WHITE PAPER:

Factors Affecting the Mechanical Strength of Reflowed Solder Joints for Surface Mount Technology (SMT) Products

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EXECUTIVE SUMMARY

At present, the PEM SMTSO product line is used for providing mechanical fastening to Printed Circuit Boards (PCB). The most important parameter in this fastening system is torque-out attainability, with the primary determiner of this value being the solder joint.

This paper explores how solder joint strength is affected by reflow curves, and what the impact is of lower reflow temperatures and the use of lead-free solders. The peak temperature (PT), time above liquidus (TAL), and cooling rate that drives PennEngineering's current maximum performance is shifting as the direction the Printed Circuit Board Assembly (PCBA) industry shifts. That being said, PennEngineering will continue to attain the performance values of their SMTSO at lower peak reflow temperatures.

Abstract

At present, PennEngineering's largest Surface Mount Technology (SMT) product line is used for providing mechanical fastening to PCBs. There is also a growing trend to use the SMTSO & SMTSOB standoffs to conduct electrical current to the board. However, this is a secondary use. With the advent of lower reflow temperatures and the use of lead-free solders, the mechanical strength of the fastener to the board joint is reduced. This paper explores those factors which influence joint strength.

Factors Affecting the Mechanical Strength of Reflowed Solder Joints for SMT Products

The traditional solder joint using SnPb (Tin-Lead) solder was designed to provide good electrical conductivity and resistance to mechanical shock. Since all components at that time were Plated Through Hole (PTH), they were inherently mechanically rigid, and the solder was used to keep components in place.

Over time, hand soldering was replaced with wave soldering – the main technology that brought about the consumer electronics boom of the 1970s and 1980s. With the progress of continued miniaturization over the past 30 years, all but a few PTH components have been replaced with SMT (see PEM training document).

This new surface mount technology also shifted soldering techniques to reflow soldering. In this process, the PCB is screen printed with solder paste, a component is placed upon it, and the entire assembly is "reflowed" to melt the solder and create the joint in a reflow oven (imagine a pizza oven, but one that is up to 10 meters long).

The increasingly smaller form factor and development of lighter components means that solder joint mechanical strength is not as critical for those components. However, in the case of a component being used for its mechanical strength, i.e. an SMTSO standoff, one of the critical parameters is the Torque-Out value. In this paper, we examine the factors that affect this mechanical strength – specifically reflow curves and lead-free solder pastes.

How Soldering Works

Soldering works by joining together two metal surfaces by using a third filler metal (solder). In this process, the solder is melted and flows across the surface of the base metal. Provided there is no contaminant present, wetting will take place. This scenario is shown in Fig. 1.

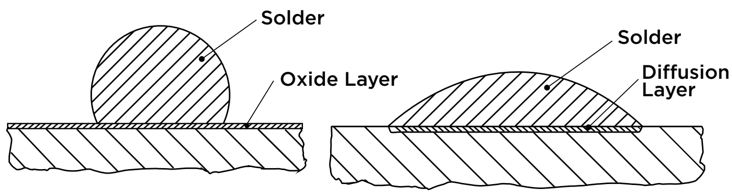


Fig. 1 (Wassink, Pg. 36i)

Wetting means that the solder atoms are now able to come so close to the base metal atoms that they attracted to each other and form an alloy at the interface. This alloy ensures good electrical contact and good adhesion.

For wetting to occur, the oxide layer needs to be removed to ensure the solder can come into contact with the base metal. Any contamination of oxides on the surface will prevent wetting. Flux, a component of the solder paste, performs a few different tasks. One is to act as a light acid and remove the oxide layer (see Fig. 1) from the base metal, allowing wetting to occur.

The formation of the alloy at the interface makes it impossible for the pre-wetting condition to be recovered. The extent to which liquid solder spreads across the surface is dependent on the surface tensions of the interfaces involved and any contamination therein.

The solder flux also aids in cleaning and reducing the surface tension of the molten solder. Due to the surface tension of the solder, a curved surface like a wire is more difficult to wet than a flat surface. And a sharp corner is almost impossible to adhere solder to. The alloying of the solder to the base material at the interface leads to the creation of intermetallic compounds (IMC) at the diffusion layer.

An IMC is a type of metallic alloy that forms a solid-state compound exhibiting defined stoichiometry and ordered crystal structure. The IMCs created during the soldering process are critical to the strength of the soldered joint. The most prevalent IMCs in lead-free SAC solder joints are Cu_3Sn, Cu_6Sn_5 and Ag_3Sn.

Lead & Lead-Free Soldering

The 2003 introduction of the Restriction of Hazardous Substances Directive (RoHS) 2002/95/EC, which led to an effective ban on lead in Europe in 2006, was the main reason the electronics industry moved from Tin-Lead solder to lead-free alternatives. Tin-Copper (SnCu), Tin-Silver (SnAg), and Tin-Silver-Copper (SnAgCu or SAC) are the most common alternatives to Tin-Lead, with Tin-Copper (99.3% Sn, 0.7% Cu – sometimes called pure tin) being the lower-cost, lead-free alternative. SAC305 (Sn 96.5%, Ag 3.0%, Cu 0.5%) is another commonly used solder alloy.

A eutectic solder alloy is a solder that has the same temperature for melting and solidifying, i.e. the Liquidus and Solidus are the same temperature. The Tin-Lead (SnPb6337) solder was a eutectic alloy with a melting point of 183°C that was widely used in the electronics industry prior to the ROHS directive. A peak reflow temperature of 215°C was used, as this gave good results with respect to electrical connectivity, and also provided satisfactory results from a mechanical perspective.

The replacement lead-free solder SAC305 has a liquidus of 220°C and a solidus of 217°C. The higher temperatures have a negative impact on the entire Printed Circuit Board Assembly (PCBA) and its reliability. The most critical concern is component integrity – the impact that elevated reflow temperatures have on the individual electronic components. IPC is attempting to develop new standards (component temperature) for the lead-free soldering process (020B specification).

A second concern with implementing a lead-free soldering process is the qualification of a lead-free solder paste that can handle a very large process window. Ideally, the manufacturer would like to have a solder paste that is capable of reflowing at both very low temperatures (230°C) and at very high temperatures (260°C). The former is potentially more important; if a very low processing temperature is possible, component integrity may not be an issue.

In recent years, a growing trend is to use the low reflow temperature (230°C) in conjunction with vapor-phase reflow to ensure PTs are never exceeded. This also ensures that reliability is not affected due to "cooking during reflow".

Mechanical Strength of the Reflowed Solder Joint

As previously mentioned, the creation of the IMCs within the solder joint is critical to giving it tensile strength, but IMC overgrowth can lead to brittleness and a poor solder joint. One of the critical issues is the effect of reflow profile on lead-free solder joint reliability since reflow profile would influence wetting and the microstructure of the solder joint.

Solder paste needs adequate reflow temperature to melt, wet, and interact with the copper pad or other board metallization and component metallization to form the solder joint. The intermetallic layers, which act as the bond, will form during the reflow and cooling process.

A suitable reflow profile is essential to form a good solder joint (Pan et al., 2006ii). Research studies show that the PT and TAL during the reflow process are the most critical parameters impacting solder joints reliability (Arra, 2002iii; Salam, et al., 2004iv). For SnAgCu reflow soldering, a commonly accepted minimum PT of 230°C is necessary to achieve acceptable solder joints.

The maximum temperature, on the other hand, depends on the board size, board thickness, component configuration, material thermal mass, oven capability, and other factors. These factors result in different temperature delta crossing the board, which can sometimes be as high as 20-25°C.

Moreover, larger components and thicker boards lead to a higher temperature delta across the board. In addition, greater complexities of component configuration demand a longer TAL to maintain uniform PT across the entire PCB (Pan, et al., 2006).

A good solder joint strength mainly depends on two parts: the microstructure of bulk solder joint and the intermetallic layer. The microstructure of SnAgCu solder joints is different from that of SnPb joints due to the presence of Cu6Sn5 (note that in SnPb solder joint, Cu6Sn5 is present only at the interface between SnPb solder and the Cu pad) and Ag3Cu IMC in the bulk solder (Salam, et al., 2004).

The intermetallic layer is a critical part of a solder joint because it facilitates bonding between the solder and the substrate. The thickness of this intermetallic layer determines the strength of the joint, but too thick of a layer can result in a brittle joint. "Up to 4mm of IMC thickness is generally considered to be acceptable within the electronics industry." (Pan et al., 2009v).

Compared to lead-based solders, SnAgCu solders require a higher reflow temperature which leads to accelerated diffusion rates and hence a thicker IMC layer. With a higher reflow temperature and a longer TAL, more substrate metallization is dissolved and more intermetallics are formed (Arra, 2002). An optimum combination of PT and TAL is important to achieve this "Goldilocks" zone of IMC thickness. Finally, a fast cooling rate is desired, so a finer grain size of solder joint is achieved. But this is limited by the cooling rate of the board and components.

What's Best for PEM Parts

For PEM parts and specifically SMTSO standoffs (SMTSOB also), the max temperature does not apply, as the component performance is not impacted by a high peak reflow temperature (260°C). Also, thermal shocking (heating or cooling too quickly) does not impact the PEM part either, as the substrate material is steel or brass.

From research, it is shown that a higher PT and a shorter TAL combined with an aggressive cool down rate will give the best tensile strength in a solder joint. See Fig. 2 and Fig. 3 (Pan et al, 2006).

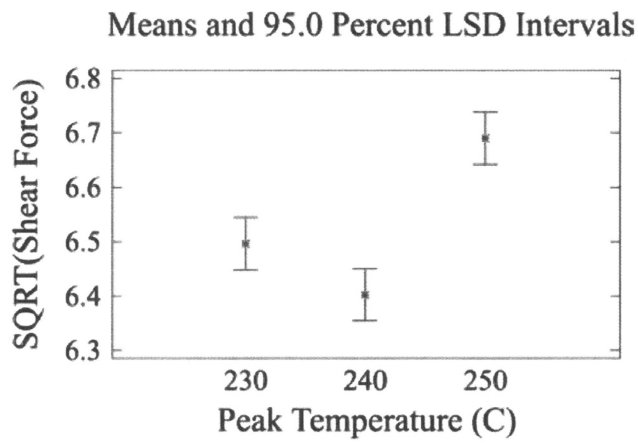


Fig 2. Effect of Peak Temperature on SAC305 solder joint shear force

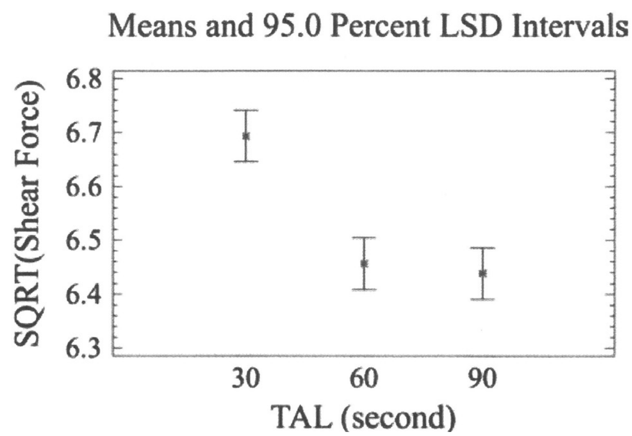


Fig 3. Effect of TAL on SAC305 solder joint shear force

"Cooling rate influences not only microstructure of solder alloy but also the morphology and growth of IMCs formed between solder and its metallization. All these have a significant effect on the mechanical integrity of the joint, and it can be concluded that as the cooling rate increases, the strength also increases." (Hardinnawirda et al, (2016) vi. Therefore, we should construct a reflow profile for PEM parts that gives a high PT (260°C), a short TAL, and an aggressive cool down rate.

However, due to the relatively large thermal mass of PEM fasteners (they are usually one of the largest items on the PCB), it can be difficult to achieve this ideal scenario. In addition, there are many other board components deemed more important, which tend to get the reflow profile that suits them. It is fair to say that unless the PEM part is falling out of the board, very little attention will be paid to its requirements when choosing the reflow profile.

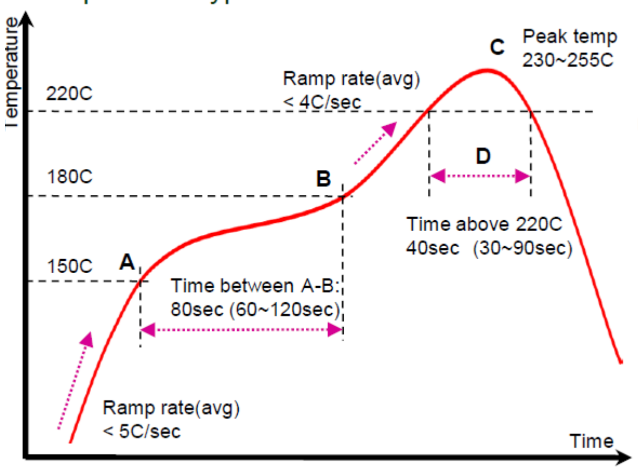
Reflow Curves

There are two types of reflow curves:

1. Trapezoidal type or Ramp-Soak-Spike (RSS)
2. Delta type or Ramp-To-Spike (RTS)

An example of each reflow curve is presented in Fig. 4 and Fig. 5.

1. Trapezoidal type

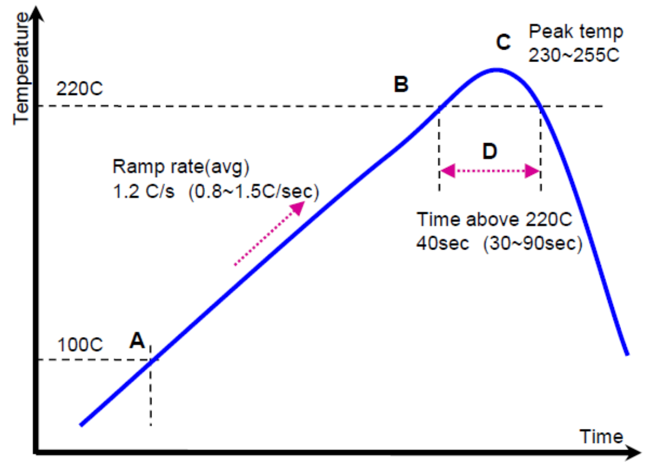


Point		Standard	Upper	Lower
A	Pre-heat start point	150C	160C	140C
B	Pre-heat end point	180C	200C	160C
A-B	Pre-heat time	80sec	100sec	60sec
C	Peak temperature	240C	255C	230C
D	Time above 220C	40sec	90sec	30sec

M705-S101ZH-S4 AC305 Solder paste
Senju Metal, Japan

Fig. 4 Trapezoidal Type Reflow Curve

2. Delta type



Point		Standard	Upper	Lower
A	Pre-heat start point	100C	-	-
B	Pre-heat end point	220C	-	-
A-B	Pre-heat time	100sec	150sec	80sec
Ramp up rate to Peak temp		1.2 C/sec	0.8C/sec	1.5C/sec
C	Peak temperature	240C	255C	230C
D	Time above 220C	40sec	90sec	30sec

Fig. 5 Delta Type Reflow Curve

If the board is simple and there are no complex components such as BGAs or big components like large PEM SMTSO standoffs on the board, the Delta type profile is the better choice, as it reduces the impact of high temperatures on the lifetime of the components.

Therefore, a suggested reflow profile is necessary which will allow board assemblers to use PEM parts on boards with other SMT components, as displayed in Fig. 6.

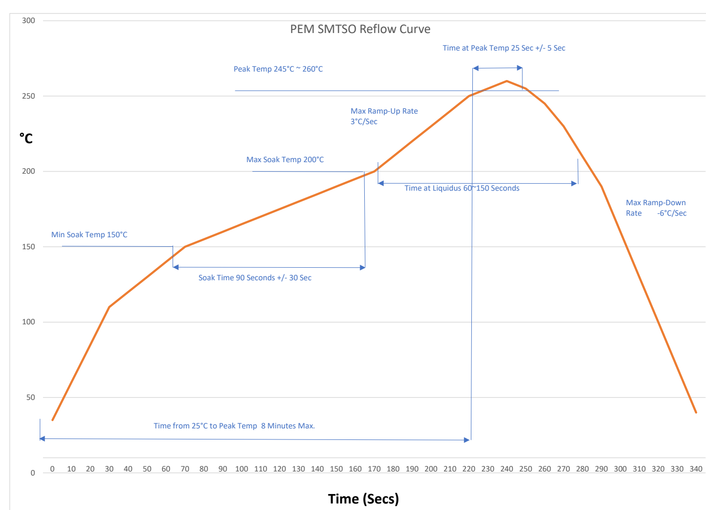


Fig. 6 PEM Reflow Profile

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Reflow Trends and Their Impact

The most significant trend within the PCB industry which would affect PEM SMT products is that of reducing the reflow peak temperature. The industry is actively pursuing this, as every °C reduction in reflow temperature leads to a corresponding improvement in lifetime reliability of active components. This is due to the high transistor density and smaller trace width designs needed for further miniaturization and reduction in power consumption – which in turns leads to more features and longer battery life in consumer electronic products.

A very popular solder paste is Alpha OM-338-PT, which is an SAC305 and has a recommended peak of 240°C, but can be run at a lower peak temperature of 230°C.`

Using vapor-phase reflow, the lower temperatures can be guaranteed as the maximum the board will experience. Vapor-phase reflow was invented along with SMT in the 1980s but was not embraced as the gases used were toxic and environmentally unfriendly. Since the creation of Perfluorinated polyethers (Galden), both challenges have been overcome and vapor-phase is gaining traction as an SMT process, as it is much easier to run than forced convection processes.

i Klein Wassink, R. J. , Soldering in Electronics (1994)

ii Jianbiao Pan, Brian J. Toleno, Tzu-Chien Chou and Wesley J. Dee (2006)
The effect of reflow profile on SnPb and SnAgCu solder joint shear strength.
California Polytechnic State University.

iii Arra, M., Shangguan, D., Ristolainen, E. and Lepisto, T. (2002)
“Effect of reflow profile on wetting and intermetallic formation between Sn/Ag/Cu solder components and printed circuit boards”, Soldering & Surface Mount Technology, Vol. 14 No. 2, pp. 18-25.

iv Salam, B., Virseda, C., Da, H., Ekere, N.N. and Durairaj, R. (2004)
“Reflow profile study of the Sn-Ag-Cu solder”, Soldering & Surface Mount Technology, Vol.16 No. 1, pp. 27-34.

v Jianbiao Pan, Tzu-Chien Chou , Jasbir Bath , Dennis Willie, Brian J. Toleno (2009)
Effects of reflow profile and thermal conditioning on intermetallic compound thickness for SnAgCu soldered joints.

vi K. Hardinnawirda, A. M. Zetty Akhtar, I. Siti Rabiatull Aisha & I. Mahadzhir (2016)
A review on the effect of surface finish and cooling rate on solder joint reliability.