On Solder Joints Reliability and Component Damage of Hand Soldered Lead-Free PTH and SMD Components

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Abstract
Due to the European legislations (RoHS and WEEE) consumer products need to be soldered with lead-free solders from the first of July 2006. Since several properties (physical, chemical, mechanical and most pronounced but less severe visual) of lead-free solders are thought to be degenerated compared to the lead-containing variants, thorough investigation of the solders and of the solder processes is necessary.

In this research, different types of PTH and SMD components are hand soldered with lead-free solder (Sn-Ag-Cu, shortened SAC) on PCB's with four finishes (Ag, Ni/Au, Sn and OSP). The as-soldered boards are analyzed, but also some boards were first exposed to thermal cycling tests for either 168, 336, 772 or 1008 cycles before analysis. The results are compared to the results for tin lead soldered PCA. Analyses have been performed by means of tensile strength tests and metallographic research by optical microscopy.

Most properties of the solder joint of lead-free SAC are inferior compared to lead containing solders: wetting behavior, formation of cracks and voids are more often observed for lead-free soldered assemblies than for SnPb soldered assemblies. It is also observed that the lead-free solder joints exhibit poor fatigue properties compared to lead containing joints. After thermal cycling tests, cracks are observed more frequent and their character is more sever. This can be contributed to the less ductile behavior of the lead-free solder. Cracks propagate intra- as well as intergranular for both alloys. However, the formation of cracks is also thought to be stimulated by defects introduced during the hand soldering process.

The tensile tests show that the lead-free SAC solder gives a mechanically stronger connection compared to SnPb. In addition lead-free soldered components on a board with a Ni/Au or Ag finish give a stronger connection compared to components soldered on PCBs with an OSP or Sn finish.

Introduction

The forthcoming European legislation in nineteen's has led to many research activities on lead-free solders1-6. On February 13, 2003, the Waste Electrical and Electronic Equipment7 (WEEE) and Restriction of Hazardous Substances8 (RoHS) directives officially came into force. The implementation of this directive is due at July 1, 2006. Then, all electronic products containing lead (excluding those products that are exempted) cannot be produced in or shipped to any of the EU countries.

Therefore, a good knowledge of the lead-free solders and lead-free solder processes is required. This research deals with hand soldered SMD and PTH components in the lead containing variant (soldered with SnPb37) and the lead-free variant (soldered with SnAgCu). The soldered boards are exposed to thermo cycling tests for a different number of cycles. The soldered components are investigated by optical microscopy and shear stresses are measured to compare the properties of the solder joints. In conjunction with this, four types of board finishes are investigated (OSP, Sn, Ag and Ni/Au) all only in combination with the SMD components.

Experimental
All components are hand soldered with the PACE, series SENSATEMP MBT solder machine.

To get a good inside in the behavior of the components in a lead-free solder joint, a lifetime simulation setup is performed by means of thermal cycling tests. The maximum number of cycles is 1008, depending on the board. The procedure for these tests is described by IPC and the time-temperature characteristics are shown in Figure 1

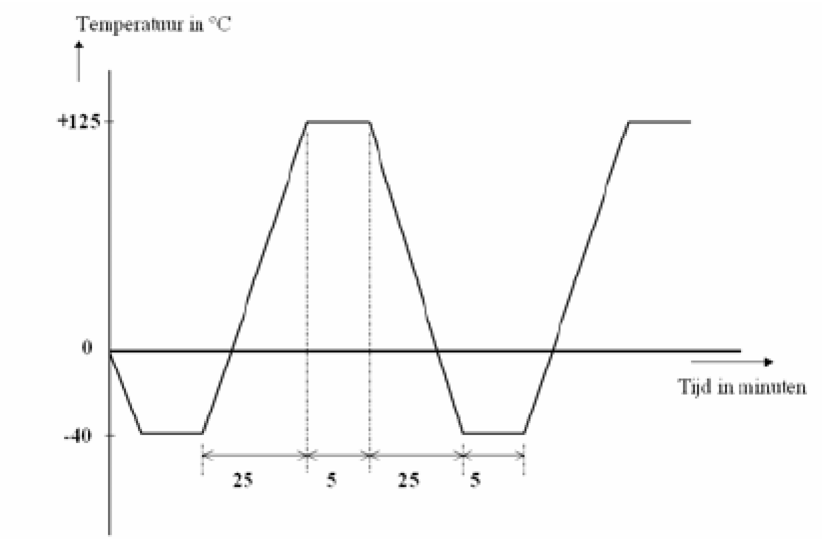


Figure 1 - Schematic of the Thermal Cycling Tests (TCT)

To analyze the effects of the solder type, board finish and aging two types of investigation are performed: optical microscopy (Olympus BX60M) and a tensile test (Zwick Z010).

Optical microscopy
All 38 boards are hand soldered by Neways Advanced Applications. All 32 SMD board contained the same components, but the six PTH boards all contained different components. Sixteen SMD and three PTH boards were soldered with a lead-containing solder and the others (16 SMD and 3 PTH-boards) in the lead-free variant. The soldering temperature was is all cases about 320°C . The conventional solder process was carried out with PbSn37 and the lead-free process was performed with a cored wire SAC (SnAgCu) solder. In Table 1 the number of board used in each configuration is schematically shown.

Table 1 - Number of Boards for Each Configuration; Leadfree or Lead-Containing Solder and TCT-Life-Times

TCT-cycles	SMD-components		PTH-components	
	SAC	PbSn	SAC	PbSn
0	4	4	1	1
168	4	4	1	1
336	4	4	-	-
772	-	-	1	1
1008	4	4	-	-

The board finishes used for the lead-free soldering process (‘SAC’) are OSP, (HASL) Sn, Ag and Ni/Au respectively. The boards with PTH components are all covered with a (HASL) Sn finish.

On all SMD-boards, each containing seventeen components, four components were selected to be investigated by optical microscopy: S016 with a SnPb finish, C1206 with an AgPd finish, R1206 with a SnPb finish and C0805 also with a SnPb metallization.

The six PTH-boards all contained different components, of which three components (a connector (CON), a capacitor (CAP) and a transistor (TRS)) were selected for investigation by optical microscopy.

The defects found during optical microscopy are labeled A to Z, as indicated in Table 2.

Table 2 - Defect List Used for the Optical Analysis

A	Unbalanced Component
B	Excessive Solder (solder touches component or solder meniscus is spherical)
C	Decentred Position of the Lead
D	Voids
E	Damaged Component (heat cracks, grinding)
F	Bad Shaped Meniscus
G	Microvoiding along Interface
H	Cracks along Interface
I	Contaminated Solder
J	Cracks in Solder
K	Bad Fluidal Behaviour
Z	Not enough data

Tensile testing

Only SMD-components were subject to tensile testing. Tensile tests are performed according to Figure 2. One lead of an S016-component was used to perform these tests. All board finishes are investigated with respect to tensile behavior, but not all tests succeeded since the components are very tiny. In Table 3 the parameters of the solder situation are given for which the tensile tests gave reasonable results.

None of the PTH-components were investigated for their tensile behavior.

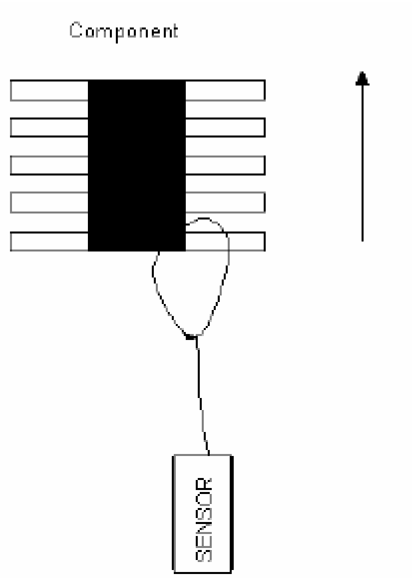


Figure 2 - Schematic Drawing of the tensile Strength Test

Table 3 - Successful Tensile Tests for the SMD-Components

TCT-cycles	SAC				PbSn			
	OSP	Sn	Ag	Ni/Au	OSP	Sn	Ag	Ni/Au
0	✓	✓	✓	✓	-	✓	✓	✓
168	✓	✓	✓	✓	-	-	-	✓
336	✓	✓	✓	-	-	-	-	-
1008	✓	✓	✓	✓	-	✓	-	✓

Before TCT
In optical microscopy both lead and lead-free soldered boards with SMD components show several defects like voids (see Figure 3a and b), excessive solder (see Figure 3b and d) and irregular shaped menisci (see Figure 3c).

Lead-free soldered connections also showed inferior fluidal behavior and voids along a line at the interface (for both see Figure 3c). In Table 4 the defects observed in the component joints soldered with SnPb and in Table 5 the joints soldered with SAC are listed.

Analysis of the PTH components (see Figure 4) revealed that the lead-free soldered connections contained voids more frequently and also of a larger size. In Table 6 the defects found in the PTH joints are listed.

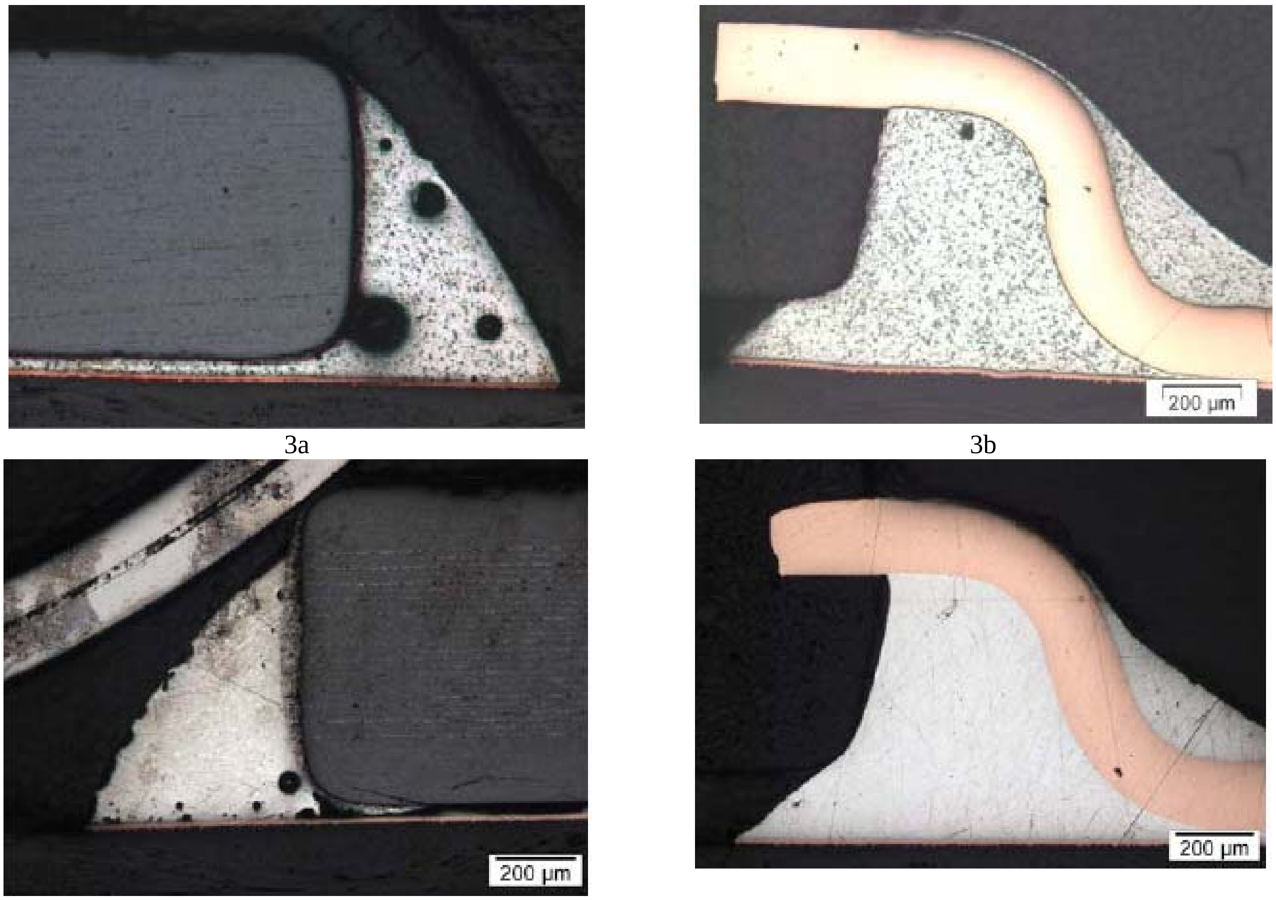


Figure 3 - SMD Components before TCT for a) SnPb (solder), Sn- (Board)Finish, SOT (Component); b) SnPb, Snfinish, Capacitor; c) SAC, Ag-Finish, Capacitor; d) SAC, Aufinish, SOT

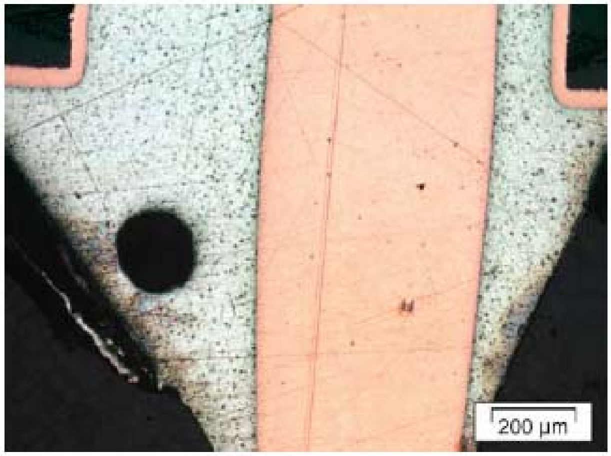


Figure 4 -PTH Component before TCT for SnPb Solder

Table 4 - Defects Found for SMD Components Soldered with a SnPb Solder before TCT (in Brackets: Less Pronounced Defects)

Board finish	S016	C1206	R1206	C0805
Sn	D, B	D	F/B	F
OSP	K	D, F/B	D, (B)	D
Ag	B, K	D		D
Ni/Au	D, B	D	F/B	F/B

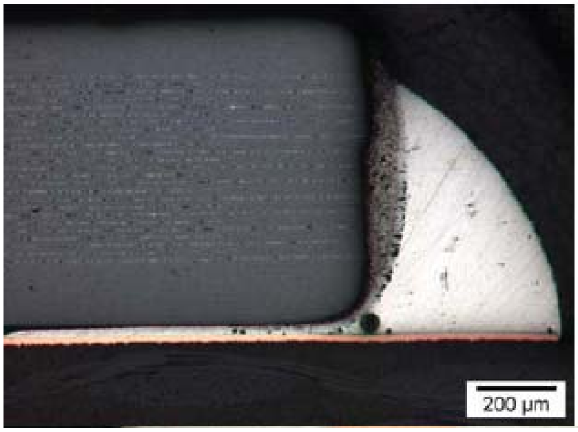
Table 5 - Defects Found for SMD Components Soldered with a SAC solder before TCT (in Brackets: Less Pronounced Defects)

Board finish	S016	C1206	R1206	C0805
Sn	K	D, E, F	D, F, A	D, E
OSP	B, K	E, F	D, F/B, A	D
Ag	D, B, K	D, E, G, K	F, A	F
Ni/Au	D, (B), K	D, G, K	F	E

After 168 cycles

Along with the defects noticed during the metallographic analyses on the lead-free boards before TCT, in the boards exposed to 168 TCT-cycles also other defects have been observed.

Microvoiding along the interface is found to occur in the lead-free solder joints of the boards with the Ni/Au finish and the AgPd metallization of ceramic capacitor 1206 (see Figure 5a). Cracks caused by the aging process (TCT) occurred at this AgPd finish. It is suspected that these microvoids are Kirkendall voids9. Lead soldered connections showed no anomalies compared to the connections of the boards without TCT. Cracks were also observed at lead-free soldered PTH components (Figure 6). These cracking seemed to be enhanced by voiding. All defects for 168 cycles are listed in Table 6, Table 7 and Table 8.



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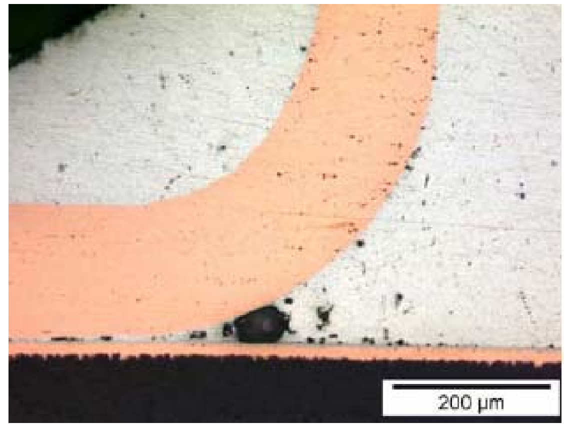

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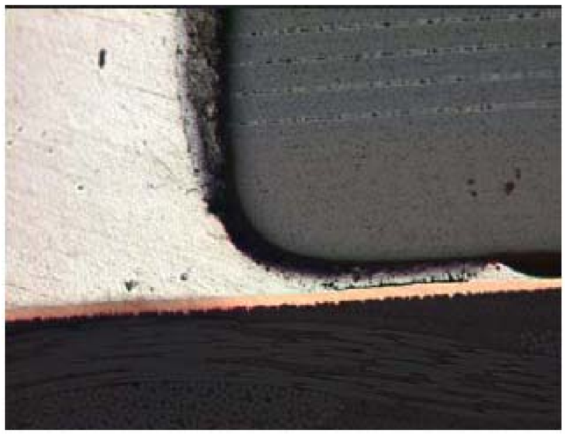

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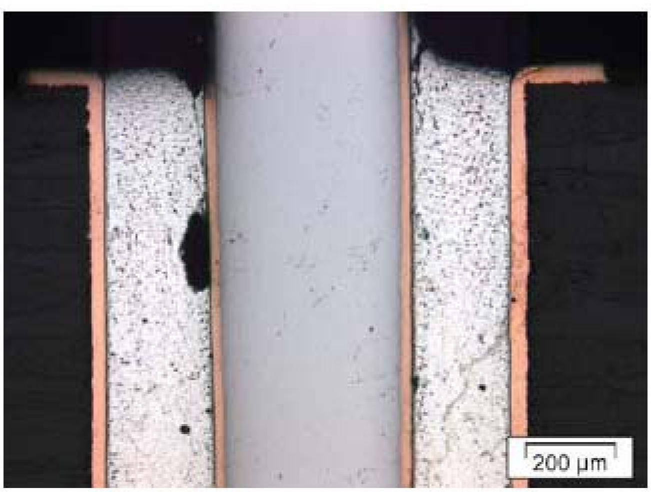
Figure 5 -SMD Components after 168 TCT-Cycles for a) SAC (solder), Au (Board)Finish, Capacitor; b) SAC, Aufinish, SOT; c) SAC, Ag-finish Capacitor



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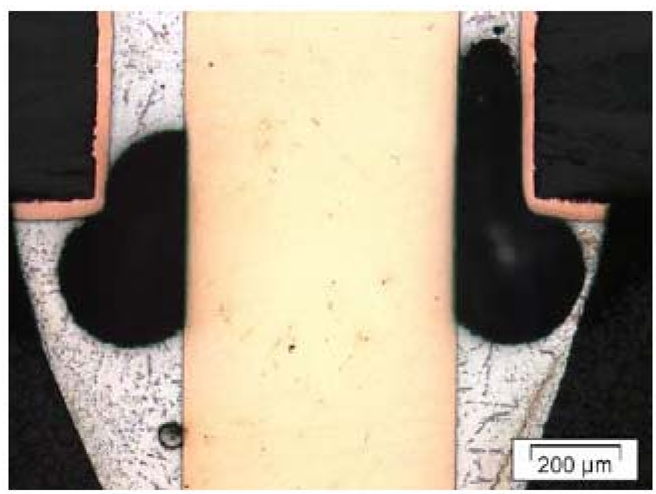


6b

Figure 6 -PTH componeNts after 168 cycles a) Lead-free Snfinish Capicator, b) Lead-Free Sn-Finish Transistor

Table 6 -Defects Found for PTH Components Soldered with SnPb and a SAC solder before TCT, after 168 and 772 Cycles (in Brackets: Less Pronounced Defects)

	CON	CAP	TRS
SnPb			
0-hours	D	D, C	D, C
168 cycles	D		D
772 cycles	D, H		C
SAC			
0-hours	H, K	D, K	K
168 cycles	D	D, G, H, K, C	(D), K, C
772 cycles	D, K	D, H, K	G?

Table 7 -Defects Found for SMD Components Soldered with a SnPb Solder after 168 TCT-Cycles (in Brackets: Less Pronounced Defects)

Board finish	S016	C1206	R1206	C0805
Sn	(D), B	D, E		F, A, B
OSP	B, K	D, H	(Z)	D, A
Ag	B, K	D, E, F		D, H
Ni/Au	B, K	D, E, F/B		

Table 8 -Defects found for SMD Components Soldered with a SAC Solder after 168 TCT-Cycles (in Brackets: Less Pronounced Defects)

Board finish	S016	C1206	R1206	C0805
Sn	D, B, K	D, F, B	K	
OSP	B, K	(B)	F/B	D, E, F/B
Ag	D, K	Z	Z	D
Ni/Au	D, B, G	D, G, K	D, (Z)	

After 336 cycles

The effects of the TCT after 336 cycles were more pronounced compared to the boards before TCT testing and after 168 cycles. In three of the four board finishes (Sn finish excepted) cracks were found at the interface between the AgPd finish of the 1206 ceramic capacitor and the solder (Figure 7). The cracks observed in the SnPb soldered connections were wider (Figure 7b), but in the joints soldered with SAC the cracks had propagated through the microvoids and thus were longer (Figure 7a).

In Table 9 and Table 10 the defects observed in the SMD-solder joints after 336 TCT-cycles are listed.

7a 7b

Figure 7 - a) Lead-Free Ag-Finish Capacitor, b) Lead Containing Ag-Finish Capacitor

Table 9 - Defects Found for SMD Components Soldered with a SnPb Solder after 336 TCT-Cycles

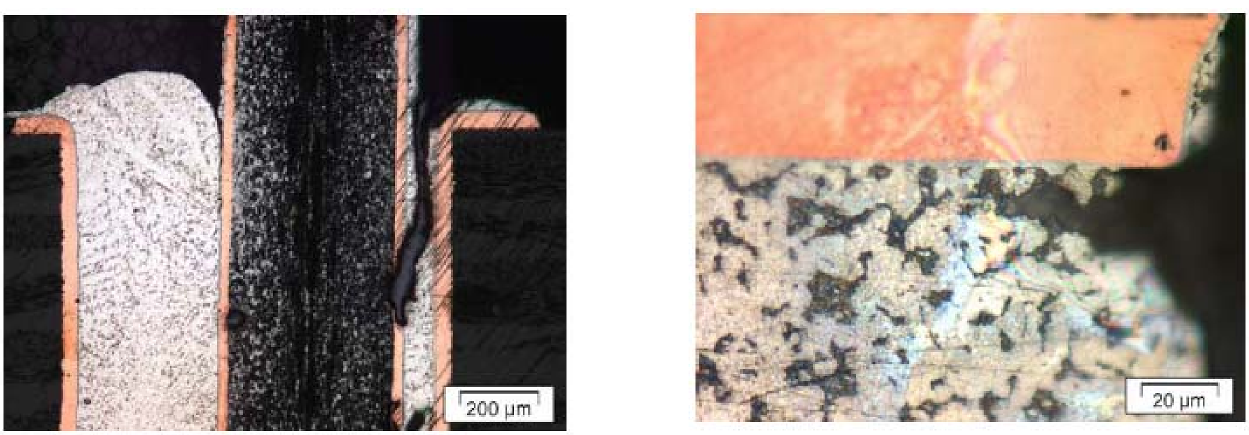
Board finish	S016	C1206	R1206	C0805
Sn	H, K	E, K	D, F	I
OSP	B, K	D, H	D	D, E
Ag	D, B, J	D, H	D, H	E
Ni/Au	B	D, F/B, H	D	F

Table 10 - Defects Found for SMD components Soldered with a SAC Solder after 336 TCT-Cycles

Board finish	S016	C1206	R1206	C0805
Sn	D	E, G	D	
OSP	K	D		
Ag	B, K	E, G, H		D
Ni/Au	D, K	E, H	Z	

After 772 cycles

The board exposed to 772 cycles TCT were only the PTH boards. The observed cracks here are less pronounced. This can be contributed to the fact that no large voids were found earlier where cracking is enhanced. The cracks in the lead-free solder joints (see Figure 8a (on the left of the lead) and Figure 8b) were of a larger size compared to the cracks found in the lead containing connections. The defects observed are previously listed in Table 6.



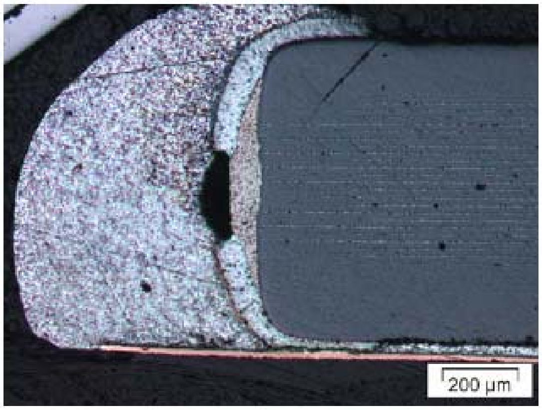
8a 8b

Figure 8 - PTH Components after 772 cycles a) SAC, Sn-Finish, Capacitor, b) SnPb, Sn-Finish, Connector

After 1008 cycles

After testing 1008 TCT cycles, the 1206 ceramic capacitor showed severe cracks (Figure 9). These cracks were larger at the lead-free interfaces. Several cracks continued through the complete solder-component interface. The cracks in lead containing connections were smaller and more confined. Other components also exhibited cracks but not to the extent of the ceramic capacitor.

In Table 11 and Table 12 the defects observed in the SMD solder joints after 1008 TCT-cycles are listed.



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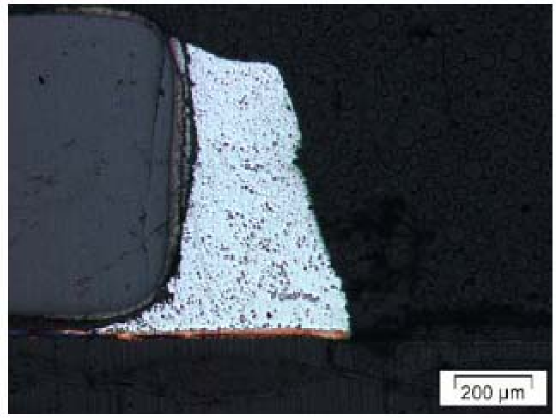

9b

Figure 9 - a) lead containing solder, Ag board finish, capacitor, b) lead-free solder, Ag board finish, capacitor

Table 11 - Defects found for SMD Components Soldered with a SnPb Solder after 1008 TCT-Cycles (in Brackets: Less Pronounced Defects)

Board finish	S016	C1206	R1206	C0805
Sn	D, B, K	B	(Z)	
OSP	B, K	D, H	B	D, B
Ag	D, B, K	D, B, H	D, (Z)	D, F, A
Ni/Au	B, H, K	H, K	(Z)	D, B, H

Table 12 - Defects found for SMD Components Soldered with a SAC Solder after 1008 TCT-Cycles

Board finish	S016	C1206	R1206	C0805
Sn	D, K	D, E, F, H		F
OSP	B, H	E, K	F	D, F
Ag	(Z)	F, H	H	A, H or E
Ni/Au	H	D, E, H		H

Tensile strength test

As indicated before not all tensile measurements succeeded. However the average maximum forces measured in the solder joints of the lead of the S016 component are determined for several cases. In Figure 10 these forces are plot, grouped by the board finish.

It should be mentioned that the strength of the OSP board after 336 cycles is probably higher because the test was preformed in one of the central leads of the component instead of the regular end lead.

The lead-free solder joints are on average stronger than the connections soldered with SnPb. Within the leadfree solder joints the strength on average for the boards with an Ag or Ni/Au are on one level within deviation and the boards finished with an OSP or Sn metallization are on a somewhat lower level within deviation.

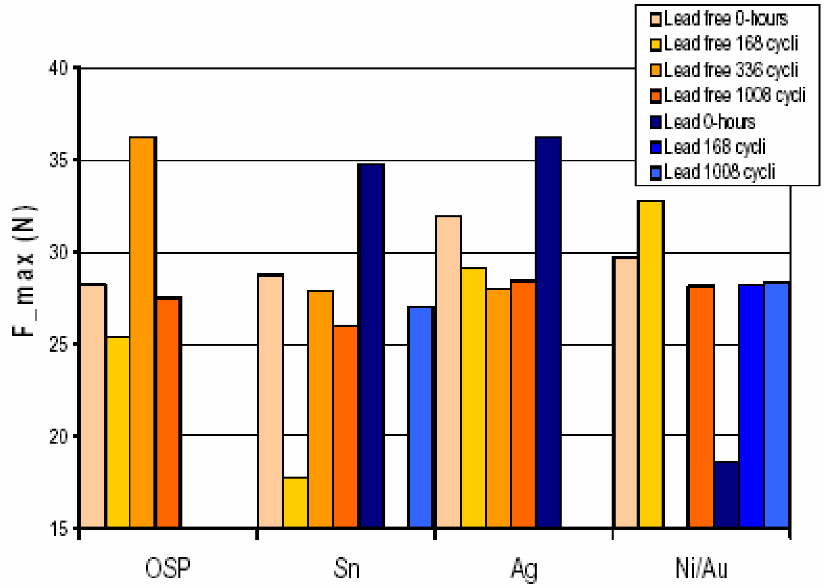

Figure 10 - Tensile strength test results: The maximum force on the corner lead of the S016 component grouped by board finish and displayed for the lead-free and lead containing joints, after a specified number of TCT-cycles.

Conclusions

The investigation reveals that most properties of the solder joint of lead-free SAC are inferior compared to lead containing solders: wetting behavior, formation of cracks and voids are more often observed for lead-free soldered assemblies than for SnPb soldered assemblies. It is also observed that the lead-free solder joints exhibit poor fatigue properties compared to lead containing joints. Aging has a more pronounced effect on lead-free connections compared to lead containing connections. This can be contributed to the less ductile behavior of the lead-free solder. Most critical are components with Ag/Pd finishes, especially with lead-free connections. The Kirkendall voids occur through diffusion, which enhances crack initiation and propagation. Cracks propagate intra- as well as intergranular for both alloys. However, the formation of cracks is also thought to be stimulated by defects introduced during the hand soldering process.

The excessive solder might also be a result of the soldering process itself: it might be the inexperience with hand soldering with SAC-alloys.

The tensile tests show that the lead-free SAC solder gives a mechanically stronger connection compared to SnPb. In general the lead-free soldered components on a board with a Ni/Au or Ag finish give a stronger connection compared to components soldered on PCBs with an OSP or Sn finish

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