Solidification Shrinkage Defects in Electronic Solders

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Alloys that undergo solidification over a wide range of temperatures generally exhibit a difference in the contraction behavior of the ensuing solid and liquid phases. Furthermore, dissolution of substrate metals during process reflow can lead to shifts in phase composition, additional primary phases, and volumetric contraction artifacts. The extent and frequency of surface roughness, shrinkage voids, fillet lifting, and hot tearing seen in lead-free solders are different than for eutectic tin lead solder. Shrinkage effects have been reported in Sn/Pb, Sn/Pb/Ag, Sn/Ag/Cu, and Sn/Cu/Ni solders for various components, but few studies have examined their impact on solder joint reliability. Nevertheless, they warrant proper identification due to the shift toward lead-free solders. This article is a review of the effects of shrinkage in Sn-Pb and lead-free solders as well as a discussion of some of the factors that contribute to their formation.

INTRODUCTION

Environmental and health concerns have driven legislation in the European Union and elsewhere that restricts the use of lead, traditionally used in Sn-Pb solder in electronics. Thus, a transition from traditional Sn-Pb eutectic alloys to lead-free alloys is imminent. Several lead-free alloys are being investigated as replacement alloys, with the most popular being Sn/Ag/Cu (SAC), Sn/Cu, and the Sn/Ag alloys.[1–3] The surface topography and the microstructure of a solder joint are of critical importance in assessing its mechanical properties and reliability. The topography and microstructure are, in turn, dictated by the joint constituents (solder, plating finish of the component, and the printed circuit board [PCB] substrate materials) as well as the assembly process parameters. Volumetric contraction during solidification is a characteristic that is universally exhibited by all alloys and plays a role in the formation of the surface topography and microstructure of the solder joint. Although volumetric contraction, or solder shrinkage (as it is commonly known), has gained attention with the advent of lead-free solders,[3–5] it has been also seen in Sn/Pb solders. Several commonly observed phenomena such as surface roughness, shrinkage voids, fillet lifting, and hot tearing are attributed to volumetric contraction observed in both surface-mount technology and plated-through-hole (PTH) joints.

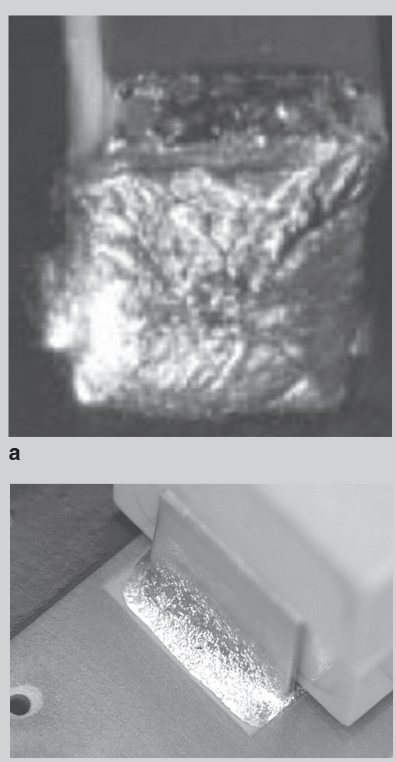


Figure 1. Images of (a) "disturbed" Sn-Pb solder joint (defects) and (b) "striated" acceptable lead-free solder joint (normal).

SURFACE ROUGHNESS

A rough and dull solder joint appearance is a well-documented, common characteristic of many lead-free alloys. This appearance is in complete contrast to the smooth and shiny surface typically produced by Sn-Pb solders as shown in Figure 1 and is addressed in several recent lead-free training documents[1,4] as well as in the recent update to the IPC-A-610 visual inspection criteria for electronic solder joints in Revision D of IPC-610 Requirements for Soldered Electrical and Electronic Assemblies.[6] The solder joint appearance is widely used in the electronics manufacturing industry as a generic indicator for the acceptability of a solder joint in terms of its assembly process and reliability.

A smooth and shiny Sn-Pb solder joint is considered to be an indicator of acceptable soldering process, while a dull and grainy looking Sn-Pb solder joint, commonly referred to as a "disturbed solder joint" or "cold solder," is considered an indicator of an unacceptable soldering process.[6] Cold solder joints are a result of improper process parameters (e.g., insufficient peak reflow temperature, little time above liquidus, or wrong choice of flux vehicle).

For Sn-Pb, the appearance is caused by mechanical disturbance or vibration to the solder joint during solidification as shown in Figure 1a or due to incomplete reflow of the solder paste. On the other hand, Figure 1b shows a completely reflowed SAC solder joint with the same characteristics. The dull and grainy looking lead-free solder joints have met the preliminary reliability assessments made by the electronics manufacturing industry and, hence, a modification was put forth in IPC 610-D, the latest revision to accept lead-free solder joints having a dull and grainy appearance.[6] Contamination of solder joints by the plating material of the end termination of chip components or substrate dissolution can lead to dull and grainy solder joint appearance even in Sn-Pb solder

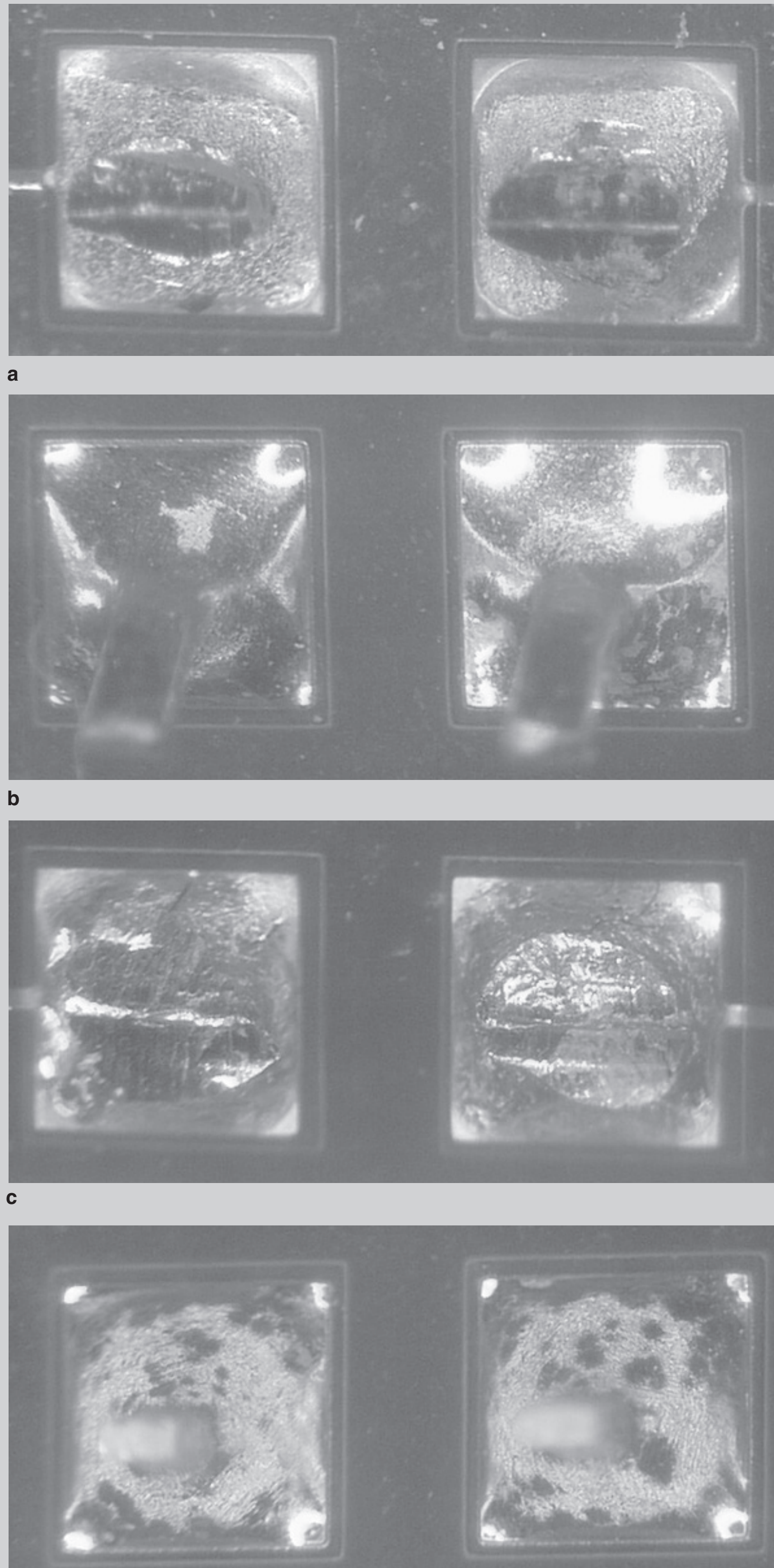
The surface on the topside of the component shown in Figure 2 appears to have a rough and dull finish, which is a characteristic of a lead-free joint. However, there is a marked difference between the appearances of the bottom side fillets of the two joints. Lead from the Sn-Pb component lead has significantly influenced the solder joint appearance, making it shinier. An increase in the lead content of an SAC alloy is expected to result in a greater temperature range for η dendrite formation as well as an increased complexity of (Sn), η, and ε dendrite formation.[7]

The pick-up of tin and copper from the Sn-Cu lead, on the other hand, can be expected to dilute the silver content of a joint and result in an increase in the amount of (Sn) dendrites.

In the polarized light images shown in Figure 3, it was observed that the orientation of the dendrites was different for the two joints. The lead-contaminated bottom side solder joint has coarse homogenously nucleated dendrites that lack directionality while the dendrites in the completely lead-free solder joint are fairly directional. The effect of this orientation on the surface finish is under further investigation. The direction in which solders are cooled also has an impact on their appearance. For bumps that are cooled in a manner in which the surface at the top cools last and heat is extracted out or cooled from the bottom of the bump, the surface is smoother (Figure 4a) than when the heat is removed uniformly from over the surface (Figure 4b).[8] It is possible that when the heat is extracted from the bottom side, it may cause a faster cooling rate at the top surface, which reduces the dendrite colony size and hence results in a smoother surface appearance.

SHRINKAGE VOIDS

Shrinkage voids in lead-free solder joints are also a result of volumetric contraction of the eutectic fluid from tin-rich dendrites as the solder joint solidifies. Shrinkage voids have been observed in different types of alloys[8,9]



a

b

c

d

Figure 2. Photographs showing two representative leads of through hole components plated with Sn-Pb (a: top side and b: bottom side) and plated with Sn-Cu (c: top side and d: bottom side) using Sn-Ag-Cu wave solder alloy.

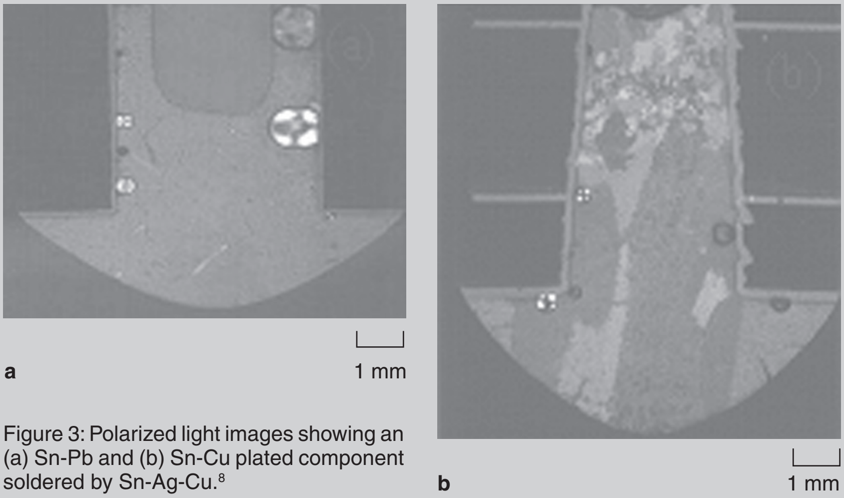


Figure 3: Polarized light images showing an (a) Sn-Pb and (b) Sn-Cu plated component soldered by Sn-Ag-Cu.[8]

and components.[8,9] There have been no reported failures attributed to shrinkage voids. Voids integral to a solder joint can be caused by flux out-gassing (i.e., the evaporation of moisture from laminate) or solder shrinkage. Figure 5 shows an example of a void caused by solder shrinkage. With its rough internal surface, the void is clearly caused by shrinkage.

HOT TEARING

An analogous phenomenon is hot tearing, which occurs when contraction stresses cause the solidifying solder to tear apart along surfaces that are the last to solidify, typically in interdendritic eutectic regions. Cooling rates influence the issue, as well as the presence of contaminants such as lead or bismuth in SAC solder joints. Faster cooling rates may minimize the occurrence of hot tearing as they may reduce the temperature delta between the different regions of the solder joint. Pockets of lower-temperature melting phases may exist within the bulk solder. In most cases, the industry considers tearing in the bulk solder to be benign. Hot tearing in test pad locations may influence the contact performance of pin probes in in-circuit tests. These locations can also act as pockets and water-soluble flux residues, etc. can become entrapped. If not removed, these entrapped residues raise reliability issues.

FILLET LIFTING

Fillet lifting is similar to hot tearing. The separation here occurs typically at the solder/ PCB or lead interface, while hot tearing occurs over the solder surface. Fillet lifting is characterized by a separation of the bulk solder fillet from the PCB pad or the component terminal. Fillet lifting has not been identified as a reliability issue in published literature.[4,5,7,11] Because fillet lifting is difficult to detect by visual inspection, it is usually characterized by cross sections. A fillet-lifting occurrence in an SAC and Ni-Au plated solder joint is shown in Figure 6. Fillet lifting can be used as a process indicator to potentially suggest that the solder alloys may be contaminated by trace elemental additions of either lead or bismuth or that there has been a shift in the composition of the alloy during supply or during use.

Based on the location of separation, fillet lifting has been characterized as acceptable in IPC-610-D.[6]

PAD LIFTING

If laminates are not designed to withstand the lead-free reflow or wave-soldering temperature, there is potential for laminate breakdown to occur at the pad and PCB laminate interface. Due to this breakdown, the adhesion between the pad and the laminate material may be weakened. As the solder joint cools, the section toward the central circumference of the solder joint cools down last and exerts a pull on the sections at the interfaces that cool first, that is, those toward the pad and the lead.[12] The bulk solder has formed an intermetallic at both these interfaces, and the interfaces

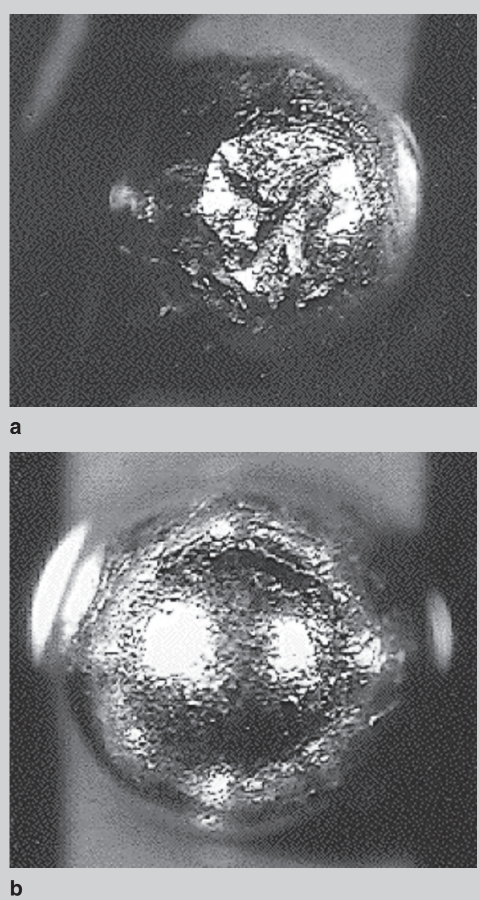


Figure 4. A bump with (a) a wrinkled and (b) a smooth finish.[8]

Figure 5. A micrograph showing a void due to shrinkage and outgasing.

pull away from the lead and the PCB pad. If the weakened section is not able to hold the adhesion between the pad and the laminate material, the pad may lift away from the laminate. Such pad lifts are considered a reliability risk. The previous sections discussed the occurrence of various phenomena such as surface roughness, shrinkage voids, hot tearing, fillet lifting, and pad lifting, resulting from volumetric contraction and differential solidification of solders. One or a combination of several factors contribute to these phenomena.

SOLDER ALLOY COMPOSITION

Alloys containing a higher percentage of tin and/or alloys that undergo dendritic solidification over a broad range of temperature are prone to exhibit a disparity in contraction behavior of the solid and liquid phases. This disparity can lead to several features in solder joints such as surface roughness, shrinkage voids, fillet lifting, and hot tearing. In non-eutectic solders, primary phases nucleate and grow first during solidification. This primary phase in the case of tin-based alloys such as Sn-Ag, Sn-Ni-Cu, or Sn-Ag-Cu alloy happens to be β-Sn dendrites that are almost pure tin and nucleate at temperatures close to the tin melting point (232°C). The remaining liquid, which eventually reaches the eutectic composition, solidifies in the interdendritic space and shrinks away from the dendrite arms. The composition of solder alloys dictates melting and solidification temperature, while the cooling/solidification rate of the solder joint during assembly influences the evolution of dendritic phases. Even for eutectic or near-eutectic alloys, the evolution of a primary phase can occur as a result of external factors such as contamination or changes in the process parameters, which result in undercooling and the metastable shift of eutectic compositions. For non-eutectic alloys such as some of the Sn-Ag-Cu solders, differential solidification may occur independent of process parameters due to its broad pasty range. Behaviors of eutectic or near-eutectic alloys are very sensitive to contamination. Alterations to their composition during manufacturing or during assembly due to leaching can shift the alloy percentages, and in such cases it is possible to see surface shrinkage for alloy systems that inherently do not exhibit it.

CONTAMINATION OR SUBSTRATE DISSOLUTION

Substrate dissolution can cause changes in dendrite formation during solidification and alteration of solder joint appearance. The dissolution of lead-free platings such as silver or tin from the end termination of the chip component or copper from the substrate can influence dendritic evolution. The vertical sections[13] shown in Figure 7 at 1 at.%Cu, 2 at.%Cu, and 3.1 at.%Cu show that copper dissolution into a eutectic Sn-Ag alloy should lead to the formation of primary tin dendrites. It is very likely that increasing amounts of copper dissolution in molten solder further increases the volume percent of primary tin dendrites as well as a higher possibility for surface shrinkage. For the PTH example shown in Figure 3, there could be some possible explanations (or a combination of explanations) for the smoother appearance of the solder joints with an Sn-Pb plated component on the bottom side and grainier appearance on the top side. It is also possible that the bottom side of the joint cools more rapidly than the top. The lead contamination lowers the surface tension of the solder and hence gives it a smooth and shiny appearance.[14] It is also possible that as the solder is pushed to the top side, it picks up some solute that segregates at the top.

Figure 6. A micrograph showing fillet lifts in an Sn-Ag-Cu and Ni-Au plated solder joint.

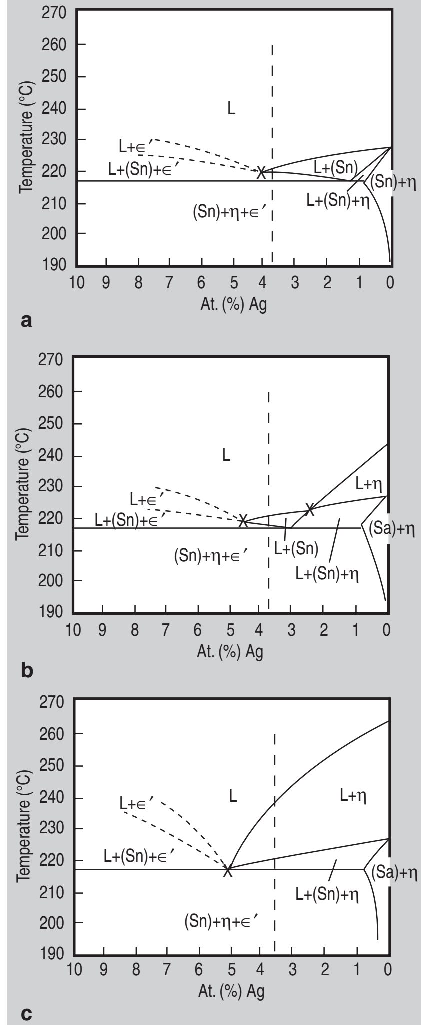


Figure 7. Dendrite evolution for (a) 1 at.% Cu, (b) 2 at.% Cu, and (c) 3.1 at.% Cu in an Sn-Ag binary system.[13]

PROCESS PARAMETERS

The direction of the cooling may influence volumetric contraction. During unidirectional cooling, the liquid/solid

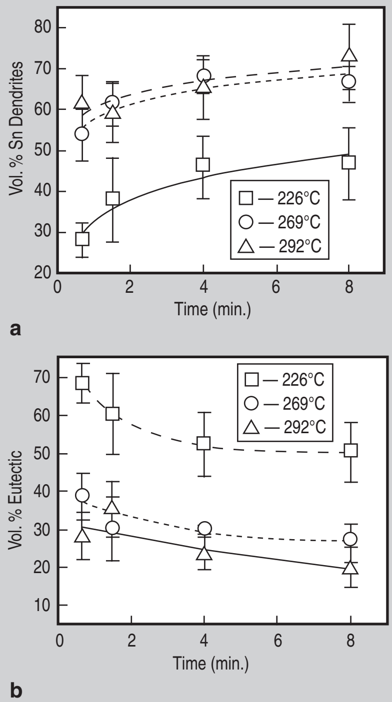


Figure 8. The volume % of (a) tin dendrites and (b) eutectic phase.[13]

interface advances in one unique direction and is believed to minimize the wrinkling on the surface. Due to this, the surface of the bump is smooth. However, when the ball grid array bump is cooled uniformly from all directions, wrinkling occurs at the surface. This causes shrinkage of the solder surface and gives it a rough appearance.[8] The cooling rate affects the secondary dendrite arm size and spacing of the tin-rich phase. Rapid cooling reduces the dendrite arm size and, hence, a high quantity of fine dendrites is developed reducing the spacing between the tin-rich dendrites. Rapidly cooled alloys show a microstructure that consists of the primarily crystallized tin-rich dendrites and the quasi-eutectic phases in between. Rapid cooling reduces the time allowed for diffusion and results in a finer grain structure. This results in a smoother solder joint appearance.

It also results in greater undercooling for the eutectic reaction and the consequent metastable shift of the eutectic to higher silver content. This results in a higher volume fraction of (tin) dendrites. The peak reflow temperature and time at peak temperature influences the percentage volume fraction of tin dendrites and eutectic phase. Based on the experimental data reviewed in Chada et al., in Figure 8[13] it is observed that increased peak reflow temperature or time leads to an increase in the volume percent of tin dendrites and a decrease in the volume percent of the eutectic fluid. This will potentially lead to an increased occurrence of solder shrinkage.

CONCLUSION

It is expected that the effects of volumetric contraction will increase with lead-free processing as it involves an inherently non-eutectic alloy composition. The alloys will have higher peak reflow temperature and time as well as exhibit dissolution from substrates and platings with different plating chemistries. The observations made in the microstructure orientation as it relates to the differences on surface finish appearance in the lead-contaminated and completely lead-free solder joints need further investigation.

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