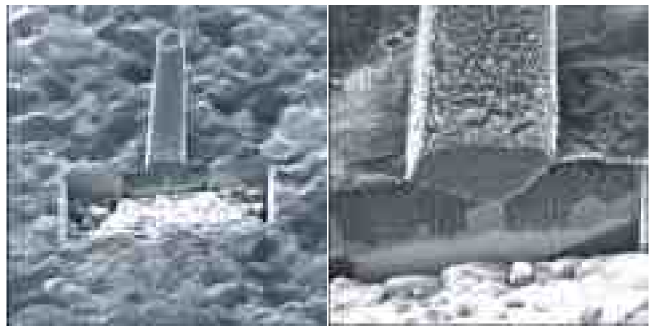
Lead-free Component Finishes – A Market & Technical Analysis

By John Swanson & Yun Zhang

In this edited version of a paper given at SUR/FIN® 2001—Nashville, a marketing perspective of the change and transition to lead-free alternatives for component finishes is presented. What drives the change? Legislation, the corporate "environmental conscience," market needs, or a combination of these factors?

The authors report on the status of current, worldwide legislation, and compare and contrast the status of developments and transition dynamics to lead-free alternatives in the different regions of the world market. Opportunities and risks are also assessed and discussed, considering current market knowledge and conditions.



A tin whisker is cross-sectioned using focused ion beam technology (FIB). The base of the whisker shows intermetallic copper-tin forming as a precurser to whisker growth. The photos are the same—the one on the right is an enlargement of the left photo.

Evolution of the "Pb-free" Issue

In recent years, the electronics industry has been pressured to eliminate lead from its products and manufacturing processes. The "Pb-free" issue has been evolving for several years, with its most direct origin from enacted and proposed legislation in Japan and Europe. These legislations, combined with growing expectations for corporate environmental responsibility, have a broad and far-reaching effect on organizations throughout the electronic materials supply chain. From the consumer perspective, manufacturers of goods such as laptop computers, camcorders, and PDAs are finding that "green labeling" associated with Pb-free products can often translate to a more profitable product line. Further up the chain, suppliers and manufacturers with an interest in the plating and surface finishing industry are dramatically affected.

When considering Pb-free conversion issues confronting the manufacture and assembly of electronic products and components, three basic segments of focus can be defined:

1. Pb-free finishes for printed wiring boards (PWBs)
2. Pb-free soldering materials (pastes and solders)
3. Pb-free surface finishes for electronic components

While this article will focus on the challenges and driving forces associated with Pb-free component finishes, the issues surrounding conversion in the PWB and soldering materials segments are also briefly summarized.

PWB Finishes

In this segment, traditional tin/lead finishes are applied via a process generally known as hot air solder leveling (HASL). A variety of HASL alternatives has been growing in popularity for several years. The more popular alternatives (electroless nickel, immersion gold, immersion tin, immersion silver, and OSPs), while bringing the clear benefit of being Pb-free, are primarily desirable because of other tangible benefits: process cost (both capital and process materials), improved surface planarity, and in some cases, better compatibility with other board materials. In short, more traditional drivers of change are hastening the conversion to Pb-free finishes: cost and efficiency.

Pb-free Soldering Materials

Pb-containing pastes and molten metals serve as the bridge joining electronics components to board surfaces or other devices. The materials are traditionally based on a 60/40 tin/lead alloy and are highly suited to electronic assembly for a variety of reasons—low melting point, low cost, and excellent solder performance (wetting speed, wetting force, joint strength, and joint durability). A wide variety of Pb-free alternatives to traditional solder continue to be investigated, but alloys based on Sn/Ag/Cu and Sn/Cu have emerged as the most popular alternatives. Unfortunately, Sn/Ag/Cu and Sn/Cu do not offer the operational advantages provided by alternate PWB finishes, discouraging the speed at which conversions are likely to occur. Sn/Ag/Cu and Sn/Cu solders both melt at much higher temperatures than Sn/Pb, significantly complicating assembly processes. Materials containing silver result in an obvious cost disadvantage. Few of these alloys can match the inherently superior soldering characteristics of tin/lead.

Driving Forces for Conversion: A Regional Analysis

Significant contrasts can be observed in the evolution of the Pb-free movement in the three major economic regions: Asia, Europe, and North America. When considering the electronics industry, the leading edge of technological change, product evolution, and overall gross industrial product for the Asian region is certainly found in Japan.

Japanese legislation affecting the recycling of Pb-containing consumer goods such as televisions, refrigerators, washing machines, and other durable goods was written in the 1990s and formalized in 2001. A large proportion of original equipment manufacturers (OEM) and consumer electronics firms headquartered here have reacted with internal initiatives to meet this legislation, and expand proactively beyond it. This can be tangibly observed in commercially available, Pb-free goods, such as mini-disc players, available from Panasonic. Additionally, electronic component suppliers are beginning to announce product line conversions. Fujitsu recently announced a number of Pb-free semiconductor packages, and the intent for full product line conversion by the end of 2002.

Design changes by these industry leaders are having an effect beyond Japanese borders. Contract assemblers, component manufacturers, and plating shops in areas such as Taiwan and Southeast Asia supply this market, and are increasingly being asked to supply Pb-free materials and finishes. The Asia demand for Pb-free process materials (such as solders and electroplating solutions) far exceeds that of other geographic areas.

Looking at Europe, this region is obviously a collection of independent economies, governments, and cultures with deviations in opinion and environmental world view. However, some collective generalizations can be made. A will for environmental responsibility and conservation pervades in the bulk of the region. The individual populace frowns upon excessive waste and lack of environmental conscience by corporations. This, combined with the competitive influences of a global marketplace and legislative issues, results in Pb-free initiatives at the OEM level similar to those cited for Japan. This stated, the gross demand for Pb-free process materials in Europe has been significantly reduced by a shift to lower-cost manufacturing sites in Asia.

European Union—the WEEE Directive

In terms of the European regulatory landscape, the key positioning document is the Waste Electrical and Electronic Equipment (WEEE) Directive. This has been drafted to curtail lead, mercury, cadmium, hexavalent chromium and halogenated flame retardants. The objectives of this Directive are to:

Prevent waste
Reduce the amount going into landfill
Re-use and recycle wastes
Promote design & production to facilitate the ability to repair, upgrade, re-use, dismantle and recycle
Encourage use of materials that can be easily recycled
Minimize environmental risks and impacts from treatment and disposal of end-of-life equipment

It is the producer's responsibility to mark consumables with separate collection symbols and to supply data on quantities for each category. Components containing substances that are listed in the Directive would need to be removed prior to landfill, incineration or recovery.

The scope of the draft Directive covers all electronic and electrical equipment in the following exhaustive list of categories:

1. Large household appliances
2. Small household appliances
3. IT and telecommunication equipment
4. Consumer equipment
5. Light equipment
6. Electrical and electronic tools
7. Toys
8. Medical equipment systems (with the exception of all implanted and infected products)
9. Monitoring and control instruments
10. Automatic dispensers

In each category, there is a list providing examples of products covered by each respective category.

The development of the draft Directive has involved detailed consultation and attracted intense discussion involving industrial associations (EECA, PCIF, EMIF), governmental and associated bodies (DTI, NPL in the UK; IPC, NEMI and NIST in the U.S.), as well as individual companies around the globe.

During this process, the implementation dates have been adjusted and readjusted. From initial work in 1991, the process has progressed through various stages resulting in the first, second (July 1998), and third (July 1999) drafts, followed by the most recent draft in 2001, proposing implementation of the lead ban by January 2007.

Two EU Parliament committees (the Enterprise Committee, which has adopted a less ambitious stance, and the Environment Committee, which has been more proactive) are currently scrutinizing the draft proposal and will put forward recommendations to the European Parliament for a vote. The Environment Committee has drafted an opinion suggesting that the implementation date be brought forward to 2004.

At the EU national level, there are many examples of the regulation of lead-containing products and particular uses of lead such as:

- In Austria, there are restrictions on the lead content of fertilizers and on the use of sewage sludge if the heavy metal content in the soil or the sludge exceeds certain limits. Similar ordinances have been adopted by Finland and drafted by the German government.
- In Denmark, a regulation on lead-containing products is under way. The draft regulation contains a general prohibition (with exemptions) on the sale of products containing lead substances. The sale of a range of specified products containing lead is also prohibited.
- In Sweden, there are initiatives to phase out lead use in many products including cables, solder, light bulbs, cathode rays and keels.

The pragmatic and understandable response on a significant part of leading European electronics manufacturing companies (> 60%) has been to hope for the best and prepare for the worst. In practical terms this has meant learning from the experience derived from Japan and being ready to implement a technically feasible lead-free solution when legislation demands it at the least.

North America, in contrast with Japan and Europe, lacks a legislative movement directly focused on lead issues in the electronics industry. In the U.S., a number of state-specific legislations relating to lead hazards do exist. These are numerous, but some of the common elements involve the presence of lead in landfills, drinking water, and paints. Closer to the electronics industry, the California Department of Toxic Substance Control has recently published language condemning the presence of lead in cathode ray tubes.

Despite the lack of a legislative push, global competition is naturally catalyzing lead-free initiatives at North American firms focused on the electronics industry. Lead-free programs at consumer-focused firms like Motorola, Hewlett Packard, and IBM are well underway and characterized by individual product conversions and test cases. Major North American component suppliers like Tyco and Molex are moving to meet their customers' requirements and expectations. The "trickle down" of these initiatives to contract suppliers and plating job shops has been limited, though. At least two explanations can be offered. First, full product line conversions at the end of the supply chain have not yet occurred, so demand is limited. Additionally, the severe economic downturn in the electronics industry has resulted in layoffs, plant closing, and a curtailing of "non-essential programs" such as lead-free conversions (this is certainly true globally, not just in North America).

Lead-Free Component Finish Alternatives

Against this backdrop, the technical feasibility (some more than others) of the main alternatives can be considered. In the context of lead-free alternatives for component finishes, a range of candidates presents themselves. However, has the choice truly become more difficult? The accompanying table compares the advantages and disadvantages of tin and tin alloy finishes as alternative lead-free component finishes:

Tin & Tin Alloy Finishes

Finish	Advantages	Concerns/Issues
Sn 232°C	Compatible with SAC* alloy Simple process control	Whisker formation
Sn(2-5)Bi 220-225°C	Compatible with SAC alloy Lower melting point	Whisker formation Immersion plating Alloy control & measurement
Sn(3.5)Ag 221°C	Compatible with SAC alloy Lower melting point	Whisker formation Very narrow process window Cost increase Environmental issue with Ag
Sn (0.7-1.5)Cu	Compatible with SAC Alloy Lower melting point	Whisker formation Immersion plating Accelerated Sn (II) oxidation

**SAC alloy: SnAgCu alloy*

Animated discussion has surrounded the question of the whisker phenomenon as it relates to all of the alternative lead-free component finishes listed in the table. Conventional wisdom suggested that an "alloy" finish would suppress whisker formation. Numerous independent reports have shown that the "alloy" lead-free alternatives form whiskers, some more prolifically than pure tin. In addition, experience and investigations have shown that it is not simply a question of alloy versus pure tin, but rather total process parameters and control. Many lead-free alloy plating processes suffer common deficiencies such as immersion plating and accelerated oxidation of Sn (II). Until these deficiencies are sufficiently addressed, and whisker growth mechanism adequately understood, it is unrealistic to foresee a massive conversion from tin-lead plating processes to these lead-free plating processes without implications of increased cost and product reliability.

In Japan, where the earliest progress in switching to lead-free alternative finishes was made prior to the availability of current results, manufacturers were suspicious of pure tin with initial interest focusing on SnCu, paying limited attention to the wider practical difficulties that attend its use. Furthermore, collective experience indicates that SnCu appears to have higher whisker growth propensity when compared to pure tin. Recent interest has focused on SnBi—considered by some to achieve whisker freedom. In addition to the process issues mentioned previously, a key concern regarding SnBi involves its compatibility with conventional tin-lead solders or tin-lead finishes. Have the potential liability issues raised by the possibility of cross-contamination between batches been underestimated? The potentially massive implications this incompatibility could cause (particularly during an apparently protracted change-over period) should be given serious consideration.

The technical and practical difficulties surrounding the plating of SnAg have been acknowledged as probably the most challenging of all the current lead-free alternatives. Pending further significant process development, it is an unlikely contender for widespread use in the electronics industry.

These considerations leave pure tin, which in terms of compatibility and simplicity, the most logical and compatible drop-in replacement finish for tin-lead, capable of meeting the requirements of a vast range of applications. As described elsewhere, the whisker phenomenon is relinquishing its mystery enabling the deposition of finish with a controllable outcome/performance/behavior in relation to whisker formation.

The benefits of the overriding environmental objective of removing lead from the environment have generated widespread interest and approval in many quarters. Given the popular interest and sensibility towards this issue, it is reasonable to expect the change as inevitable. Equally, in contemplating the transition to lead-free assembly technology, it has been shown that a complex set of issues needs careful consideration. The debate around the transition to "lead-free" component finishes has revolved around the whiskering issue—perhaps for too long in isolation of the other significant and important parameters when selecting the optimum lead-free process. Consideration of the complete spectrum of aspects such as plating process compatibility and product compatibility (whiskering behavior, solder joint reliabilty etc.), provides the most sound basis for the choice of a new technology. **P&SF**

About the Authors

John Swanson is the global business manager for electroplating chemicals at Electroplating Chemicals and Services (EC&S), an organization of Lucent Technologies Inc., Staten Island, NY. He earned an MBA from the University of Pittsburgh in 1994 and a BS in chemical engineering from Grove City College in 1989.

Over his 12-year career, Swanson's responsibilities have span a diverse variety of electroplating applications. He began his career in a research and development capacity at Weirton Steel Corporation. He left the R&D role to become a quality engineer at the production level, inside the largest steel strip plating facility in North America. Before joining EC&S, Swanson functioned in a variety of capacities at LeaRonal Inc. (later the Shipley Company of Rohm and Haas), a specialty chemical producer in Freeport, NY.

Dr. Yun Zhang received a PhD in inorganic chemistry from Brown University in 1991. She has been a postdoctoral fellow at Purdue University and Brookhaven National Laboratories. Currently, she is a manager of R&D with the Electroplating Chemicals & Services of Lucent Technologies, 236 Richmond Valley Rd., Staten Island, NY 10309. Her primary interest is with electrodeposition at molecular level, and providing economical and robust electroplating chemistries and processes for the electronic industry. She is the principal investigator of the Advanced Technology Program (ATP) titled "Development of Lead-free Solder Electroplating Technologies," awarded by the U.S. Department of Commence.

Dr. Zhang has written numerous scientific publications, one book chapter titled "Tin and Tin Alloys for Lead-Free Solder" in Modern Electroplating, and has contributed to two textbooks. She was the recipient of Circuit World's "Most Outstanding Paper Published Award" in 1998. She holds two U.S. patents, and has five others pending.