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Developments in Vapor Phase Soldering Technology

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Abstract
Vapor phase soldering is in discussion of the recent past. Some of the topics of our own work are presented in this paper, like the combination of vapor phase reflow soldering with wave soldering process. This combination makes it possible to solder printed circuit boards with SMT and THT components in one step. Additional the inert vapor atmosphere takes on the protection of liquid solder from oxidation. Another current development is an inline condensation soldering system. In a laboratory construction a lot of experiences were collected. The studies shows the importance of understanding the connection of partial pressure and temperature as well the mechanism of flow and heat transfer. First results were tested by soldering of true electronic assemblies and with lead free solders.

Introduction
Because of lead free soldering the discussion on alternative soldering methods and its application was provoked. Unless the tin-bismuth or tin-indium alloys all alternative lead free solders have noticeable higher melting temperatures or melting ranges than common lead containing solders. This is involving that soldering temperatures must increase too. Table 1 shows the relations between melting point and processing temperatures for typical examples. It must be pointed out that it is not sufficient to exceed the liquidus temperature of the solder by some degrees. Miscellaneous investigations have shown, that a overheating of 10% at least is demanded to ensure well solderability and process run as fast as possible. For lower temperatures increases the danger of poor wetting and enclosing of blowholes or cavities. Other special measures like vacuum treatment or extending soldering time have to be taken to prevent these known problems of lead free soldering.

For calculation of this demanded overheating it must be noted, that temperatures have to set in absolute Kelvin temperature. On the other hand the maximum allowed temperature for most of components and materials is very limited, often 260°C or even 240°C. In consequence of this relation the process window for soldering becomes smaller and smaller.

This problem leads to a demand for improved methods of heating or heat transfer at the time. The well-known principles of vapor phase soldering are showing such advantages particularly relating to constancy and distribution of temperatures on electronic assemblies. Nevertheless the introduction of vapor phase soldering in industrial processes meets with several problems. Only in the recent past true inline machines for vapor phase soldering are available. Usually the electronic manufacturers have no experience with vapor phase soldering and the common standards for temperature profiling and limits don't fit for such processes.

Table 1 - Temperature Relations for Lead Free Solder Alloys

temperatures in °C	SnPb	SnAgCu	SnAg	SnCu
eutectic melting temperature	183	217	221	227
soldering with 5% overheating	206	242	246	252
soldering with 10% overheating	229	266	270	277

Just as important as technical properties are the economical aspects of different vapor phase processes. The applied standard for the valuation of these aspects is the today's convection soldering. Especially the throughput of printed circuit boards, the flexibility for different board sizes and the consumption of vapor phase media will determine the process efficiency. A well-designed lock or cooling trap and an uncomplicated convey system are the key factors for this characteristics.

Fundamentals of Vapor Phase Soldering
Vapor phase soldering is in discussion at present, but nevertheless it is not a new technology. First works in this field were done in the seventies, the first patented solutions is shown in Figure 1 and was published by R.C. Pfahl[1] and H.H. Ammann[1].

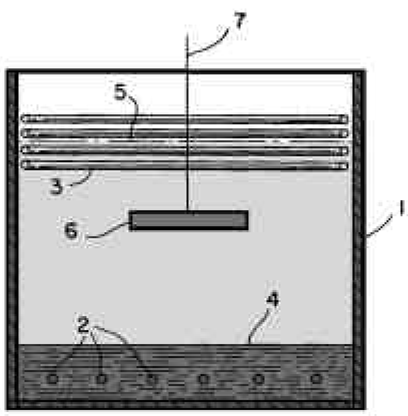

Figure 1 - First Published Vapor Phase[1]

A high boiling liquid is needed, which is covered by a saturated vapor. For retaining this vapor between the boiling liquid and a cooler coil, it should have a higher density than air. If an assembly such as printed circuit board will be immerged in the saturated vapor cover, it will condense at its surface immediately. Because this process will transfer the total heat of evaporation to the assembly, the temperature rise is very rampant.

If the assembly has reached the condensation temperature of the used media, the heat transfer must terminate inevitably, because condensation is not any longer possible. An overheating of components higher than condensation temperature is completely excluded.

Two of the main problems for this technology right from start were the high gradient of temperature as well the losses of media. This leads to the further development of a two-layer vapor phase[2], shown in Figure 2.

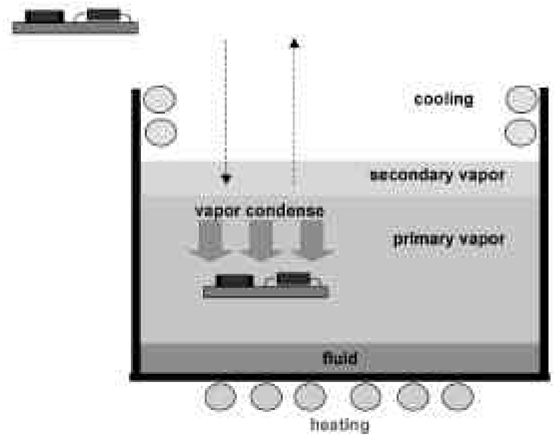

Figure 2 - Modified Vapor Phase Process with Two Different Vapor Covers[2]

The secondary vapor with a lower density and a lower boiling temperature covers the primary vapor, which is allotted for soldering. By the secondary vapor the assemblies can be preheated and the discharging of primary media can be inhibited. Because of the difficult use and separation of media, this principle did not asserted.

Another important step for an effective use of vapor phase in assembly of printed circuit boards was the development of a controllable atmosphere with an unsaturated vapor[3]. The principle of this technology makes it possible to dose the quantity of vapor corresponding with the specific need of the assemblies. This technology is also used for today's vapor phase lines.

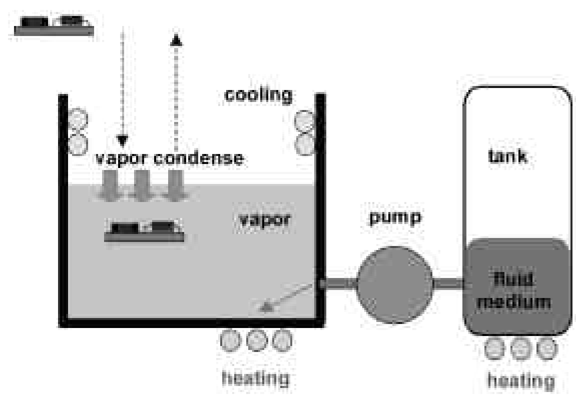

Figure 3 - Vapor Phase Soldering with Unsaturated Vapor Atmosphere[3]

Combined Reflow and Wave Soldering
The potential of vapor phase soldering is unsounded today. But by the oncoming problems with lead free and higher melting solders, the development got a new stimulus. This situation leads to the idea, to combine a vapor phase reflow soldering process with a wave soldering process in one system. Figure 4

shows the principle of such a combined reflow and wave soldering system.[4]

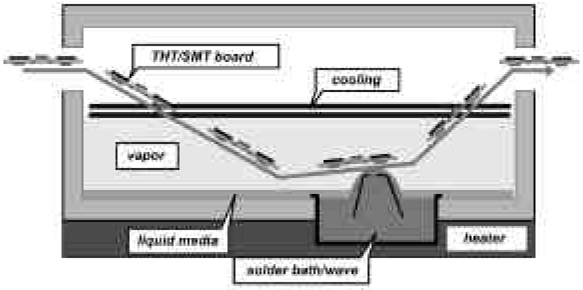

Figure 4 - Combination of Reflow Soldering and Wave Soldering in a Vapor Phase[4]

The vapor atmosphere has the function to transfer the heat for reflow soldering of components on the top side of boards and simultaneously to prevent the solder bath and wave from oxidation. On the other hand the solder bath can be used for heating the vapor phase media. The practical testing of soldering with a first laboratory machine shows a harmonious interplay between both processes, provided that intense turbulence can be avoided. It was observed, that a turbulent flow of solder wave would affect an increasing generation of droplets in form of an aerosol. The boundary of vapor cover becomes whirling, the loss increases. For this reason a electrodynamic jet wave with a very homogeneous solder flow was preferred. This special wave is driven by the Lorentz force with an inductor like a linear motor and contains no rotating parts. Additional for this type of wave no entrances for rotating shafts were needed.

The electronic assemblies will be immerged into the vapor cover, where the reflow heating starts immediately. In the vapor cover the assembly moves on a carrier horizontal across the jet wave, where the wired components will be soldered. Because of the high speed of the solder flow and the developing suction of the hollow wave, the process works also in a quite horizontal direction without solder excess or bridging. In contrast to common wave soldering no angle in transport line is demanded. For the printed circuit board and the components is this combined reflow and wave soldering process more careful than two separate processes, because only a single thermal stress cycle has an effect on it. Additional the demanded bath temperature is lower than for standard wave soldering.

First prototype of the combined vapor phase reflow and wave soldering machine works very reliable in a production line since several years[5] and for long periods nearly maintenance-free. Figure 5 shows a view in this machine during such a combined reflow and wave soldering process. The needed flux for wave soldering will be deposited with a common spray-fluxing device in a separate module.

A special feature of this prototype machine was developed by G. Thumm[5]. By using a carrier with two levels for printed circuit boards, it is possible to solder a SMT and a THT board simultaneously. This supplementary feature is useful for a very flexible application with a high number of assembly models with low quantities of pieces. Additional the use to capacity can step up considerable. A photo of this tandem carrier with boards for soldering in front of the inlet of machine is shown in Figure 6.

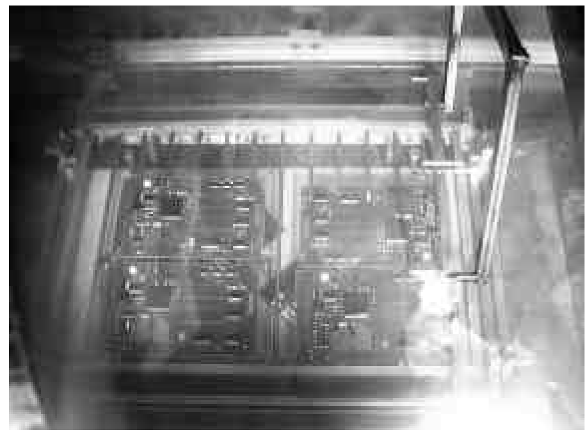

Figure 5 - Printed Circuit Board in the Process Chamber during Wave Soldering in Vapor Phase[4]

Figure 6 - Tandem Carrier with Printed Circuit Boards[4]

In this case the prototype includes a standard tin-lead solder bath and the chosen temperature for wave soldering is 230°C. The vapor media has a temperature of 215°C, which is also matched to standard solder pastes. But higher boiling media and temperatures are also possible. Further developments of the combined reflow and wave soldering technology were related with controlling the height of vapor cover. By limiting this variable and sharp above the wave, it will be possible to process sensitive components like electrolyte capacitors or thermoplastic elements too. They can jut out from the vapor while the remaining board will be soldered. For this purpose an adaptable system of cooling coils and plates was tested,[6] which allows to change its position.

Inline Condensation Soldering Machine

One drawback of most of the vapor phase soldering machines is, that they are no true inline machines. This limits the throughput as well the flexibility and complicates the service. For that reason it is the purpose of a current project, to developed a process based on heat transfer by condensation, which allows to realize a true inline soldering without any changes in transport direction. Figure 7 shows the concept of such an inline machine. Because the experience from other soldering processes has proven that preheating and cooling is even important, the concept shows multiple zones for all temperature regions.

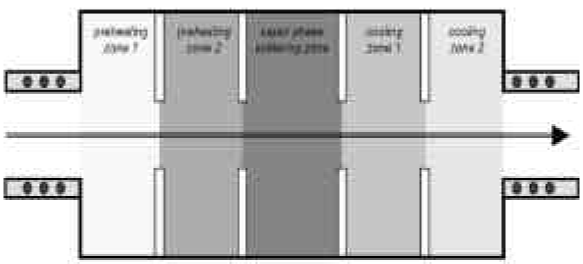

Figure 7 - Structure of a True Inline Condensation Soldering Machine

The most important precondition for a true inline vapor phase is avoiding the need for a vapor cover. On the other hand an unsatturated vapor can't ensure reaching of the full desired maximum temperature, because of the partial pressure which is explained below. The actual solution can meet this requirements by shower the assemblies with an overheated vapor[7]. This vapor will be generated in a separate module and flows into a nozzle block inside of the process chamber. In the heated nozzle block the vapor will be overheated to a definite amount. Condensation happens on the bottom of chamber, where also the outlet for liquid media is. Liquid and vaporized media flow in a continuous circulation. It is important to note, that the condensation temperature on the board can't increase with overheating the vapor as so long as soldering chamber itself has a normal pressure (see also Figure 9).

Theoretical deflections and practical trials have also shown, that condensation of vapor on a surface not only stopes the further heat transfer by condensation but also is limiting any heat transfer, by overheated vapor too. In the moment when a closed film of condensed liquid covers the sample, this acts as an thermal insulation, because the liquid media has a very low heat conductivity in the range of 0.05 W/mK. For comparison, the heat conductivity of water is 0.68 W/mK.

Figure 8 - Laboratory Machine for Experimental Investigation of Inline Condensation Soldering

Figure 8 presents the realization of this process in an experimental soldering machine. This machine is a half open chamber, to simulate the conditions in a real open inline machine. The space under the nozzle block is enough for a printed circuit board with the size of 200 x 250 mm^2 and a height of 50 mm.

First trials with this machine had shown a condensation of vapor on test boards with a temperature, which was notable lower than the expected temperature of 260°C. The reason for this was found in the vapor-pressure diagram, visible in Figure 9. It shows that each lowering of pressure below the normal atmospheric pressure will affect a decrease of boiling/condensation temperature. In this case we had a constant total pressure, but a low partial pressure. This is caused by the turbulent mixture of vapor leaving the nozzle with air. For example a media with a boiling temperature of 260°C at normal pressure is mixed with 20% air, which is an unsaturated vapor. In this mixture with a total pressure of 1000 mbar (normal) the vapor has only a resulting partial pressure of 800 mbar. Following from vapor-pressure diagram the condensation temperature drops to 247°C.

By knowing this relationship it was possible to find suitable measures to avoid the mixing with air. With an optimization of nozzle shape and overheating as well chamber design it was possible to ensure a constant condensation temperature of 260°C.

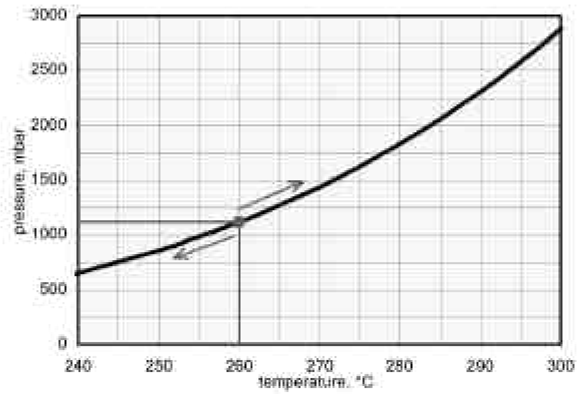

Figure 9 - Boiling/Condensation Temperature of a 260°C Media Depending on Vapor Pressure

Practical Results of Inline Condensation Soldering

After optimization of the laboratory machine the testing with real printed circuit boards started. For supporting this trials an international manufacturer of telecommunication systems[8] provides demanding boards from production. Figure 10 shows the measuring board, prepared with thermocouples. It is a multilayer board with large and heavy ceramic devices beside other conventional components.

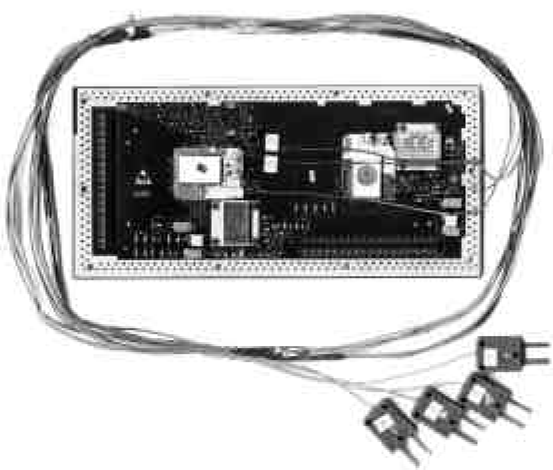

Figure 10 - Temperature Test Board for Practical Investigation[8]

The measured temperature profiles are shown in Figure 11. It is visible, that after a preheating phase all measured curves rising nearly simultaneous up to maximum temperature during only two minutes. Only the graph direct measured in atmosphere is a bit steeper than the other. After three minutes the differences between board and atmosphere is only 3K.

Table 2 shows an overview of selected values for comparison. Only the free separate mounted thermocouple shows 2K higher temperature. The surfaces of components and board are 1K or 0.5K together. With a stable maximum about 259°C documents the very high purity of vapor in the region below the nozzles.

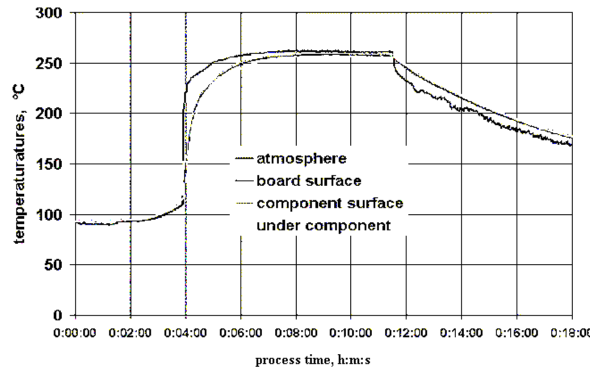

Figure 11 - Measured Temperature Profiles for Condensation Soldering in the "Inline" Machine

Table 2 - Selected Temperature Values

	atmos-phere	board surface	comp. surface	under comp.
30 s	259,5	252,5	254,5	249,5
1 min	260,5	255,5	256,5	253
2 min	262	258	259	255,5
max	262	259	259,5	257

With the same test board different soldering processes and machines were investigated. The most important comparisons are with forced convection, which is today's dominating reflow soldering method, and of course with batch vapor phase, because it is the principal form of the developed process.

To derive an objective scale to compare the different soldering processes, a standard solid with a thermocouple was designed. With this standard solid in the form of a small copper cube the measured soldering profiles were evaluated. So it was possible to calculate the coefficient of heat transfer α. For an industrial forced convection soldering machine a value in the range of 40 W/m²K was calculated. The α value for the open laboratory condensation soldering machine is in the range of 100 W/m²K. This is considerable higher even if the heat transfer of an industrial batch vapor phase machine is about 300 W/m²K. The direct compare between the present inline condensation soldering profile and an industrial batch vapor phase is shown in Figure 12.

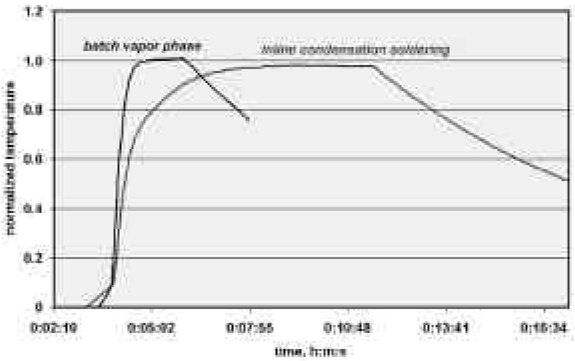

Figure 12 - Comparison of Temperature Rise for a Standard Batch Vapor Phase and the "Inline" Condensation Machine

The test results and experiences are taken into consideration for the conception and design of the prototype of an inline condensation soldering machine, which will be adequately larger with improved thermal insulation, temperature control and a true inline transport. So it will be possible to achieve further increase of α. On the other hand it is known, that the very steep gradient of common vapor phase is not always desirable. Because of the achieved high partial pressure and the successful realization of nearly maximum condensation temperature, it is taken into consideration to continue with lower boiling media, e.g. 240°C.

Other practical trials deal with the application of lead free solders. At first the wetting behaviors of SnAg, SnCu and SnAgCu for condensation soldering were observed and evaluated. Moreover printed circuit boards and components were soldered successful. Assemblies and solder joints with lead free solders are taken to reliability testing at the time.

Conclusions

The investigation of basics for reflow combined with wave soldering in vapor phase were finished in the meantime. It is recognizable that there is a great potential of this method. The decision on further developments have to be made by the manufacturer of soldering machines.

First experimental works with the laboratory test machine for inline condensation soldering were finished very successful and confirm the theoretical reflections. The transfer of this positive results to a prototype machine in an industrial scale has started. With this machine it is demanded to qualify the control temperature profile, in particular the transition to preheating and cooling zone, and to determine the loss of media. Especially for the application of lead free solder alloys, the investigation of actual needed temperatures and minimum of process window is important.

Acknowledgements

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