Optimizing the inert wave soldering process with hot nitrogen knives

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Abstract

The current decade has brought many innovations to wave soldering. One of the primary improvements to the process is soldering in an inert environment. Although the nitrogen environment reduces oxide production and improves solderability, the improved wetting can also lead to increased solder bridging. To reduce the incidence of bridging, wave solder equipment manufacturers have introduced several new features, such as steeper peel-off angles and hot nitrogen knives. The hot gas knives are an excellent debridging tool, but they are known to entrain air into the inert environment, thereby reducing the effects of the inerting process.

This paper addresses the use of hot gas knives and their effect on oxygen entrainment and process economics/defect rates. It outlines optimization studies performed on inert environments with hot gas knives and the modifications to process parameters that strike the best balance between dross formation and solder joint quality/defect levels.

Background

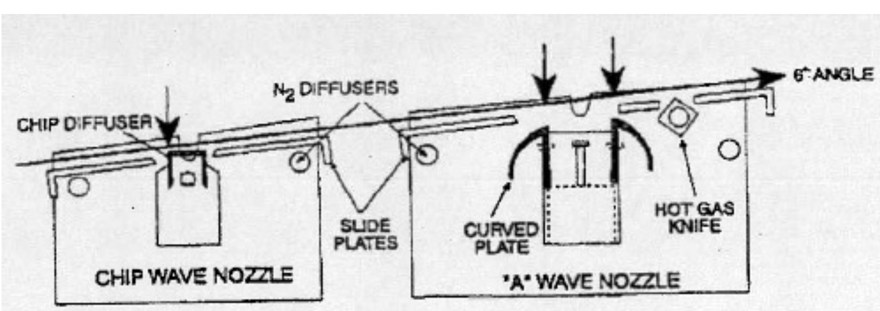
The use of inert atmospheres for soldering processes in the microelectronics packaging industry over the past decade has been proven to be valuable to printed circuit board (PCB) manufacturers/assemblers for quality improvements and cost reductions.[1, 2, 3, 5, 6] Improved solder wetting, better joint quality, and the use of less active fluxes are benefits realized as a direct result of the inert atmosphere's ability to control oxidation of the solder and the metal components being joined. These improvements have led to very high quality, cost-effective no-clean processes, finer pitch component geometry, higher-density boards, and a general explosion of the use of surface mount technology (SMT) in PCB manufacturing. Although technology packaging roadmaps[8] have predicted a continual progression toward smaller devices and integrated components, a significant demand continues in the electronics industry for products requiring pin-through-hole components and backside SMT chip devices that require wave soldering to complete the assembly. Thus, efforts at providing cost-effective inert atmosphere environments using nitrogen for wave soldering applications have also continued.[4, 9]

The benefits of inerting the wave soldering environment are twofold: solder joint quality improvement and reduction of solder dross formation. The improvement in solder joint quality is a direct result of the improved wetting achieved by minimizing oxidation of the metal components and the liquid solder. Mitigation of oxide inclusion in the solder joints also increases joint strength, providing better long-term joint reliability and higher resistance to thermal or mechanical stresses. Simultaneously, the lack of oxygen in the vicinity of the molten solder that forms the solder wave minimizes the generation of the lead and tin oxides which constitute solder dross, leading to extended process periods between required solder pot maintenance and lower costs associated with reduced dross removal/disposal and solder replacement.

Interestingly, while inerting the wave soldering environment typically increases the process window regarding joint quality and dross formation, the improvement in wetting can actually cause solder defects such as bridging of joints, especially when normal board design parameters are violated and joints are placed too close together. Before inerting, the dewetting effect of oxidation would prevent such design faults from causing bridging defects, most likely at the expense of increasing other types of soldering defects such as open or insufficient joints. Therefore, to realize the benefits of inerting without suffering from bridging defects on tight geometry boards, at least one wave solder machine manufacturer has installed a debridging device in the vicinity of the wave. This device is composed of a nitrogen knife installed horizontally beneath the conveyor carrying the PCBs, located just after the boards pass over the laminar wave performing the final joint soldering. A jet stream of nitrogen is directed in a slightly angled, horizontal plane at the bottom of the board, directly behind the point where the laminar wave of solder peels off from the bottom-side joints. The device employs this method to use the force of the nitrogen gas to prevent excess solder from clinging to the joints, which might have previously resulted in solder bridging from joint to joint. Aiding this is the fact that the nitrogen fed to the knife is preheated, typically to temperatures in excess of the solder's melting temperature so that the hot nitrogen stream will be exerting force against liquid solder and not against joints solidified by cool gas. Figure 1 illustrates the location of the wave solder environment and its associated components, including the hot nitrogen knife.

Experimental and production results making use of the hot nitrogen knife have shown that it appears to be highly effective in reducing the incidence of solder joint bridging. A question has been raised, however, as to its impact on other types of board defects, its effect on dross formation, and the best configuration of process parameters to optimize the system's performance. These questions revolve around the known fact that the nitrogen knife will entrain oxygen into the wave solder inert environment, resulting from a proposed venturi effect of the knife's nitrogen stream itself, pulling air (~21% oxygen) from the un-inerted areas of the system.

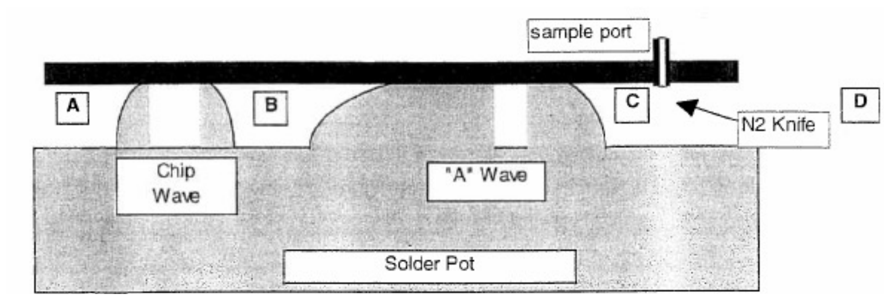
Figure 1: Wave Solder Layout[7]



Experimental Test Setup

To evaluate the knife's effect on the soldering environment's oxygen levels and the joints being formed by the chip wave and "A," or laminar, wave, a special test board was constructed to simulate a PCB passing over the wave(s) while allowing atmospheric samples to be taken from the solder side of the board. This configuration was used because the system of inerting the soldering environment is highly dependent upon the board's acting as a barrier as it passes across the wave(s), effectively sealing nitrogen beneath the board in the vicinity of the joints and excluding the oxygen-contaminated chamber from the joining process. Figure 2 illustrates the test board setup and its placement in the wave solder environment.

Figure 2: Wave Solder Components in Test Setup



The test board material was a 3-mm glass-filled epoxy that is typically used to make wave solder pallets for passing PCBs of varied dimensions through the wave solder machine. A stainless steel fitting was inserted into the epoxy board with compression joints that allowed a gas sample of the soldering environment to be pulled from beneath the board by the force from a vacuum pump and fed to an oxygen analyzer before exhausting the sample to the outside air. Two types of oxygen analyzers were used for taking measurements: a Teledyne Model 311 for low-level readings (e.g., <10,000 ppm oxygen), and a Servomex Model 571 for high-level readings (e.g., >1% oxygen).

The wave solder unit being investigated was an Electrovert Econopak Plus® fitted with an inerted, motorized, rotary chip wave and the CoN2tour Plus® inerted laminar wave with hot nitrogen knife feature. This particular machine had been newly installed at Siemen's Business Communication Systems facility in Cherry Hill, N.J. Production boards run on the unit had shown remarkable quality improvement over the previously used wave solder machine that had not been inerted.

Initial testing was focused on evaluating changes in oxygen levels and board defect levels by varying process parameters such as the nitrogen pressure to the hot nitrogen knife, the knife angle, and the knife temperature. What was discovered, however, was that board defects were only observed when the nitrogen knife was disabled, causing bridging between closely set components. Solder splatter was also discovered to be a problem when the pressure and/ or angle of the knife was set excessively high, hurling liquid solder onto the topside of the boards, but bottom-side defects were nonexistent. Since bottom-side defects were not a problem with the knife activated, efforts were redirected on measuring oxygen levels under different knife conditions in order to assess the knife's impact on dross generation.

Results and Observations

Testing began by taking oxygen level readings at various locations within the wave solder environment under baseline conditions. Table 1 below shows the machine setpoints used for the baseline readings, as well as the oxygen measurements for each point.

Table 1: Nitrogen Knife Test Data

Process Parameters	1	2	3	4	5	6	7	8
Chip Wave Front Nitrogen Diffuser	N/A	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh
Chip Wave Rear Nitrogen Diffuser	N/A	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh
Laminar Wave Front Nitrogen Diffuser	N/A	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh
Laminar Wave Rear Nitrogen Diffuser	N/A	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh
Nitrogen Knife Pressure	N/A	5 psig	Off	5 psig	Off	5 psig	Off	5 psig
Nitrogen Knife Angle	N/A	65°	65°	65°	65°	65°	65°	65°
Nitrogen Knife Temperature	N/A	800 F	800 F	800 F	800 F	800 F	800 F	800 F
Sample Location	House Nitrogen	A	A	B	B	C	C	D
Oxygen Level Measurement	**2.6 ppm**	**>1%**	**14 ppm**	**>1%**	**14 ppm**	**>1%**	**4.5 ppm**	**9.8%**

The data above show the immense effect of oxygen entrainment into the soldering area caused by the action of the nitrogen knife. With the knife off, Locations B and C experienced very low oxygen levels with the test board in place, serving as a seal to maintain the inert environment produced by the four nitrogen diffusers located aside the waves. Activating the knife, however, caused an immediate jump in the oxygen levels at all locations. Investigation using a smoke aerosol visually confirmed that the knife was creating a current of air that draws in the oxygen contamination from the back end of the machine.

Subsequent testing was performed using the Servomex Model 571 oxygen analyzer to more accurately identify the oxygen levels being generated by the action of the nitrogen knife. Figure 3 below illustrates the relationship between the nitrogen knife pressure and the measured oxygen level at Location C for a series of trials in which other process parameters were also varied. The parameters for each trial are listed in Table 2 below. These variables included attempts to seal the wave solder chamber from the outside air, adjusting diffuser flow rates, changing the knife preheat temperature and diverting some of the nitrogen flow to the knife into the back end of the chamber.

Figure 3: Nitrogen Knife Oxygen Entrainment

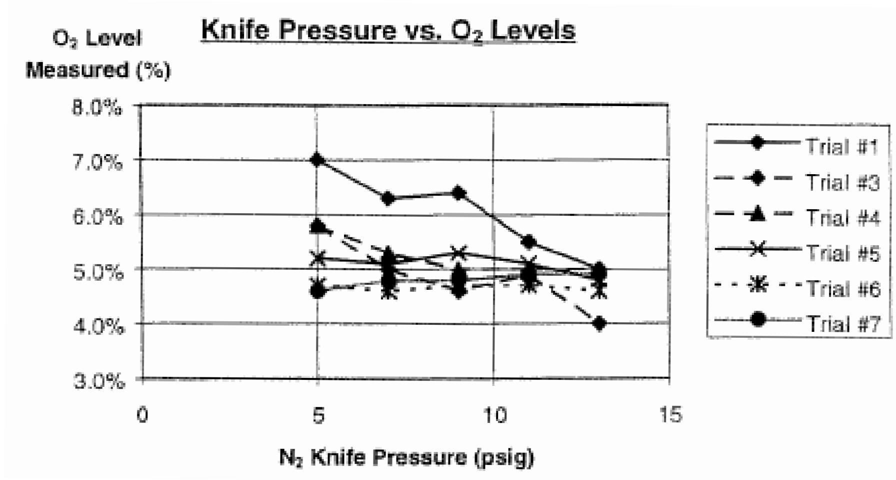


Table 2: Trial Parameters

Process Parameters	1	2	3	4	5	6	7
Chip Wave Front N_2 Diffuser	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh
Chip Wave Rear N_2 Diffuser	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh	200 scfh
Laminar Wave Front N_2 Diffuser	200 scfh	200 scfh	200 scfh	300 scfh	300 scfh	300 scfh	200 scfh
Laminar Wave Rear N_2 Diffuser	200 scfh	200 scfh	200 scfh	300 scfh	300 scfh	300 scfh	200 scfh
N2 Knife Pressure	5 psig	5 psig	5 psig	5 psig	5 psig	5 psig	Off
N2 Knife Angle	65°	65°	65°	65°	65°	65°	65°
N2 Knife Temperature	800 F	800 F	650 F	800 F	650 F	650 F	800 F
Chamber Seal	Open	Closed	Closed	Closed	Closed	Closed	C
N_2 Knife Flow Diverter	Closed	Open	Open	Open	Closed	Closed	4.5 ppm

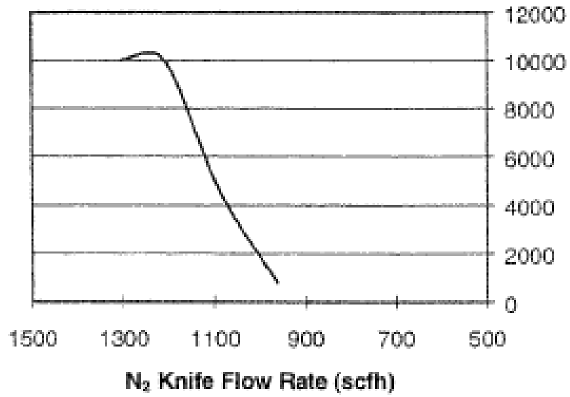
It was observed that, although there appears to be a general trend of decreasing oxygen levels with increasing knife pressure, there were still extremely high levels of oxygen present (e.g., >40,000 ppm) in the area of the laminar wave under all conditions. It was believed that the decreasing oxygen trend was due to saturation of the wave solder chamber, caused by high flow rates of nitrogen from the knife and diffusers. While nitrogen saturation was potentially effective in lowering oxygen contamination, it did not appear to be capable of reaching the low levels customarily believed necessary for effective dross reduction. Furthermore, to achieve chamber saturation would require heavy nitrogen consumption, raising material costs above current levels. Therefore, to directly address the venturi effect of the knife while still keeping an eye to process economics by controlling dross production and nitrogen consumption, further testing with reduced nitrogen flow rates to the knife was performed.

Subsequent tests were performed at Electrovert's Center for Advanced Technology and Training in Grand Prairie, Texas on a wave solder machine identical to the unit installed at Siemens. One change was made to this unit, however: the installation of a flow control valve retrofitted into the knife's pneumatic circuit to allow for testing at reduced nitrogen flow rates.

Baseline readings were again taken to ascertain the oxygen levels within the wave solder environment before testing. Measurements again confirmed that the oxygen levels at Locations B and C were fairly low with the knife off. When the knife was activated, a gradual increase in oxygen was observed at Location B (between the waves), reaching a peak of approximately 10,000 ppm (i.e., 1%). Figure 4 below shows the change in oxygen levels achieved between the waves on the Electrovert machine by using the flow control valve to control the nitrogen flow rate to the hot knife at a consistent pressure setting of 5 psig.

Figure 4: Oxygen Control in Econopak Plus With Hot Knife

Knife Flow Rate vs. O_2 Level Between Waves

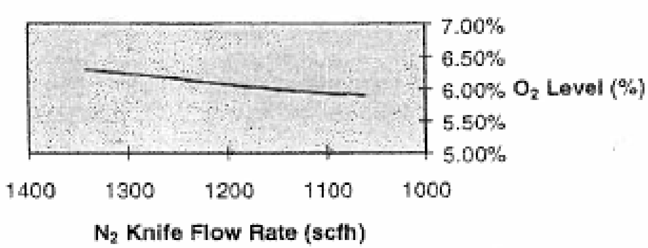


The oxygen level was further minimized between the waves by increasing the nitrogen flow rate to the laminar wave diffuser located on the chip wave side. Increasing the flow rate from 200 scfh to 300 scfh at the diffuser reduced oxygen levels from 800 ppm to 250 ppm. Because 500 ppm or less is considered a good soldering environment, the combination of reduced flow rate at the knife and increased flow rate at the diffuser should be considered the optimum soldering atmosphere for this machine configuration. Subsequent board soldering debridging trials and dross production tests were run under these optimized conditions.

Following the above tests, the sample port was then relocated to Location C, behind the laminar wave, to determine the relationship between oxygen level and nitrogen knife flow rate at that point. Figure 5 below illustrates this, again taken at a constant pressure to the knife of 5 psig with the flow rate constrained by the use of the flow control valve.

Figure 5: Oxygen Entrainment at Laminar Wave

N2 Knife Flow Rate vs. O_2 Level @ Laminar Wave



Debridging Tests

To confirm that the lower nitrogen flow rate of the hot nitrogen knife would provide sufficient force to successfully debridge assembled PCBs passing through the wave solder machine, a number of circuit boards were assembled and run under the throttled-back conditions. Debridging at the lower flow rate was successful on chip components, SOT-23's and 100-mil center pin-through-hole parts. It should be noted, however, that debridging at lower flow rates may not be successful in all cases. Parameters for controlling the effectiveness of the nitrogen knife include angle, height, and temperature, as well as flow rate. Controls for debridging also include the height of the laminar wave and the amount of warp in the circuit board.

Dross Generation

The final tests involved evaluating the amount of solder oxide, or dross, generated by exposure of the turbulent solder waves to the oxygen-contaminated atmospheres produced by the use of the hot nitrogen knife. Dross production tests were performed at Electrovert's Center for Advanced Technology and Training and are summarized in Table 2. The same wave solder unit used for the above oxygen-level testing was de-drossed prior to the dross testing, operated under each set of conditions for 4 hours, and de-drossed again using Kleenox oxide separating agent. Dross production tests were performed under worst-case conditions where the waves operated continuously with no circuit boards being soldered. The dross produced was weighed, and the total weight was divided by the four hour running time. As shown in table 2 dross production was reduced by approximately 17% with the nitrogen flow rate reduced by approximately 21%.

Table 2: Dross Production

System Configuration	Oxygen Level (Between Waves)	Dross (lbs./hr.)
Nitrogen Knife @ 1300 scfh	10000	2.93
Nitrogen Knife @ 1017 scfh	250	2.43

Costs associated with dross are estimated to be approximately $1.00 per pound. Although the prices of solder and dross vary throughout the world and depend on the price of the lead and tin commodities, they vary proportionally. As the price paid for new solder rises and falls, so does the price received for reclaimed dross. If the price received for dross is subtracted from the price paid for new solder, the difference is typically between $.75 and $1.25 per pound. Therefore, dross savings realized by reducing the flow rate of the knife is approximately $.50 per hour per machine.

Nitrogen costs, just like solder and other material costs, vary widely throughout the world as well. Regardless of location, however, a 21% reduction in nitrogen consumption can have a large impact on material costs associated with a continuous wave solder operation. Together with dross cost reductions, a total savings of $1.00 per machine per hour is not unreasonable. For an assembly operation of five machines running 24 hours per day over a 360-day working year, annual savings of over $40,000 in operating expenses are possible.

Discussion

It is apparent from the test results that the hot nitrogen knife, even at minimum pressure settings of 5 psig, entrains a significant amount of air. This, however, does not appear to adversely impact product quality as measured by visible soldering defects. Thus, what must be remembered is that the gaseous environment where debridging occurs is secondary to the fact that debridging is occurring. The benefits of the hot nitrogen knife far outweigh the cost of its use in terms of the improved product quality obtained versus solder expense from dross generation. Joints are clean and shiny, despite non-standard design practices on the circuit boards.

After acknowledging the benefits of using the knife, however, it is apparent that the environment where wetting occurs can still be improved in order to take advantage of the benefits of soldering in an inert atmosphere. By using a flow control valve retrofitted into the knife's pneumatic circuit, the flow rate of nitrogen to the knife was minimized. Oxygen levels decreased by an order of magnitude between the waves, which is a critical area for both wetting and dross production. Therefore, it appears that another process parameter, namely nitrogen knife flow rate, needs to be considered and controlled, since a high flow rate will entrain excess oxygen but a low flow rate may result in insufficient debridging.

The oxygen levels measured at the soldering locations and the environment behind the nitrogen knife suggest that the drawing action of the nitrogen knife is resulting in a 50/50 mix of sealed system nitrogen and ambient environment. Because of the high oxygen levels in the stream delivered at the debridging site, a high-purity, cryogenic nitrogen supply may not necessarily be required for effective knife operation. If the stream of gas acting on the solder joints is a 50/50 mix of nitrogen from the knife and ambient atmosphere, then downgrading the purity of the nitrogen feeding the knife to 99% purity will only result in a stream purity change from 5% oxygen to 5.5% oxygen. This being the case, product quality and dross production are unlikely to change significantly, yet nitrogen costs may be reduced if consumption levels can justify a noncryogenic nitrogen generator being installed for just such a purpose. It must be remembered that higher-purity nitrogen would likely still be required for the nitrogen diffusers inerting the waves; thus, use of noncryogenic nitrogen for the knife only would necessitate a dual nitrogen system to supply both purity levels. If multiple wave solder machines are present, nitrogen demand could potentially achieve volumes that would make such a scenario economically feasible. A total cost of ownership review would be recommended before pursuing this option.

System configuration is a consideration that can also significantly impact debridging and has as large an impact on the amount of dross produced as the oxygen level in the soldering environment. The difference between the various types of solder waves should be noted, as well as the method of inerting. Lambda® waves resemble traditional laminar waves, whereby a standard Lambda® nozzle setup allows 90% of the wave to flow over the front (load end) of the nozzle and 10% of the solder to flow over the back (unload end) of the nozzle. The front and rear plates of the nozzle are straight and oriented vertically. The peel-off angle on the Lambda® wave is equal to the incline of the conveyor, usually 6°. The CoN2tour® wave's nozzle configuration differs from the Lambda® wave's in the geometry of the nozzle and the flow ratio. The CoN2tour® nozzle employs curved plates on the front and rear of the nozzle, encouraging more laminar flow of the wave as it reenters the pot. A CoN2tour® standard nozzle setup allows 80% of the solder to flow over the front curve plate and 20% to flow over the rear. The curved nozzles and greater flow over the back provides a steeper peel-off angle and more assistance from gravity when debridging. It is hypothesized that CoN2tour® waves operated in air would increase dross production due to the high backflow of solder, and Lambda® waves operated in a nitrogen environment would demonstrate increased bridging due to the shallower peel-off angle. Because these modes of operation are considered nonstandard practices, data are not available for these scenarios.

To summarize, improved assembled printed circuit board quality can be achieved with the use of the hot nitrogen knife for debridging. Production costs, however, in the form of solder and nitrogen expenses can be improved by controlling the flow rate of the knife.

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