

TOMBSTONING IN REFLOW SOLDERING OPERATIONS: *Does Inerting Cause Tombstoning?*

*M. Theriault, Air Liquide N. America;
P. Blostein & C. Carsac, Air Liquide, France;
A. Rahn, Ph.D.; rahn-tec consultants inc.; Canada*

Abstract

Although not the most frequent defect in reflow soldering, tombstoning has attracted a lot of attention because of its peculiar appearance. Many have also been puzzled by this phenomenon which seems to counteract gravity itself. Although there are various remarks and comments in the literature, very few general discussions are available. We found it time to survey the literature, explain on a scientific basis how this event can occur and add advice on how to avoid it stemming from our own experience and test results. We also address the question whether tombstoning is caused by the use of nitrogen during reflow since a number of applications seem to indicate such a correlation.

Introduction

One of the more troublesome occurrences in reflow soldering is the defect of tombstoning. Although a number of relatively humorous names have been attached to it [Manhattan Effect, Drawbridge], extensive analyses and the defect itself are anything but 'funny'. Nevertheless, it is striking that prejudices abound with regard to tombstoning and that some companies have no such incidents, whereas others, seemingly operating under the same conditions, are greatly troubled by them. For example, some companies that inerted their reflow process reported higher incidents of tombstoning and deduced from this that inerting produces tombstoning. They overlooked the fact that many other lines are operating under nitrogen without tombstoning defects. This obvious lack of understanding of the phenomenon justifies a reexamination of tombstoning on the basis of the theory, experiments, experience, and of published information.

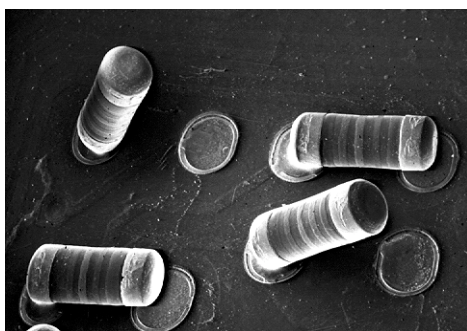


Fig. 1: Tombstoning

Tombstoning, is defined in [1] as 'the component has lifted to a lesser or major degree' and thus produces an open (Fig. 1). In extreme cases, the component may actually be vertical, always connected only on one side to one pad. There is no question about how the event occurs. The two forces of wetting and surface tension acting together on the component produce the tilting. As long as there is no equalizing force acting on the other side of the component, the piece may be moved if it is light enough. We have to remember that one of the functions of surface tension is to minimize the surface of the liquid solder. If this requires that the component be moved, such movement will be accomplished as long as the weight of the component (i.e. the third force acting here: gravity) is not 'overpowering' the other forces. The model as presented by [2] is basically correct, however, does not cover all the aspects of this phenomenon.

The question of why these episodes happen is much more involved. The causes range from layout errors to inadequate solderability of components and include many other possible reasons.

The Physics of Tombstoning

Let us first concentrate on how tombstoning may happen because a proper understanding of the underlying mechanism will make it easier to examine the questions arising when tombstoning happens in the soldering process.

Due to a number of interactions between the molecules of the molten solder and the contacting gas (air or nitrogen), we observe a resultant force, applied to 1 cm² of the surface layer, directed inwardly towards the solder. This resultant force

minimizes the exposed surface of the liquid solder. Whenever we want to increase the surface area, we must move molecules from the interior of the solder into its surface. This movement requires the performance of work and thus increases the *surface energy*. An isothermal expansion of the surface layer increases the *free surface energy*:

$$A = (\overline{F_s - F_v})N$$

Here $\overline{F_s - F_v}$ is the average difference between the free energy at the surface F_s and the interior volume F_v , and N is the number of molecules in the surface layer of the solder.

The work done to form 1 cm² of surface is called the *surface tension* σ . We write:

$$\sigma = (\overline{F_s - F_v}) n_1$$

and n_1 is the number of molecules in the 1 cm² of surface.

For our purpose it may be more convenient to rewrite this formula as

$$\sigma = F / S$$

and here F denotes the change in surface energy, whereas S indicates the change in surface area. The value of σ has been measured for a number of materials and is mostly given in ergs per cm². For molten solder it is found to be in the range of 40 microjoules/cm² [@ 185 °C] and thus explains the rather strong force that may produce the tombstoning effect.

If we add a component to this situation, we have to talk about *wetting*. The free surface of solder is curved near the metallized surface of the component; we commonly refer to this curved surface as the *meniscus*. The wetting angle ϑ characterizes the phenomenon of wetting.

By using Laplace's Law, it is even possible [3] to derive an estimate of the additional pressure exerted on the solder:

$$P_{\text{add}} = 2\sigma H$$

Where

$$H = \frac{1}{2}(1/R_1 + 1/R_2)$$

uses the principal radii of curvature.

Naturally, the exposed surface of the molten solder on the pad does not amount to 1 cm² and the force has to be prorated accordingly. Nevertheless, we recognize that significant forces apply.

Basic Reasons

The aforesaid explains that tombstoning can only happen, if the two sides of the component show unbalanced wetting forces. The question on why these defects occur thus reduces itself to considerations about reasons for unbalanced wetting forces.

Solder wets to metallized surfaces dependent on:

- the type of solder,
- the temperature,
- the quality of the wetted surface,
- the activity of the flux used, and
- the quality of the atmosphere / environment.

Dr. Rolf Strauss, who is credited with the invention of wave soldering, puts it succinctly: "Lack of symmetry is behind the phenomenon of 'tombstoning'. ... The better end wins..." [4]. This imbalance can be produced by a number of things. Basically it may be related to either a significant difference in wetting force from one end of the component to the other or a time delay in the onset of wetting. In the former instance, the difference must be significant enough to actually move the component. That means, in the extreme case, one of the ends must exhibit a zero force. If we deal with a time delay, the temporal shift must be such that wetting on one end is nearly complete prior to the onset of wetting on the second end. Only then would there be enough 'strength' available to actually lift the component.

The questions to ask are therefore:

- a) what are the possible causes for the imbalance in wetting force, and
- b) what could cause a delay in the onset of wetting?

To start with, we have to look at the design of the board [5].

Design and Layout

Considering the distance between the metallizations of common chip components that are liable to be lifted, one wonders whether the

T [ΔT denotes any temperature difference noted on the board or assembly, in particular, e.g. the largest temperature difference measured.

Thus $T = T_{\max} - T_{\min}$. Whereas T is given in °C, the temperature difference T is given in K {Kelvin}} could be large enough over such a small area to cause a lag in melting of the deposited paste. However, on examining a number of tombstoning defects where a layout error was suspected to cause them, one quickly discovers that the two pads are situated or connected differently with respect to metal mass. It is either interior ground planes or other strong metallizations, which drain energy from one of the pads thus keeping one side sufficiently cooler to cause the necessary delay in melting of the paste.

When designing assemblies for reflow soldering, one must consider during the layout stage that

- a) different materials heat differently (especially when IR heat transfer is employed – and remember, even full convection still has a certain percentage of radiation energy heat transfer), and
- b) that the inhomogeneous mass distribution, particularly with regard to the metallization, plays a major role in producing large T s, i.e. the temperature differences measured on the board. [6] found that heat transfer dynamics are ‘mostly PCB layer copper weight and circuit design layout driven’.
- c) It is understood that the impact of the component must be assessed. It is not only the size of its body but also the extent of the metallization. Dimensioning the pads accordingly will not only limit the float off, but also minimize the tendency to tombstone.

Several years back one manufacturer’s soldering expert actually recommended to mount the components upside down to avoid tombstoning [17]. Obviously, the metallization was unfavorably distributed around that particular manufacturer’s components and thus promoted tilting during the wetting process. We have to remember this a little later again, when properties of the component must be considered.

Luckily, recent research has indicated again that as far as reliability of the solder joint is concerned, size is not a decisive factor and thus small solder joints are entirely acceptable [7]. Those findings and resulting recommendations may be incorporated when deciding on the correct footprint pattern.

Other Heat Sinks

Heat sinking is produced by a reflow situation where energy is easily conducted into one area, which by its very nature requires more energy to acquire the same temperature than a neighboring area. Under this premise, we have to consider - during layout - two other sources for heat sinking action:

1. Heavy components next to small components, and
2. Fixtures, straighteners and other tools.

Any such geometrical arrangements are also unfavorable. Heat sinks, heavy connectors, power components and the like are found in the immediate vicinity of small resistors and diodes etc. From the point of view of even heat distribution, such grouping should be avoided. As their pad sizes differ greatly, printing of paste also becomes problematic, adding to the general detrimental situation on the board.

They also offer a different profile to the heat source that may either shadow (e.g. in IR) or obstruct the flow (in convection particularly when laminar flow is present) of the heated gas.

If fixtures, board straighteners or other implements are employed, these can severely change the heat distribution on the assembly. It has been demonstrated in our experiments that tombstoning was caused entirely by the action of holding fixtures [8]. When fixtures were removed – all other parameters of processing kept constant – tombstoning disappeared on our test boards. Even rails and the cross belt T of some equipment have contributed to tombstoning in the past.

Paste and Paste Printing

It is no secret that up to 60 percent of defects attributed to the reflow process originate with pastes, paste storage, paste handling, and paste printing. We distinguish two distinct parameters associated with pastes: the flux wetting speed and the solder wetting speed [9]. One relates to the mobility of the flux constituent, the other to the activity level with regard to acid action and the amount of tin in the solder.

Given unequal wetting of the component terminations, too active a paste may contract wetting times such that tombstoning occurs. I.e., the speeding up of wetting for the ‘good’ side pushes the onset of wetting of the ‘bad’ side just far enough out of range to hinder a balancing of the forces. At the same time, the increased speed

may also impact the rotational moment acting on the component.

Unequal amounts of solder paste may be one of the more critical aspects that causes the Manhattan effect. The larger deposit must evaporate more solvent, having a cooling effect on the paste, and the amount of metal, which has to be fused, is larger. These two parameters will cause a delay in the start of the melting process compared to the smaller deposit. If the hesitation is large enough, tombstoning will become practically unavoidable.

Old paste, paste that has been badly handled or stored improperly, would certainly display some of these shortcomings. Anyone, who has seen the color change that occurs in paste left too long on the printer or the increased brittleness after a production intermission, cannot be surprised about a deterioration of its performance. This does not only apply to the activity of the flux constituents but also impacts the tackiness and thus the holding power of the paste.

Placement

It is becoming more and more critical to control not only x and y coordinates but also the z coordinate. Extensive research carried out by a team of the Technical University of Dresden [10] about the performance of placement equipment has come up with some startling results. Periodical deviations are just one incident of placement error that is difficult to detect. Regular checks of machine capability may be in order.

When considering drawbridging, the key lies in the contact of the component with the paste. Both ends of the component have to immerse into the paste to the same depth without 'squashing' it. Besides the holding power of the paste's tackiness, it is the exposure and contact area between the metallization of the component and the paste that will decide whether a problem occurs during reflow or not.

Heat Transfer

It is a rare assembly, which has been laid out ideally for the reflow method at hand. We distinguish between radiation (in our case IR or LASER) and convection heat transfer, where the latter subdivides into gas convection and condensation methods. The efficiency may be ranked: IR > Condensation. > Convection [12].

A thermal profile, detailing the ramping as well as the reflow properties of the process usually indicates the heat transfer for a particular assembly. The part of the profile, which impacts tombstoning, is the interval just prior to the occurrence of wetting. In this area attention should be paid to the gradient as well as to the spread of temperatures on the board, referred to generally as T . As the different processes act differently as to the efficiency of heat transfer, the type of process has to be taken into consideration and the profile adjusted accordingly. Whereas IR reflow usually requires a long 'plateau' in order to bring together the diverging temperatures on the assembly prior to reflow, such plateaus may not be necessary for convection and condensation methods. In any case, the gradient just before fusion of the alloy should be flattened to ensure simultaneous melting of the paste on both pads.

Atmosphere

The advantages of inerting the soldering atmosphere has been extolled often. There are several aspects to the improvement:

- a more reliable joint [13] [14],
- fewer defect totals (Fig. 2 & 3) [15],
- use of less aggressive flux vehicles,
- easier cleaning (if needed at all),
- safer processing – no lead oxides,
- larger process window, a term often misunderstood, etc.

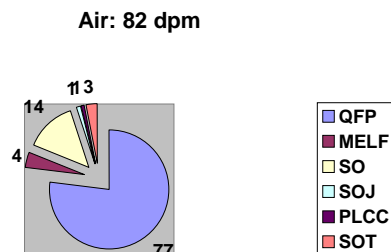


Fig. 2: Siemens Defect Levels in Air [14] (dpm=defects per million)

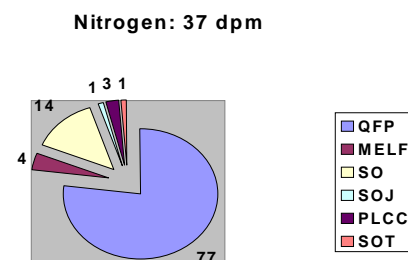


Fig. 3: Siemens Defect Levels in Nitrogen [14] (dpm = defects per million)

Although a number of processes lead to a general decrease in all defects when a change is made from air to nitrogen soldering, some have experienced increases in tombstoning. The reason for the difference lies either in design and layout variance, component wetting or control of the printing process. The fact that wetting under excellent nitrogen coverage is improved, may emphasize differential wetting properties of the component. Experiments have indicated that if the atmosphere is 'less perfect', the tendency of tombstoning is curtailed without sacrificing the beneficial effects of nitrogen [16].

The effects of nitrogen have been recorded thoroughly and amount to better wetting, faster wetting and a larger wetting force. However, these beneficial results, may impact precisely that area of the profile, which has some influence on the defect of tombstoning. A highly pure, i.e. oxygen-free, atmosphere may be undesirable. Evidence seems to mount that if tombstoning is encountered when inerting, a very low residual oxygen level (ROL) is neither necessary nor desirable. The above listed benefits seem to accrue to the user already at ROLs below the 1000 – 500 ppm O₂ [15]. Since tombstoning is reduced as one increases the O₂ level, the user may introduce nitrogen to reap its benefits without running into tombstoning problems. Mr. Uwe Hennings, Motorola Germany underlined, during his talk at the TAC line session at Nepcon West '98 that: "Tombstoning occurs somewhat more frequently at low ROL. We have increased our ROL with the effect of eliminating tombstoning". Other papers are pointing in the same direction. Thus, instead of following equipment manufacturers' suggesting to operate the process below 20 ppm ROL, we see the optimum just below the 100 ppm level.

It would be wrong to assume that nitrogen causes tombstoning. {A similar mistake was made in nitrogen wave soldering. Here, solder balling was first blamed on the inerting process but after extensive research it was proven that it is mainly the solder mask that causes solder balling and that nitrogen plays a very minor role in this defect too.} Although the first evidence may point in this direction, too many successful operations indicate that nitrogen may only reveal an underlying problem that is mostly caused by a violation of layout rules, wrong dimensioning, bad solderability or insufficient solderability.

Wetting

For nearly all defects, solderability plays a major role. Users tried a large number of different surface finishes in order to preserve the boards' solderability during storage. One of the most popular was HAL and it is precisely this one that contributes to several defects. The uneven solder coating, i.e. the lack of co-planarity creates problems during paste printing, component deposition and reflow. Hence, new surface finishes are considered. One of the trendy types is classified as OSP [Organic Solderability Protection]. However, if used successfully it usually means an inerted soldering process with the above-mentioned proviso for ROL [11].

Components, too, may be one of the root causes for tombstoning. Some components have been metallized in such a way that they are prone to tombstoning. A change in supplier may be the best solution. Others exhibit differential wetting ability at their ends and tests have revealed wetting onsets delayed long enough to cause tombstoning (Fig. 4). It is thus a prerequisite to have 'good' components to populate the PCB.

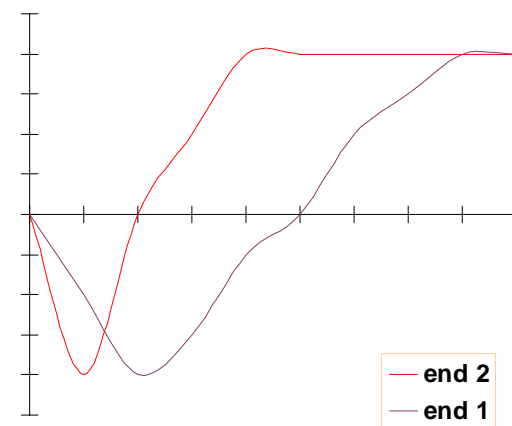


Fig. 4: Delay in wetting of component terminations
(x = time, y = wetting force)

Flux acts on the oxides within the paste, on the PCB, and component. It is on record that aggressive fluxes contribute to tombstoning. This plays into the hands of the general trend towards milder fluxes, as cleaning will become more and more complicated.

Solder

Different solders perform differently with respect to tombstoning. Reaction in tin/lead solders

depends largely on the amount of tin in the alloy. Thus, higher tin content usually relates to a more active reaction. The oxide content is of great importance too. On the one hand, lower tin oxide levels necessitate less activity from the flux constituent. On the other hand, melting is more uniform as can be seen when high speed photography is used to record the melting behavior of pastes [18].

At one time a special solder paste developed by a major US assembler targeted the problem of tombstoning. The approach taken involved a metal powder which was a combination of pure tin powder and pure lead powder in the proportion of 63/37. The special melting behavior of this powder delayed wetting long enough to ensure proper action on both sides of the component and thus largely eliminating the drawbridge defect.

Equipment

Finally: the equipment. If the T is considered one of the main culprits in tombstoning, then a good piece of equipment will greatly improve the process. The industry presently favors convection reflow. However, machine is not equal to machine. There are still differences with regard to heat transfer efficiency and homogeneity. When choosing a system, we have to make sure that it is our assembly, which is tested for its thermal profile. Strange as it may sound: there are no standardized methods available to measure the performance of reflow equipment. Thus published data about an achieved T is largely meaningless.

Besides the cross-belt T , it is the general T that is of interest to us. (Make sure that the thermocouples are mounted properly!) Furthermore, drifting of temperatures during an 8-hour shift is not permissible.

Vibration of the conveyor is another point. Mechanical interference has more than once dislodged components prior to soldering. And if one side is no longer sticking to the paste, the component may tombstone. This is true for the machine conveyor as well as for all the in-line conveyors between component mounting and reflow. Therefore, prior to reflow, all unnecessary handling should be avoided!

Heat transfer and 'profilability' must be designed into the equipment. Thermal smudging between stages or cool spots are an indication that equipment has not been designed properly.

Rails may add to the problem by acting as heat sinks and in addition deflect, bend, twist or warp with heating because the extrusion has a 'memory' of former twists or no allowance has been made for heat expansion.

Suggestions

A rational approach when defects are observed is to track them to the root cause rather than to try to patch the process by some temporary means. In the case of tombstoning the culprit is usually some shortcomings in the design. Since a design change is frequently the most difficult one to obtain for the people managing the line, checking the parameters of the process would be a first line of attack. Concentrating on the paste and the paste printing process will yield the best results as up to 60% of defects are traced to these two items.

A thorough knowledge of the thermal profile for a large number of critical points on the assembly will be extremely helpful as well. Based on this the settings of the equipment may be changed to meet demands for smaller T s. Such parameter changes may mean a longer plateau or a slower temperature increase in the peak zone.

Good control with regard to the solderability of boards and components is certainly one of the prerequisites for a successful operation. But it is not sufficient to have special criteria in place for the boards and components on arrival, they have to exhibit good solderability when put into the process. Therefore storage and handling are factors that have to be added to the controlled parameters.

If the design and layout is so unfavorable that tombstoning should become more frequent under inerted conditions, experience has shown that operating under somewhat higher ROLs will be helpful and the process does not lose the overall benefits of a nitrogen operation. But convincing layouters to properly design the board may be the ultimate test!

Conclusion

The theory of tombstoning leads directly to a discussion of the different potential root causes. The quality of wetting and temporal delay of the onset of wetting must be seen as the actual causes for tombstoning.

Reference:

- [1] rahn-tec CD-01: SOLDER DEFECTS AND THEIR CAUSES © rahn-tec 1998
- [2] R.J. KleinWassink; MANUFACTURING TECHNIQUES FOR SURFACE MOUNT ASSEMBLIES, Electrochemical Publications, Ayr, Scotland, 1996
- [3] B. Yavorsky & Detlaf, A.; HANDBOOK OF PHYSICS, MIR Publishing, Moscow, 1972
- [4] R. Strauss; SMT SOLDERING HANDBOOK, 2nd ed., Butterworth-Heinemann, Oxford, 1998
- [5] A. Rahn; LÖTFEHLER IN DER PRAXIS, Pronic, 1, Feb. 1994
- [6] J.A. Shriver III et al.; A STUDY OF TOMBSTONE AND OFF-REGISTRATION EFFECTS, Proceedings of the Technical Conference, Nepcon West '96, Anaheim, CA, 1996
- [7] ZUVERLÄSSIGKEIT VON SMT-WEICHLÖTSTELLEN IM VISUELLEN GRENZBEREICH; Verbundprojekt im Rahmen des Programms Mikrosystemtechnik des Bundesministeriums für Bildung, Wissenschaft, Forschung und Technologie, Kompendium, VDI/VDE-IT1996
- [8] R. Diehm & Rahn, A.; SEHO laboratory tests; unpublished results – 1996
- [9] Ning-Cheng Lee; PROBLEMS AND ISSUES IN SOLDER REFLOW, Surface Mount Technology Magazine, January 1998
- [10] W. Sauer et al.; ESTIMATION OF MACHINE CAPABILITIES OF PLACING MACHINES - THEORY, PRACTICAL MEASUREMENT, Examples and Results, Proceedings of the Technical Conference, Nepcon West '96, Anaheim, CA, 1996
- [11] Verbockhaven, G. Conard ; OSP COATINGS : INFLUENCE OF A NITROGEN ATMOSPHERE ON THE SOLDERING PERFORMANCE , Nepcon West '96 proceedings, pp. 1161 - 1167
- [12] A. Rahn & Diehm, R.; THEORIE, KONZEPT UND ANWENDUNG BEIM REFLOW: EIN VERGLEICH DER REFLOW-METHODEN STRAHLUNG, KONVEKTION UND KONDENSATION, Hochschulkolloquim Weichlöten in Forschung und Praxis, 7. Löttagung, 19 & 20. Nov. 1996 Technische Iniversität München
- [13] G.E. Reichelt et al.; INVESTIGATIONS ABOUT THE RELIABILITY OF ATMOSPHERIC AND INERT WAVE-SOLDERED 1812-CAPACITORS AT VARIOUS FOOTPRINT-CONFIGURATIONS. Proceedings of the technical conference, Nepcon West '94, Anaheim, California, 1994 [inclusive hand-outs during the talk].
- [14] Lhote, S. Mellu, B. Maire, D. Navarro; REMOVE AIR AND BOOST QUALITY OF IR REFLOWED SOLDER JOINTS, Electronic Packaging & Production, July 1991
- [15] M. Gerhard & Kiecker, E.; QUALITÄTSVERBESSERUNG DURCH DIE ANWENDUNG DES REFLOWLÖTENS UNTER STICKSTOFF, Proceedings of the Technical Conference, Productronica, Munich, 1995
- [16] C.C. Dong et al.; OXYGEN CONCENTRATION IN THE SOLDERING ATMOSPHERE – HOW LOW MUST WE GO, Proceedings of the Technical Conference, Nepcon West '96, Anaheim, CA, 1996
- [17] KleinWassink, R. & M. Verguld; DRAWBRIDGING OF LEADLESS COMPONENTS, Hybrid Circuits, 9, Jan. 1986
- [18] personal communication: Bonsels, Mercedes Benz Research Laboratory, Frankfurt, Germany.