Overcoming the challenges of lead-free wave soldering

The myths and realities of boundary nitrogen hood and full nitrogen tunnel wave soldering

Albrecht Beck, President & COO Ersa North America Inc. Plymouth, WI, USA

Over the past several years, the electronics assembly industry has witnessed a significant shift toward the miniaturization of SMT components while at the same time through-hole components remain a viable format for many applications. The advent of lead-free solder alloys has placed additional focus on the efficiencies of the wave soldering process. This paper explores the key considerations and issues that surround the use of boundary nitrogen hood and full nitrogen tunnel wave soldering technologies, in an attempt to dispel the myths, realities and misunderstandings regarding the roles each of these systems play in today's electronics manufacturing environment.

Introduction

Even though component technology is continuous evolving, there are applications within the electronics industry where either SMT components are not available or where thermally sensitive SMT devices cannot withstand reflow soldering peak temperatures. Because of this, wave soldering technology is still in demand for soldering of printed circuit board assemblies (PCBA) with through-hole (TH) components as well as SMT and TH mixed-technology boards. Lead-free solder alloys generally have a narrower process window cause by the greater thermal demand and higher soldering temperatures. In order to enlarge the process window, either the component heat resistance must be increased by selecting suitable materials, or the heat transfer during soldering must be more effective.

From a technical standpoint, the use of an inert gas such as nitrogen is highly effective in reducing oxidation, increasing surface tension of the molten solder, and increasing the process window all of which translates into greater product reproducibility. However, many legacy PCBAs do not always require the use of nitrogen because of either their straightforward design or the use of traditional tin-lead (SnPb) solder.

Nitrogen versus Air

Traditionally wave solder machines have used a solder pot equipped with either a single laminar wave, or dual chip and laminar waves, open to the ambient air atmosphere for soldering with tin-lead alloy. While this method has been used for many years it has several disadvantages, primarily excessive dross formation as well as high solder and flux consumption.

A common method for applying nitrogen to a wave soldering machine is a boundary hood in which a 'blanket' of nitrogen gas is bled into the solder pot by means of porous diffusers that are enclosed in a frame or plenum surrounding the solder pot. This results in a non-controlled or 'partial atmosphere' in which the printed circuit board/solder wave interface will see reduced oxygen content only when a PCBA is over the frame or plenum since the PCBA functions as an integral part of the method and functions as a sort of seal over the solder waves. Measuring the oxygen content with a boundary hood system in parts per million (PPM) is distinctively more difficult than a full nitrogen tunnel system. The printed circuit board/solder wave interface may see approximately 50-100 PPM for the few seconds a board is present directly above the waves. However, the oxygen level is very difficult to measure and varies in a wide range and can go as high as 8,000-8,500 PPM when a printed circuit board is not present above the solder waves.

Principal among the advantages of using a boundary nitrogen hood in the wave soldering process is a significant decrease in the production of dross which equates to reduced solder consumption as well as environmental, health and production benefits. Estimates vary, but the rate of dross production can be reduced by as much as 50-70% when compared to soldering in an open ambient air environment where the solder is directly exposed to oxygen.

A new technology has been recently introduced that uses heated nitrogen for wave solder machines equipped with a localized boundary nitrogen hood and has shown to offer benefits for both tin-lead and lead-free solder alloys. By preheating the nitrogen the heat transfer properties are increased and the temperature drop between the chip and laminar waves is reduced[1].

There are several advantages in using a full nitrogen tunnel wave soldering system as opposed to a boundary nitrogen hood system including a significant reduction in the production of dross, a substantial improvement in the wetting behavior of lead-free solder alloys, and reduced consumption of solder, flux and nitrogen (Table 1). Test results have shown that the amount of dross produced in a full nitrogen tunnel system is approximately 20 times less when compared to what is generated by a boundary nitrogen wave soldering machine. Data has also shown that the quantity of flux required for a full tunnel system is approximately 25% less than a boundary nitrogen system.

Parameter	Full Nitrogen Tunnel	Boundary Nitrogen Hood	Open Air Atmosphere
Solder Consumption	0.55 lb./shift (0.25 kg/shift)	13.2 lb./shift (6.0 kg/shift)	26.4 lb./shift (12.0 kg/shift)
Dross Generation	0.31 lb./shift (0.14 kg/shift)	7.9 lb./shift (3.6 kg/shift)	15.8 lb./shift (7.2 kg/shift)
Flux Consumption	1.05 gal/shift (4.0 liter/shift)	1.45 gal/shift (5.5 liter/shift)	1.95 gal/shift (7.4 liter/shift)
Nitrogen Consumption	425-530 SCFH (12-15 M^3/hr.)	530-670 SCFH (15-19 M^3/hr.)	None
Power Consumption	15.0 KWh	20.0 KWh	20.0 KWh
Typical Solder Defects	Refer to Figure 3 below	Refer to Figure 3 below	Generally higher

Table 1. Comparison of full tunnel, boundary hood and open atmosphere wave soldering

The advantages of using a boundary nitrogen hood as compared to wave soldering in an open air atmosphere include better wetting, less production of dross, reduced solder and flux consumption and better reliability and reproducibility. Typically solder pot maintenance can be reduced from being performed 4-5 times a shift with an open air atmosphere to once per shift with a boundary hood.

Numerous benefits are apparent in using a full nitrogen tunnel wave soldering system as compared to the 'partial atmosphere' of a boundary nitrogen hood system including a wider process window, better solder quality, reduced solder defects, the ability to use less aggressive fluxes, and substantial cost savings because of reduced consumption of solder, flux and nitrogen (Table 2). The increased process window provided by a full nitrogen tunnel system results in a thinner layer of oxides that requires less flux activity and therefore a less aggressive flux can be used to promote wetting more effectively while at the same time increasing surface tension of the molten solder. The use of a full nitrogen tunnel system also results in less oxidation of boards with organic surface protectant (OSP) surface finish during preheating, especially on the topside of the board where typically there is little flux coverage, which results in better hole fill and topside solder fillet formation.

Consideration Factor	Full Nitrogen Tunnel	Boundary Nitrogen Hood	Open Air Atmosphere
Wetting	Substantially improved because of full inert nitrogen atmosphere	Limited due to varying effects of 'partial inert atmosphere'	Wetting dependent upon oxidation and flux activity
Solder Consumption	Significant reduction of 20X less compared to boundary hood	50-70% reduction compared to soldering in open air	More solder required to replenish loss due to dross
Dross Formation	Significant reduction of 20X less compared to boundary hood	50-70% reduction compared to soldering in open air	Production of tin-oxide is high because of direct air exposure
Flux	25% less flux and the ability to use less aggressive fluxes	25% reduction compared to soldering in open air	More flux is required because of increased oxidation levels
Maintenance	Virtually maintenance-free with continuous gas cleaning	Frequent cleaning of nitrogen diffusers and solder nozzles	Continuous maintenance due to continual production of dross
Nitrogen Consumption	Consumption is up to 20% less compared to boundary hood	Can be as high as 1,000-1,400 SCFH (30-40 M^3/hr.)	None required
Solder Quality	Extremely stable wave height with Woerthmann nozzle	Reliant on board impingement, parallelism and dwell time	Dependent upon oxidation, flux activity and solderability

Table 2. Full tunnel vs. boundary nitrogen hood vs. open atmosphere comparative summary

A significant advantage of using a full nitrogen tunnel wave soldering system is that it opens the process window and allows the use of lower cost lead-free solder alloys such as SN100, SN100C or SACX. These lead-free alloys typically have shorter zero force wetting times when compared to SAC305 alloy at a given temperature, which translates into improved wettability performance when used in a full nitrogen tunnel system thus decreasing operating costs and providing greater process flexibility. An additional benefit of a full tunnel system is the use of a Woerthmann type wave nozzle which has an extremely stable wave height control and virtually no maintenance issues because of minimal dross clogging.

Process Stability

Full nitrogen tunnel wave soldering systems offer a distinct advantage over boundary nitrogen hood systems since they have a fully sealed tunnel (Figure 1), which provides a fully inert atmosphere as compared to a 'partial atmosphere.' This fully inert atmosphere is typically maintained in the range of 100-150 PPM for residual oxygen which is ideal for lead-free wave soldering since the decisive level of residual oxygen can be precisely monitored and continuously sustained. Lower residual oxygen levels mean less oxidation and less oxidation in turn results in better wetting characteristics for the lead-free soldering process. To ensure a stable and low residual oxygen level, the process tunnel is continuously purged with pure nitrogen with the purity of the source nitrogen normally between 5-10 PPM and at a constant flow rate. In addition, a residual oxygen measuring unit can be installed to continuously monitor and regulate the residual oxygen level with full closed-loop control within the tunnel at all times[2].

Fig 1. Sealed nitrogen tunnel to ensure stable and low residual oxygen levels

In order to guarantee reproducibility and stability of the soldering process, the preheat temperatures of a full tunnel system are continuously monitored and adjusted to ensure a constant preheat thermal profile. Typically the tunnel is equipped with a combination of medium and short wave length infrared elements as well as convection modules to provide uniform heating of high thermal mass assemblies and efficient evaporation of water-soluble fluxes.

Elimination of Flux Vapors

A potential issue of closed tunnel systems is the possible contamination of the process zones due to vapors that can result from outgassing of the flux as well as the printed circuit board or other materials. However, from an engineering perspective, containment of flux vapors can be effectively controlled by means of continuous filtering and re-circulation of the process gas (Figure 2). This multi-phase cleaning system extracts the process gases from the preheat zone upstream of the solder pot, as well as over the solder pot and the downstream cooling zone.

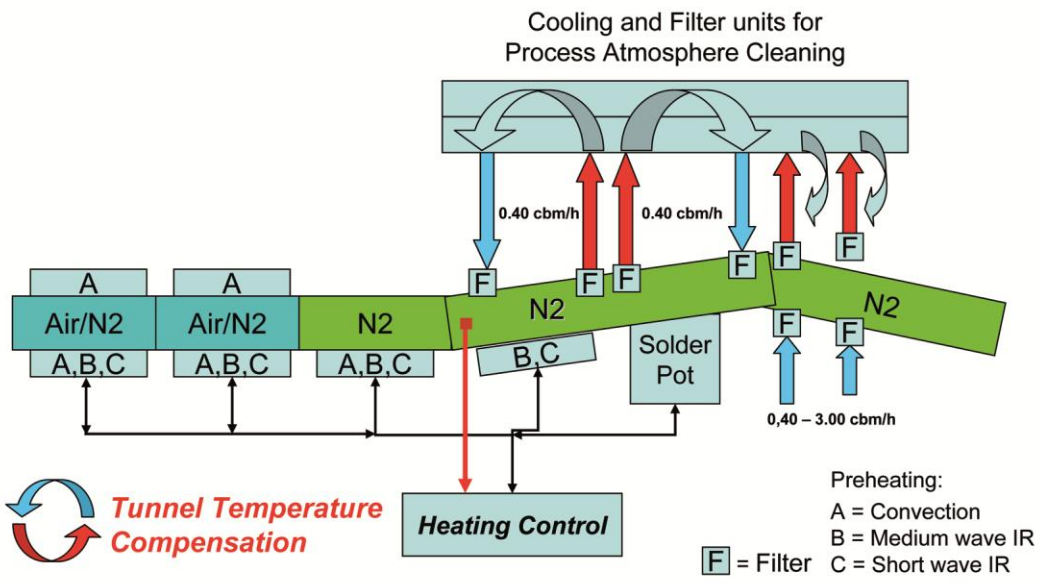


Fig 2. Re-circulation and filtration of process gas preventing condensation of flux vapors

A portion of the inert atmosphere is continuously extracted, cleaned and returned to the same modules successfully removing contaminates from the inert atmosphere. A positive benefit of this continuous process gas cleaning and re-circulation is that the system delivers cooled gas into the cooling zone thus stabilizing thermal conditions within the tunnel.

Cost of Ownership

An effective method to determine the direct and in-direct costs associated with running a wave soldering system is a true cost of ownership calculation. When the cost of major consumables including electricity, nitrogen, flux and solder are analyzed, a full nitrogen tunnel system is considerably less expense in comparison to a boundary nitrogen hood wave system or soldering in an open air environment in terms of total operating costs (Table 3). The comparison below is based on the use of tin-lead solder. It should be remembered that the worldwide cost of electricity and nitrogen varies significantly by global region with extremes ranging between $.05-.12/KWh for electricity and $.01-.05/SCFH for nitrogen.

Consumable	Cost Basis	Full Nitrogen Tunnel	Boundary Nitrogen Hood	Open Air Atmosphere
Electricity	$.05-.09/KWh	$4,312-7,762	$5,750-10,350	$5,750-10,350
Nitrogen	$.01-.02/SCFH	$27,427-54,855	$34,500-69,000	None
Flux	$42-45/gal	$33,075-35,437	$45,675-48,937	$61,425-65,812
Solder	$12-14/lb.	$4,950-5,775	$118,800-138,600	$442,800-516,600
Total operating costs per year =		$69,764-103,829	$204,725-266,887	$509,975-592,762

Notes: Solder alloy = Sn63/Pb37
Flux = no-clean
Operating environment = 3 shifts/day, 23 hours/day
Operating hours = 5,750 hours/year

Table 3. Total cost of ownership for full tunnel, boundary hood and open air atmosphere (SnPb)

A true cost of ownership calculation when using SAC305 lead-free solder alloy further shows that the cost of consumables including electricity, nitrogen, flux and solder for a full nitrogen tunnel system are substantially less expense for a full nitrogen tunnel system when compared to a boundary nitrogen hood wave soldering machine in terms of total operating costs (Table 4). It is generally not recommended to wave solder with SAC305 solder alloy in a wave soldering machine using an open air atmosphere due to the high rate of dross production because of direct air exposure

Consumable	Cost Basis	Full Nitrogen Tunnel	Boundary Nitrogen Hood	Open Air Atmosphere
Electricity	$.05-.09/KWh	$4,312-7,762	$5,750-10,350	Not recommended
Nitrogen	$.01-.02/SCFH	$27,427-54,855	$34,500-69,000	Not recommended
Flux	$42-45/gal	$33,075-35,437	$45,675-48,937	Not recommended
Solder	$31-35/lb.	$12,787-14,437	$255,750-288,750	Not recommended
Total operating costs per year =		$77,601-112,491	$341,675-417,037	Not recommended

Notes: Solder alloy = SAC305
Flux = no-clean
Operating environment = 3 shifts/day, 23 hours/day
Operating hours = 5,750 hours/year

Table 4. Total cost of ownership for full tunnel, boundary hood and open air atmosphere (SAC305)

The above total operating cost comparisons are based on use of 16” or 18” (400 or 450mm) wide wave soldering systems, which can vary depending upon the size of the wave soldering system as well as its usage. It should be noted that the above total operating cost comparisons are based on a high-volume 3-shift per day operating environment in an Asian-based factory. The above cost of ownership calculations can therefore be reduced for a 1-shift per day or 2-shift per day operation.

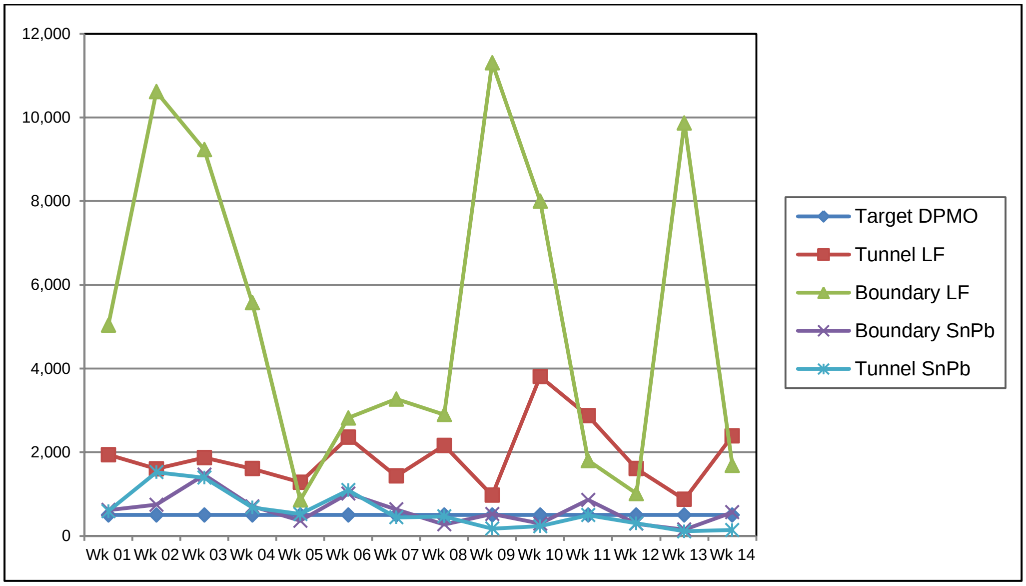
Narrowing the Gap

A common industry metric for quality measurement is defects per million opportunities (DPMO) which is often used to establish a baseline for in-process quality and to monitor follow-on process improvements. World-class in-process quality for SMT assemblies typically varies between 50-200 DPMO while through-hole (TH) assemblies are considerably higher at between 2,000-3,500 DPMO due to an increased number of material, component and assembly variables.

User experience has shown that the number of solder defects is dramatically reduced with a full tunnel system thus improving overall product quality and first pass yield (FPY), as well as reducing both the frequency and cost of post-solder rework and repair. The use of a full nitrogen tunnel wave soldering system also reduces equipment maintenance because of continuous process gas cleaning.

In monitoring the DPMO quality of several board assemblies wave soldered in a production environment with both lead-free (SAC305) and tin-lead (SnPb) solder alloys, in was found that the assemblies wave soldered with a full nitrogen tunnel system had considerably better quality (Figure 3). These board assemblies consisted of industrial multi-layer printed circuit boards having undergone either single-sided or double-sided reflow soldering, followed by wave soldering in selective aperture wave pallets. Over a 14-week production period, the quality level of various SAC305 board assemblies soldered with a full nitrogen tunnel system ranged between 857-3,807 DPMO, while assemblies soldered with a boundary nitrogen hood system were between 872-11,307 DPMO.

In addition, various SnPb assemblies soldered with a full nitrogen tunnel system ranged between 152-1,392 DPMO, while assemblies soldered with a boundary nitrogen hood system were between 175-1,461 DPMO. With both the SAC305 and SnPb assemblies, the frequency of solder defects including solder bridges, solder balling and solder skips, was substantially less for the assemblies soldered with a full nitrogen tunnel wave soldering system.



Notes: Production Line 1 = Full nitrogen tunnel using SAC305
Production Line 2 = Boundary nitrogen hood using SAC305
Production Line 3 = Boundary nitrogen hood using SnPb
Production Line 4 = Full nitrogen tunnel using SnPb

Fig 3. In-process DPMO for lead-free and tin-lead assemblies over 14-week production period[3]

In real-world cases the payback period for a full nitrogen tunnel wave soldering system can be as low as 12-17 months based upon the cost savings in consumable materials alone. This return on investment is improved when quality savings and direct/in-direct costs of reduced rework and repair are considered.

Conclusion

To some degree defect-free wave soldering with lead-free alloys remains a challenge. However, the use of a full nitrogen tunnel wave soldering system as compared to a boundary nitrogen hood system is advantageous in terms of improved solder quality, fewer solder defects and reduced rework and repair. This advantage is borne out by a sizeable difference in true cost of ownership for annual operating costs.

References

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