Drop in Replacement of Tin/lead Solder Alloy In Wave Soldering Process – Lead Free Solders

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Introduction

Tin/Lead alloy has been a material widely used in the field of interconnect due to its cost and properties. For decades, components and substrate are being developed to meet the requirements in the electronics and microelectronic field based on all the existing data available on the existing lead containing alloys. In the wake of calls to ban lead due to it's toxicity level and effects on children, industry especially the material suppliers geared themselves up to develop lead free alloy. Within a span of 10 years, various patent on lead free alloys has been published, NCMS has also performed a series of test on various type of lead free, lead free organization was set up to look into the lead free issue etc. Industry has by now trying very hard to standardize a specific lead free alloy to be the industry norm for example Sn/Cu , Sn/Ag/Cu etc.. Due to this specification, equipment suppliers also jump into the bandwagon of developing new equipments to meet the requirement, components suppliers are trying their very best to study into new components that could also meet the requirement of the lead free materials.

Criteria For Lead Free Replacement

1. Non Toxic – Any elements that the industry chooses to replace lead in the solder must not be harmful to people and environment. Table 1 shown elements rank by their toxicity level .

2. Acceptable Processing Temperature. – Any design alloy must be able to perform a good wetability under the current processing temperature or close. For all the years, components, pcbs and also equipment has been developed based on the current processing temperature and thus any change of alloy must have the acceptable processing temperature to avoid any reliability or cost that will arise from it.

3. Narrow Plastic Range - This will minimize any reliability or the formation of weak phase that may have resulted by the large plastic range.

4. Good Wetting – Any design alloy must have good wetability in the current process temperature.

5. Joint Reliability – Any design alloy must exhibit similar or better joint reliability as the current tin/Lead alloy.

6.Manufacturable Material – Any design alloy must be manufacturable to all various form such as bar, ingot, wire, stick and powder.

7. Availability And Affordability – All elements chosen as the candidate for the lead free alloy must be available at a reasonable price.

8. Compatibility -- Any design alloy must be compatible to materials used in the PCBA and also equipment. For example, alloy should be compatible with materials used on the board in term of formation of metal to metal bonding, thermal expansion coefficient whereas the material must also be compatible with the material used in the equipment and should not etch the material especial in the wavesoldering pot easily.

What is Drop In Replacement?

Tin Lead solder has been used in the soldering industry apart from being low cost and its abundance, its good physical and mechanical properties such temperature, solderability, cycle fatigue resistance, tensile strength, ductility, thermal expansion coefficient etc. Therefore, for any lead free alloy to be acceptable as a drop in replacement of tin/lead alloy, they must first have the following properties:

- Minimal or no process change
- Alloy design should be environmental friendly
- Alloy design should be similar or better than existing tin/lead alloy

The Issue Encounter by most of the Lead Free Alloys

Temperature. Most of lead free alloys have higher melting temperature than tin/lead alloys and hence manufacturing assembly, board and component status issues have to be address first.

Joints Quality and Reliability. Most lead free alloys have projected the image of having a higher or similar joint strength as compared to tin/lead alloy except for tin/copper alloy. But as tin/lead alloy is more ductile, long term reliability has proven otherwise where some of these lead free joints fail under fatigue and ageing faster than normal tin/lead joints.

Wetability. Most of the lead free alloy has poor wetability in comparison with the conventional tin/lead alloy. Wetability only improves with higher temperature. In some cases, stronger fluxes are needed to improve on the wetability aspect of these lead free.

The Developed

In the process of developing a suitable lead free alloys, binary alloys are most preferred as it is the easiest to control but unfortunately, such alloys eg. Tin/Copper, tin/Silver, tin/bismuth, tin/indium etc. has the problem of either high temperature or poor mechanical properties. For instance, tin/copper alloy, though it is an eutectic alloy and has been used by some companies as a replacement for tin/lead, its shortcoming such as high temperature, lower tensile strength and poor cycle fatigue resistance has been an issue that the industry will need to seriously look into.

Ternary alloys will be next category of lead free alloy the industry turned to. Institute such as NCMS, IPC lead free organization, Japanese Industry have strongly recommending tin/silver/copper as the replacement alloy for wave soldering process and also surface mount whereas tin/silver/bismuth for surface mount application and future wavesoldering application when all components are free of lead elements. Looking into these alloys, though most of them has tensile strength and cycle fatigue resistance that are similar or slightly better than tin/lead alloys, their high temperature will be an issue that needed to be looked into. The wetability of the alloy only improves with higher temperature and thus issue on temperature sensitive components, boards warpage etc. have to be address before any of such implementation. (Refer to table 1)

Solder Temp (oC)	Wetting Time (Sec)						
	63Sn37Pb	Sn96.5/3.5Ag	99.3Sn/0.7Cu	95.5Sn/4.0Ag/0.5Cu	96Sn/2.5Ag/1.0Bi/0.5Cu	Viromet 349	Viromet 347
235	0.767	2.189	1.411	3.368	1.86	1.156	1.171
245	0.606	1.352	1.034	1.946	1.235	0.716	0.573
255	0.546	1.05	0.682	1.284	0.824	0.544	0.464

Table 1: Comparison on Wetting Time against temperature between lead free alloys and tin/lead alloys

To achieve a real drop in replacement for tin/lead, we will probably need to go beyond ternary alloy to quaternary or even pentanary alloys etc. Singapore Asahi “Viromet ®“ series of alloys which comprises of tin/silver/copper/indium(Viromet 300 Series) composition are some good examples of a drop in replacement alloys. The targeted temperature for an alloy to be able to use as a drop-in should not exceed more than 210 degC liquidus temperature and process temperature of not more than 245 deg C for wave soldering and not more than 235degC for reflow soldering. (Refer to table 2).

Properties	Type of alloys						
	63Sn/37Pb	99.3Sn/0.7Cu	96.5Sn/3.5Ag	95.5Sn/4Ag/0.5Cu	96Sn/2.5Ag/0.5Cu/1Bi	Viromet 349	Viromet 347
Melting Temp.(^{o}C)	183	227	221	194-218	196-218	187-210	202-207
CTE(um/m^{o}C)	23.3	19.3	22.7	21.5	14.5	22.9	21.9
SG (g/ml)	8.4	7.31	7.38	7.4	7.38	7.4	7.4

Table 2: Physical Properties of Lead free alloys as compared to tin/lead alloy

These “Viromet®” series alloys have also proven to have good mechanical properties such as tensile strength, thermal expansion coefficient and good cycle fatigue resistance. (Refer to table 3)

Solder Composition	Max. Tensile Strength (MPa)	Load at Max Load (kN)	Modulus (Aut Young) (MPa)	Max. Percent Strain (%)	Energy to Yield Pt (J)	Energy to Break Pt (J)
63Sn/37Pb	40.307	1.14	5351.08	38.865	0.135	9.556
99.3Sn/0.7Cu	28.482	0.805	9296.346	87.38	0.05	14.861
96.5Sn/3.5Ag	35.898	1.015	7377.109	60.003	0.075	12.535
95.8Sn/3.5Ag/0.7Cu	38.869	1.099	8634.897	47.424	0.074	10.495
Viromet 349	41.716	1.18	6505.133	73.662	0.086	18.918
Viromet 347	53.24	1.505	7826.216	38.91	0.141	13.106

Table 3: Mechanical Properties of the lead free alloys annealed at 125^{o}C for 24 hours.

As observed from the tensile chart, Tin/copper, Tin/Silver/Copper/Indium(Viromet 349) has shown very good strain properties. In comparison with Tin/Lead alloy , Tin/Silver/Copper/Indium alloy has shown to have a better strength and strain whereas Tin/Copper though has good strain properties but has a poorer strength. Therefore, in the low cycle fatigue test, the Tin/Copper alloy is unable to have a higher cycle fatigue and thus resulted to joint failure under high fatigue cycle.

Alloy	**Melting T**	**N_f**
88.5sn/3.0Ag/0.5Cu/8In	195-201	>19,000
Viromet 347	202-207	
91.5Sn/3.5Ag/1.0Bi/4.0In	208-213	
92.8Sn/0.7Cu/0.5Ga/6.0In	210-215	10,000-12,000
85.2Sn/4.1Ag/2.2Bi/0.5Cu/8.0In	193-199	
Viromet 349	205-210	9812
93.3Sn/3.1Ag/3.1/Bi/0.5Cu	209-212	6,000-9,000
96.2sn/2.5ag/0.8Cu/0.5Sb	216-217	
95.4Sn/3.1Ag/1.5Cu	216-217	
Viromet 217	199-209	
96.5Sn/3.5Ag	221	4,186
63Sn/37Pb	183	3,650
99.3Sn/0.7Cu	227	1,125

Table 4: Thermal Cycle Fatigue Resistance of lead free alloy as compared to tin/lead alloys

Wave Soldering Process

In the wave soldering process, fluidity of the molten solder is utmost important. In order to achieve the fluidity of the alloy, pot process temperature has to be set high enough. Currently, in tin/lead application, normal pot temperature used is 245 +/- 5^{o}C. without inert environment. In order to be able to work as a drop in replacement in wave soldering, lead free selected alloys must be able to performed under similar process temperature as tin/lead. Any increase in temperature will most probably result to change in material such as pcb and sensitive components. In view of the wetability data, based on the JIS or IPC standards, in order to have a good solderability, the wetting time should be less than 1 sec. This is because in wave soldering process, the dwell time of board going through the solder wave is normally around 1 to 2 secs. If the board stays longer than these expected time, there are tendencies that the board especially the FR1 or paper phenolic board will experience warpage and will also cause some problem on the plastic or sensitive components.

Apart from having good material properties proven to be similar or better than tin/lead alloys, process application and reliability must also be proven to be compatible to tin/lead process. In this section we will look into solderability, contamination and product reliability issue of the lead free alloys in the wave soldering process.

Process Application

Solderability of any alloys depending very much on its fluidity or surface tension for it to adhere and soldered onto the substrate that need to be soldered. The alloys must achieve such properties in a process temperature at least similar to tin/lead alloy, 245 degC. In the solderability section, defects such as skip, bridging, blow hole, excessive solders, insufficient solder etc. are basic issue that should be looked into when sourcing for a good replacement solder.

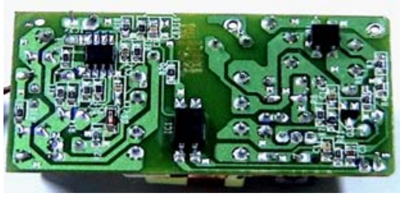
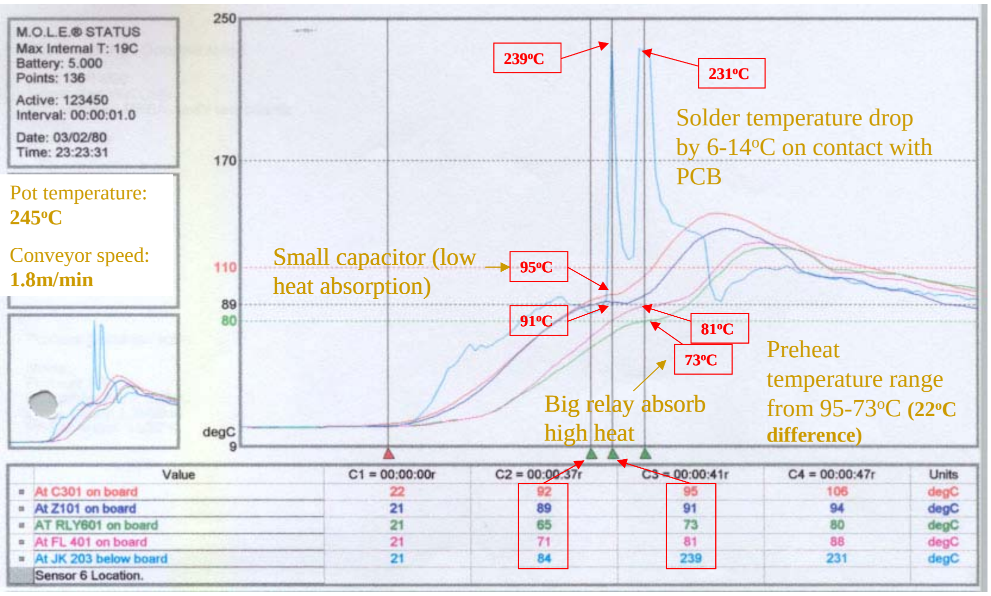


Figure 1. Samples of pcb waved with Viromet 349 alloys at 245°C.

Viromet 349 alloy has run successfully in various wave soldering applications at 245oC with minimal or no skip, blow hole, insufficient solder, bridging and excessive solder in comparison with tin/lead alloy. In this process, the solder works very well with rosin fluxes without any inert environment.



M.O.L.E.® STATUS
Max Internal T: 19C
Battery: 5.000
Points: 136
Active: 123450
Interval: 00:00:01.0
Date: 03/02/80
Time: 23:23:31

Pot temperature: **245°C**

Conveyor speed: **1.8m/min**

Value	C1 = 00:00:00r	C2 = 00:00:37r	C3 = 00:00:41r	C4 = 00:00:47r	Units
At C301 on board	22	92	95	106	degC
At Z101 on board	21	89	91	94	degC
AT RLY601 on board	21	65	73	80	degC
At FL 401 on board	21	71	81	88	degC
At JK 203 below board	21	84	239	231	degC
Sensor 6 Location.					

Figure 2: A general Wave soldering profile using Viromet 349 Lead free alloy.

Pot Contamination

Pot contamination monitoring for lead free solder is similar to normal conventional alloy. In lead free solder , lead become one of the main contaminants that needed to be monitored very closely as higher lead will lead to lead segregation in the joint which will result to joint reliability issue. In Viromet 349 alloy, lead contamination was also been monitor very closely as not all through hole components currently are lead free. It is found that lead contaminants stabilized after a certain concentration as these lead contaminants was also found in the dross. Hence, most of the lead has in fact dross out from the solder and thus maintaining low lead contaminants in the solder thus reflects the stability of the alloy in normal mass production.

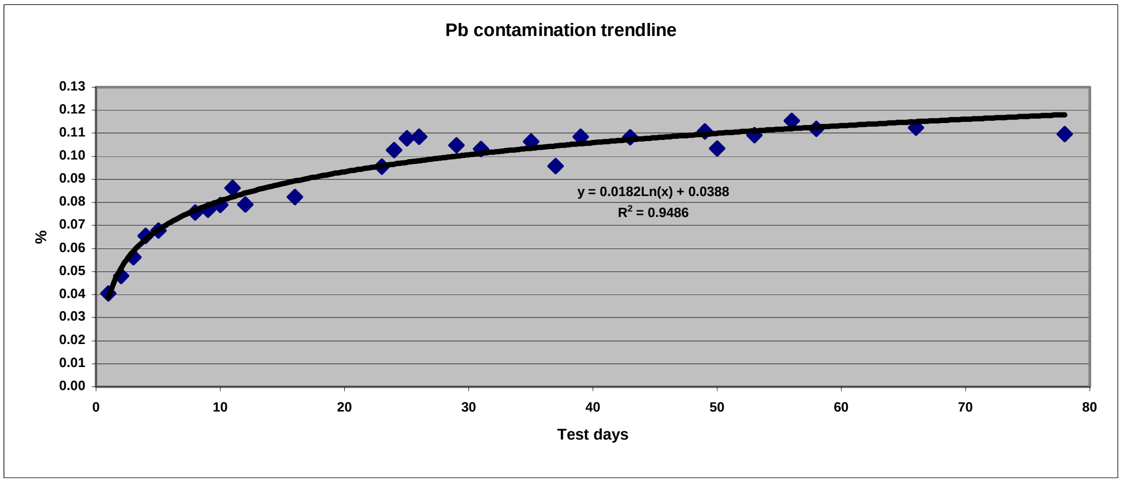


Table 4: Trendline of Pb contamination in the wave solder pot during mass production

Pot Stability

Currently, lead free pcb coating (HASL process) has not been materialized yet and hence most of the PCBA industries have switched to using bare copper substrate on the pcb. With the high amount of expose copper on the boards, dissolution of copper into the solder pot has becoming a concern for lead free solders pot stability. This will altered the whole compositional structure of the alloy that may result to melting point changes. This in turn will result to changed in fluidity of the solder if the melting point temperature is to be increased as the elements composition changes. All these will subsequently lead to solderability issue if no proper action is taken to rectify the pot stability.

In the event of Viromet 349 alloy, it was found that this alloy is very stable even after prolong running in a production condition. Refer to Table 6 for Pot stability. Trendline has been studied on all the elements in the pot run for a period of time. A studied on the melting temperature with the slight increase on copper element has proven to be of no effect on the base alloy. From the trendline prediction and correlation with pot that has run for more than 1 year, it is found that dissolution of the copper into Viromet 349 stabilise below 1.0%.

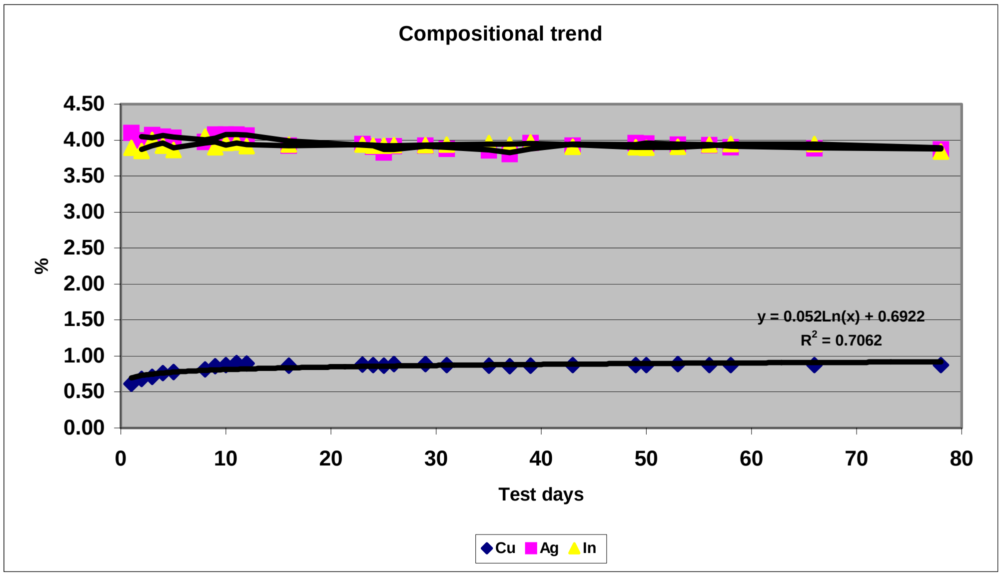


Table 5: Trendline on pot stability of Viromet 349 during mass production

Another important criteria will be the contamination of the alloy in the pot. This will determine the amount of dross collected which will reflects the amount of wastages and also the frequency of pot change due to the contamination level in the pot. All these will need to be determined against the normal operation of tin/lead. (Refer to table 5)

Table 6: Comparison chart on dross collected for common lead free alloys against tin/lead alloy.

Solder Alloy	1	2	3	4	Total (g/h)
Sn63/37	6.55	6.80	7.05	6.80	27.2
Viromet 217	3.8	5.50	5.60	6.90	21.80
Viromet 349	7.20	6.41	5.45	5.88	24.94
Sn/Cu0.7	10.36	10.71	10.70	10.10	41.87
Sn/Ag/Cu	13.95	10.95	10.50	12.85	48.06

Reliability Aspect

Any lead free solders that can be used in the current process but failed in term of reliability can still not be regarded as a drop in replacement solder for tin/lead. In this section, we will look into the aspect of reliability of the joints after soldering. Common reliability test such as Thermal shock, High Temperature Test, Vibration Test, Pull / Push strength test, Drop / Impact Test etc. are to be carried out based on individual industries requirement.

Here, I will share some of the reliability test result that has been carried out based on certain industries requirement. Common reliability tests such as

- Pull and Shear Strength Test
- Thermal Shock Test
- Thermal Cycling Test
- High Temperature Aging Test
- Vibrational Test
- Whisker Test
- Drop Impact Test

are usually performed by most electronic industry based on their application requirements and may defer from one company to another. In this paper, we will discuss basically on 3 most common tests, Pull and Shear Strength Test, Thermal Shock Test and Drop Impact Test.

Pull and Shear Strength Test

No	**Platin Type**	**Component**				
			Sn/Pb	**Sn/Cu**	**Viromet 349**	**Sn/Ag/Cu**
1	SnPb	D5	8.4	9	10.41	9
2	SnPb	D4	10.35	6.6	11.1	9.6
3	SnPb	C4	2.2	1.7	2.6	2.9
4	SnPb	C5	2.2	2.9	2.5	2.7
5	SnPb	IC40	9.2	12	15.4	15.3
6	SnPb	O40	7.2	6.6	7.3	4.8
7	SnPb	R5	2.6	1.65	3.4	2.65
8	SnPb	R6	3	2	3	2.9
Ave			5.644	5.306	6.964	6.231

Table 7 : Comparison of Terminal Shear Test For Lead Free Alloys

No	Plating Type	Component	Solders			
			Sn/Pb	**Sn/Cu**	**Viromet 349**	**Sn/Ag/Cu**
1	Ag	JK10	5.3	10.0	9.75	6.35
2	Ag	SW50	14.35	17.85	17.4	19.2
3	Sn	FC30	7.55	8.15	8.70	8.55
4	Sn	FL40	1.35	2.45	4.75	3.25
5	Sn	CN60	3.15	3.95	4.95	4.15
6	SnPb	T20	10.8	14.6	14.2	16.45
7	SnPb	R21	5.7	6.85	8.05	7.15
8	SnPb	IC602	4.4	4.75	4.80	5.4
Ave			6.575	8.575	9.075	8.813

Table 8 : Comparison On Pull Strength For Lead Free Alloys

Thermal Shock Test

Thermal shock is to test the resistance of solder towards the sudden changes of temperature. The temperature ranges used in the thermal shock test depending very much on the type of industries or products produced. The following result of thermal shock test is based on the following criteria –25oC to +85oC, 4 hours soaking for a duration of 200 cycles.

Failure Mode Analysis

The failures were located on only two (2) locations: RL008/018 (Resistor) and LL005 (Big Transformer). The failure on RL008/018 for both SnPb and Viromet 349 is Lead Plating and Intermetallics failure. SnPb shows catastrophic joint failure at transformer LL005, but Viromet 349 display non-catastrophic internal crack at this component. Hence, it can be concluded that Viromet 349 is a more superior alloy than SnPb solder

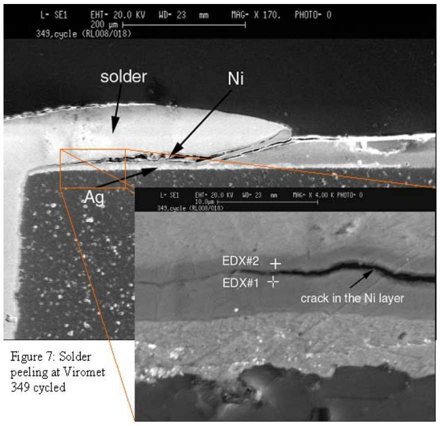


Figure 3:
RL008/018 components.
Similar failure mode was observed in both Viromet 349 and SnPb solder.
EDX shows presence of Ni only. Hence, this failure is considered a Lead Plating Failure.

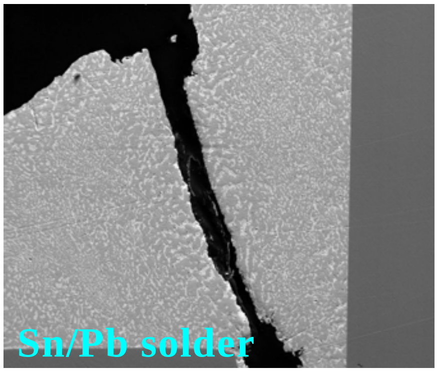
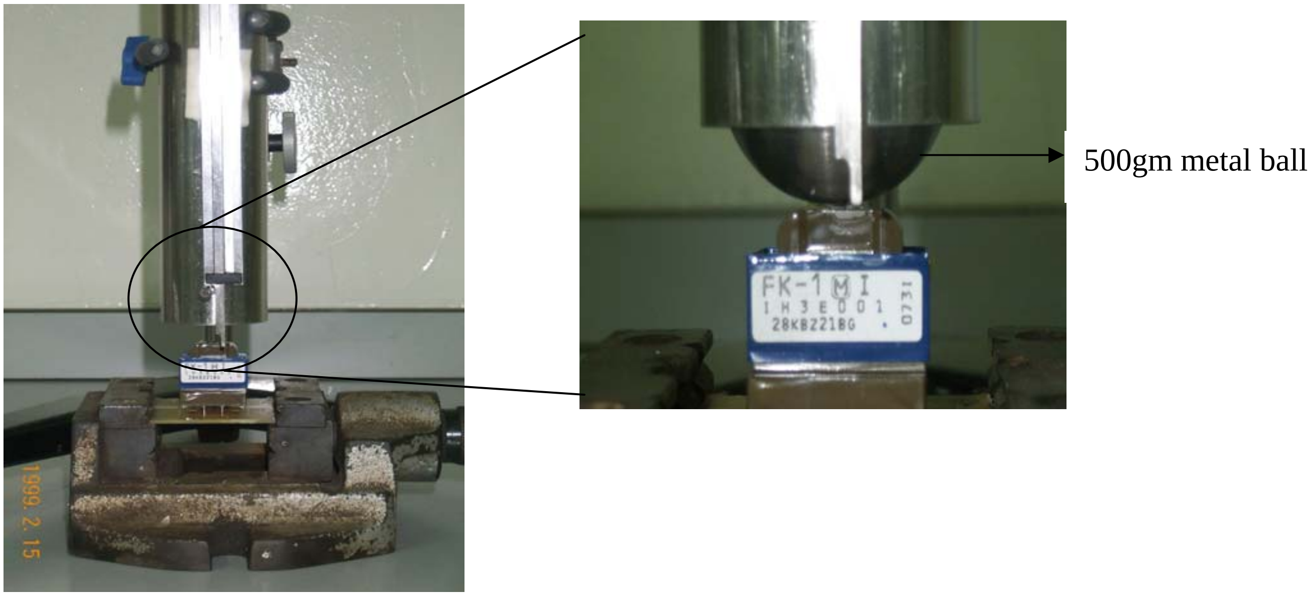


Figure 4:
Transformer.
Full crack was observed on the SnPb joint under this thermal shock condition.

Drop Impact Test.

Drop Impact test are normally carried out by many industry where the products has a tendency to drop which may result to system failure, component damage and even solder crack. There are many ways of performing this test as it differs from industry to industry. In the telecommunication industry, phones are being dropped at different angle in a specific height to determine the impact of the drop, similarly, in consumer electronics industry, products are being drop at a specific height to determine the impact of the drop. In this discussion, we have devised a method where we quantify the load of impact onto the board at a certain distant to provide a direct impact onto the PCB board and the joint.

Figure 5: Drop Impact Test Set up

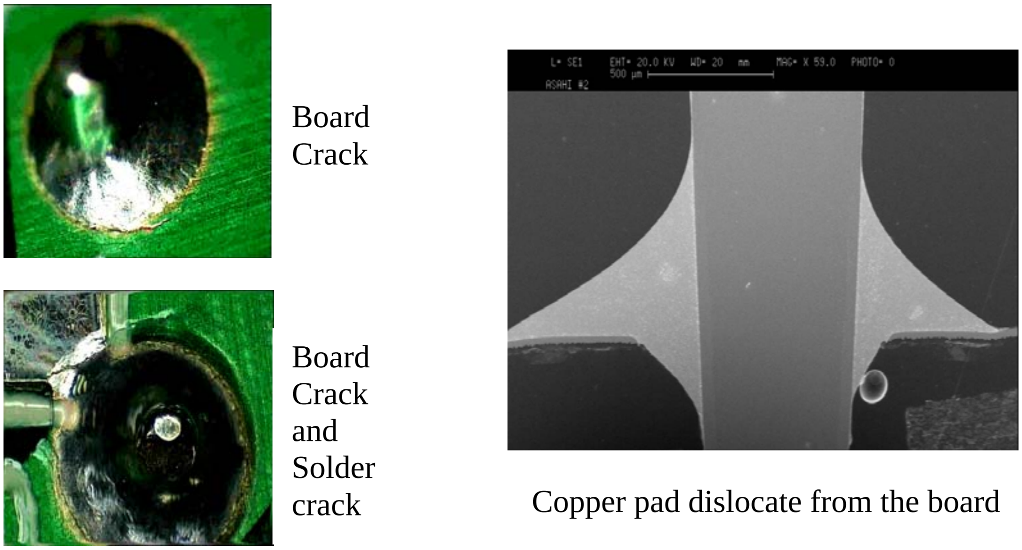


Failure Analysis Mode

Table 9: Comparison on crack phenomena found on boards with Sn/Pb and Virometⁿ 349 solder

Solder Alloy		**No of Drops To Failure (Constant at 25mm)**				
		1st Drop	**2nd Drop**	**3rd Drop**	**4th Drop**	**5th Drop**
Sn/Pb	**Sample 1**	**BF**	**BF**	**BF**	**BF**	**BF**
Sn/Pb	**Sample 2**	**SF/BF–L2**	**SF/BF–L3**	**SF/BF–L3**	**SF/BF – L4**	**SF/BF – L4**
V349	**Sample 1**	**BF**	**BF**	**BF**	**BF**	**BF**
V349	**Sample 2**	**BF**	**BF**	**BF**	**BF**	**BF**

Note: BF: Board failure: SF: Solder Failure : L1.2.3.4 degree of crack(90.18.270.360^{o})



Board Crack

Board Crack and Solder crack

Copper pad dislocate from the board

Figure 6: Examples of crack phenomena found on the boards

In this drop impact test, Viromet 349 alloy has proven to have good joint strength which does not crack under high impact stress.

Conclusion

There are few criteria to ensure a good drop in replacement.

- Temperature similar to normal Sn/Pb alloy.
- Fast soldering speed – as high as 1.8m/min
- Solderability similar to Sn/Pb alloy
- Reliability of Thru'-hole joints are good and at certain test has proven to be better than Sn/Pb alloy.
- Viromet 349 has proven to has no fillet lifting issue in plated thru' hole boards faced by most lead free alloys and sometime by Sn/Pb alloy.
- Similar wave soldering machine as Sn/Pb could be used without machine alteration.
- Running under normal condition without any requirement of inert environment.