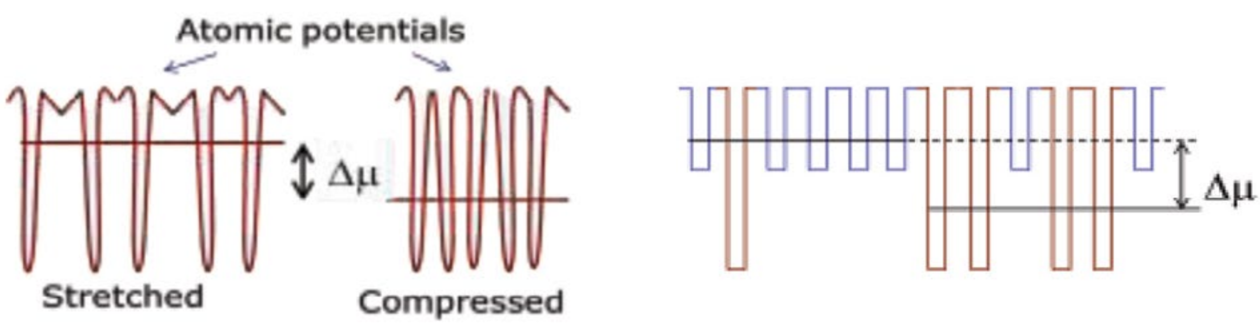

Figure 13: Variations in chemical potentials in a locally deformed (left) and locally chemically Non-uniform (right) metals.

Figure 14: Sketches of wrong grain facets orientation (left) and oxides or other dielectric layers capable of charge accumulation, or ionic contamination spots (right).

Patch structured electric fields near metal surfaces have been found in multiple works. The measurements reveal the work function fluctuations of ~0.5 eV induced by L~10 μm patches in some metals.

The charged patch model enables one to estimate the average electric field vs. distance r from the surface. At distances r<<L, the field is close to uniform due to the dominance of the closest uniformly charged patch. At distances r>>L, fluctuations become essential and the average field amplitude decays inversely proportional to r. In addition, given the above model, it is straightforward to see that far from the surface, r>>L, the electric field vectors are directed on average perpendicular to the surface having a considerable dispersion in angles,

$$\frac{\langle E_{\perp}E\rangle}{\langle E^2\rangle}=\frac{\langle E_{\parallel}E\rangle}{\langle E^2\rangle}=\frac{1}{2}$$

Equation 1

where $E_{\wedge}$ and $E_{\parallel}$ are respectively the field components perpendicular and parallel to the surface, and angular brackets represent averaging.

9. The above estimates lead to the following scenario of whisker evolution. (i) Stage 1: Whiskers nucleate in time intervals of one subsecond to one day (reflecting fluctuations in nucleation barriers due to the local field fluctuations); their dimensions upon nucleation are h~10–100 nm and d~1–10 nm, with the average orientation perpendicular to the metal surface and significant angular dispersion. (ii) Stage 2: Whiskers grow up to the patch size, say L~0.1–10 μm. This takes a much longer time t_0~10^4–10^5 that can be experimentally identified as the whisker incubation time. The growth rate at this stage is very low for almost entire time interval t_0, with drastic acceleration in the nearest proximity of t_0 (see Figure 6). (iii) Stage 3: Whiskers grow way above patch size at the average constant rate possibly with some degree of winding or kinking (beyond the current theory). At this stage, random field configurations induced by uncorrelated patch charges make growth rates of individual whiskers fluctuating, some of them blocked. The random distribution of blocking barriers determines the statistical distribution of whisker lengths. (iv) Stage 4: If whiskers grow above lengths where feeding by thermal radiation dominates, they evolve further in lateral directions parallel to the metal surface (not discussed here).

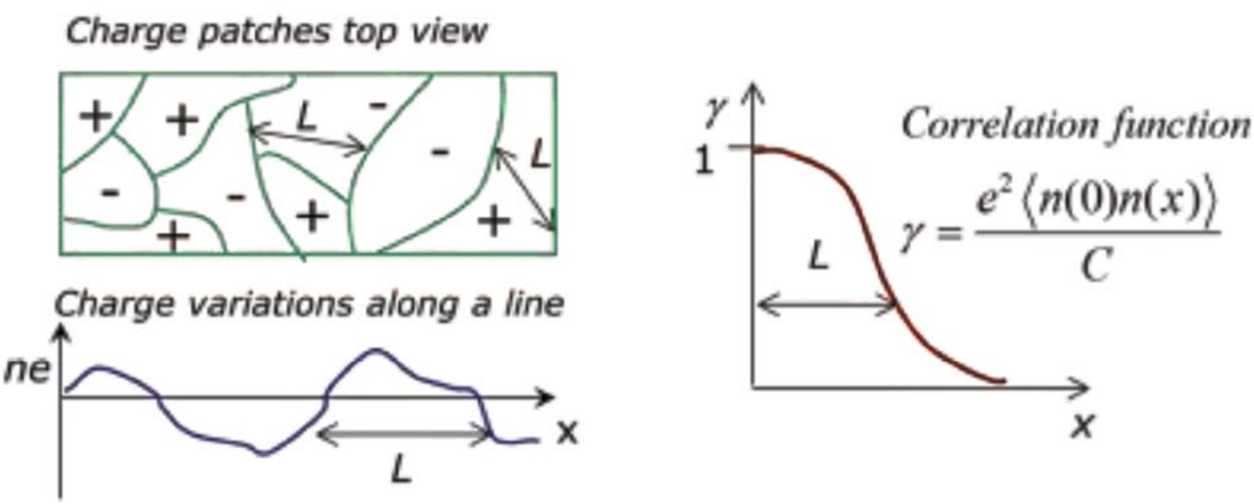

Figure 15: Charged patch model. The correlation function g(x) can be approximated as the delta-function (i.e., uncorrelated disorder) at distances x>>L.

10. Conclusions

The above theory describes metal whickers as a result of metal nucleation and growth in random electric fields induced by charged patches on metal surfaces. The underlying approaches are typical of the physics of phase transitions and disordered systems. This work presents the first whisker theory yielding simple analytical results more or less consistent with the observations. The successes, the remaining questions, and possible experimental verifications of this theory are summarized next.

10.1 What is understood

1) Why whiskers are metallic: High (metallic) electric polarizability is required for sufficient energy gain due to whisker formation in external (surface) electric fields.

2) Why whiskers grow more or less perpendicular to the surface and yet can have configurations parallel to the surface: Such are the dominating directions of the surface electric field that include significant fluctuation along the surface.

3) Why whisker parameters are broadly statistically distributed: This reflects fluctuations in metal surface fields induced by mutually uncorrelated charged patches.

4) Correlation between whiskers and versatile morphology factors, such as (i) grains whose orientation is different from the major orientation of the tin film, (ii) dislocations and dislocation loops, and (iii) mechanical stresses capable of surface buckling, surface contaminations; all related to local surface charges and their induced electric fields. Some metals are more prone to develop whiskers because they can easier form charged patches by absorbing ions, and creating dislocations, grain boundaries, or stresses.

5) Why external electric bias can significantly affect whisker growth. (It is rather difficult, yet possible, beyond this paper framework, to understand how the electric bias can be not a significant factor in whisker kinetics.)

6) Why the characteristic whisker evolution exhibits a certain pattern: long incubation period followed by almost constant growth rate that eventually saturates. The predicted incubation (dormant) time and subsequent growth rate agree with the observations.

7) Why whisker parameters are broadly distributed statistically. The predicted distribution of whisker lengths is close to the observed log-normal statistics around its central part.

10.2 What is not understood

1) The microscopic nature of whiskers, their correlation with specific surface defects, chemical aspects of whisker development.

2) The role of whisker crystalline structure in their evolution process.

3) Whisker growth in 3D random electric field. This includes whisker winding and kinking.

4) Possible role of surface (or grain boundary) diffusion limiting whisker growth.

5) Possible hydrodynamic drag moving surface material uniformly along with ions.

6) Inter-whisker interactions limiting their concentration and affecting growth. This includes the stage of whisker ripening.

7) Role of Pb in suppressing whiskering.

10.3 Possible experimental verification

The predicted dependencies of nucleation and growth kinetics vs. electric field, temperature, and controlled contamination could be verified experimentally.

1) Whisker nucleation and growth in external electric fields. This can be attempted, e.g., in flat plate capacitor configuration for a whisker inside SEM where the electric field is readily controlled, or under e-beam in an accelerator. In all cases, care should be taken to avoid significant Joule heating and/or electron drag effects (i.e., using voltage rather than current power source). An ongoing project in our group has generated preliminary results showing that the electric field in combination with high relative humidity can lead to anomalously rapid whisker growth (one week under 3000 V/cm in a capacitive configuration; 10–20 hours of medical accelerator e-beam charging a glass substrate under Sn film).

2) Whisker nucleation and growth under controlled contamination of metal surface with solutions of charged nano particles.

3) Whisker nucleation and growth under the conditions of strong surface electric fields

induced by surface plasmon polariton excitations. This technique could be used for controlled growth of metal nanowires of desirable parameters on metal surfaces.

4) Applications to modern large area thin film photovoltaic technology where whiskers can shunt through the device, thereby causing significant reliability concerns (which has not been sufficiently addressed yet). Properly replacing those device metal contacts or surface treatments mitigating whisker growth can improve the device reliability and stability with respect to shunting.

Acknowledgement

The author is grateful to D. Shvydka, A. Vasko, G. Davy, S. Smith, B. Rollins, J. Brusse, A. Kostic, and the entire tin whisker teleconference group for useful discussions. The NASA Electronic Parts and Packaging (NEPP) Program is greatly appreciated. SMT

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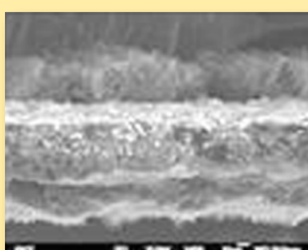
Victor Karpov is professor of physics at the University of Toledo. He has published about 200 papers on condensed matter, physical chemistry, photovoltaics, and device physics.

Laser-induced Graphene Vital for Flex Electronics

Rice University scientists advanced their recent development of laser-induced graphene (LIG) by producing and testing stacked, three-dimensional supercapacitors, energy-storage devices that are important for portable, flexible electronics.

The Rice lab of chemist James Tour discovered last year that firing a laser at an inexpensive polymer burned off other elements and left a film of porous graphene, the much-studied atom-thick lattice of carbon. The researchers viewed the porous, conductive material as a perfect electrode for supercapacitors or electronic circuits.

Members of the Tour group have since extended their work to make vertically aligned supercapacitors with laser-induced graphene on both sides of a polymer sheet. The sections are then stacked with solid electrolytes in between for a multilayer sandwich with multiple microsupercapacitors.



The flexible stacks show excellent energy-storage capacity and power potential and can be scaled up for commercial applications. LIG can be made in air at ambient temperature, perhaps in industrial quantities through roll-to-roll processes, Tour said.

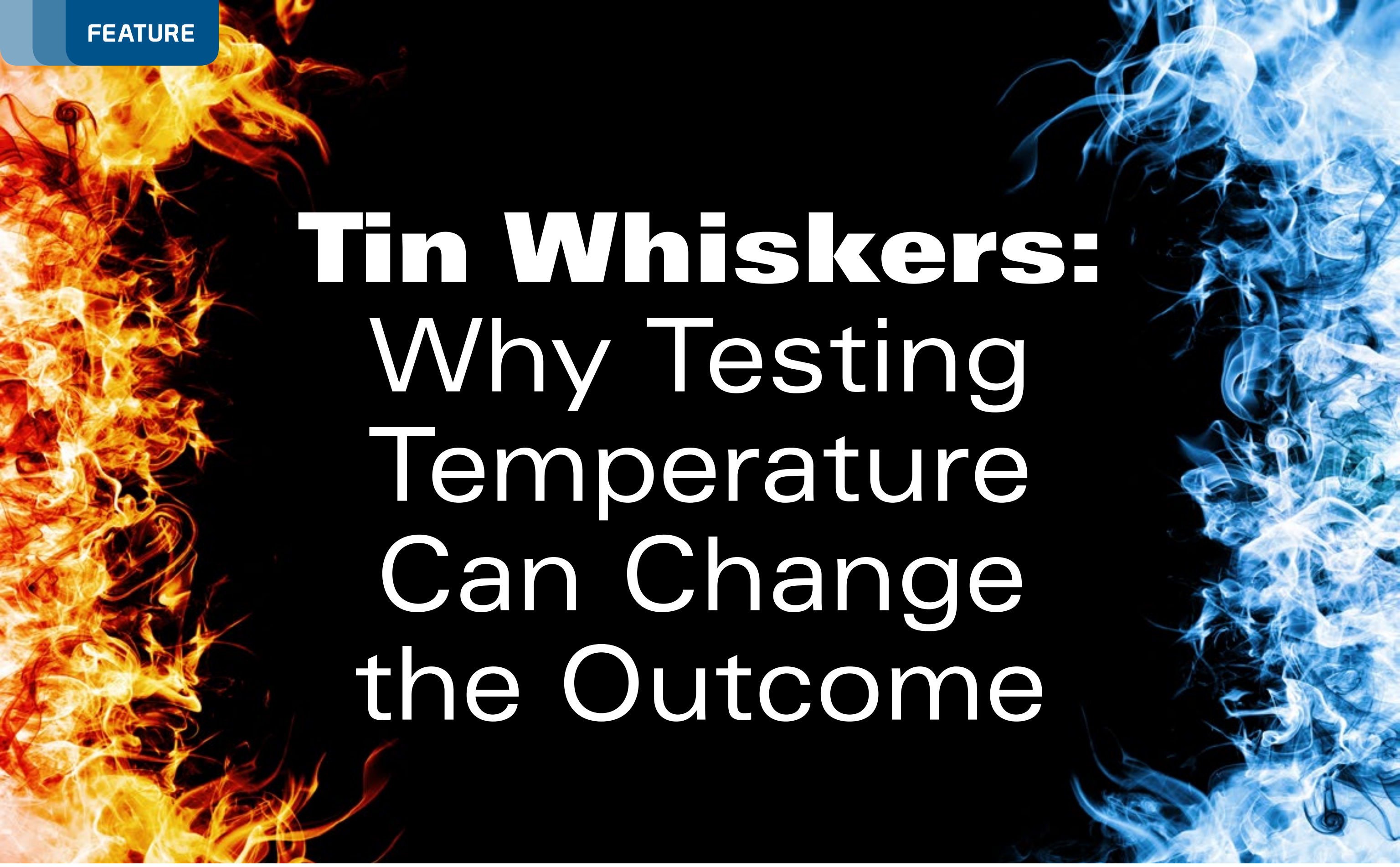
The research was reported this week in Applied Materials and Interfaces.

LIG supercapacitors appear able to do everything capacitors can do, with the added benefits of flexibility and scalability. The flexibility ensures they can easily conform to varied packages—they can be rolled within a cylinder, for instance—without giving up any of the device's performance.

"What we've made are comparable to microsupercapacitors being commercialized now, but our ability to put devices into a 3-D configuration allows us to pack a lot of them into a very small area," Tour said. "We simply stack them up.

"The other key is that we're doing this very simply. Nothing about the process requires a clean room. It's done on a commercial laser system, as found in routine machine shops, in the open air."

Ripples, wrinkles and sub-10-nanometer pores in the surface and atomic-level imperfections give LIG its ability to store a lot of energy. But the graphene retains its ability to move electrons quickly and gives it the quick charge-and-release characteristics of a supercapacitor. In testing, the researchers charged and discharged the devices for thousands of cycles with almost no loss of capacitance.



Tin Whiskers: Why Testing Temperature Can Change the Outcome

by Dr. Jennie S. Hwang
CEO, H-TECHNOLOGIES GROUP

Tin whisker phenomena have been observed and its potential mishaps have been recognized for more than six decades in electronic, electrical and industrial applications. For the recent several years, concerns about tin whiskers have been escalating, especially in the sector of high-reliability products. Increasing number of studies and tests has been carried out at various facilities, generating significant amount of quality reports and publications. In my recent tutorial at SMTA International Conference/Exhibition last September[1, 2] there were comments requesting to further discuss the plausible theories behind tin whiskers. When we examine the theories, temperature is one of the key variables that drive the phenomenon, mechanism and how the underlying science operates. So, let's dedicate this article to the impact of external (testing) temperature and the science behind the impact.

JEDEC Solid State Technology Association (formerly known as the Joint Electron Device Engineering Council) has published several documents that address and/or are related to the testing of tin whiskers[3, 4, 5].The testing temperature as set in the documents are: ambient temperature storage (30 ±2°C and 60±3% RH); elevated temperature storage (60 ±5°C and 87+3/-2% RH); and temperature cycling are, practically speaking, as good as can be. However, refinements and selection of the testing temperature needs to be made when testing an "unknown" system. The system may possess specificities and contain certain compositions (e.g., active or inert additives [impurities]).

In metal whiskering, the physical metallurgy engaged in the process is complex and intricate—a compositional shift and /or an addition of extraneous elements to a base alloy system, regardless of sources, can change its whisker propensity enormously. As is known, the evidence of recrystallization and grain growth prior to whisker formation is presented for the "bright tin" deposit—large irregular shape grains are the precursors for whiskers. Recrystallization plays a part in tin whiskering process. To complicate further, however, tin whiskering is more than a classical recrystallization process and it is more than a classical stress relief phenomenon. I would say that, for a given tin-

based material that is made by a given process, there is a "threshold strain" and a "threshold temperature" that cause tin whiskering.

This threshold temperature is not necessarily the same as the recrystallization temperature. It is critical to recognize that the recrystalization temperature changes with the system (composition) and can also be affected by the initial strain level and initial grain size. Thus it is important to be able to capture the anticipated changes from the pure tin when an impure tin system is used. How a selected testing temperature is related to the threshold temperature is the key to what test results will be obtained.

Threshold strain and the threshold temperature work hand-in-hand. Tin whiskering engages both nucleation and grain growth. The energy to drive grain growth is relatively low and its growth rate is slow and easily slowed further or impeded to a halt by the presence of second phase particles or solute atoms in the lattice. The measured activation energy for grain growth of impure metals is often very high. On top of that, tin has a low recrystallization temperature as well (the recrystallization temperature of pure tin is nominally at 30°C), thus the impact of the testing temperature can be very tricky. For instance, how the applied testing temperature in relation to the solubility temperature of impurities or its de-anchoring temperature from the grain boundaries dictates the grain growth pattern—growth within the lattice or the growth out of surface. That is when the testing temperature is just below the solubility/de-anchoring temperature; when the testing temperature is above this temperature makes difference. The external temperature (testing temperature) drives the kinetics of defect dynamics in the tin layer by affecting stress relaxation, grain boundaries and atomic mobility-related mechanisms. When applying a high temperature (relative to tin's recrystalization temperature), it is expected to impede the continued grain growth along the protruding direction, resulting in short whiskers. It is also worth noting that tin's recrystallization temperature changes with the level of its purity. In other words, when adding elements into tin, tin's behavior in relation to the external temperature (testing temperatures) will change since its recrystallization temperature is elevated.

The propensity of a tin deposit to grow whiskers strongly depends on its intrinsic structure and the state of energy including the level of strain, grain size and crystallographic orientation, composition, surface condition, and the external temperature (or testing temperature). The threshold temperature is lowered when there exists a higher level of strain in the tin material. When the strain is sufficient, the lower threshold temperature results in longer and needle-like whiskers in contrast to many short and nodular whiskers that are favored by a higher temperature due to higher nucleation rate. When impurities are present, whiskers also tend to grow in short and nodular form.

> **"When the strain is sufficient, the lower threshold temperature results in longer and needle-like whiskers in contrast to many short and nodular whiskers that are favored by a higher temperature due to higher nucleation rate. When impurities are present, whiskers also tend to grow in short and nodular form."**

Grain boundaries play a key role in the mechanism of whisker formation. Whiskering can be much facilitated when the grain boundary structure contains both the recryslallized grain boundaries in low-energy state and the high angle, high-energy grain boundaries. To obtain both types of grain boundaries, the adequate temperature is a prerequisite. On the other hand, when the applied temperature is too high, the driving forces and the mechanism for whiskering will be annihilated. A higher temperature alters the relative diffusion rate between grain boundary diffusion and the lattice diffusion. So where is the "green house" temperature? Finding this green house temperature is the main task in designing the test.

As mentioned in my previous columns, testing the tin whisker propensity, due to its underlying mechanisms, is a more challenging endeavor than testing solder joint reliability, particularly in defining the optimal testing temperature for a system. To understand grain boundaries, it requires substantial micro-scale and atomic-scale analyses. In addition to performing electron backscatter diffraction (EBSD) and energy dispersive X-ray spectroscopy (EDS) for identification of phases and uncovering texture, transmission electron microscope (TEM) and ideally atom probe scanning electron microscope-focused ion beam (SEM-FIB) system are needed to examine the grain boundary structure and its interaction with impurities, which is often characterized by the inhomogeneous distribution of impurity atoms between the grain boundary and the grains.

As selecting testing parameters that are in sync with the intrinsic properties of the system is a critical step, it is plausible to choose the test parameters based on the anticipated underlying process and/or a postulated "theory" so that the tests can capture the "action." Just as important, the tests for the intended purpose are to gauge the relative susceptibility to whiskering. When proper test parameters are identified, especially the testing temperature, testing the absence of whiskers is as meaningful as the presence of whiskers.

For determining the testing temperature, identifying the endgame is a real thing—is the testing temperature intended to demonstrate the occurrence of tin whiskers, or is it to demonstrate the absence of tin whisker, or is it that under the most plausible condition for the specific system to see tin whisker will or will not occur? Determining plausible testing temperature is a challenge, but it should be considered before carrying out the test.

A different testing temperature can change the outcome, qualitatively or quantitatively. **SMT**

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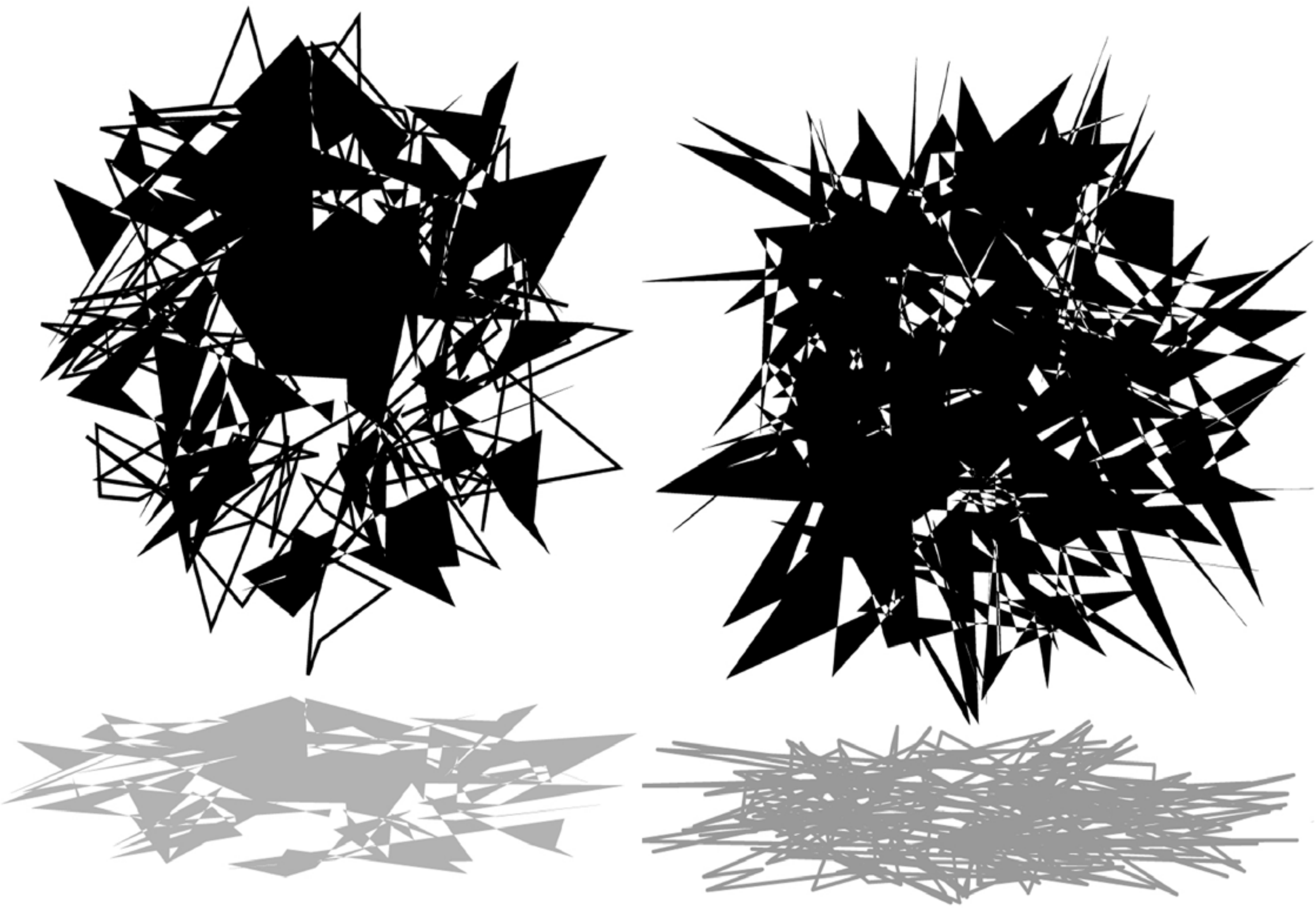
Upcoming Appearances

Dr. Hwang will present a lecture on "Preventing Manufacturing Defects and Product Failures" at IPC APEX EXPO on February 22, 2015, San Diego, CA.

Dr. Hwang, an international businesswoman and speaker, and business and technology advisor, is a pioneer and long-standing contributor to SMT manufacturing since its inception, as well as to the global lead-free electronics implementation. Among her many awards and honors, she is inducted to the International Hall of Fame—Women in Technology, elected to the National Academy of Engineering, and named an R&D-Stars-to-Watch. Having held senior executive positions with Lockheed Martin Corp., Sherwin Williams Co., SCM Corp, and CEO of International Electronic Materials Corp., she is currently CEO of H-Technologies Group, providing business, technology and manufacturing solutions. She has served on the U.S. Commerce Department's Export Council, Chairman of Assessment Panel on DoD Army Research Laboratory, various national panels/committees, and the board of Fortune 500 NYSE companies and civic and university boards. She is the author of 400+ publications and several textbooks, and an international speaker and author on trade, business, education, and social issues. Her formal education includes four academic degrees as well as the Harvard Business School Executive Program and Columbia University Corporate Governance Program. For further info, visit JennieHwang.com. To read past columns, click here.



Tin Whiskers Remain a Concern

by Michael Osterman
UNIVERSITY OF MARYLAND

The elimination of lead in electronic equipment due to governmental regulations (European Union End of Life Vehicle Directive and European Union Restriction of Hazardous Substances Directive) has increased the risk of electrical shorting due to the formation of tin whiskers in electronic products. Tin whiskers are hair-like tin structures that grow sporadically on surfaces coated with tin. Whiskers are often difficult to detect due to their small cross-sectional dimensions, typically ranging between 1 and 5 micrometers, which may be 10 to 50 times finer than a human hair. While their cross-sectional dimensions are small, whiskers can grow to lengths greater than a millimeter. Such lengths are sufficient to bridge the distance between tightly spaced electronic parts. Despite the difficulty of detecting them, tin whiskers have been identified as a cause of failure in medical, aerospace, power, and automotive equipment. In particular, control systems, such those found in automotive applications, have been found to have significant tin whisker failure risks[1]. Further, coupled with the increased use of tin as a surface finish in electronics, the continued trend towards higher interconnect densities and compact electronics is expected to increase the failure risk presented by the formation of tin whiskers.

With the use of tin-based solder materials for creating electrical connections, tin is used extensively in electronics. With regards to

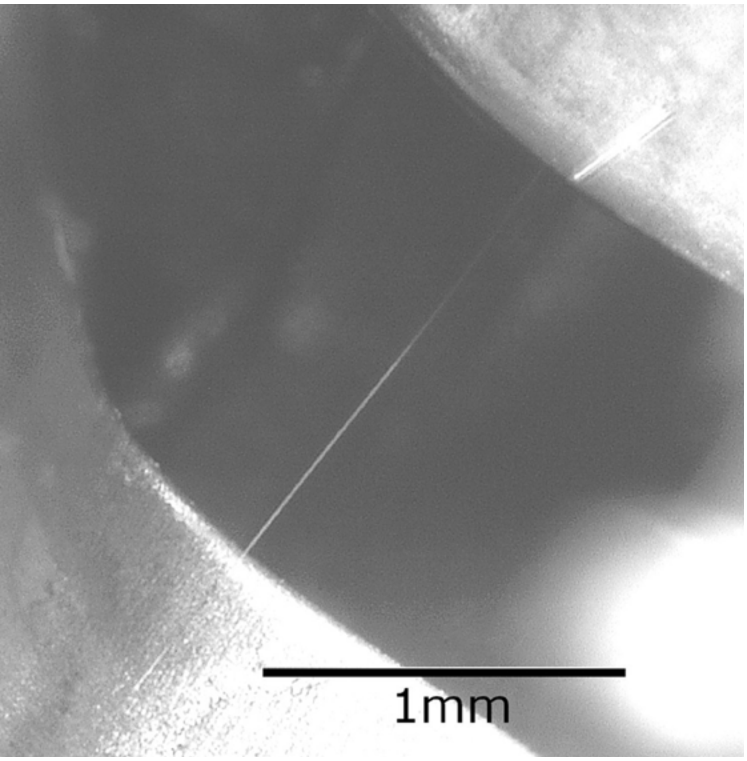


Figure 1: Tin whisker bridging adjacent terminals on feed-through tin-plated connector of an accelerator pedal position sensor that led to intermittent resistance between the two terminals[2].

electronics, advantages of tin include low cost and excellent engineering properties, including high corrosion resistance and solderablity. With the elimination of lead, tin has become a common surface finish for plated package terminations used on electronic devices. Research dating back to the 1950s has demonstrated that the addition of lead to tin significantly mitigates the occurrence of tin whiskers. While quality control tests for tin whiskers have been established, no tests are available to assess the long-term elimination of the tin whisker failure risk[3]. Tin whiskers are electrically conductive and can carry, depending on their cross-sectional area, sustained electrical current up to 10 mA without fusing. At higher current levels, the tin will melt and break the electrical circuit. In the presence of a high in-rush current (>1000A/s) and with voltages at or above 12 V, tin whiskers can strike a metal vapor arc operating at temperatures in excess of 1000°C. Once initiated, a metal vapor arc can be sustained with continued voltage, current, and material[4]. For electronics, the formation of an unintended electrical short can cause a product to malfunction. For control systems, such as an automotive engine control or automotive stability control system, a tin whisker-induced malfunction can create unsafe operating conditions.

While extensive research has been conducted into whisker formation, methods to effectively assess the propensity of tin-finished surfaces to form whiskers in long-term service applications remain elusive. Research indicates that tin whiskers form in response to stress imbalance in the tin film. Vianco et al., have recently reported that tin whiskers form through dynamic recrystallization when the strain within the tin film is greater than a critical value[5]. Even as our understanding of the processes promoting whisker formation increases, the challenge of finding effective test methods to predict long-term tin whisker growth remains. This challenge stems from a variety of factors, both external and internal, which can change the stress state in the tin film, giving rise to whisker growth. For instance, contact forces in connector applications have been shown to give rise to rapid whisker growth. In field applications, environmental factors such as corrosion and surface oxidation can promote whisker formation. Additionally, temperature cycling of tin-plated systems can give rise to stress states within the tin film due to the mismatch of temperature expansions rates between the tin and substrate to which the tin is applied. Internally, the formation of intermetallic compounds between the tin and the substrate material to which it is plated can also over time create a stress state favorable for whisker formation. Further, grain structure and plating thickness have been demonstrated to play a role in whisker growth.

For part manufacturers, the use of matte tin plating, high-temperature annealing, and the application of a nickel underlayer have become common approaches for mitigating tin whisker formation. With regard to matte tin plating, this specification typically denotes a dull surface appearance that arises from larger (approximately 1 to 5 micrometer) surface grains. As whiskers form from new grains at or near the free surface of the tin layer, the larger grain size means fewer locations for tin whiskers to form compared to bright tin with finer (less than 1 micrometer) surface grains for the same surface area. However, matte tin should not be interpreted as being whisker-free. With regard to high temperature annealing, this process provides relief from whisker formation by promoting a uniform and enlarged interfacial intermetallic layer between the tin film and the substrate and reducing stress in the tin film. However, research indicates that the stress state continues to evolve, delaying, but not eliminating, whisker growth. With regard to a nickel underlayer, the porosity of the nickel layer may still allow for an evolving stress state favorable to whisker formation. Further, neither annealing nor a nickel underlayer prevents external stress sources from promoting whisker formation. As a result, equipment manufacturers should not consider part manufacturer mitigations to be sufficiently effective, particularly in electronic systems where failure can result in significant losses. However, advancements in tin plating and treatment of substrates prior to plating continue to show promise as further reducing whisker growth.

To assist equipment manufacturers of high performance systems with mitigating the potential risks associated with tin whisker formation, the GEIA-STD-0005-2:2012, "Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems," has been developed. For mitigation strategies, this document identifies the use of hard non-conductive barriers, encapsulation, and conformal coating. The document also identifies the separation of tin-finished surfaces as a strategy as well as the use of tin-lead solder-covered tin surfaces with solder occurring in the reflow and wave soldering process. For the reasons previously discussed, GEIA-STD-0005-2:2012 does not consider part-manufacturer-applied tin whisker mitigation methods to be sufficiently effective to stand alone. However, the document does indicate that tin-finished parts that have been subjected to part-manufacturer-applied tin whisker growth mitigation methods are preferred over tin-finished parts with non-defined tin whisker growth mitigation methods. In addition to mitigation strategies, the document identifies program control levels for handling tin-finished materials in electronic products. The control levels are created to allow organizations to consider the consequences of failure and the use of appropriate tin whisker mitigation strategies, with the highest level, Level 3, calling for the complete prohibition of lead-free tin.

While a complete ban on the use of tin, particularly for safety-critical applications, would be preferred, the cost and potential risks of eliminating tin-finished parts may be prohibitive. Further, manufacturer mitigation methods, such as encapsulation, conformal coating, and fault tolerant circuit analysis, may be sufficient for safe operation. However, any mitigation strategy should be assessed for its effectiveness prior to implementation and should be audited to ensure that the proscribed mitigation method meets the defined requirements. For instance, the coverage of tin-finished surfaces provided by current conformal coating processes may be insufficient to prevent whisker-induced

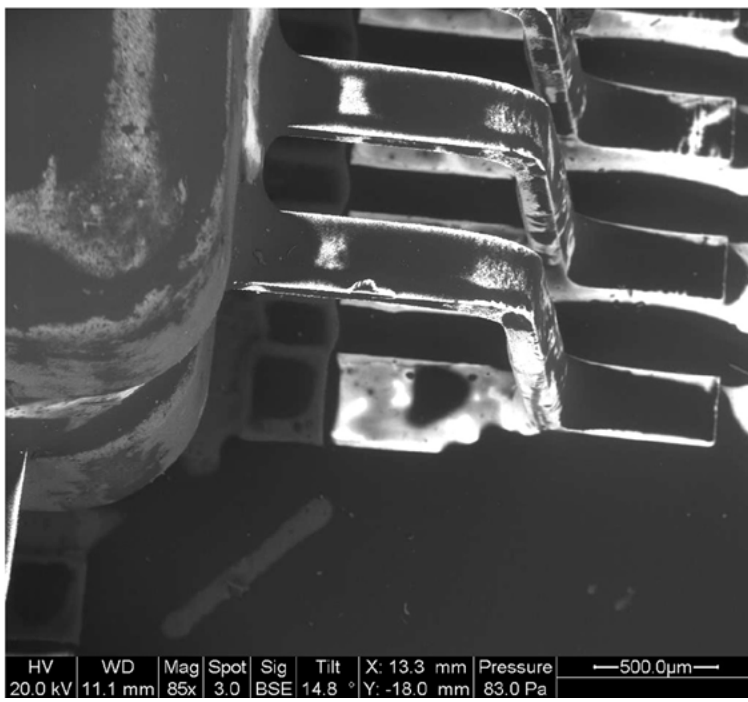


Figure 2: Poor coverage of acrylic conformal coating (bright areas on lead wire represent little to no coating). (Courtesy of CALCE/University of Maryland.)

failure[9]. Figure 2 depicts an acrylic conformal coating that does not completely encapsulate the lead wires of a quad-flat package. To address this issue, the IPC 5-22ARR J-STD-001/Conformal Coating Material and Application Industry Assessment Task Group has conducted a round-robin study to characterize the coverage provided by commonly used conformal coating materials with existing application processes. The study includes 26 different material combinations, and the results are expected to be used for updating measurement and evaluation standards.

In designing safety and control electronics, the risks of using tin must be carefully assessed. To this end, methods for assessing failure risk have been developed[6]. For example, the risk of a tin whisker–induced short can be estimated by identifying tin-finished surfaces, distances from the identified surface to surfaces at a different electrical potential, and knowledge of whisker growth statistics. Tin whisker lengths can vary dramatically; however, they have been found to follow a lognormal distribution[7]. The density of whisker growth can also vary dramatically. For assessment, software[8] using measured whisker growth statistics has been published in the open literature. With these methods, a probability of failure can be assigned to the tin whisker failures, and the effect of tin whisker failure mitigation strategies that rely on separation and coating coverage can be assessed.

Thus far, the ban on the use of lead in most electronics has not resulted in public concern about tin whiskers. This result is likely is due in large part to the development of industry standards, research by industry and academic groups, engineering functions within organizations to address this reliability threat, as well as closed discussion related to product failures, in general. However, this does not mean the risk to electronics posed by tin whiskers has been eliminated. Research into whisker mitigation strategies and the tests for assessing whisker risk should continue to be supported. As long as the electronic industry continues to use tin, tin whisker risk must be addressed. Tin whiskers are a known problem, and forgetting to account for their potential failure risk will cost organizations dearly. **SMT**

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Michael Osterman is a research scientist at University of Maryland, Center for Advanced Life Cycle Engineering.

FEATURE

Tin Whisker Growth on the Surface of Tin-Rich Lead-Free Alloys

by A. Skwarek, K. Witek, M. Pluska and A. Czerwinski
INSTITUTE OF ELECTRON TECHNOLOGY

The introduction of lead-free technology into electronics has intensified concern over tin whiskers phenomenon. Tin whiskers are crystals growing from the alloy surface as the result of compressive stress relaxation. This paper presents the dependence of tin whisker growth on copper and oxygen surface content. The observations and measurements were done using scanning electron microscopy with energy-dispersive X-ray spectroscopy. The results show that whisker growth is strongly related to increased copper and oxygen surface content in whisker neighborhood.

Introduction

Soldering is one of the oldest processes known to mankind. The proper solder joint is created by producing the metallic bond between the soldered elements and solder. In the 20^{th} century, the most popular solder was Pb-37Sn63 eutectics. From July 2006, the use of Pb in solders is banned in the European Union as a consequence of RoHS directive. Actually, most of the lead-free alloys are based on Sn, containing in their composition also Ag, Cu, and small additions of Ni, Co, Ge or Sb. The introduction of tin-rich lead free solder has renewed the con-

cern over, known for ages but limited by lead addition, phenomenon: tin whiskers. This phenomenon can significantly influence the reliability of solder connection and as a result influences the work of the entire PCB.

Tin whiskers are the crystals growing from the tin or tin alloy surface which can be dangerous for circuit reliability because of electrical current leakage and shorting due to bridging of adjacent conductors, metal vapor arcing (plasma) at low pressure, increased electromagnetic radiation, and damage from device littering by debris and contamination[1, 2]. The growth of tin whisker is caused by the compressive stress relaxation[3]. The copper intermetallic compounds and surface layer of oxygen can strongly influence whisker growth. This paper presents the results of energy-dispersive X-ray spectroscopy (EDS) studies showing the relationship between tin whisker formation and copper and oxygen surface content in whisker neighborhood.

Experimental

To estimate the dependence of tin whisker growth on copper and oxygen surface content, the test samples were prepared using PCB technology. In the experiment, the glass-epoxy laminates with a Cu foil of 17 µm thickness were used. One part of the samples was prepared with an electroless Ni immersion Au sub-layer, using a Pd activator. The Ni thickness varied from 4–6 µm and the plated Au layer was about 0.05 µm. The conductive pads were covered with Sn100 and Sn99.3Cu0.7Ni solder alloy. The alloys were applied by hand soldering with water flux application. The soldering temperature was dependent on the alloy composition. The thickness of all Sn layers was in the range from 10–20 µm. The samples were subjected to long-term exposure at temperature of 60°C and relative humidity 87% RH for 3000 h. Scanning electron microscope (SEM) images and EDS were performed with a Philips XL30 microscope. To determine the local content of elements—in particular copper and oxygen—X-ray spectra produced under the influence of the incident electron beam were performed in a scanning electron microscope. EDS analysis was performed for several points of the specimen: on the whisker body and on the whisker base.

For the comparison purpose the same analysis was performed in the random places far from the nearest whisker, in the middle at the edge of solder pad. The electron beam energy, used for EDS analysis, was at the level of 10 keV, so the penetration range of electrons in tin calculated according to the Kanaya-Okayama model for the 10 keV is 0.65 µm[4].

Results

For the samples exposed for 3000 h in 87% RH and 60°C whiskers were found on

Figure1: SEM images of the samples soldered directly on Cu layer after 3000 h exposure at 87% RH and 60°C—the edge of the solder area. (A) Sn100, (B) Sn99.3Cu0.7Ni.

all four types of samples (i.e., on Sn100 and Sn99.3Cu0.7Ni soldered both directly on the Cu layer, as well as the Ni/Au sublayer, as shown in Figures 1 and 2). However, they were found only at the edge of the solder (where the solder thickness is significantly smaller than typical) while not at the typical thickness of the solder.

Copper Content

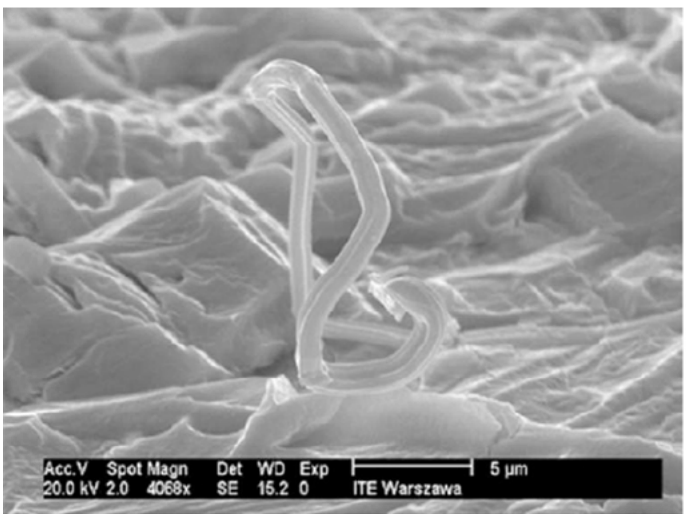
Cu content, measured directly on the whisker (found as mentioned earlier at the edge of solder pad) was amounted to 0.46 wt%. This value can be regarded as negligible, because less than 1 wt% can be related to the EDS fluctuation signal. So it means that the whisker body was free from Cu content.

On the base of 70% of whiskers the copper content significantly increased—from 7.4 to 9.32 wt%. At the base of 30% of whiskers the copper content was at the level of 1 wt%. It does not mean, however, that at the base of the whiskers the increased copper content has not occurred. It may only mean that it was not detected by specific settings at the EDS studies. Namely, if on the way of the incident beam there is a whisker, then it partially covers the base against the electron beam and the precise measurement cannot be done. No particularly distinguished copper content in the other areas of tin was noticed, regardless if the analysis was done at the edge or in the middle of the soldered pad.

Oxygen Content

For measuring the oxygen content, the method including the elimination of surface contamination was used. This method involves measuring of the carbon content and the calculation of approximately constant dependence of oxygen on carbon content (which corresponds to their constant relation in the chemical compounds or in the conglomerate forming contamination of the sample). On this basis, it is possible to determine how much oxygen is associated with sample contamination and how much with tin oxides.

On the whisker body (found as mentioned earlier only at the edge of solder pad) the detected oxygen content was at the level of 2.3–3 wt%. The oxygen content on the whisker base reached from 14–21wt%. For comparison, oxygen content on the alloy surface located in the middle of the pad was from 4.6–9 wt%. Such high oxygen content in the area of whisker base is related to the formation of tin oxide. When the measured oxygen content exceeds 12 wt% it suggests the occurrence of $SnO2$[5] and in lesser degree, SnO. The exemplary EDS spectra for Sn99.3Cu0.7Ni (with signals from contaminations removed), presenting the results described above, are shown in Figure 3.



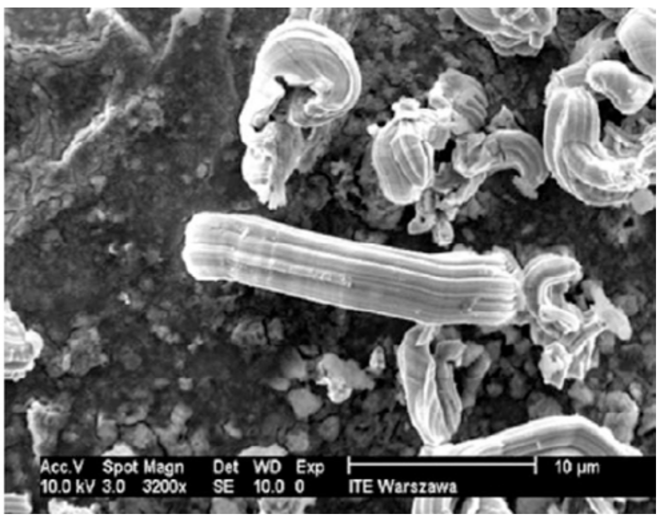


Figure 2: SEM images of the samples soldered directly on Cu layer after 3000 h exposure at 87% RH and 60°C—the edge of the solder area.

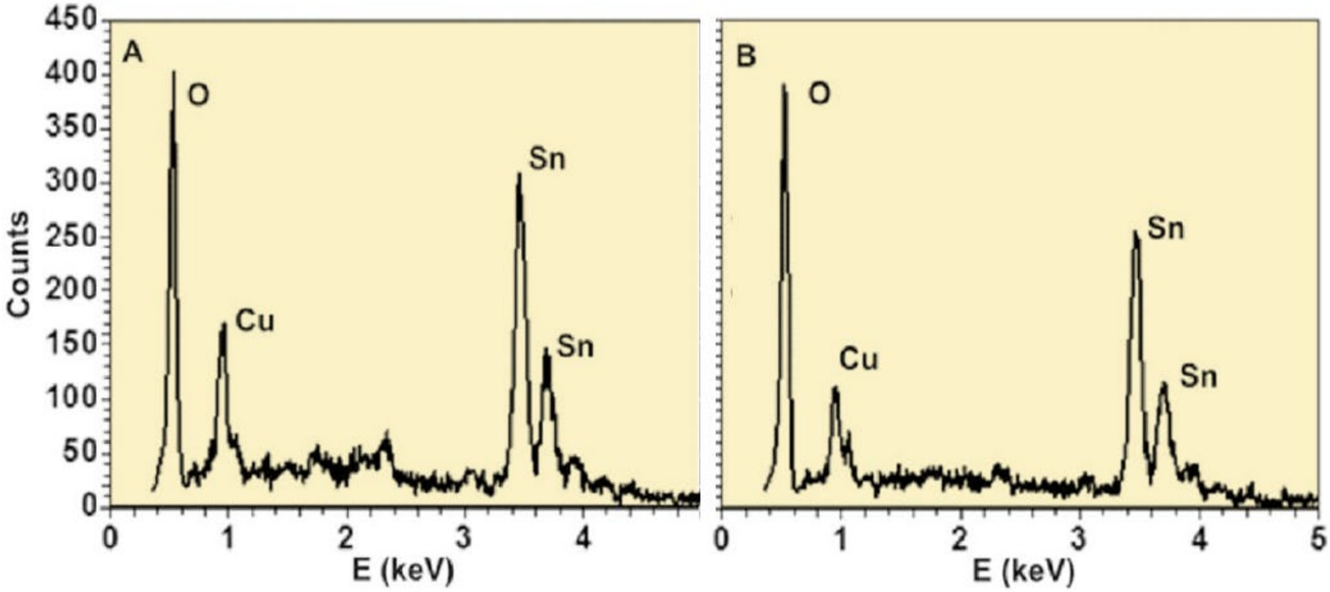


Figure 3: EDS spectra of the samples of Sn99.3Cu0.7Ni, after 3000 h exposure at 87% RH and 60°C soldered on (A) NiAu sublayer and (B) directly on Cu layer.

Conclusions

The increased copper content in the area of whisker base can be related to the presence of intermetallic compounds (in particular the presence of Cu6 Sn5). The increased oxygen content is caused by the presence of tin oxides on the surface of the solder, particularly at such a high content of oxygen—the presence of SnO2. Both, increased copper and oxygen contents at the whisker base are strongly related to whisker growth. **SMT**

Acknowledgments

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Andrzej Czerwinski (PhD, DSc) is associate professor and head of Department of Materials and Semiconductor Structures Research, Institute of Electron Technology, Warsaw, Poland.

Agata Skwarek (PhD) is an assistant professor in the Department of Microelectronics in the Institute of Electron Technology (Krakow Division), Poland.

Mariusz Pluska (PhD) and Jacek Ratajczak (PhD) are assistant professors with the Department of Materials and Semiconductor Structures Research, Institute of Electron Technology, Warsaw, Poland.

Krzysztof Witek (M.Sc. Eng.) works in the Institute of Electron Technology (Krakow Division), Poland as manager of Implementation and Production Department.


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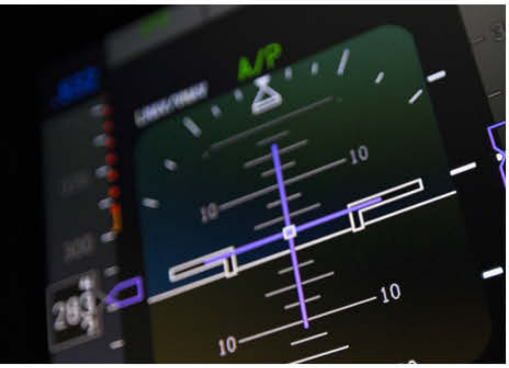

FEATURE

The Unpredictability of Tin Whiskers Endures

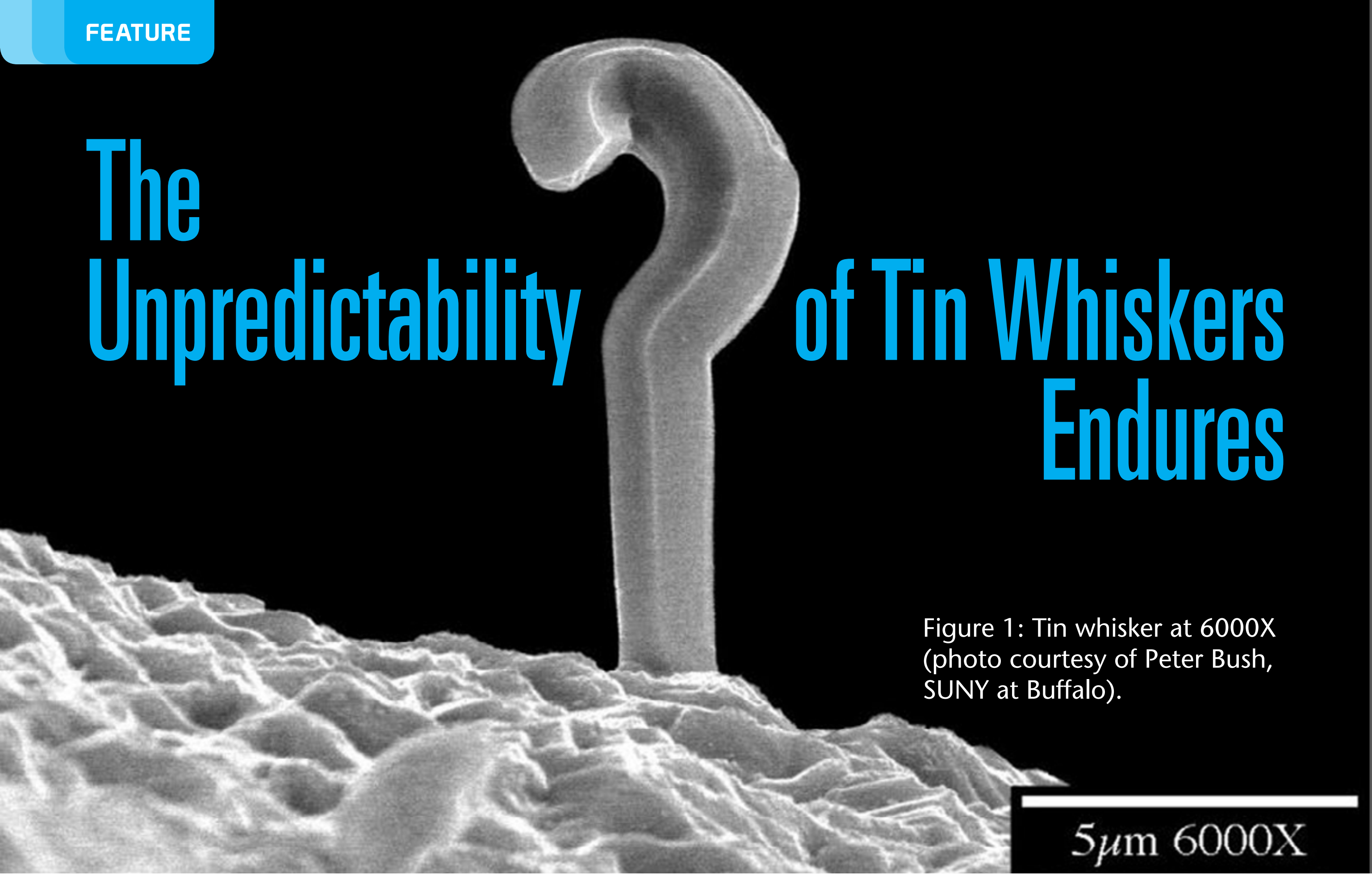

Figure 1: Tin whisker at 6000X (photo courtesy of Peter Bush, SUNY at Buffalo).

by Scott Sentz
AEM INC.

Into decade number two of the European Union's RoHS and REACH restrictions for the use of lead in electronic components, the risk of tin whiskers in critical circuitry continues. The global environmental directives to implement lead-free initiatives resulted in the obsolescence of commercially available electronic components with tin-lead finishes.

Even though some countries provide exemptions for special industry segments that require lead, the reality is that there are fewer and fewer components available in the tin-lead termination finish.

Lead-free initiatives pose reliability issues due to tin whisker formation, which has resulted in failures due to electrical short circuits. Applications requiring high-reliability components have to identify solutions to either self-mitigate or fully mitigate RoHS components not available with tin-lead finishes.

This article will explore a tin whisker mitigation process for surface mount electronic components applicable to both passive and active components.

Introduction

The European Union (EU) RoHS 1 Directive took effect July 1, 2006. This directive restricts the use of six hazardous materials in the manufacture of various types of electronic and electrical equipment including lead. It is closely linked with the Waste Electrical and Electronic Equipment Directive (WEEE) 2002/96/EC, which sets collection and recycling targets for electrical goods to minimize e-waste. The EU RoHS 2 Directive is the next generation of the original directive taking effect January 2, 2013. It deals with the same substances as the original directive, while gradually broadening its requirements to cover additional electronic and electrical equipment and parts.

Adoption of no-lead finishes seem ideal from an environmental perspective if it were to be accomplished without risks to reliability of critical hardware. Pure tin, defined as tin with less than 0.1% lead, is a high reliability risk because of its propensity to form tin whiskers. Actually, there is a consensus in the

high-reliability industry that at least 3% lead is needed for best practice.

What are Tin Whiskers?

Tin whisker growth was documented as early as 1946. Tin whiskers are single crystal growths which are known to achieve lengths of up to and over one inch. Tin whiskers grow unpredictably on pure tin surfaces, and whiskers can cause catastrophic short circuits as they are electrically conductive. The current theory is that compressive stresses in the tin layer are relieved with whisker growth. Compressive stresses can come from the plating conditions, from the substrates, or from external scratches or bends on the pure-tin surface. There are a number of other circumstances that promote the occurrence of tin whisker growth through intermetallic formulation, including mechanical, thermal, and electrical stresses from the surrounding environment of the pure tin surface.

Tin whiskers have even been known to grow from the surfaces of hardware sitting on a shelf only exposed to typical ambient storage conditions. AEM has been able to grow whiskers with either precious metal ceramic chip capacitors (silver electrodes, silver termination and nickel barrier below the tin) or base metal (nickel electrodes, copper termination and nickel barrier below the tin) versions of the same OEM device. Both versions of this pure-tin ceramic chip capacitor grew measurable whiskers after 88 temperature cycles between -50°C and +85°C.

Issues with Lead-Free Electronics

Components need to withstand higher circuit board assembly temperatures related to lead-free implementation. Lead-free solders typically require re-flow temperature 40°C above that of tin-lead alloys. Instead of 220°C for tin-lead, lead-free solders are typically recommended to re-flow at 260°C. Components and circuit boards built to withstand typical tin-lead soldering temperatures have to be re-qualified to withstand the 40°C higher process temperature. Equipment conversion and other associated process and material changes have resulted in billions and billions of dollars of global manufacturing costs related to meeting the various environmental directives.

The most critical lead-free issue has to be the propensity of pure-tin plated components to develop whiskers. There is as yet no pure-tin plating that can claim to be whisker-free. Whiskers appear at unpredictable times and neither the onset conditions nor the growth habits are precisely understood. The fact is that pure tin, in its popularly used configurations, whether plated or dipped,all grow tin whiskers under various conditions. There are many documented failures where whiskers are believed to be the root cause; the NASA website captures a good number of examples, as does the CALCE website.

Prevention of Tin Whiskers

Tin whiskers risks are foremost in the minds of design and component engineers in indus-

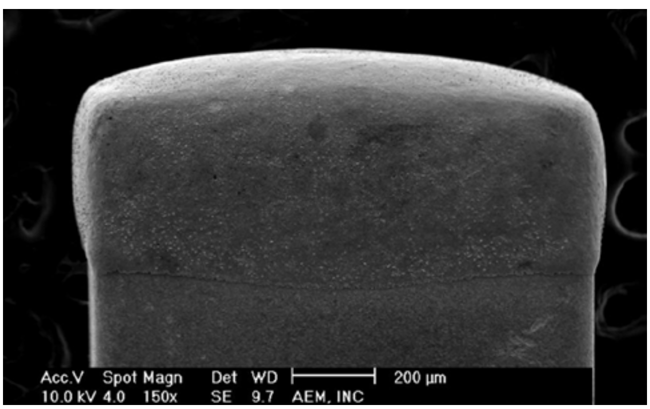

Figure 2: Example of typical component end metallization with 100% tin plate prior to temperature cycles.

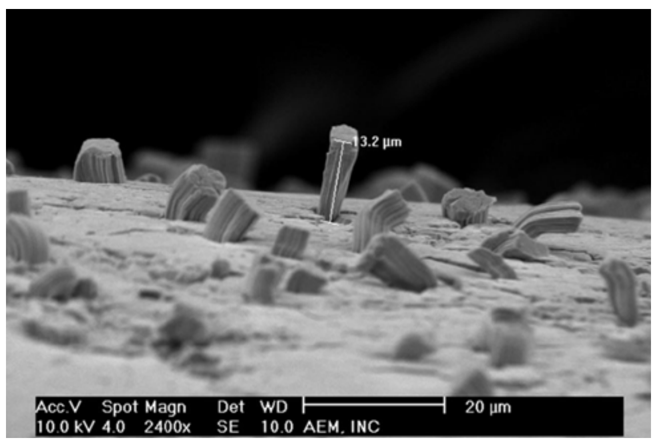

Figure 3: Precious metal base construction MLCC (Ag electrodes, Ag termination, Ni & Sn).

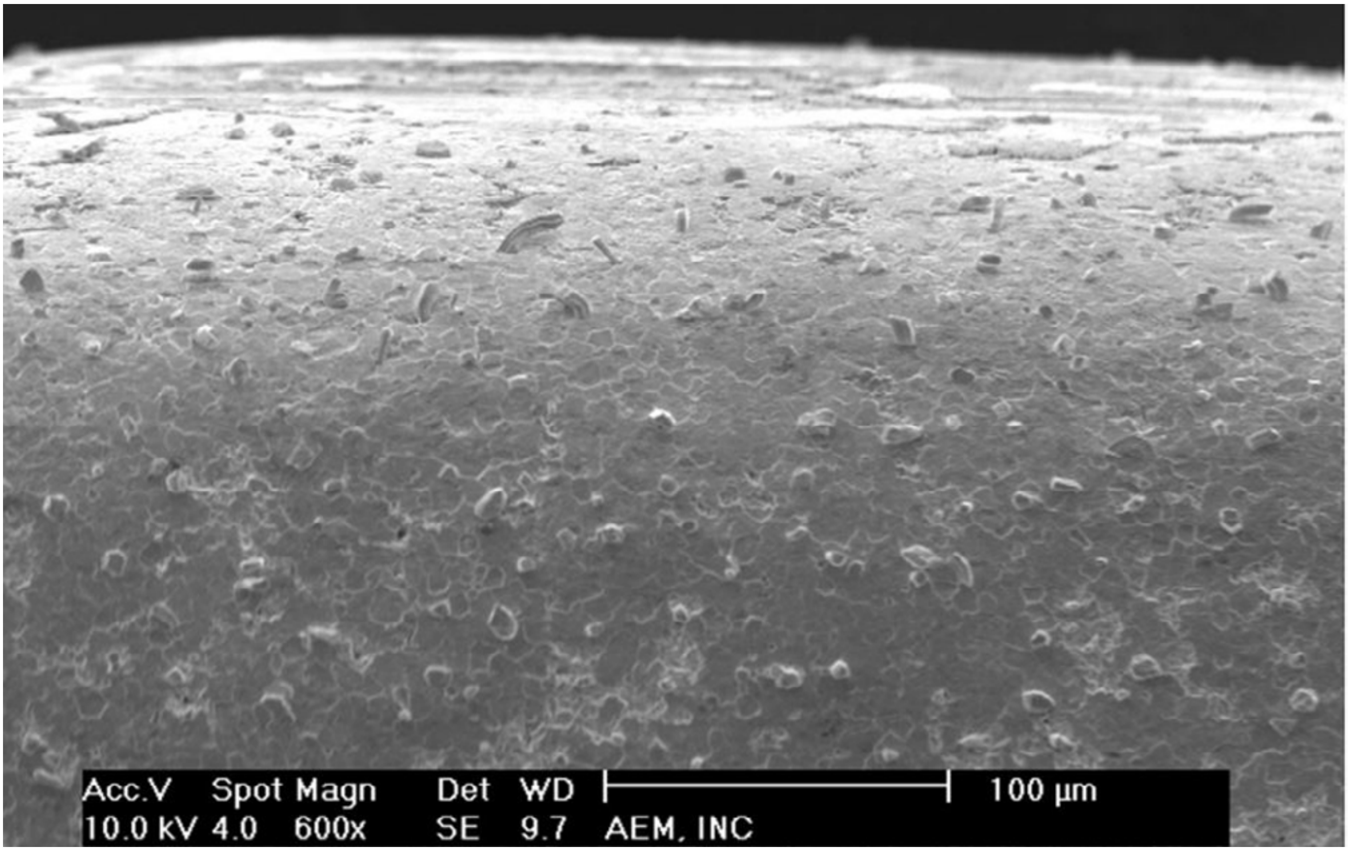

Figure 4: Base metal base construction MLCC (Ni electrodes, Cu termination, Ni & Sn).

tries where reliability is top priority. Mitigation of pure-tin plated components is essential. Empirically, minimum 3% lead addition into the pure tin composition is currently the only way to ensure severe tin whisker growth does not occur. As research to mitigate tin whisker growth on PCBs continues in chemical, coating, and processes, there are two main approaches for conversion of 100% tin terminal finishes.

1. Leaded active or passive devices

Pure-tin plated active devices can be dipped in standard tin-lead solder. Preheating can prevent thermal shock, which can lead to cracking and delamination. Robotic handling can improve precise dipping angle and travel. However, it is very difficult to dip inside the meniscus at the lead egress points of leaded devices.

2. SMT chip-size active or passive devices

Pure tin plated chip-size devices (01005 case size and larger) are too small to dip in tin-lead solder. To do so would either invalidate the physical size specification or risk thermal shock, microstructural cracking of certain material systems due to the hot solder bath "plunge." The ideal mitigation would convert pure-tin into the typical, and previously universally used "solder plate" with at least 3% lead content.

Conclusions

Tin whisker growth is an unpredictable, high-reliability risk when pure tin is present anywhere in the electronics assembly. For electronic components where no source of tin-lead plated terminations are available, solder dipping appears to be the best short term solution for leaded components. **SMT**

Scott Sentz is the marketing and business development director/export compliance manager at AEM Inc.

Electronics Industry News
Market Highlights

Manufacturing Sector All Set for Recovery

The Great Recession was devastating to manufacturing and the subsequent prolonged recovery permanently took away years of potential growth. The sector's structure has changed; industries that comprised one-quarter of manufacturing value-added fell substantially short of their pre-recession production levels and are still recovering. Manufacturing as a whole, meanwhile, is in an economic expansion.

The Era of Connected Devices

Imagination Technologies reports that an impressively broad range of products at the recent International CES 2015 incorporated one or more of its technologies, reflecting a growing recognition of Imagination's leadership capabilities helping to drive industry trends such as higher quality graphics, audio and video; high-performance and highly-efficient processing; and on-chip connectivity.

Internet of Things Stimulates MEMS Market

Worldwide market revenue for MEMS directly used in industrial IoT equipment will rise to $120 million in 2018, up from $16 million in 2013, according to IHS Technology. Additional MEMS also will be used to support the deployment of the IoT, such as devices employed in data centers. This indirect market for industrial IoT MEMS will increase to $214 million in 2018, up from $43 million in 2013.

Home Automation, Control Market at $12.81B by 2020

According to a new market research report published by MarketsandMarkets, the market is expected to grow at a CAGR of 11.36% between 2014 and 2020, and reach $12.81 billion by 2020.

Global Connected Car M2M Connections, Services Market

ReportsnReports.com adds Global Connected Car M2M Connections and Services Market research report that says big data analytics and smart phone apps will foster the growth of the global connected car M2M connections and services market by 2019.

Retail Automation Market to See 16.7% CAGR

The global retail automation market is expected to reach $275.43 billion by 2020, at a CAGR of 16.7% between 2014 and 2020. The lucrative growth rate of the retail market in future is the major factor driving the retail automation market.

Data Recorder Market to Grow at 4.52% CAGR

The data recorder market forecast report offers a complete analysis of the market during the forecast period of six years from 2014–2020. It analyzes factors driving the market, restraining market growth, opportunities, and challenges faced by the industry.

ASP of Ultrabooks, Tablets Down 7.8% in 2014

According to market intelligence firm ABI Research, the average weeks of household income needed to buy a tablet or ultrabook both declined by approximately 30% YoY, making these devices more affordable to a wider range of consumers.

Satellite Communications Market to Generate $3.1B by 2023

NSR's newly released Unmanned Aircraft Systems (UAS) via Satellite report projects impressive growth for satellite-based UAS in all regions, with revenues rising from $1.3 billion in 2013 to $3.1 billion in 2023.

Investment in Microgrid-enabling Tech Tops $155B

Offering the ability to isolate from the wider electricity grid during power outages, as well as a high capacity to integrate renewable, distributed energy resources, microgrids have become a growing phenomenon in the global energy sector in the last few years.

Tin Whisker Risk Assessment of a Tin Surface Finished Connector

by David Hillman and Ross Wilcoxon
ROCKWELL COLLINS

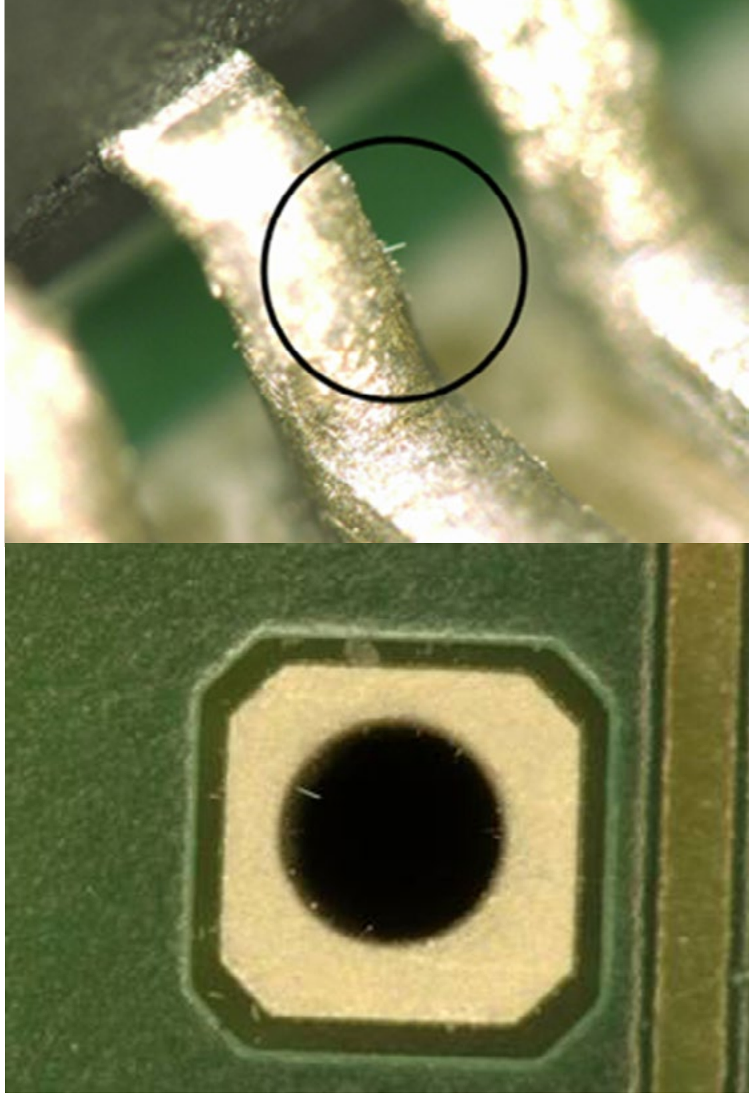

Figure 1: Tin whiskers observed on a component lead (top) and in a plated thru-hole (bottom).

Abstract

Rockwell Collins initially investigated and qualified Samtec's SEARAY solder charge connector (hereafter referred to as "the connector") technology with a focus on solder joint integrity. However, the connector in question, which has a matte tin finish on the solder tail, was found to have a potential risk of tin whiskers due to a small region of the connector that was not protected by either solder poisoning or the connector's mechanical configuration. An investigation was conducted in accordance with modified JESD201 tin whisker susceptibility protocols to assess the possible tin whisker risk concern. The investigation results, coupled with plating and reflow soldering data inputs, demonstrated that the connector's tin whisker risk was extremely low and deemed acceptable.

Background

The implementation of the RoHS European Union Directive in 2005 led to the use of pure tin as an accepted surface finish for PCBs and component terminations. A drawback of pure tin surface finishes is the potential to form tin whiskers. Tin whiskers are a metallurgical phenomenon that is associated with tin rich/pure tin materials and has been a topic of intense industry interest[1–6]. Figure 1 illustrates tin whiskers observed on a component lead and in an immersion tin surface finished plated thru hole that was incorrectly plated.

The acceptance and usage of pure tin by the electronics industry component fabricators is understandable as the pure tin surface finishes are inexpensive, are simple plating systems to operate and have reasonable solderability characteristics. However, the commercial electronics segment, which uses the majority of electronic components, often has product life cycles that are measured in months. In contrast, high performance/harsh environment electronics typically have product life cycles that are measured in decades and therefore are much more sus-

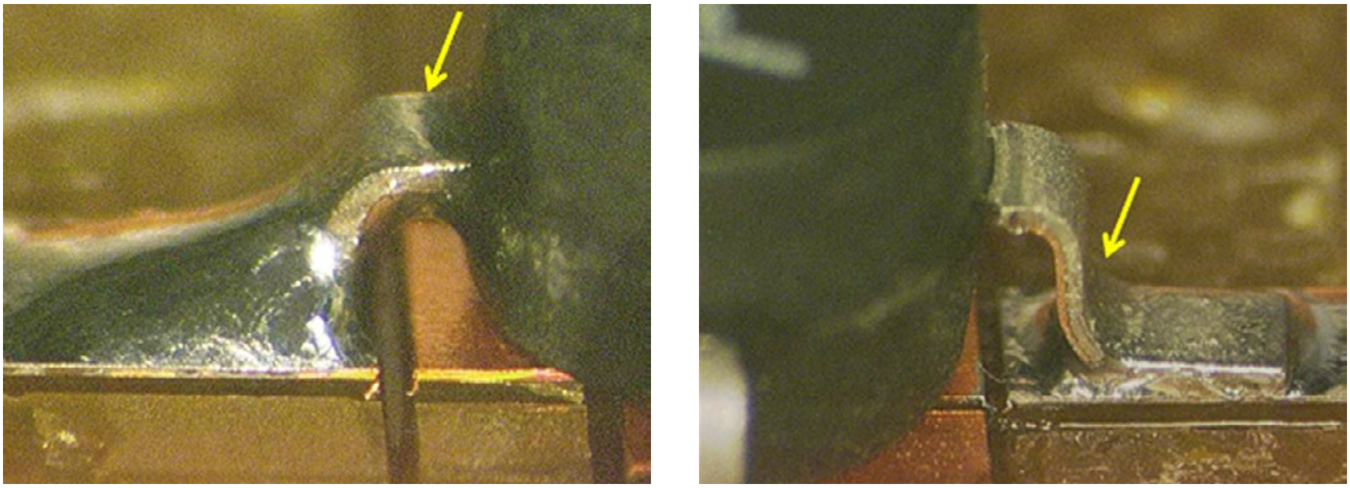

Figure 2: Solder process poisoning (left) acceptable and (right), inadequate. Yellow arrow defines highest point of solder flow.

ceptible to the potential long term threat of tin whiskers. Industry studies have shown[7,8] that pure tin surfaces can be "poisoned" with tin/lead solder provided the tin plating is consumed/converted during the soldering process. With many short components such as resistors or capacitors, the soldering process consistently and repeatedly eliminates any tin whisker risk. However, the component lead geometry, solder paste deposit and component pad dimensions all factor into whether a component can be successfully poisoned by the soldering process. Figure 2 illustrates two components, with one being successfully poisoned and one inadequately poisoned.

Connectors are typically not an issue, in terms of solder poisoning, as connector suppliers utilize the connector housing design/configuration to eliminate potential shorting from a tin whisker or ensure that the areas with pure tin surface finishes will be poisoned as part of the soldering process.

Previously, Rockwell Collins completed a connector technology qualification that included the Samtec SEARAY solder charge connector[9]. The connector had very robust thermal cycle solder joint integrity and utilized a matte tin (i.e., pure tin) surface finish on the non-contact pin surfaces. During metallographic cross-sectioning phase of the connector's qualification effort, it was observed that a region of matte tin was not poisoned during the soldering process nor was the tin whisker shorting potential in this region mitigated by the connector design/configuration. Figure 3 illustrates this region of the connector after assembly. An investigation was conducted to determine if this region of the connector posed a tin whisker risk threat.

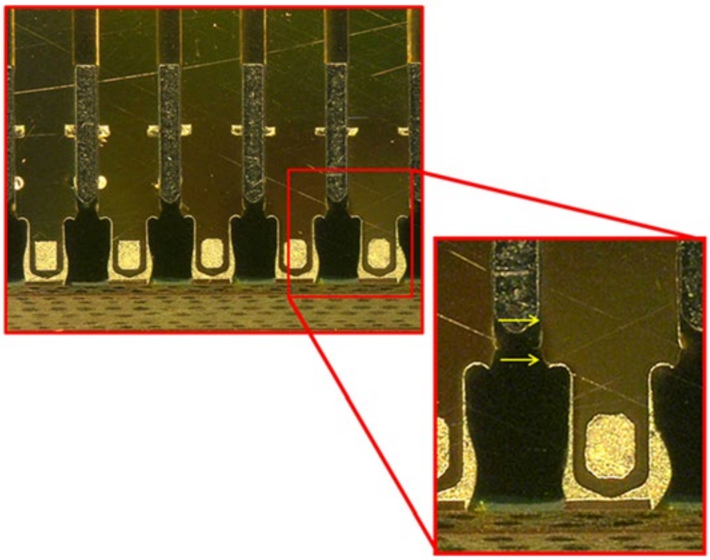

Figure 3: Samtec SEARAY Connector after assembly soldering (yellow arrows indicate the exposed area of un-poisoned tin plating that represents potential tin whisker risk).

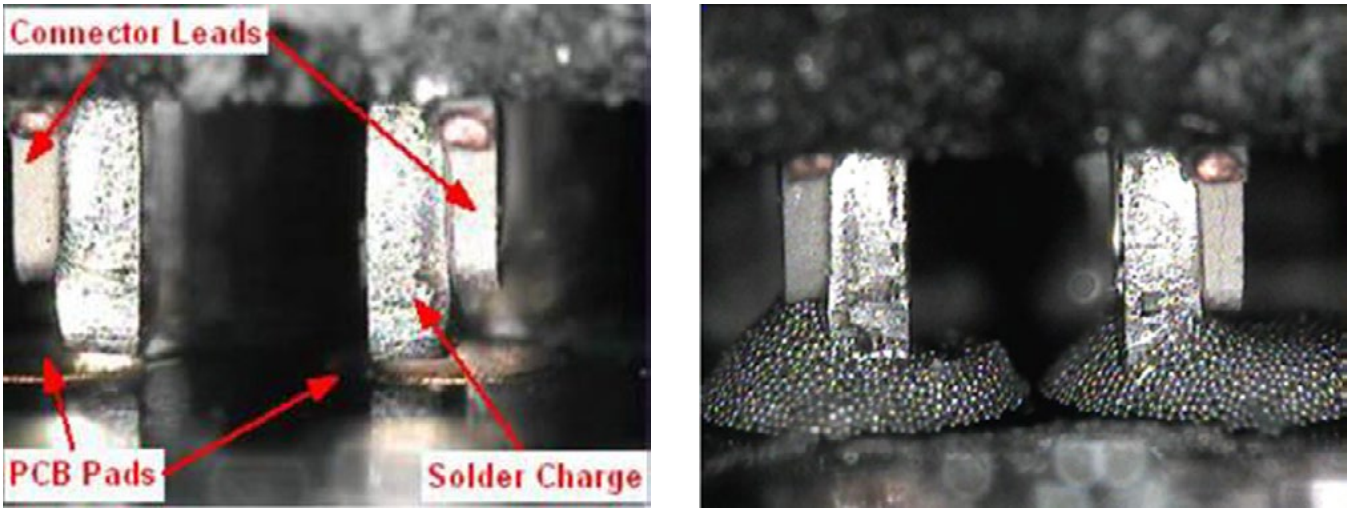

Figure 4: Samtec SEARAY connector technology.

Objective

The objective of the investigation was to determine if the connector has a tin whisker shorting risk that would compromise printed circuit assembly integrity.

Test Procedures

Test Component

The connector is a departure from the traditional connector configuration due to the inclusion of a solder preform on a blade lead geometry (Figure 4). The purpose of the solder preform is to increase the overall solder joint volume and final solder joint geometry. This high-density connector allows for maximum routing and grounding flexibility and performance up to 18 GHz/pair. The connector tail plating was matte tin over 50 µin of nickel on a copper alloy base metal alloy.

Testing Parameters

A modified JESD201 test parameter matrix was followed for the testing. The specific test parameters were:

- A representative plating lot was tested
- A total of 27 connectors were tested
- The inspection interval was 500 hours (3 connectors/540 total leads at each inspection interval)
- No JESD201 process ‘preconditioning’ was conducted on the connectors
- Conditioning parameters:
  - Temperature/Humidity: 4000 hours, 85°C and 85% RH, non-condensing environment

Inspection Criteria

Scanning electron microscope (SEM) inspection was conducted on three connectors (540 individual leads) after every 500 hours interval of temperature/humidity conditioning. SEM inspection was conducted using 100X to 5000X magnifications. A different set of three connectors was inspected at each interval. Once a connector was removed from temperature/humidity conditioning and inspected, it was not returned to the chamber.

Test Results

It should be noted that the test vehicles were not cleaned during the entire conditioning sequence duration to prevent the accidental removal of tin whiskers. Assessment of the test vehicles at the 0, 500, 1000, 2000, 2500, 3500 and 4000-hour inspection intervals revealed no tin whisker observations on the SMT pads or PTHs. An isolated instance of a tin whisker was observed at the 1500 and 3000 hour inspection intervals. The 500, 1500 and 3000 hour inspection intervals are covered in detail in the following sections.

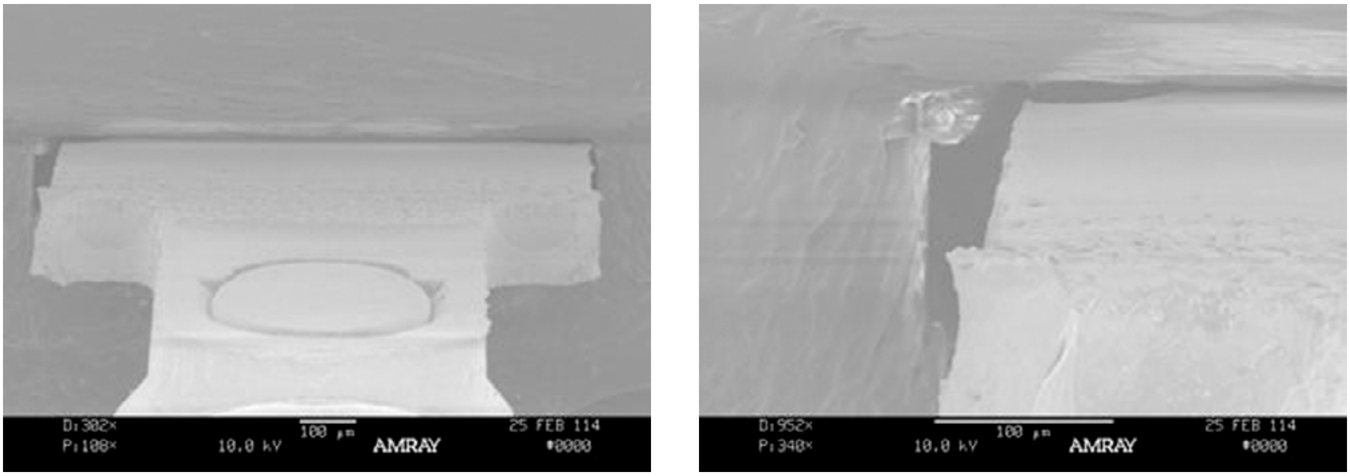

Figure 5: No tin whisker observed at 500 hours.

500 Hour Inspection Interval

No tin whiskers were observed on the connectors at the 500 hours inspection interval. Figure 7 and Figure 8 illustrates the typical observed condition of a connector leads.

1500 Hour/Cycle Inspection Interval

One tin whisker was observed on the 540 individual leads inspected at the 1500 hours interval. The tin whisker observed was approximately 20 microns long and had a very contorted shape. The tin whisker was observed in a region where solder would flow during the automated reflow process (7 and 8).

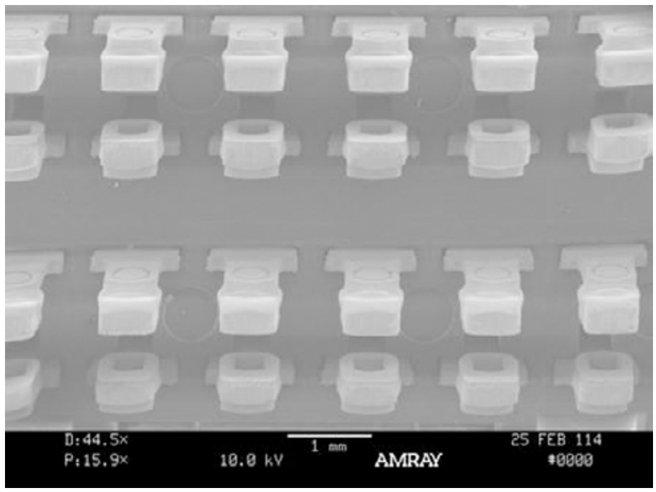

Figure 6: Typical connector observation at 500 hours.

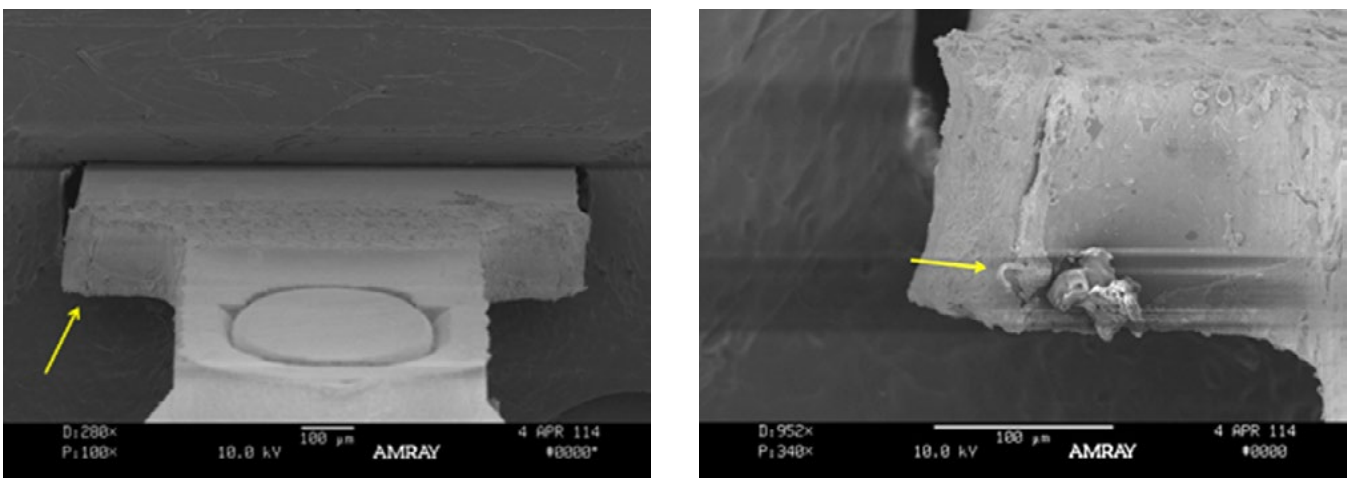

Figure 7: Single tin whisker observed at 1500 hours.

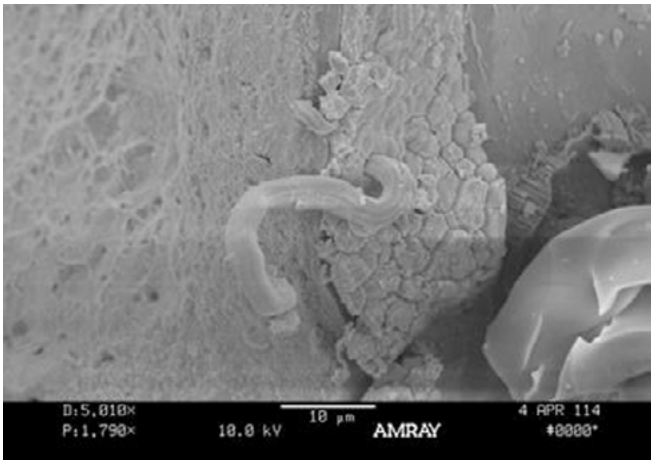

Figure 8: Magnified view of single tin whisker observed at 1500 hours.

3000 Hour/Cycle Inspection Interval

Several small tin whiskers were observed at the 3000 hours inspection interval. The tin whiskers observed were approximately 20 microns long and had very contorted shapes. The tin whiskers were observed in a region where solder would flow during the automated reflow process (Figure 9). Their location was in the same region as the single tin whisker observed at the 1500 hours inspection interval.

SEM Examination of Reflowed Connectors

In response to the two samples that were observed to have tin whiskers after 85°C/85%RH testing, a series of connectors that had been reflow soldered were examined using SEM analysis. Figures 10 and 11 illustrate the regions of focus during the SEM examination. During the 4000 hours of testing, tin whiskers were not observed in the region of whisker risk concern (Figure 11, Region A) but instead in the region where solder would wet/flow during the reflow process (Figure 11, Region C). Verification of solder wetting in this region would demonstrate that the tin whiskers that were found during the 85°C/85%RH testing in Region C would not present a tin whisker risk in products.

High magnification examination revealed good solder wetting and coverage in Region C of the reflow soldered connectors (Figure 12). The connector plating was also confirmed during the SEM examination, with Region A being comprised of tin plating over nickel plating on a copper based lead material. Diffusion of the tin plating into the nickel plating, as a result of the exposure to reflow soldering temperatures, was found.

Simplified Short Circuit Risk Modeling

A simplified model to predict the risk a tin whisker creating an electrical short between two adjacent leads on a component has recently been developed[11]. This model accounts for the geometry of leads, the effect of voltage between the leads, the effects of conformal coatings and the view factor between surfaces (the

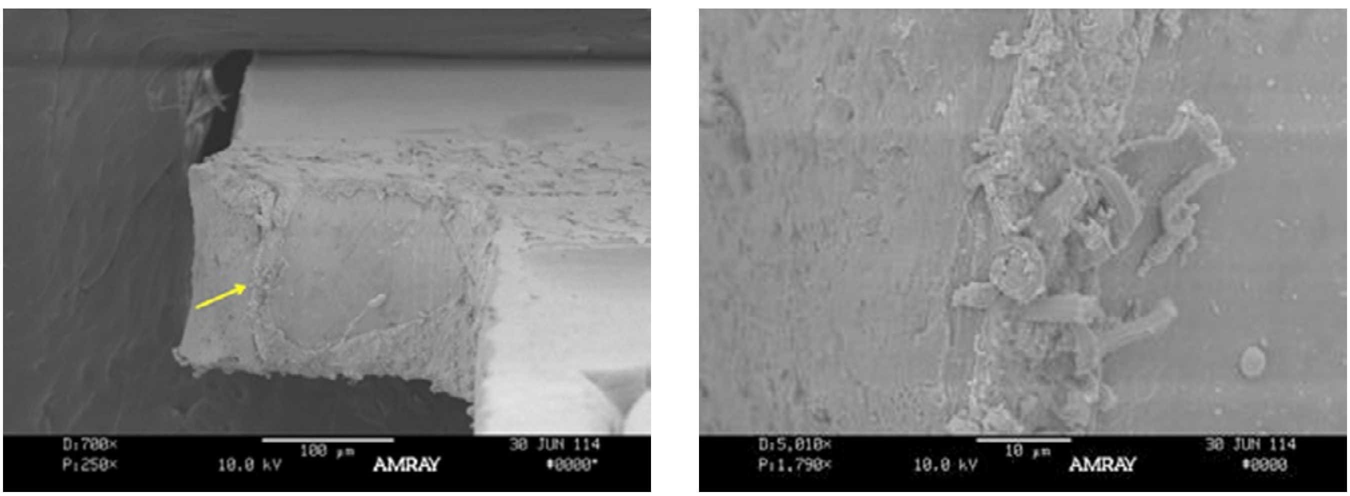

Figure 9: Tin whiskers observed at 3000 hours.

probability of straight whisker emanating from a point on one surface and making contact with an adjacent surface. The configuration of the leads used in that model is shown in Figure 13. This model requires inputs, typically based on experimental data, for the density of whiskers in various regions of the component lead and some estimate for the length distribution.

The model from reference [11] has been implemented in a spreadsheet tool that allows the user to estimate the number of shorts between leads for a given set of conditions. While this model was developed for leaded components such as a quad flat pack, it does allow the user to input lead geometry to define extremely short portions of the lead to effectively set them as zero length. To assess the tin whisker risk for the connector, the lead parameters for the model were set to values to produce straight leads that were either the full length of the lead (~1.1 mm) or the worst-case unsoldered length of the lead (0.3 mm).

The testing in this study observed ~7 whiskers occurring on two leads out of 14,580 total

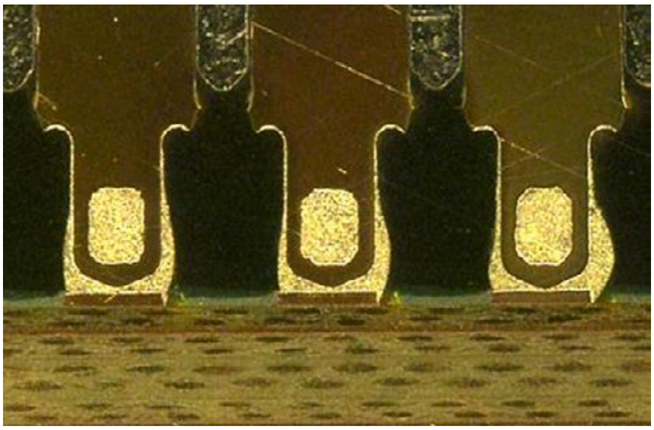

Figure 10: Cross-sectional view of connector after reflow soldering.

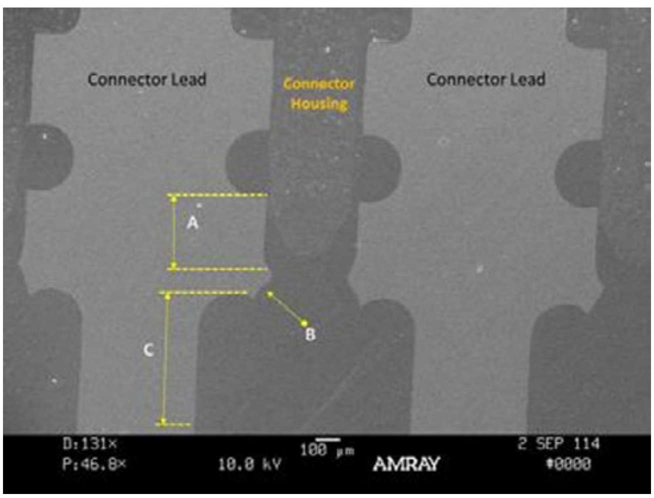

Figure 11: SEM cross-sectional view of connector after reflow soldering illustrating specific regions of interest: A = whisker risk region, B = lead frame breakoff tab region, C = solder coverage region.

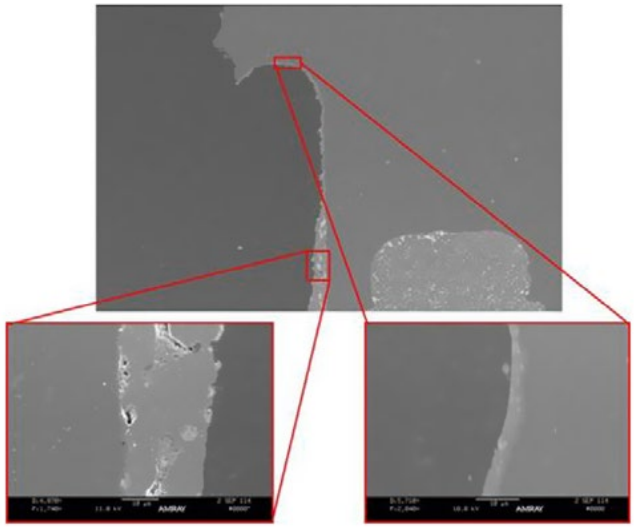

Figure 12: SEM assessment illustrating complete solder wetting and coverage for Region B.

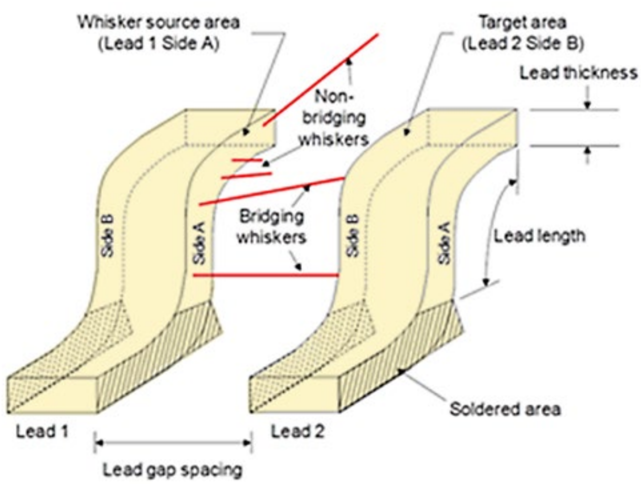

Figure 13: Bridging by tin whiskers between component leads[11].

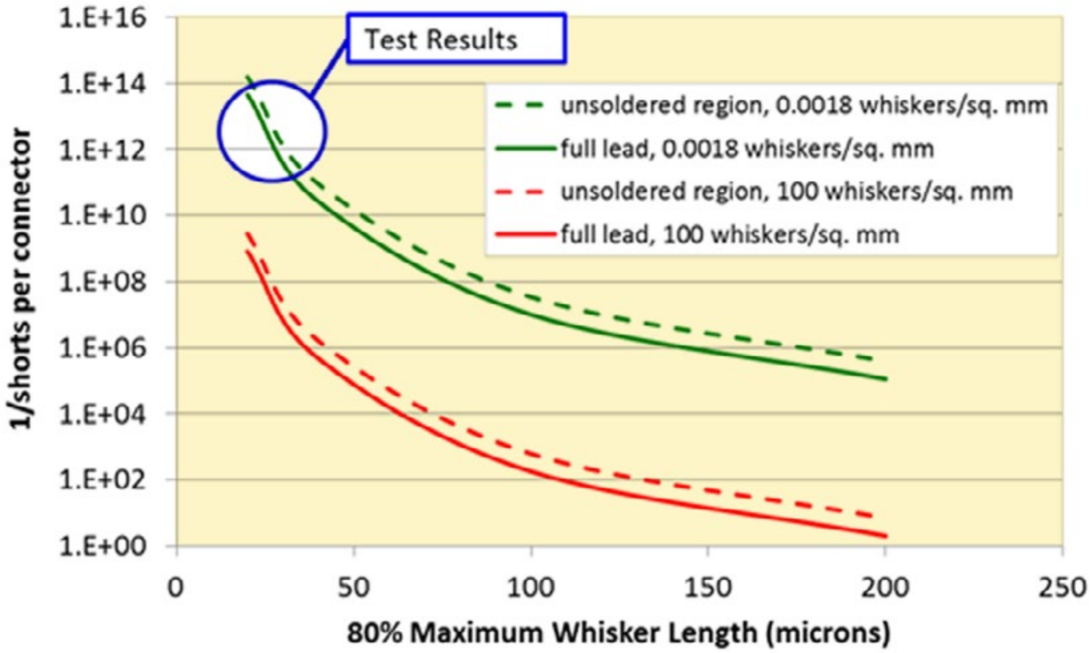

Figure 14: Estimated inverse connector failure rates.

leads in the test. Given the exposed edge area of these leads, this corresponds to a whisker density of 0.0018 whiskers per square mm. Recognizing that this density is extremely low, a higher whisker density of 100 whiskers/mm^2 (~50,000x higher than tested) was also used in the model. SEM analysis of the whiskers in this study found that the longest observed whisker was ~20 microns in length. This was then used as a baseline for estimating lengths for a lognormal distributions with the 80% long whisker length set to 1, 2, 5 and 10x this length (20, 40, 100 and 200 microns) and the 7% short whisker length set to be 25% of the long value. These parameters are admittedly somewhat arbitrarily selected, but with the paucity of tin whiskers observed on these components there was limited data with which to justify alternate values. Because no whiskers were observed or expected on soldered areas of the connectors, the 'solder' and 'pad' whisker densities for the model were set to zero and only the 'lead' whisker parameters were adjusted.

The connector had 30 rows of 6 leads, which resulted in a total of 168 sets of adjacent edge surfaces that could potentially be shorted with a tin whisker. The model estimates the number of shorts that would occur within a given connector. In this analysis, the voltage between leads was assumed to be 5V; a larger voltage difference would be predicted to lead to more shorts resulting from whiskers making contact with an adjacent surface. Figure 14 shows results of the model for the two whisker densities (0.0018 and 100 per mm^2) for both a full (unsoldered) connector and the portion of the connector that is not poisoned by solder. These results are depicted in terms of the inverse of the shorts per connector—which indicates the size of the population of connectors needed to expect one to have a tin whisker induced electrical short. For the present test results (with extremely low whisker density and only short whiskers being observed), this plot shows that the risk of a tin whisker electrical short is exceedingly low (less than one per trillion connectors). If whiskers grow to be 10x larger than those observed in this study, but have the same low density, the probability of a short falls to ~ one in a million. If whiskers formed with a much higher density and did grow to be significantly longer than the ones in this study, the model ultimately predicts that virtually all connectors would experience a tin whisker electrical short.

To effectively use the model described in Reference [11] for these connectors, the model should be explicitly adapted to allow the user

to model the actual lead geometry rather than 'fooling' it with artificial values for some aspects of the lead definition. Also, further testing of components should be conducted to better define the actual whisker densities and length distributions that could be expected in these parts. Despite these limitations, the model does appear capable of providing reasonable insight into whisker shorting risks, even with minimal test data.

Discussion

The maximum allowable tin whisker length values specified in the JESD201 specification are shown in Table 1. Rockwell Collins utilizes the Class 2 values to assess tin whisker risk. The maximum tin whisker length permissible for the high temperature humidity conditioning sequence is 40 microns after 4000 hours.

The authors consider the risk of a tin whisker issue for the Samtec SEARAY connector to be very low based on the following investigation results and observations:

• The 85ºC/85%RH testing produced two leads on which tin whiskers were observed, both with lengths of less than 40 microns being recorded. In total, two leads out of a total of 14,580 leads on the parts included in the test (0.014%) exhibited whiskers in this investigation.

• The two instances of recorded tin whiskers that were observed on non-soldered components occurred in a region of the connector that would be covered with solder as a result of the reflow soldering process. Industry publications[4, 6] have shown that tin whiskers do not initiate and grow in regions where there is solder coverage.

• The portion of the exposed connector lead that is considered at risk for tin whisker initiation/growth (because it is not covered with solder by the reflow process) has an underplate of nickel. The SEM assessment revealed that a portion of the pure tin in this region of the lead forms intermetallic phases during the reflow soldering process. The reduction of the pure tin thickness and the use of nickel as an underplate are both accepted industry tin whisker risk mitigation reduction methodologies[4].

• In addition, the majority of the lead area that is considered at risk for tin whisker ini-

<table>
<tr><th rowspan="2">Considerations (Component Type, Lead Pitch or Operating Frequency)</th><th colspan="4">Maximum Allowable Whisker Length</th></tr>
<tr><th>Class 3</th><th>Class 2</th><th>Class 1</th><th>Class 1A</th></tr>
<tr><td>2 Lead SMD Components</td><td rowspan="4">Pure tin and high tin content alloys are not typically allowed</td><td rowspan="4">40 µm for Temperature/Humidity Storage and High Temperature/Humidity Storage

45 µm for Temperature Cycling</td><td>67 µm[1]</td><td rowspan="3">50 µm for Temperature Cycling and High Temperature/Humidity Storage

20 µm for Temperature/Humidity Storage</td></tr>
<tr><td>Multi-Leaded Components</td><td>67 µm[1]</td></tr>
<tr><td>High Frequency Components[2]</td><td>50 µm</td></tr>
<tr><td>Components with a minimum lead-to-lead gap >320 µm</td><td>100 µm</td><td>75 µm</td></tr>
<tr><td colspan="5">NOTE 1 This spacing accounts for up to 0.05 mm bent leads. The maximum of the 67 µm accounts for adjacent discrete components.
NOTE 2 It is reported that the susceptibility to electrical performance degradation associated with tin whiskers increases with frequency. (RF Components >6 GHz, or Digital Components T_{rise} <59 ps).</td></tr>
</table>

Table 1: JESD201 maximum tin whisker length criteria[10].

tiation/growth is somewhat isolated from adjacent leads by the configuration of the connector plastic housing (Figure 11). While the plastic housing configuration does not completely isolate adjacent leads, it does significantly reduce the view factor, which describes how likely a whisker growing from one surface will make contact with another surface, thereby further mitigating the risks of tin-whiskers induced failure.

Conclusions

The solder charge connector was found to be in compliance with the JESD201 Class 2 acceptance criteria in accordance with modified JESD201 test parameters used. The investigation data, including SEM assessment of reflow soldered connectors, indicates that the tin whisker risk is extremely low for the component. Product design teams should be aware that the tin whisker risk is not zero and some segments of high-performance customer base may not accept the connector in their designs due to the lack of zero risk. It is recommended that for an extreme environment, long-life application, a program should consider customizing parts with gold plating on the solder tail in place of the standard matte tin finish.

Acknowledgements

The authors would like to thank Corey Bryant, Component Application Engineering CAMEL Laboratory, for outstanding SEM analysis efforts. SMT

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Note: This paper was presented at the 2014 IPC/CALCE International Symposium on Tin Whiskers.

David Hillman is a principal materials and process engineer in the Advanced Operations Engineering Department at Rockwell Collins Inc.

Ross Wilcoxon is a research and development engineer with more than 15 years of experience in mechanical packaging of electronics used in harsh environments.

ACROSS THE BOARD

Minimizing the Risk of Tin Whisker Formation in Lead-Free Assemblies

by Mitch Holtzer
ALPHA

Although tin whiskers are very small crystalline fibers, typically 1–3 µ in diameter and 100 µ or less in length, they have reportedly caused multiple NASA satellites to become inoperable[1], automotive accelerator pedals to become unusable[2] and a nuclear reactor to malfunction[3]. Despite the catastrophic potential of these failures, the risk to high-reliability telecom and infrastructure, automotive, medical and aerospace applications can be minimized by specifying material sets that are less likely to produce tin whiskers.

As many circuit designs in these end-use markets finally convert to lead-free technology, the choice of lead-free solder alloy, component IO finish, PCB surface finish and the use of a robust conformal coating process have each been shown to greatly reduce the probability of tin whisker growth. Although no accelerated tin whisker growth test is widely known, creating a high stress tin plating (brass substrate and fine grain bright tin plating) has been used to purposely create tin whiskers[4].

There is evidence that alloying small amounts of metals with tin can reduce/eliminate whisker growth. As little as 3% Pb (still 30x the RoHS allowed limit) has shown to mitigate tin whisker growth[5]. This means that SAC alloys, with silver and copper alloyed into the tin, are less prone to whisker growth than 100% tin alloys, especially after the stress relieving process of solderpaste reflow. However, a team of scientists from Beijing University were able to create whiskers by adding a stress inducing dose of 1% Cesium/Erbium/Yttrium alloy[6]. However, I do not see a future for this alloy in high-volume manufacturing.

Component leads are commonly plated with pure tin. Bright tin, with fine grain structure (0.5–0.8 µ grains) is known to be a common source of tin whiskers. Lead frames plated with bright tin, then formed into shapes are even more likely to produce whiskers due to the increased stress on the plating. Matte tin plating chemistry, with lower stress, larger grain structures (1–5 µ grains) are commonly used to


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electroplate IO finishes to mitigate the risk of whisker growth. Annealing the matte finish is also reported to further reduce the risk by reducing the stress forces that produce whiskers[7].

Tin is a popular surface finish for PCBs used in automotive electronics. During the days of eutectic tin-lead solder, it proved to be a very solderable finish, without the issues of co-planarity associated with tin-lead HASL. However, with the advent of lead-free technology, soldering the backside of a once reflowed board could mean soldering to Cu_6Sn5 if the PC fab shop was in a hurry with the immersion tin process and did not allow a sufficient layer thickness of tin to form over the copper substrate. The formation of Cu6Sn5 underneath a tin finish also causes stress on the tin. Cu6Sn5 has 58% more molar volume than the base metals used to form the compound[9].

Producers of the tin chemistry also have developed matte tin finishes that lower the chances of whisker formation in any areas not covered with solder. The remelting/annealing associated with SMT and through hole processing also removes stress from the tin surface finish.

Conformal coatings have also been shown to inhibit the effect of tin whisker formation[4]. Parylene conformal coating may not eliminate the formation of whiskers, but one study shows that it prevents whiskers from breaking through the parylene coating, eliminating shorts or other issues with whisker formation. Urethane conformal coatings have also shown to be effective in eliminating the effect of whisker growth. Dipping assemblies in conformal coating also eliminate shadow effects associated with spray application of conformal coating. Even if a whisker forms, and breaks through the conformal coating, it will not create a short circuit if it contacts an adjacent component lead covered with the coating.

"Parylene conformal coating may not eliminate the formation of whiskers, but one study shows that it prevents whiskers from breaking through the parylene coating, eliminating shorts or other issues with whisker formation. Urethane conformal coatings have also shown to be effective in eliminating the effect of whisker growth."

In summary, tin whiskers can cause cataclysmic failures in long life, high-reliability circuits. When developing an approved material list for lead-free assemblies, OEMs who need to protect their brand names should consider specifying SAC alloy solder, matte tin plated components, matte tin surface finish and the use of parylene or urethane conformal coatings to reduce or eliminate the risks associated with tin whiskers. **SMT**

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Mitch Holtzer is global director of customer technical service (CTS) for Alpha. He may be reached at mholtzer@alent.com. His column, Across the Board, will be appearing monthly in *SMT Magazine*.

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2015 IPC APEX EXPO Show Guide

Opening Keynote Address:
Tuesday, February 24, 2015
8:30–9:30 a.m.

The Xbox Story: Lessons in Strategy, Team Management and Entrepreneurship

Robbie Bach

Former President of Entertainment & Devices at Microsoft, Xbox visionary and civic activist

Chances are you or your kids own an Xbox, or at least have played games on one. But do you know the story behind this groundbreaking game console? The Xbox saga— from garage-shop inception, through numerous crises and challenges, to ultimate business success—is a multi-faceted tale with several compelling story lines. Bach joined Microsoft in 1988 and worked in various marketing and management roles for 22 years. Beginning in 1999, he led the development of the Xbox business, including the launch of the original Xbox and the highly successful follow-up product, Xbox 360. Bach will speak from his experience as the chief Xbox officer, taking the audience "behind the scenes" and sharing the triumph of a strategic process that brought together a disparate group of talented individuals. Bach will explain how this collection of individuals transformed into a powerful team that applied entrepreneurship principles to build a successful consumer business within the larger Microsoft structure.

XBOX 360

Day Two Keynote Address:
Wednesday, February 25, 2015
9–10 a.m.

Flying Saucers and Science/ Science was Wrong

Stanton Friedman

Nuclear Physicist, UFO Researcher

Do you take UFOs seriously? Nuclear physicist and lecturer Stanton T. Friedman does. Friedman will challenge the audience as he draws on more than 40 years of research on UFOs, and his work on a wide variety of classified advanced nuclear and space systems. He will answer a number of physics questions in layman's terms, and establish that travel to nearby stars is within reach without violating the laws of physics. The audience will journey with Friedman to locations in the universe where aliens reside, learn why they've come to Earth and their motives to cover-up their visits. You'll never feel the same about the universe again.

Friedman was a nuclear physicist for 14 years for companies such as GE, GM, Westinghouse, TRW Systems, Aerojet, General Nucleonics and McDonnell Douglas, working in such highly advanced, classified, and eventually canceled programs as nuclear aircraft, fission and fusion rockets and various compact nuclear power plants for space and terrestrial applications.

Since 1967, Friedman has presented at more than 600 colleges and 100 organizations across the 50 U.S. states, 10 Canadian provinces and 18 other countries in addition to various nuclear consulting efforts. He has published more than 90 UFO papers and has appeared on hundreds of radio and TV programs, including three appearances on Larry King (2007 and 2008) and in several documentaries.

2015 IPC APEX EXPO Show Guide

Free IPC APEX EXPO Buzz Sessions

Find out what's got the industry buzzing at the many complimentary sessions that are designed to keep attendees in the loop. This year's topics include a diversity of great discussions:

- Advanced Fabrication Instruction Exchange Between Design and Manufacturing: IPC-2581B Model
- U.S. Federal Funding Opportunities: Grant Programs and Public-Private Partnerships for R&D and Advanced Manufacturing
- California Chemicals Regulations
- PERM Discusses Pb-free—Are we there yet? (Panel Discussion)
- Electronic Technology Roadmaps
- IPC Worldwide Events 2015–2016
- More!

For a full listing of Buzz Sessions, click here.

EMS and PCB Management Meetings

Designed to help industry members become better leaders, management meetings at IPC APEX EXPO 2015 offer exclusive learning and networking opportunities with senior-level managers and executives of PCB fabricators and their suppliers. The management program meetings address issues related to improving executive decision-making in the industry, focusing on market trends, customer requirements and the economy.

EMS Management Council Meeting—Executive Level

Monday, February 23, 2015
7:15 a.m. (welcome breakfast) to 5:30 p.m.
- For a complete agenda, click here.

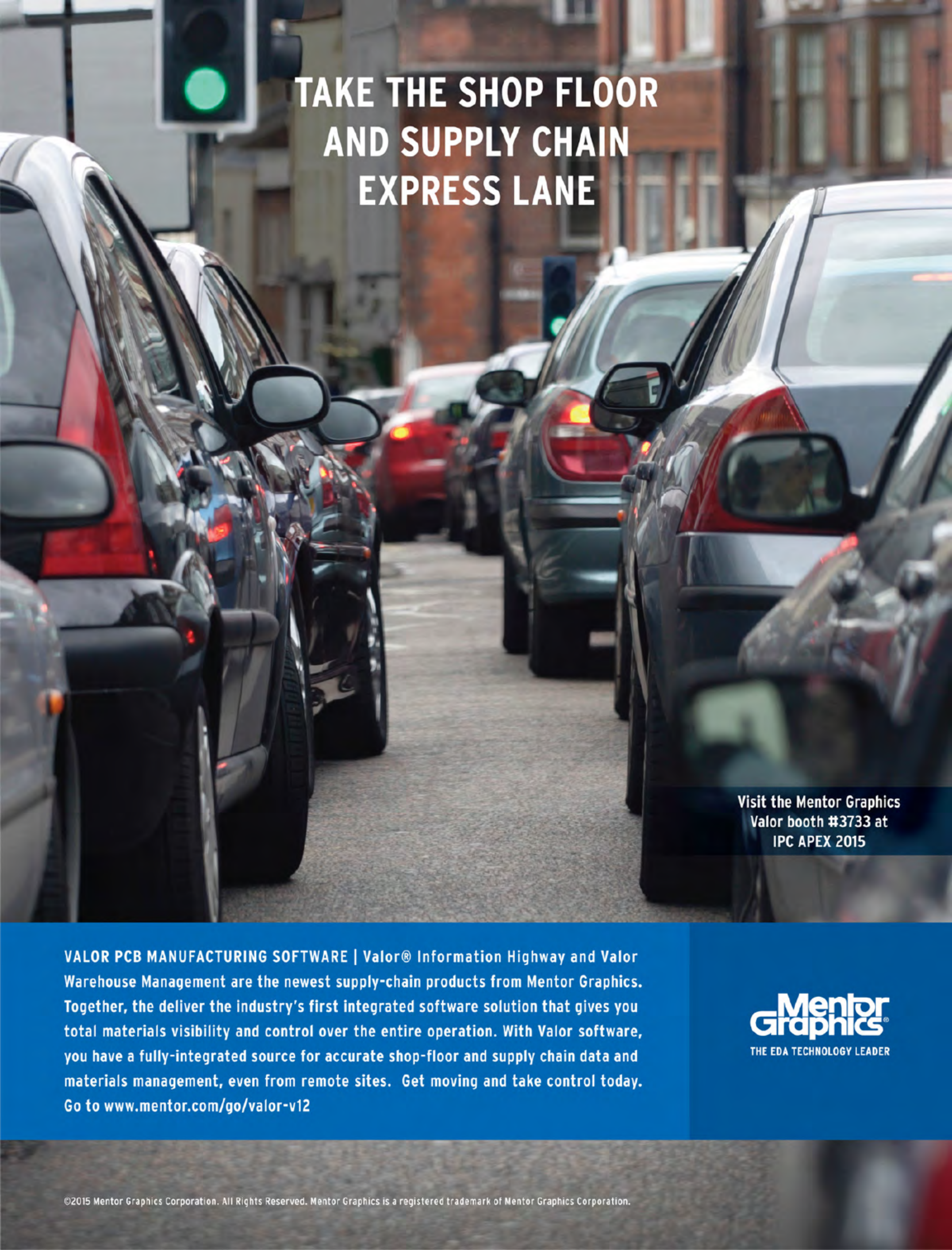
PCB Supply Chain Leadership Meeting—Executive Level

Monday, February 23, 2015
7:15 a.m. (welcome breakfast) to 5:30 p.m.
- For a complete agenda, click here.

IPC APEX EXPO 2015 Technical Conference

Recognized worldwide as the most selective in the world, the IPC APEX EXPO 2015 technical conference will present new research and innovations from experts in the areas of board fabrication and design, electronics assembly and test. Course moderators are carefully selected from within the electronics industry community.

Sign up for one day, the full conference or an All-Access Pass. Click here for complete registration information and forms.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2015 IPC APEX EXPO Show Guide

Professional Development Courses

Sunday and Monday, February 22–23
Thursday, February 26

Learn about the latest in design, lead-free technologies, materials, process improvement, solder joint reliability and more at IPC APEX EXPO 2015. Choose courses by general topics to help you focus on the sessions that best meet your professional needs. This year's tracks include:

- Assembly processes for lead-free and tin-lead
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Real Time with...

This year, I-Connect007 and the Real Time with...program return to sunny San Diego to bring our readers video coverage of IPC APEX EXPO 2015. Expect to see our team of editors, guest editors, and videographers roaming the show floor throughout the event, to capture one-on-one interviews with the industry's top technologists, engineers, and business leaders—as the action happens!

Visit Real Time with... during the show for updated information about IPC APEX EXPO 2015.

Mil/Aero007 News Highlights

DoD Awards Accreditation of Trust to Hunter Technology

The company announces that it is one of only 60 suppliers to achieve an Accreditation of Trust from Defense Microelectronics Activity (DMEA), and is the only accredited EMS provider owned and operated exclusively in the U.S. As an accredited trusted supplier, Hunter addresses counterfeit risk using a proprietary system that meets all 12 requirements set forth by DFARS.

EMS Providers Could Ride on Aerospace Sector Growth

Aerospace and defense (A&D) original equipment manufacturers increasingly depend on electronic manufacturing service providers to address risk management, logistics and aftermarket service needs. EMS providers with a global supply chain and advanced technological capabilities are in the best position to exploit this trend.

Elbit Secures $106M Contract to Support Brazilian Army

Elbit Systems of America LLC, a subsidiary of Elbit Systems Ltd., has received a directed subcontract from the Brazilian Navy to upgrade four Grumman C-1A aircraft.

Global EMS Providers Market for Aerospace & Defense

The study analyzes the opportunities that would open for EMS providers in the aerospace and defense industry. The trends that would shape the EMS providers market in this space have been discussed in detail, with a special focus on factors that are driving the market and an in-depth view on what is impeding market growth.

Sparton Acquires Industrial Electronic Devices

"Although not material in size, the addition of IED meets the criteria of our growth strategy by growing our ruggedized electronics platform with additional ruggedized display and touch screen offerings in the harsh and demanding sectors of the industrial and marine markets, diversifying our customer base, and increasing the utilization of our existing assets," stated Cary B. Wood, Sparton president and CEO.

Colognori Joins Zentech's Mil/Aero, Space Market Initiative

Zentech Manufacturing is pleased to announce that Jay Colognori has joined the team as director, Business Development, Mil/Aero and Space Markets. He is widely respected in the Mid-Atlantic market and beyond for driving innovative engineering solutions to solve the most challenging of PCB requirements.

Smart Electronics Offers Five-year Warranty for CCAs

Expanding market opportunities and increased technology and manufacturing investments have resulted in Smart Electronics being able to offer an unprecedented 5-year warranty for its CCA and RFCCA products.

Orbit's Power Group Nets New Orders

Orbit International Corporation announced that its Power Group, through its Behlman Electronics Inc. subsidiary, has received two new orders valued in excess of $1,675,000 for its COTS division.

Bright Future for Aerospace Industry

90% of aerospace industry respondents to a recent poll conducted by the Performance Review Institute feel confident about the long-term future of the aerospace industry.

Survey Reveals Increase in National Security Spending

The Aerospace Industries Association has released data from a study conducted on their behalf by Harris Poll showing that after discussing present and future security threats facing the U.S., more than two thirds of registered voters (69%) say that given the evolving and increased threats to America's security, the U.S. government should increase spending on America's national security relative to the caps set more than three years ago.

Stop the SMT Conspiracy, Part 2: Abduction

by Michael Ford
MENTOR GRAPHICS, VALOR DIVISION

As I mentioned in Part 1 of this series (October, 2014), tours of SMT factories sometimes make me feel like I am in an episode of The X-Files. In Part 1, we focused on information about processes that were often out of this world, so to speak. This time, we focus on a case of abduction.

Abduction

The story starts with the reported disappearance of some key materials from the shop floor. One minute they were there, and the next, they could not be found. Rumors were started and fingers were pointed. The evidence triggered stories of strange events that sometimes took place during the night, when no one was around. CCTV was setup; footage was analyzed and cages were built to protect higher-value materials, but still, the strange disappearance of materials continued.

Time once again for Mulder and Scully to investigate. Was the disappearance caused by some alien visitation, or had an enterprising engineer simply built a teleportation device out of spare parts? The truth had to be uncovered—a task that was to become something much more complex than anyone was expecting.

The victim in this instance was quickly identified as we entered the senior manager's meeting room. Charts were displayed; groups of managers sat huddled over tablets. As we sat down, the CEO called the meeting to order. We were taken through a sequence of reports that showed that materials had been ordered by MRP, arrived, booked in, but had then never left the factory—at least not officially.

All available staff had been called on to work through the previous weekend, performing a site-wide stock check, counting all of the raw materials in the factory. The expected result had been a subtle material discrepancy between the ERP stock records and the physical inventory that could be explained by the nature of the production operation. The shocking reality, however, was an inventory inaccuracy level approaching 30%, or 10x what had been expected.

The financial team figured that the loss represented more than $3 million worth of materials at cost pricing. That's a lot of chips.

The Scale of the Problem

OEM manufacturing operations are budgeted to break even against an agreed budget, using fabricated "transfer pricing" as a tool to calculate operational performance. On the other hand, EMS companies need to make real profits, often from very small margins. A sudden impact on the business in either case can be devastating.

Shutdown of the factory over a long weekend had already meant the loss of 1% of annual productivity. For a factory making products with a total value of $150 million per year, the stock check cost $1.5 million of lost opportunity, even before considering the labor and other costs. The end-result value of the write-off of "lost" materials was estimated at more than $3 million on top. This would represent a major embarrassment for any OEM CEO and a financial disaster for an EMS, whose margin just evaporated. It was time to get out of the meeting and into action, to uncover the facts about the conspiracy behind these SMT materials shortages.

"I thought that we had just found a clue to our conspiracy. The warehouse was huge and well-stocked with materials. It must have taken ages to count. The bloated inventory was simply due to the requirement to oversupply the lines and the historical issues of unexpected material shortages."

The Scene of the Crime—the Warehouse

An anxious warehouse and logistics manager approached us. He was quick to explain that, although the materials shortages had reported been directly related to his team, all of the losses actually could not have taken place in the warehouse. He was confident in his materials operators. He thought that the materials had gone missing because of the inherent nature of SMT materials, which, while mostly based on reels, have a minimum delivery quantity. He explained that for work orders that require 1,500 pieces of a certain material, the minimum he can send to production is a single reel of 5,000. Even if he had a reel with 1,500 pieces of materials, a little extra would have been needed to compensate for the SMT machine and related spoilage, so more materials would have had to be included. This issue applied to each of the hundreds of materials on every work order, multiplied then by the number of production lines. Not only that, but because of the history of not being able to find materials for work orders when needed, each line can have several such "kits" of materials prepared in advance, meaning that if there was a material shortage at the warehouse, there should be time to do something about it before it affected production. This was the agreement that production made with the warehouse.

I thought that we had just found a clue to our conspiracy. The warehouse was huge and well-stocked with materials. It must have taken ages to count. The bloated inventory was simply due to the requirement to oversupply the lines and the historical issues of unexpected material shortages. The increase in the frequency of these shortages was what led to the need for the stock check.

The warehouse manager shrugged his shoulders and said he knows what happens during the day; it is what happens at night that he is afraid of. I asked whether the excess materials sent out to production are ever seen back in the warehouse again. The reply was that they were not—at least not all. The ERP system had difficulty tracking part-used materials, so manual management was necessary within production.

We looked across the shop floor at the banks of feeder trolleys and racks of feeders, all setup with part-used materials. With each feeder costing up to $1,000, that was a serious investment in itself. What was causing the disappearance of those materials? It was time to move on and talk with the production manager.

What Happens in Production, Stays in Production

The production manager openly admitted that his priority is to keep the production lines working at all times because that was the core of the value generation of the business. He and the warehouse manager agreed that oversupply is essentially insurance against material supply issues causing production downtime. It was thought of as a trade-off; after all, neither the warehouse manager nor any of his guys wanted to work the night shifts. Chuckling, the production manager left us momentarily to order us some coffee.

While the manager is momentarily absent, a young production engineer turned informant. He said that often the materials prepared in the warehouse kits are not enough. At night, with the machines on stop, machine operators have to go looking for materials and will take whatever they can find, which includes taking materials from the warehouse.

The production manager returned. I asked what happens to the oversupplied materials. The production manager and the engineer exchanged glances. We are told that the partly used materials should be returned to the warehouse, but with the time and effort needed for counting, this only happens for expensive key materials, and only then if there is a significant quantity. Production generally keeps materials on the shop floor to cope with cases where the warehouse undersupplies or there is a sudden spoilage issue. The undersupply happens if the warehouse manager thinks that there should be enough excess materials already issued in earlier kits that should be reused. He often gets it wrong, or at least he often cannot find it.

The spoilage issue, while averaging out as a fraction of a percentage of materials overall, can suddenly peak if reels are loaded and unloaded onto feeders several times, if the feeders have been set up incorrectly, or the material itself becomes damaged. In those cases, with the warehouse working so far in advance of production, it is up to production to manage replacements. The ERP system cannot account for materials on the shop floor, so, as the production manager explained, they take control. I suspect, however, that this is not always their highest priority. There are thousands of reels and trays of materials, stacked up on unlabelled shelves, all mixed, some on feeders, and some not. I am not surprised that materials would be difficult to find, such that in a line-down situation, it may be far easier to look in the warehouse.

The volatile nature of material spoilage around the SMT machines seems to account for some of the material losses, but surely not all. Having such bloated inventory in the warehouse and a huge quantity of unmanaged materials on the shop floor would indeed make it very difficult to identify when or where problems began and things went out of control. It was time to talk with the engineering manager, who, for some reason, was not surprised to see us.

View From the Outside

We were told that when the supply chain operation was viewed from the engineering perspective, the whole system seemed open to error, but there is yet more to the story. We were also told that in many cases where, for whatever reason, materials cannot be found on the shop floor or in the warehouse, the engineering team is called on to approve an alternative part that could be substituted in place of the original material. Engineering are required to sign off on these because the substitute part needs to perform correctly in all instances, and it needs the correct form factor to fit properly on the PCB. This happens mainly with common generic materials, like resistors and capacitors, where no one keeps a close eye.

The lack of any material, no matter how valuable, will shut down production. The engineering qualification service was already part of the engineering role, as purchasing continuously seeks to qualify alternate materials that may be less expensive and more readily available. Even after qualification, however, there can be a lot of problems with alternative materials; for example, if there is even a slightly different height, it can significantly influence the degree of spoilage, because the pickup of the part will fail more often, unless the library in the machine is adjusted.

We were told that material substitution really should happen less often than it does, and that the quality manager is continuously critical of this practice because he sees the results at test and often also as product failures in the market.

Exposure

We met again with the plant management. We have solved the mystery. There is no one to blame here specifically, just practices that have changed through years of continued evolution of production, where machines have become faster, more materials of ever-decreasing size are required for each product, and the number of product variants and mix of different products in production has been increasing. Each of the people we talked with put forward a perfectly justified story as to how they work. The problem was, however, the result was a huge loss of materials.

The root cause of the problem is that SMT-related spoilage is volatile. While some of this cannot be avoided, a significant part of it can. As spoilage happens, additional materials are needed which, because of the quite impossible task of managing partly used materials on the shop floor, trigger the disappearance of materials from the warehouse. Substitute materials cause increased spoilage on the machines and corrupt the material consumption records inside ERP, because production BOM changes are not always declared. The problem stays hidden in the mass of unmanaged partly used materials, compounding the problem day by day until a point is reached where, even with the bloated inventory, the factory cannot cope.

This results in the large amount of missing stock at the stock check. A portion is caused by SMT machine spoilage. More is from damaged parts that have been discarded, during a hectic life on the shop floor, especially MSD- or ESD-sensitive materials. Some materials will have been used as substitutes, but not accounted for, leaving the original materials misplaced, with ERP unable to reallocate them, resulting in the purchase of needless replacement stock. Although the stock-check has revealed a loss of $6 million of materials, there should also be the "discovery" of these lost materials that by now have become old, perhaps obsolete and unusable. In the meeting, the CFO looked at his laptop and confirmed that this was indeed the case.

The CEO looked frustrated. The conspiracy is real and ongoing, but actually there is no one to blame and no seemingly easy way to improve things. Everyone was working according to their priorities and goals. How then to break out of this endless cycle of needless material-related cost?

The Lean Materials Solution

The solution that we suggested brings a radical change in the way that material logistics is performed, but it was received well because it is much less of a perceived risk when considering what it replaces. We proposed keeping track of all materials on an individual reel basis, and keeping all materials in the warehouse unless actually needed on the shop floor. Connections should be made to the SMT machines and other processes, to verify the materials as they are setup, and to automatically gather the actual usage and spoilage data during process execution. ERP can then be informed of all material consumption, allowing timely adjustment of reordering to cover any actual spoilage. The last-minute reactions to compounded issues are avoided, reducing the majority of the material damage and loss.

The necessary materials are available to keep production running, but it is simulated in software rather than materialized physically on the shop floor. Retaining an accurate stock inventory measurement between ERP and the physical stock means that the artificial internal material shortages are eliminated. Everyone involved in the "conspiracy" gets what they need, as does the business. It's time to stop the SMT conspiracies! Just because "it has always been done this way" does not mean that a radical change, for example, to Lean just-in-time material management, should be overlooked. How much more compelling do the reasons for change need to be? **SMT**

Michael Ford is senior marketing development manager with Valor division of Mentor Graphics Corporation. To read past columns, or to contact the author, click here.

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2015 Expo Schedule

March 24
Dallas Expo & Tech Forum
Plano, TX

March 26
Houston Expo and Tech Forum
Stafford, TX

April 7
Intermountain Expo and Tech Forum
Boise, ID

April 15
Atlanta Expo and Tech Forum
Duluth, GA

May 5
Michigan Expo & Tech Forum
Livonia, MI

May 5
Oregon Expo & Tech Forum
Beaverton, OR

May 19
Carolinas Expo & Tech Forum
Dallas, NC

May 21
Toronto SMTA Expo & Tech Forum
Markham, ON, Canada

June 4
Huntsville Expo & Tech Forum
Huntsville, AL

June 18
Philadelphia Expo & Tech Forum
King of Prussia, PA

June 23 - 24
Counterfeit Electronic Parts Symposium Tabletop Exhibition
Hyattsville, MD

June 25
Upper Midwest Expo & Tech Forum
Minnetonka, MN

July 16
Ohio Expo & Tech Forum
Independence (Cleveland), OH

September 1
Capital Expo & Tech Forum

September 29 – 30
SMTA International Conference & Exhibition
Co-located with IPC Fall Standards Development Committee Meetings
Rosemont, IL

October 14
Long Island Expo & Tech Forum
Islandia, NY

October 14 - 15
International Wafer-Level Packaging Conference and Exhibition (IWLPC)
San Jose, CA

October 20
Austin (CTEA) Expo & Tech Forum
Austin, TX

October 20
Connecticut Expo & Tech Forum
Waterbury, CT

November 5
LA/Orange County Expo & Tech Forum
Long Beach, CA

November 12
Space Coast Expo & Tech Forum
Melbourne, FL

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SMT007 Supplier/New Product News Highlights

Congressman Price Tours Juki Headquarters

Bob Black, Juki Automation Systems' (JAS) president and CEO, invited Rep. David Price (North Carolina's 4th congressional district) to tour the facility. The company is a leading-edge technology provider in Rep. Price's district and he visited to discuss the economic outlook for manufacturing in the U.S. and hold a town hall meeting with employees.

Assembleon Acquired by Kulicke & Soffa for $98M

Bruno Guilmart, Kulicke & Soffa's president and CEO, remarked, "We are extremely pleased to welcome Assembleon and its talented employees into the K&S family. Assembleon's existing solutions and technological competencies present a very attractive strategic opportunity and further extend our ability to capitalize on the advanced packaging market."

Intertronics Releases New Dual-cure 3401

Explained Peter Swanson, M.D. of Intertronics, "Dual-cure 3401 cures rapidly and reliably under UV with low shrinkage and is moisture and thermally resistant. Post-process, it fluoresces blue under low intensity blacklight for easy inline bond inspection."

Nordson DAGE Intros New Method for Testing Thin Die

Nordson DAGE continues to meet the challenges for micro materials testing with the introduction of a new test method for the evaluation of die strength by means of cantilever bending where 3-point bending is not suitable for die with a thickness of less than 50 microns.

Dymax Debuts Guide to Light-Cure Conformal Coatings

Dymax Corporation's new Guide to Light-Cure Conformal Coatings outlines the benefits of using light-cure conformal coatings as well as cost justification, typical processing guidelines and best practices, product selection criteria, data, and industry specifications.

Manncorp Launches New Inline Stencil Printer

With the features, performance, and build-quality of systems twice its price, Manncorp's new AP430 fully-automatic inline stencil printer brings affordability to leading-edge, solder paste printing technology.

Essemtec Debuts New SMT Assembly System at APEX

Essemtec will exhibit in Booth #1211 at the IPC APEX EXPO, scheduled to take place Feb. 24–26, 2015 at the San Diego Convention Center in California. Company representatives will demonstrate the multi-functional SMT center Paraquda, Cubus SMT storage device and the new Lynx highly flexible and accurate pick-and-place system.

Amada Miyachi Europe Unveils New Products

The new MIYACHI UNITEK LMWS Laser Marking Workstation (LMWS) equipped with an ML-73 D Series fiber laser marker, the MIYACHI PECO Active Welding System (AWS) 3, and the MIYACHI EAPRO hot bar are the company's newest products.

Electrolube Achieves Record Growth in 2014

With increased growth figures year on year, 2014 has seen the biggest growth in the company's 72 year history. The Chinese R&D team, based at Electrolube's manufacturing facility in Beijing, is making rapid advances in high performance, innovative materials at a pace that is hard to match.

How to Select a Pick-and-Place Machine, Part 1

by Robert Voigt
DDM NOVASTAR

This is the second in a series of columns aimed at helping buyers analyze and select SMT equipment for PCB assembly. In this column, I'll cover manual and semiautomatic pick and place machines, for users interested in going from a couple boards a day to much higher production volumes, while a future column will cover more complex, fully automatic systems.

A pick-and-place machine is the second step in the paste, place, and reflow assembly operation. The place function follows the solderpaste function (stencil printer). The place operation selects and delivers a component over the board and drops it into position. The simplest form of pick-and-place operation is by hand; that is, manually picking a component from a bin and, with the aid of a pair of tweezers and a magnifying glass, positioning it on the board and completing the operation with a hand-held soldering iron.

This method works perfectly fine if you are only doing occasional boards. Other things to consider are the size of the components (big or small), which affect the time required to hand place and solder. Fine pitch components are another issue, where more precision and accuracy are required, and the human factor comes into play. The work then becomes more tedious and time-consuming.

Production Volume

Let's start by addressing production ranges for various types of machine-assisted manual systems. For purposes of comparison, since all circuit boards vary in size and complexity, we'll talk about volumes in terms of components per hour, or CPH. This will help you to decide what level of automation you'll need.

On the very low side of the scale—using a manual hand system—the only expense is the appropriate hand tools for non-machine assisted manual placement. At the high end of the spectrum, these machines are often modular or customized for high-speed unattended operation. Buyers in this market are likely looking more at ROI than initial cost.

Type of System	Average CPH Range	Price Range
Manual (hand)	0–50	$300–$400
Manual (machine)	75–150	$2,000–$7,000
Semi-automatic	300–1,000	$15,000–$25,000
Fully automatic (low-volume) bench-top	1,200–3,500	$ 30,000–$35,000
Fully automatic (mid-volume) free-standing	3,000–8,000	$ 40,000–$60,000
Fully automatic (high-speed) free-standing or modular	12,000–30,000	$ 100,000 +

Table 1.


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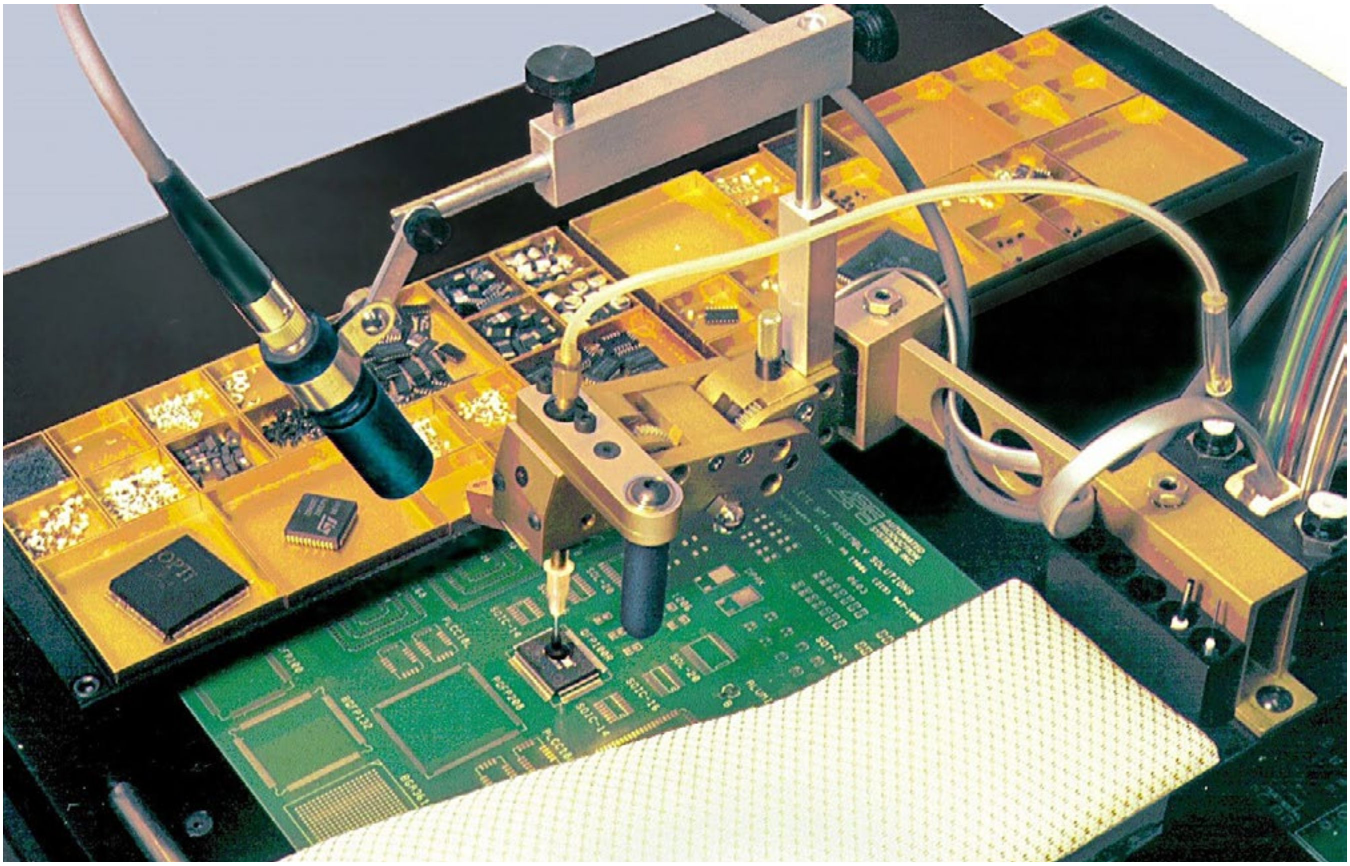


Figure 1: Example of manual head and armrest for support.

Manual and Semi-automatic Systems

A manual pick-and-place system is desirable for small, growing operations that need to increase their hand-held production volumes incrementally while also improving quality, thus reducing rework or rejects; however, the accuracy of placement is still limited by the capability of the operator. Benefits of a machine-assisted manual system include:

- Less operator fatigue
- Fewer placement errors
- Better control
- Improved yield, less rework

A machine-assisted manual system can be equipped with features such as an X-Y indexing table with vacuum pickup head or pen; ergonomic fixturing to help relieve operator fatigue; and additional fixturing for θ (rotation) and Z (height) positioning in addition to X and Y.

Some machines offer an optional liquid solderpaste dispenser, which is applied just before placing the component on the board if a stencil printer has not been used. Additional options include:

- Component handling trays
- Liquid dispenser
- Tape feeders
- Feeder racks
- Vision assist option
- Optional stands

In most cases, machine-assisted manual systems can be purchased with just the bare necessities, and desirable options can be added later as they're needed.

Semiautomatic Systems

Today there are very few semiautomatic machines still being made because of the increas-

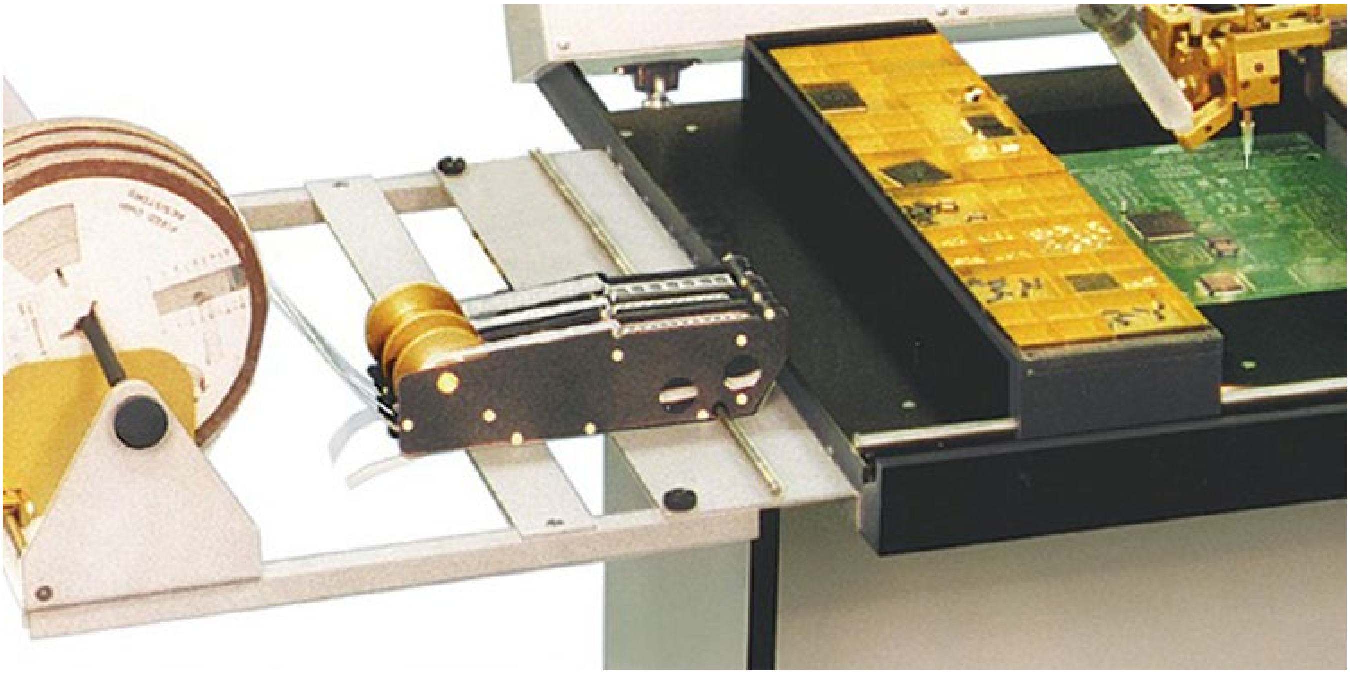


Figure 2: Component trays and feeders.

Figure 3: A vision-assisted manual machine.

ing affordability of some of the more automated systems on the market. They were originally introduced at a time when the leap from manual to fully automatic systems was just too cost-prohibitive and were made available with some features to assist the manual operation.

More correctly referred to as "enhanced manual" systems, semiautomatic pick-and-place machines typically include a computer interface with a vision system that shows where the components go, but the placement itself is still done manually. This type of machine helps the operator position ultra-fine pitch components more accurately for low-volume applications, an operation that is very difficult to accomplish using a simple machine-assisted manual machine.

Ease of Use

Most pick-and-place machines will handle a fairly wide variety of board sizes, with a work table designed to accommodate boards up to 16" x 24". There is also ease of control over the components, which aids in accuracy, along with a simple learning curve. In most cases, no training is required.

Don't overlook electrical requirements. Make sure the machine you buy will plug-and-play in your environment without pulling in new wiring or else plan on an adapter/transformer.

Vendor Support

When evaluating any type of SMT machine, consider factory support as one of the most important assets of your purchase. The best way to learn how a company treats its customers is by word of mouth. Talk to several customers to find out how happy they are with the machine, the seller, and the support they provide. Where is the manufacturing plant? Can they help troubleshoot alignment issues over the phone? Do they offer field service? Do they have spare parts in stock for immediate shipment? While there isn't much of a used market for manual, machine-assisted or enhanced manual pick and place machines, it's still a good idea to ask your supplier about their older machines in the field, and if down the road, spare parts are available, and about their capability to customize a spare part if the machine becomes obsolete. Ask what the expected life-cycle of the product is. The industry standard is seven years. Remember, there is a difference between a true manufacturer and an equipment supplier or distributor.

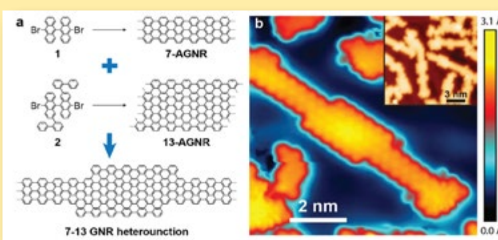
I hope this primer on machine-assisted pick-and-place machines has been helpful. **SMT**

Robert Voigt is VP of global sales at DDM Novastar Inc. He may be reached at rvoigt@ddmnovastar.com.

Researchers Manipulate Nanoribbons at Molecular Level

Narrow strips of graphene called nanoribbons exhibit extraordinary properties that make them important candidates for future nanoelectronic technologies. A barrier to exploiting them, however, is the difficulty of controlling their shape at the atomic scale, a prerequisite for many possible applications.

Now, researchers at the US Department of Energy's (DOE) Lawrence Berkeley National Laboratory (Berkeley Lab) and the University of California, Berkeley, have developed a new precision approach for synthesizing graphene nanoribbons from pre-designed molecular building blocks. Using this process the researchers have built nanoribbons that have enhanced properties-such as position-dependent, tunable bandgaps-that are potentially very useful for next-generation electronic circuitry.



The results appear in a paper titled "Molecular bandgap engineering of bottom-up synthesized graphene nanoribbon heterojunctions," published in Nature Nanotechnology.

"This work represents progress towards the goal of controllably assembling molecules into whatever shapes we want," says Mike Crommie, senior scientist at Berkeley Lab, professor at UC Berkeley, affiliated with the Kavli Energy NanoScience Institute, and a leader of the study. "For the first time we have created a molecular nanoribbon where the width changes exactly how we designed it to."

Previously, scientists made nanoribbons that have a constant width throughout. "That makes for a nice wire or a simple switching element," says Crommie, "but it does not provide a lot of functionality. We wanted to see if we could change the width within a single nanoribbon, controlling the structure inside the nanoribbon at the atomic scale to give it new behavior that is potentially useful."

For more, click here.

IPC 2015 Educational Programs

February 2
IPC/EIPC Conflict Minerals Workshop
Paris, France

February 4
IPC/EIPC Conflict Minerals Workshop
Munich, Germany

February 4–5
IPC Standards Meet High Reliability Requirements for PCBs and PCBAs
ETECH Kerkrade, Netherlands

February 6
IPC/EIPC Conflict Minerals Workshop
Woking, Surrey, United Kingdom

February 20–26
IPC APEX EXPO Conference and Exhibition
- IPC Designer Certification Sessions
- IPC Design Forum
- EMS Program Management Training
- Professional Development Courses

San Diego, CA, USA

April 29–30
IMPACT 2015: IPC ON CAPITOL HILL
Washington, DC, USA

May 13–14
IPC Technical Education
Full-day professional development courses for engineering staff and managers:
- DFX-Design For Excellence (DFM, DFA, DFT and more)
- Best Practices in Fabrication
- Advanced Troubleshooting

Fort Worth, TX, USA

June 9
ITI & IPC Conference on Environmental and Government Regulation
Discussion with international experts
N. New Jersey, USA

June 9–11
IPC Technical Education
Full-day professional development courses for engineering staff and managers:
- DFX-Design For Excellence (DFM, DFA, DFT and more)
- Best Practices in Fabrication
- Advanced Troubleshooting

Chicago, IL, USA

June 10
ITI & IPC Conference on Environmental and Government Regulation
Discussion with international experts
Chicago area, IL, USA

June 12
ITI & IPC Conference on Environmental and Government Regulation
Discussion with international experts
San Jose, CA, USA

September 27–October 1
IPC Fall Standards Development Committee Meetings
Co-located with SMTA International
Rosemont, IL, USA

September 28
IPC EMS Management Meeting
Rosemont, IL, USA

October 13
IPC Conference on Government Regulation
Discussion with international experts on regulatory issues
Germany

October 13–15
IPC Europe Forum: Innovation for Reliability
Practical applications for meeting reliability challenges like tin whiskers, with special focus on military-aerospace and automotive sectors
Germany

October 26–27
IPC Technical Education
Full-day professional development courses for engineering staff and managers:
- DFX-Design For Excellence (DFM, DFA, DFT and more)
- Best Practices in Fabrication
- Advanced Troubleshooting

Minneapolis, MN, USA

October 28–29
IPC Flexible Circuits-HDI Conference
Presentations will address Flex and HDI challenges in methodology, materials, and technology.
Raleigh, NC, USA

November 4
PCB Carolina 2015
Raleigh, NC, USA

December 2–3
IPC Technical Education
Full-day professional development courses for engineering staff and managers:
- DFX-Design For Excellence (DFM, DFA, DFT and more)
- Best Practices in Fabrication
- Advanced Troubleshooting

Raleigh, NC, USA

December 2–4
International Printed Circuit and APEX South China Fair (HKPCA & IPC Show)
Shenzhen, China

Questions? Contact IPC registration staff at registration@ipc.org or +1 847-597-2861

TOP TEN

News Highlights from SMT007 this Month

1 SMTA Seeks Papers for SMTAI 2015

The association is seeking technical papers for presentation at SMTA International 2015. Abstracts are due February 13, 2015. Proposals are also solicited from individuals interested in teaching educational courses related to surface mount technology, advanced packaging, and electronics manufacturing.

2 IPC Secures Passage of RAMI Act

President Obama has signed the omnibus spending bill into law. Included in this bill was critical advanced manufacturing innovation legislation called the Revitalize American Manufacturing and Innovation (RAMI) Act, which was a top IPC policy priority.

3 Lectronix Receives MFi License

"As an innovative electronics supplier, Lectronix is always keeping an eye on the future. We see more and more customers across diverse industries that are finding connectivity with Apple devices to be a key part of their product strategy. With this license we are now better prepared to help our customers build those solutions," said Tom Bayerl, CEO.

4 IPC APEX Features Complimentary Networking Events

"The special events at the show add tremendous value for attendees," says Alicia Balonek, IPC senior director of trade shows and events. "Most of the events are complimentary with pre-registration, whether you pre-register for complimentary exhibit hall admission or sign up for our most comprehensive educational package, the All-Access Package."

5 Javad EMS Adds Large Board Line

Javad EMS (JEMS) announces that it has added a large board line to continue meeting customer needs. With the use of HDI printed circuit boards, more densely populated boards using high pin-count BGAs, QFNs and LGAs, micro BGAs, and smaller and smaller devices including 10005s, it seems that assemblies should be getting smaller in size. However, in some cases it is the inverse: PCBs are getting larger.

6 Flextronics Opens New Facility in Detroit

The newly opened Flextronics facility will enable innovation and disruptive technology development that further supports customer's needs for differentiation. Services provided include product design and development, engineering, validation testing, development garage, prototyping and quality engineering.

7 Inventec Acquires Paste Maker SMT International

Commenting on the deal, Leigh Gesick, currently Amtech's president and now Inventec's director of U.S. Operations said, "This merging of SMT International's and Inventec's resources offers major advantages to AMTECH customers, providing broader access to an expanded range of world-class products and services, and increasing global distribution channels for AMTECH SMT solder products."

8 Corridor Capital Acquires EMS Firm Circuitronics

"We are excited to partner with the strong team at Circuitronics. They have deep industry experience at all levels of the organization and a clear strategic vision," said Corridor CEO Craig Enenstein. "We have been particularly impressed with their ability to provide the technological capabilities and quality of a large tier-one EMS supplier while maintaining an exceptional level of customer service and flexible production capacity."

9 IPC Establishes Local Presence in Korea

The Standards Committee of IPC Korea will help members to develop and revise global standards, educate and train workers, provide technology consultation, hold technology development forums, standardize electronics terminologies in Korean, and hold networking events. This will help establish a collaborative relationship among the government, electronics industry, and academia.

10 S and Y Industries Achieves Record Sales in 2014

The company's gross sales for 2014 were up 17.9% compared to a year ago. Because of S and Y's continued success, new employees have been hired and new equipment has also been purchased.

EVENTS

For the IPC's Calendar of Events, click here.

For the SMTA Calendar of Events, click here.

For the iNEMI Calendar, click here.

For a complete listing, check out *SMT Magazine's* full events calendar here.

SMTA Pan Pacific 2015
February 2–5, 2015
Kauai, Hawaii, USA

SEMICON Korea 2015
February 4–6, 2015
Seoul, Korea

MEDIX 2015
February 4–6, 2015
Osaka, Japan

LED Korea 2015
February 4–6, 2015
Seoul, Korea

EIPC Winter Conference
February 5–6, 2015
Munich, Germany

Energy Innovation Summit
February 9–11, 2015
Washington D.C., USA

MD&M West
February 10–12, 2015
Anaheim, California, USA

2015 Flex Conference
February 23–26, 2015
Monterey, California, USA

IPC APEX EXPO 2015
February 22–26, 2015
San Diego, California, USA

FPD China 2015
Shanghai, China
March 17–19, 2015

PUBLISHER: **BARRY MATTIES**
barry@iconnect007.com

PUBLISHER: **RAY RASMUSSEN**
(916) 294-7147; ray@iconnect007.com

SALES MANAGER: **BARB HOCKADAY**
(916) 608-0660; barb@iconnect007.com

MARKETING SERVICES: **TOBEY MARSICOVETERE**
(916) 266-9160; tobey@iconnect007.com

EDITORIAL:
GROUP EDITORIAL DIRECTOR: **RAY RASMUSSEN**
(916) 294-7147; ray@iconnect007.com

MANAGING EDITORS: **LISA LUCKE**
(209) 304-4011; lisa@iconnect007.com,
and **ANDY SHAUGHNESSY**
(770) 315-9901; andy@iconnect007.com

TECHNICAL EDITOR: **PETE STARKEY**
+44 (0) 1455 293333; pete@iconnect007.com

MAGAZINE PRODUCTION CREW:
PRODUCTION MANAGER: **SHELLY STEIN** shelly@iconnect007.com
MAGAZINE LAYOUT: **RON MEOGROSSI**
AD DESIGN: **SHELLY STEIN, MIKE RADOGNA**
INNOVATIVE TECHNOLOGY: **BRYSON MATTIES**
COVER: **SHELLY STEIN**

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Coming Soon to *SMT Magazine:*

MARCH:
Thermal Management (and IPC APEX EXPO Coverage!)

APRIL:
Soldering Technologies

MAY:
Paste Printing & Component Placement