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Lead-Free Implementation: Drop-In Manufacturing

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Abstract
The Lead-free electronics manufacturing has become a reality. As of this writing, a few manufacturers have rightfully reported their total completion to Lead-free production across all facilities, and some have reached partial implementation. This paper focuses on replacing63Sn37Pb (or its equivalent) solder joint material and crucial manufacturing practices without using a higher process temperature. The paper also presents some exemplary real-world production results of the drop-in manufacturing by using the properly selected Lead-free solder alloys that are able to perform as a direct replacement for 63Sn37Pb solder joint material. Based on the 14-year systematic and sustained study of Lead-free solder materials in conjunction with the 23-year SMT manufacturing establishment, the fundamental material properties and mechanical behavior of the drop-in materials in relation to production and reliability will also be briefly summarized.

Introduction
Within the Lead-free system comprising solder joint, PCB surface finish and component coating, replacing Pb-containing solder joint material (including BGA/CSP solder spheres) is relatively more demanding than coating material. In replacing 63Sn37Pb, the perceived elevated temperature (soldering process) was and is still the paramount issue. The concern about the elevated process temperature is perfectly legitimate. However, the belief in an elevated process temperature as a prerequisite requirement in converting to Lead-free is both true and false, depending on which alloy is elected to use.

There are two parallel approaches and thus methodologies. These are “Drop-in approach” and “Modification approach”. The Drop-in approach means that the primary process temperature, the equipment, PCB boards, and components per se do not need to be changed within the acceptable range of tolerances and variations. The Modification approach involves one or more changes, such as increasing the process temperature, elevating the component temperature tolerance, etc. Solder joint alloys for both approaches are equally commercially available.

SMT Manufacturing vs. Viable Lead-Free Alloys[1,2,3,4]
Combining the fundamental and practical reasons, lead-free soft solder compositions for performing in interconnecting function for electronic packaging and assembly must be made of Sn-based material. This was the basis for designing the lead-free alloys right at the beginning in late 1980s.[1,5] Sn-matrix, however, needs to be strengthened. Effective alloying and doping elements to strengthen Sn-matrix include Ag, Bi, Cu, Ga, In, Sb, Se. In this regard, metallurgical interaction (reactions) and microstructure evolution in relation to temperature-rising and temperature-changing are the critical scientific basis in developing new lead-free solders. Binary phase diagrams provide the general information about the conditions and extent of metallurgical interactions, albeit the complete phase diagrams beyond the binary system is scarce. Nonetheless, binary phase diagrams offer a useful starting point.[1,5] Reference 5 provides the scientific basis of the Lead-free alloy design and anticipated performance.

From the binary alloys to the alloys containing more than two elements, lead-free materials have been thoroughly studied throughout the dedicated 14-year research. An alloy’s viability is defined as its properties and performance being equal to or better than the established reference (63Sn37Pb). The basic material properties such as liquidus/solidus temperature, electrical/thermal conductivity, intrinsic wetting ability on the commonly used substrates, mechanical properties, and ambient shelf stability have been gauged.[1] Under the current framework, it is found that the conductivity and shelf stability are not as sensitive to the makeup of a specific alloy system as intrinsic wetting ability, mechanical performance and phase transition temperatures. To optimize all necessary properties through in-depth application of materials science and metallurgical phenomena is the key to achieving the ultimate performance of the designed alloy composition.

To serve as interconnections, equally important, Lead-free solder alloys must possess the characteristics that are compatible with the practical manufacturing techniques, other constituents of the system, and end-use environment. The understanding of practical and process parameters in relation to the fundamental alloy properties is critical to the success of Lead-free implementation. Specific attention should be drawn to the ability to accommodate a wide array of assemblies and applications. Attention should also be drawn to the capacity of absorbing the <fluctuations> inherent with SMT manufacturing so that the necessary process window required in the mainstream SMT manufacturing is provided.

For best practices and effective Lead-free implementation, the ability to separate Lead-free related issues from the SMT production issues, SnPb or Lead-free, is important to the effective lead-free implementation.

Not Requiring a Higher Temperature

In implementing lead-free manufacturing, a main concern circulated in the industry has been the higher process temperature required to perform the reflow and wave soldering during circuit board assembly. This concern has, on one hand, created additional tasks in an attempt to make all components that will be subjected to the assembly conditions to meet the "higher temperature requirement". On the other hand, the concern was transformed into much inertia in implementing Lead-free to some manufacturers.

The notion of the necessity of a higher temperature stems from the fact that the melting temperature of all viable (underscore the viability) solder alloys are higher than the Pb counterpart, which consequently resulting in requiring a higher process temperature. The thought appears to be quite natural. Indeed the process temperature is dictated by the alloy melting temperature. However, when we look into what has been established in the SMT manufacturing, the actual production conditions that have been adopted provide us much room to accommodate a higher melting temperature than 63Sn37Pb, albeit in a reasonable (confined) extent. There is a practical peak temperature for reflow and wave soldering. Thus in order to meet and exceed the manufacturing requirements in the day-in and-day-out mass production, the drop-in replacement requires the reflow peak temperature being kept below 235 °C and the wave below 245 °C, since these have been the upper peak temperature used during the 63Sn37Pb era. When the required reflow temperature or wave temperature goes higher than the above-mentioned temperatures, a modification approach is in order. Consequently, the required alloy's melting temperature is dictated by the process approach that is elected.

In addition to an alloy's melting temperature, another manufacturing parameter is the alloy's intrinsic wetting ability on the commonly used substrates in the electronic packaging and assembling process.

Alloys by Melting Temperature

Taking all relevant parameters into consideration including production environment and performance criteria, Table 1 summarizes the viable Lead-free solder alloys for SMT manufacturing. They are separate into two groups—for Drop-in and for Modification manufacturing. SnAgCu eutectic by its melting temperature requires some modification, while Enhanced SnAgCu (such as the proper compositions of SnAgCuIn) can serve as the Drop-in Lead-free alloys, which does not require a higher process temperature.

Table 1 - Two Groups of Viable Lead-Free Alloys

Drop-in approach
Sn3.0-4.1Ag0.4-1.5Cu4.0-8.0In
Sn3.0-4.1Ag1.0-4.0Bi1.0-8.0In
Sn3.0-4.1Ag0.4-1.5Cu1.0-4.0Bi
Sn0.1-1.5Cu0.1-6.0In0.01-1.0Ga
Modification approach
Sn3.0-4.0Ag.04-1.5Cu
Sn3.5Ag
Sn0.7Cu

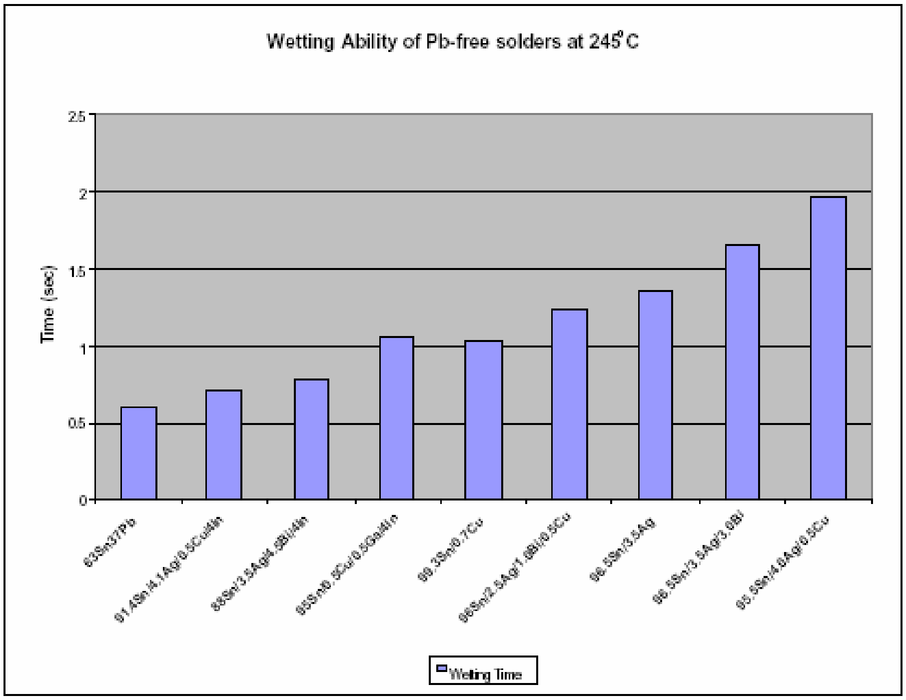


Figure 1 - Relative Intrinsic Wetting Ability of Selected Lead-Free Solder Alloys

Alloys by Wetting Ability

Figure 1 illustrates the relative wetting ability of the selected Lead-free alloys using the established Wetting Balance method, exhibiting that the "enhancement" not only lowers the alloy's melting temperature but also enhance the intrinsic wetting ability. Over a range of temperature, the test results indicate that the Enhanced SnAgCu alloys are expected to impart better wetting ability under the existing SMT process conditions than SnAgCu, SnAg or SnCu eutectic. SnAgCu, SnAg or SnCu eutectic alloys are also expected to require a higher process temperature, as clearly indicated in their melting temperature of Table 2.

Table 2 - Melting Temperature of Viable Lead-Free Alloys

Drop-in approach Melting Temperature
Sn3.0-4.1Ag0.4-1.5Cu4.0-8.0In 195-204
Sn3.0-4.1Ag1.0-4.0Bi1.0-8.0In 199-207
Sn3.0-4.1Ag0.4-1.5Cu1.0-4.0Bi 205-212
Sn0.1-1.5Cu0.1-6.0In0.01-1.0Ga 209-213
Modification approach
Sn3.0-4.0Ag.04-1.5Cu 217-220
Sn3.5Ag 221
Sn0.7Cu 227

Physical and Mechanical Properties

For alloy compositions of Sn3.0-4.1Ag0.5-1.5Cu4.0-8.0In, two representatives identified as V347 (Alloy 7) and V349 (Alloy 9) (hereinafter called alloy 7 and alloy 9, respectively) are tested and used in various manufacturing operations. In comparison with 63Sn37Pb, the corresponding physical properties including solidus/liquidus temperatures, density and Coefficient of Thermal expansion (CTE) are outlined in Tables 3 and 4, respectively. The mechanical parameters including isothermal fatigue, tensile strength, yield strength, maximum percent of strain and toughness (per ASTM methods) are summarized in Tables 5 and 6, respectively.

Overall, the mechanical properties in strength and fatigue compare much favorably with 63Sn37Pb.

Table 3 - Physical Properties of Alloy 7

Physical Properties	Alloy 7	Sn63Pb37
Solidus (°C)	202	183
Liquidus (°C)	210	
CTE (PPM)	22.9	23.3
Density (g/ml)	7.4	8.4

Table 4 - Physical properties of Alloy 9

Physical Properties	Alloy 9	Sn63Pb37
Solidus (°C)	202	183
Liquidus (°C)	207	
CTE (PPM)	21.9	23.3
Density (g/ml)	7.4	8.4

Table 5 - Mechanical properties of Alloy 7

Mechanical Properties	Alloy 7	Sn63Pb37
Cycle Fatigue	> 15,000	3650 ~ 3971
Tensile Strength (MPa)	65.9	44.5
Yield Strength (MPa)	54.2	35.8
Max Percent Strain (%)	34.5%	68.4%
Toughness (MPa)	20.1	17.2

Table 6 - Mechanical properties of Alloy 7

Mechanical Properties	Alloy 9	Sn63Pb37
Cycle Fatigue	6000 ~ 9000	3650 ~ 3971
Tensile Strength (MPa)	65.1	44.5
Yield Strength (MPa)	50.9	35.8
Max Percent Strain (%)	34.3%	68.4%
Toughness (MPa)	19.4	17.2

Manufacturing Production and Testing Results

Alloy 9 and Alloy 7 have been used in various end-use products; comprehensive and thorough tests have been conducted in comparison with 63Sn37Pb and, in some cases, compared with SnAgCu eutectic. Data and production results presented below are extracted from PCB assemblies of specific end-product manufacturers in their testing and qualification programs and/or in actual productions.[6]

Wave Soldering

Under a typical wave soldering temperature profile (with wave temperature around 245 °C), Figure 2 illustrates the resulting solder joints of various components of PCB assemblies. Joints were well formed in appearance with good wetting as shown in Figure 3. The contamination level of solder pot was monitored under a high-volume soldering assembly line over a period of approximately six months. Figure 4 exhibits that the alloy compositions remained stable in its key functional elements of Ag, Cu, In. In the meantime, the trace elements and contamination level in Al, Fe, Zn, Cd, Bi, Pb were also monitored as summarized in Figure 5, indicating that all trace elements have met the specified limits.

Since dross tendency closely affects the effectiveness and economics of wave soldering, the dross tendency has been gauged among the viable Lead-free alloys. Alloy 9 imparted less dross tendency than SnAgCu and SnCu counterparts as shown in Figure 6. A separate publication will cover the details of the study on wave soldering using Alloy 9.

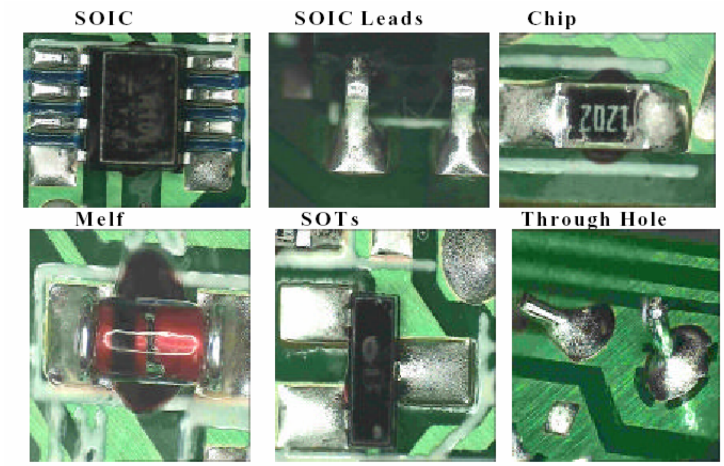


Figure 2 - Examples of Wave-Soldered Joints of Various Components

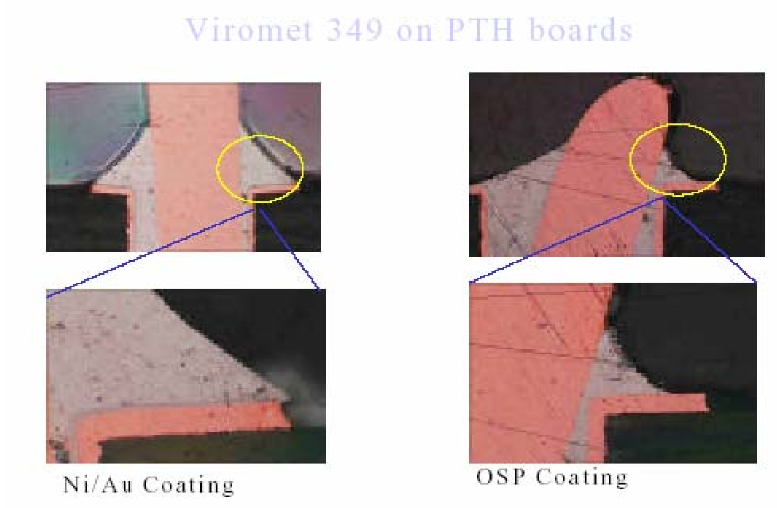


Figure 3 - Example of Wave-Soldered Joint Fillet

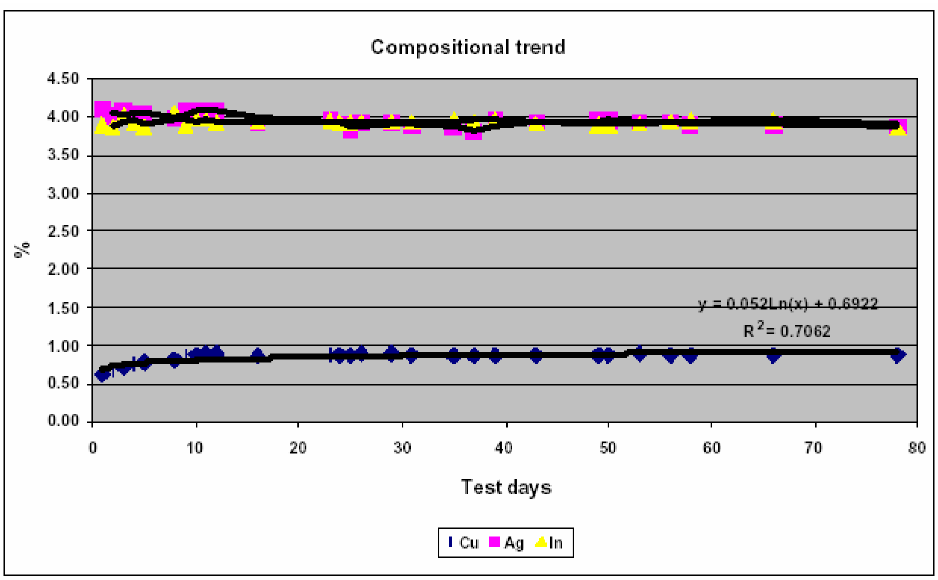


Figure 4 - Stability of Key Functional Elements of Alloy 9 in Wave Solder Pot

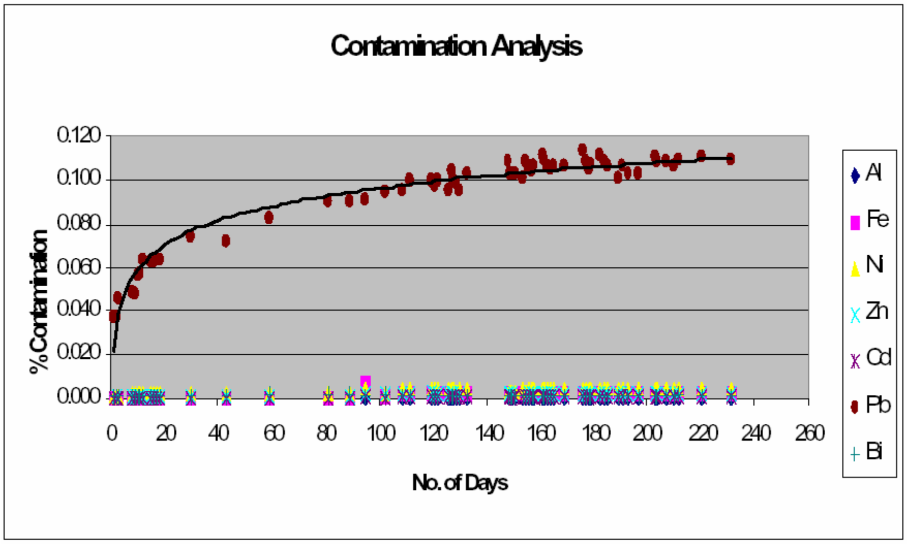


Figure 5 - Trace Element Analysis in Wave Solder Pot

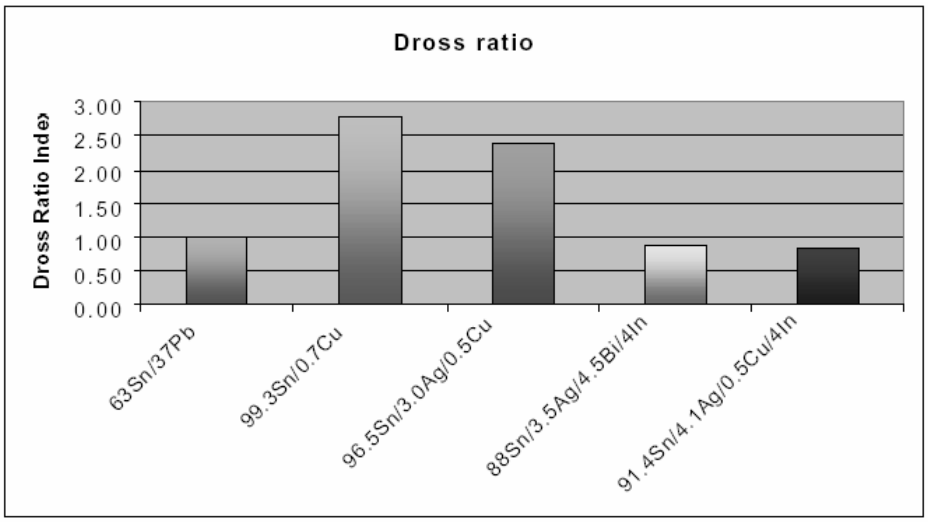
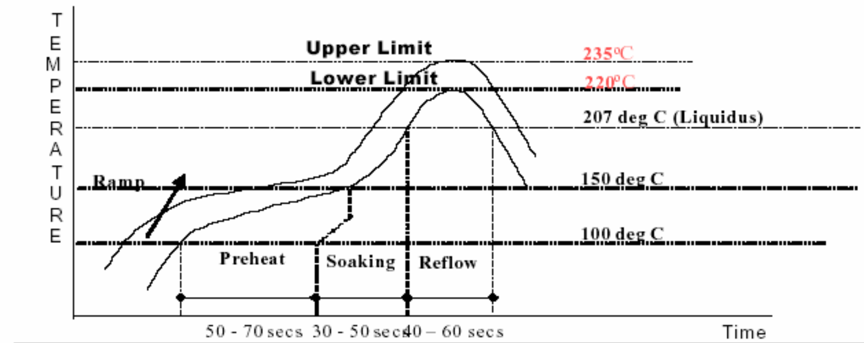


Figure 6 - Relative Dross Tendency of Selected Lead-Free Alloys

Reflow Process

SMT reflow process can be readily performed under the peak temperature in the range of 225 °C —235 °C. Figure 7 depicts a schematic of reflow temperature profile. The solder joints are well formed with good wetting on first-side reflow and on second-side reflow; some typical joint fillets are shown in Figure 8-10. For OSP PCB surface finish, some exposed Cu pads were observed. Due to the limitation on the length of this article, solder paste application characteristics and other process aspects will be discussed in a separate publication.



Temperature Range (°C)	100 -150	150 - 207	> 207
Time Taken (sec.)	50 - 80	30 - 80	30 - 60
Peak Temperature(°C)	220 - 235		

Figure 7 - Reflow Profile Representing the Existing Peak Temperature without Elevation

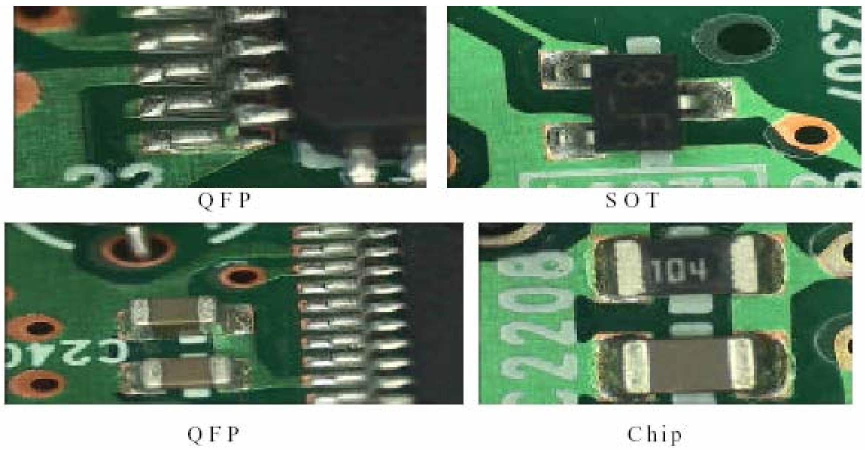


Figure 8 - Examples of Reflowed-Soldered Joints of Various Components

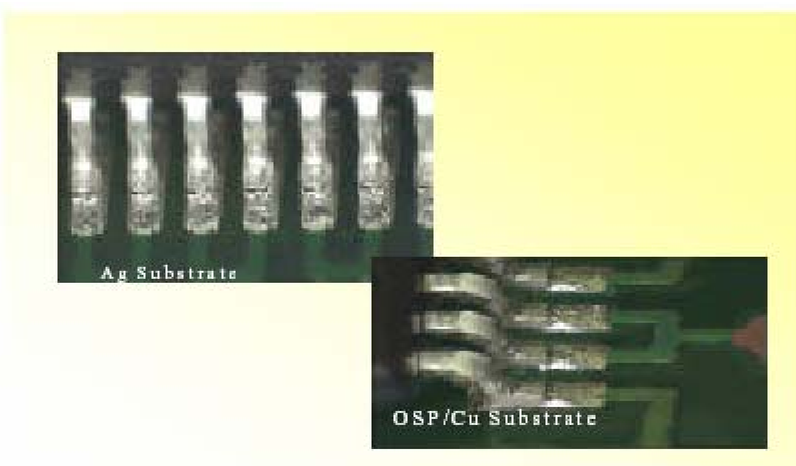


Figure 9 - Example of Reflowed-Soldered Joints of Various Components

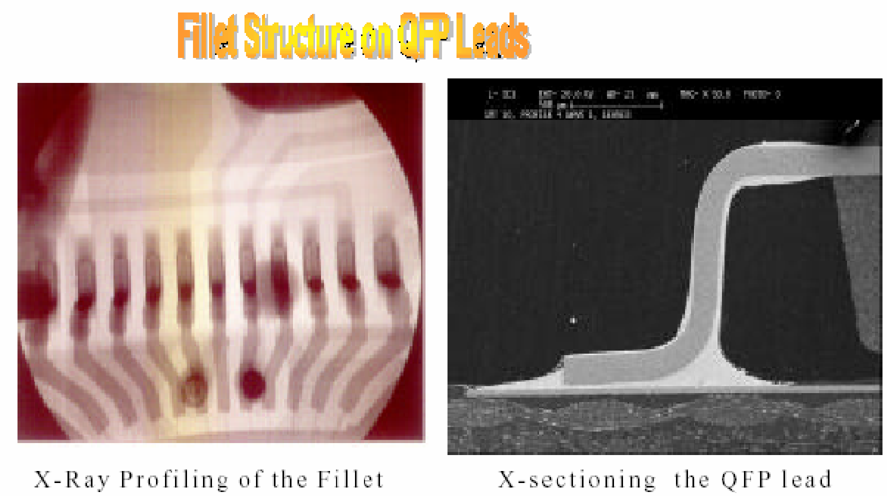


Figure 10 - Cross-Section of Reflowed-Soldered Joint

Bond formation - Intermetallic Thickness

The corresponding intermetallic thickness was measured for both wave soldering and reflow soldering processes, respectively. The data on immersion Ag and OSP substrates are summarized in Table 7. It is interesting to note that the thickness of intermetallic bonding layer is essentially comparable between Alloy 9 and 63Sn37Pb from wave soldering and between Alloy 7 and 63Sn37Pb from reflow soldering with a difference within a half micron.

Table 7 - Intermetallic Thickness of Alloy 7 vs. 63Sn37Pb on Immersion Ag and OSP PCB Substrates after Reflow or Wave Soldering

Solder	**Intermetallic Thickness (Micron)**			
	Ag		**OSP**	
	Reflow	**Wave**	**Reflow**	**Wage**
Alloy 7 or Alloy 9	2.27	2.50	2.22	2.81
63Sn37Pb	2.23	2.25	2.44	2.45

Temperature cycling and thermal shock tests

In accordance with the industry standards in conjunction with the specially designed parameters by specific manufacturers, a variety of testing parameters were performed. Table 8 depicts a variety of test conditions that are designed to qualify the Lead-free alloys and to assess the reliability of assemblies. Details of each test will not be included in this presentation. As examples, under a set of designed temperature cycling parameters (-25 °C to 85 °C, 2-4 hours dwell, 200 cycles), the solder joints made of SnAgCu exhibited surface cracks as shown in Figures 11-13, and solder joints made of 63Sn37Pb experienced catastrophic fillet cracks as shown in Figures 14-15, while the solder joints made of Alloy 9 (SnAgCuIn) remained intact.[6] Under JESD 22-A-104-B testing conditions (-40 °C to 125 °C, 15 minutes dwell time, one hour/cycle), at 1000 cycles, minor internal micro-cracks were observed for both Alloy 9 and 63Sn37Pb, although no major failure occurred. However, Alloy 9 showed less internal microcracks in number and extent than 63Sn37Pb.

Table 8 – Representation of Testing Conditions for One Manufacturer

Test Items	Conditions	Remarks	Qty	Results
General Inspection	-------	--------	26	**Passed**
High Temperature aging	+50oC, 72 hrs	Rm Temp. 3 hrs	2	**Passed**
High Temperature storage	+60oC, 72 hrs	Rm Temp: 3 hrs	2	**Passed**
Low Temperature aging	-10oC, 72 hrs	Rm Temp: 3 hrs	2	**Passed**
Low Temperature storage	-10oC, 72 hrs	Rm Temp: 3 hrs	2	**Passed**
Low Temperature dew	-10oC, 2 hrs	20oC, 65%RH, ½ hrs	1	**Passed**
Humidity aging	+40oC, 95%RH, 96 hrs	Rm Temp: 3 hrs	2	**Passed**
Humidity storage	+40oC, 95%RH, 96 hrs	Rm Temp: 3 hrs	2	**Passed**
Humidity load	+40oC, 95%RH, 96 hrs, 145kg	Impulse: 2 hrs	1	**Passed**
Static impulse and noise	20oC, 20%RH, 2/5 hrs	Noise: 5hrs	1	**Passed**
Standard drop	--------	--------	2	**Passed**
Low Temperature drop	-10oC, 2 hrs	--------	1	**Passed**
Continuous monitor CD/	CD/MD: 6 hrs, Tape: 3 hrs	--------	1	**Passed**
Vibration and stepping	--------	--------	2	**Passed**
Thermal Shock	-20oC~+60oC, 10 hrs	Rm Temp: 3 hrs and confirm after3 days	1	**Passed**
1 meter drop	---------	For sets <20kg	1	**Passed**
Mechanism life test	15K cycles	--------	2	**Passed**
CD life test	15K cycles	--------	2	**Passed**
Normal Temperature aging	1000 hrs	--------	2	**Passed**

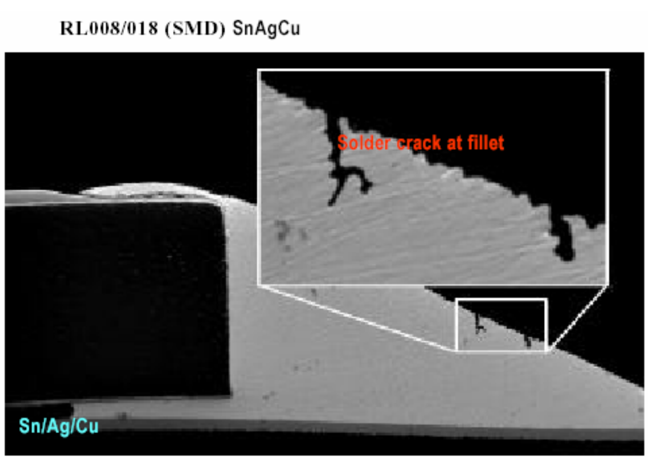


Figure 11 - SEM Microgram of SnAgCu Solder Joint after Temperature Cycling as Specified

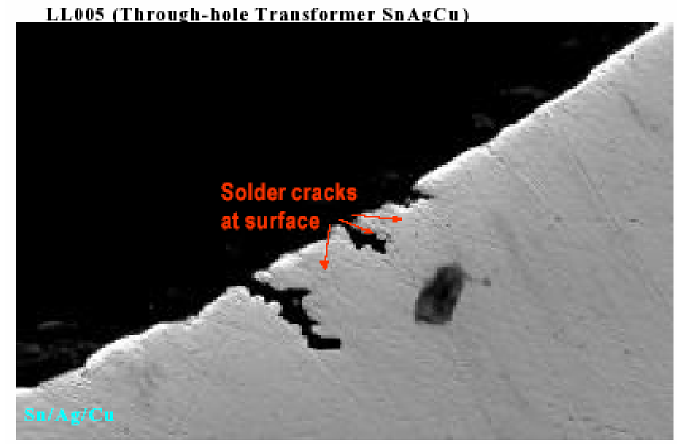


Figure 12 SEM Microgram of SnAgCu Solder Joint (Thru-Hole Transformer LL005) after Temperature Cycling Conditions as Specified

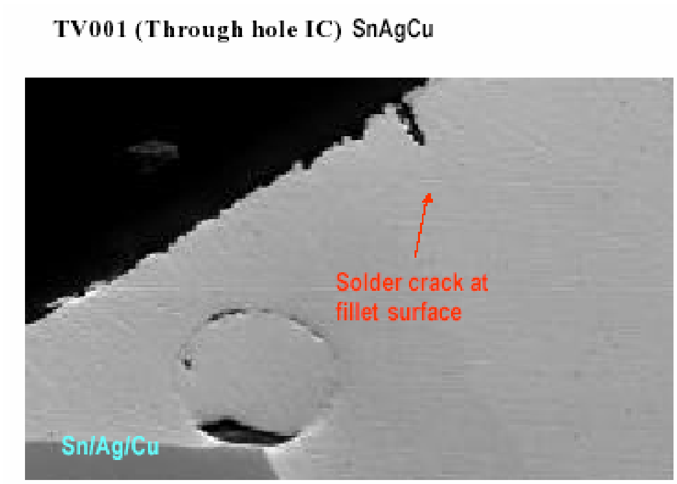


Figure 13 SEM Microgram of SnAgCu Solder Joint (Thru-Hole TV-001) after Temperature Cycling Conditions as Specified

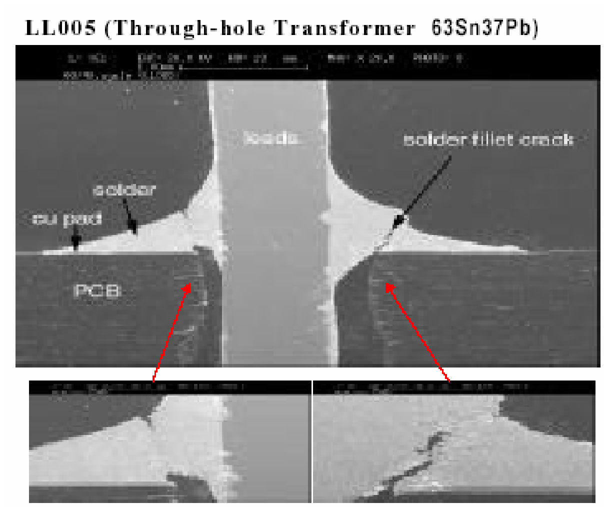


Figure 14 SEM Microgram of 63Sn37Pb Solder Joint (Thru-Hole Transformer LL005) after Temperature Cycling Conditions as Specified

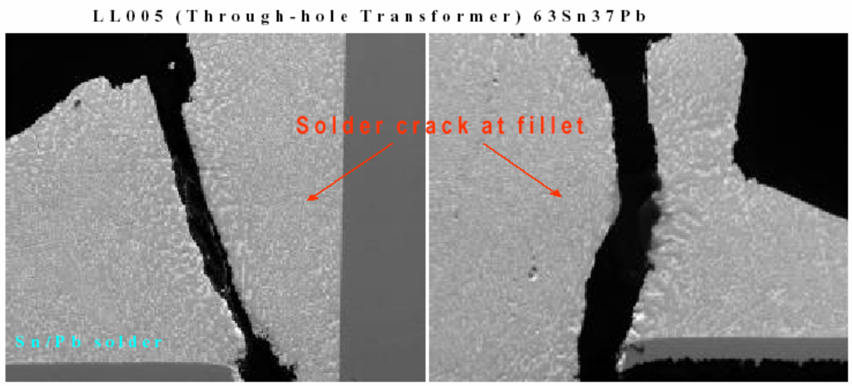


Figure 15 SEM Microgram of 63Sn37Pb Solder Joint Crack (Thru-Hole Transformer LL005) after Temperature Cycling Conditions as Specified

Solder Joint Void examination

X-ray scan was carried out to examine voids in the resulting solder joints from Alloy 7 solder paste. As shown in Figure 16, no excess voids were observed in both reflowed and wave soldered joints.

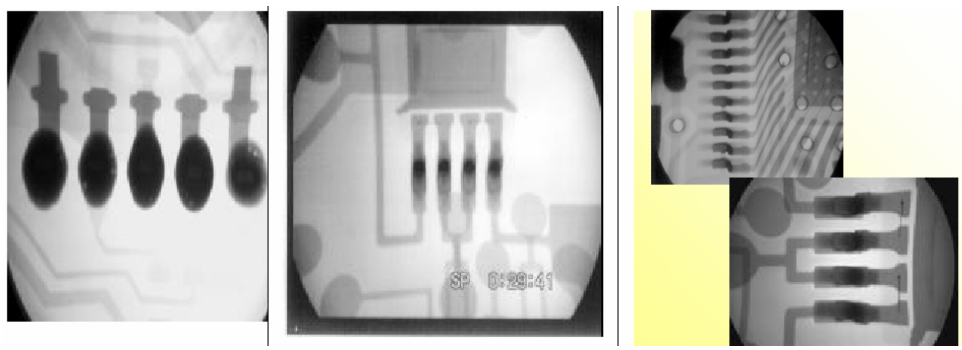


Figure 16 - X-ray Scan to Detect Voids in Solder Joints of Various Components

Whisker test

In an attempt to promote whisker growth, test conditions were set at a temperature of 60 °C and humidity of 95%, where Alloy 7 and Alloy 9 solders were subjected to for duration of 1000 hours. As shown in Figure 17, no whiskers were detected.

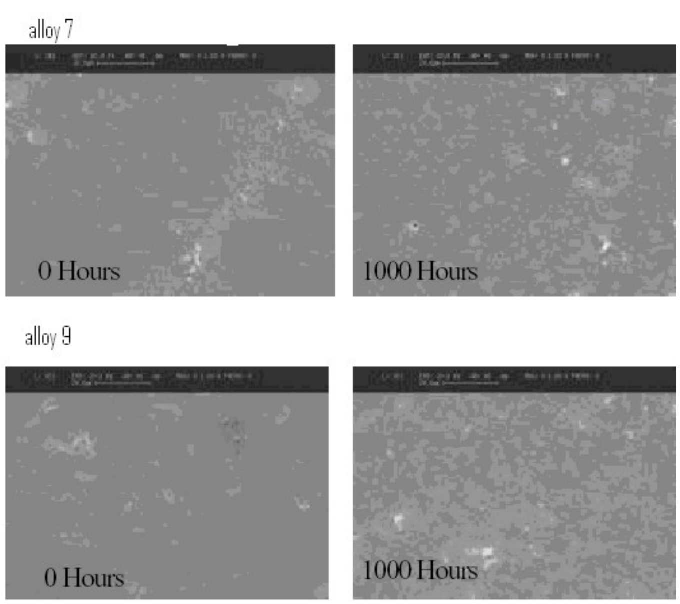


Figure 17 Whisker growth test for Alloy 7 and Alloy 9

Drop Test

PCB assembly made of Alloy 9 was inserted into its casing and a drop height was set at one meter above the ground level. The assemble was then dropped onto the concrete floor. Under inspection and examination, no failure in solder joint made of Alloy 9 was detected (failure did occur at the copper pad de-lamination).

Paste in Hole Application

With the need for certain assembly designs, solder paste Alloy 7 was used in through-hole components by depositing solder paste onto through-hole PCB pads before and after component insertion. Figure 18 illustrates the resulting solder joint. The solder fillet indicates good wetting and capillary effect on the component leads. In physical maneuvering and application, Alloy 7 solder paste performed comparably as 63Sn37Pb.

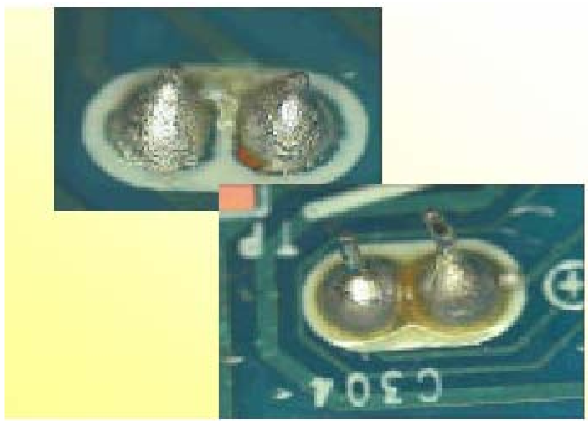


Figure 18 Example of Alloy 7 solder paste-in-hole for through-hole components

Solder Wire Ability and Application

Solder wire in various diameters can be readily drawn with Alloy 9 solder. Figure 19 depicts one application of fine wire for attaching optical components. The detailed test results will be discussed in a separate presentation.

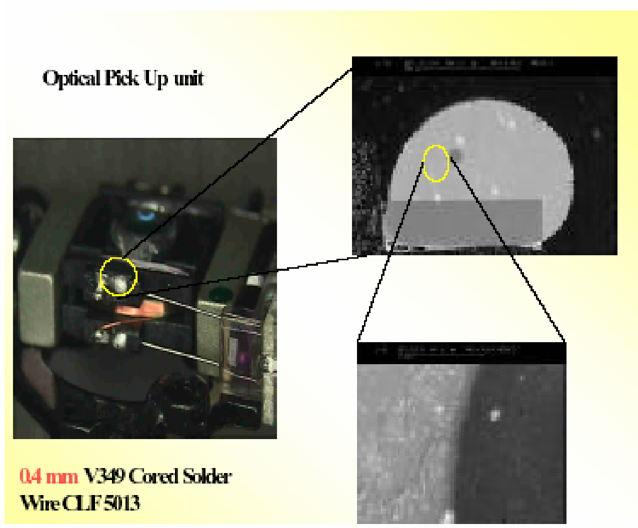


Figure 19 - Alloy 9 Solder Joint of a Fine Wire Application for Optical Devices

System Cost Assessment

Elemental cost of an alloy is one of a number of cost contributors to a system cost, which will be presented in a separate presentation.

Discussions and Conclusions

The superior mechanical properties of the Enhanced SnAgCu compositions are well understood based on the sound material science fundamentals—the alloys are enhanced not only by the hard phases but also by the solution-strengthening mechanism (i.e., Labush's statistical theory). This dual strengthening mechanisms that work synergistically are not easy to beat. For more detailed discussions, readers are directed to Reference.[7]

The "Drop-in" manufacturing works with the existing soldering process (i.e. < 235 °C for reflow + and <245 °C for wave) of the current SMT infrastructure.

To fit in with the existing soldering process, it takes Enhanced SnAgCu alloys, such as Alloy 7 and Alloy 9 (in addition to Sn3.0-4.0Ag1.0-3.0Bi1.0-8.0In compositions). Note that at the temperature around 235 oC, the Enhanced SnAgCu offered much better wetting ability than the ternary SnAgCu. This wetting property is expected to directly affect production yield. Furthermore, the enhancement extends to the reduced dross in wave soldering process as shown in Figure 6. Some Enhanced SnAgCu compositions have been successfully used in producing various commercial products over a period of time.

Some key conclusions are drawn as below:
1. A higher process temperature than what has been established in SMT would create extraneous demands as well as risk in various fronts.
2. Implementation of Lead-free does not require a higher temperature.
3. The Enhanced SnAgCu, such as Alloy 7 and Alloy 9, do not require a higher process temperature (vs. 63Sn37Pb) in both reflow and wave soldering.
4. The Enhanced SnAgCu, such as Alloy 7 and Alloy 9, work compatibly with the existing SMT operation within the established SMT infrastructure as a drop-in replacement.
5. The Enhanced SnAgCu, such as Alloy 7 and Alloy 9, provide better performance in wetting, and dross than 63Sn37Pb.
6. The Enhanced SnAgCu, such as Alloy 7 and Alloy 9, offer better mechanical behavior under a variety of stress conditions than 63Sn37Pb.
7. In comparison with SnAgCu eutectic, the Enhanced SnAgCu, such as Alloy 7 and Alloy 9, provide superior performance in wetting, dross, as well as mechanical behavior under a variety of stress conditions.
8. The Enhanced SnAgCu, such as Alloy 7 and Alloy 9, have proven working well in various production environments.
9. For best practices and effective Lead-free implementation, the ability to separate Lead-free related issues from the general SMT production issues (SnPb or Lead-free) is paramount.
10. Based on what have been learned and developed during the 23-year SMT production, the best practices on the production floor dictate not only the production yield but also the long-term reliability. Set the material/process production system correctly.

Acknowledgement
The author expresses her appreciation to many who have contributed to the Lead-free technology development over the years; also to those who are on the frontier in diligently implementing the drop-in Lead-free manufacturing without using a higher process temperature.

Reference
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9.