Vacuum reflow: A simple approach for void reduction by means of an inline reflow system

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Continental in Nuremberg specialises in the manufacture of highly complex electronic assemblies for the automobile industry. Soldered joints with a low number of pores, which cannot be produced using conventional reflow technology, are required for the manufacture of new hybrid assemblies for the automobile sector.

SMT Maschinen- und Vertriebs GmbH in Wertheim has developed a vacuum reflow soldering system which combines conventional reflow soldering with a vacuum process in order to meet the stringent demand for soldered joints with a low number of pores.

The modular design of the in-line vacuum reflow system enables heating zones with variable length, different vacuum chambers, various conveyor systems (single, dual or triple-track conveyors) and different cooling zones to be combined. The system can therefore be set up individually for the required throughput and product group. Soldering can be carried out in the system with and without vacuum and with N_2 inert gas atmosphere or with air. The user therefore has at his disposal a system which combines all the requirements of the reflow process in a single unit. The vacuum soldering process and the percentage of pores in the soldered joint are discussed below using the assemblies produced by Continental in Nuremberg as an example.

Soldered joint and pores

The assembly produced by Continental (Figure 1a) is a substrate based on DCB (direct copper bonding)
Technology on which bare dies (integrated electronic components without housings) are soldered using a lead-free reflow process. The bare dies have an area of 5.4 mm × 3.4 mm and a height of 0.3 mm.

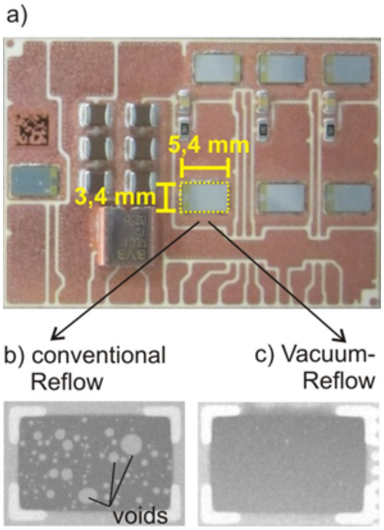

Figure 1: a) Photo of assembly. The soldered joint under investigation is marked in yellow for one bare die as an example. b) X-ray image of the bare die soldered joint after the conventional reflow process. c) X-ray image of the bare die soldered joint after the vacuum reflow process.

Pores are gaseous inclusions in the soldered joint which lead to a reduced thermal conductivity between the printed-circuit board (PCB) and the device component.[1,2] When components carry high electrical currents, as is the case with the bare dies investigated here, the resulting heat can no longer be adequately dissipated via the porous soldered joint. This can result in high component temperatures and ultimately to reduced performance or component life.[3] The percentage of pores in the soldered joint can be reduced and the thermal conductivity improved by using vacuum soldering processes. Figures 1b and 1c show X-ray images of the bare die soldered joint produced using a conventional soldering process and using the vacuum soldering process presented here. A qualitative comparison of these images clearly shows that with the conventional reflow process many pores are present in the soldered joint over a large proportion of the area, while the number of pores is reduced to virtually zero by using the vacuum process.

A schematic representation of the conventional and vacuum reflow solder paste fusing process is shown in Figure 2. The solder paste is fused in hot air or in a hot N_2 atmosphere by means of the reflow process. In doing so, gaseous inclusions are produced in the soldered joint and, in the conventional reflow process, are incorporated by the cooling and solidifying of the solder. In the vacuum reflow process used here, the solder is likewise heated and melted. This is followed by the vacuum step in which the pores expand and are removed from the surface of the joint into the vacuum. The percentage of pores in the soldered joint is reduced; the soldered joint is more solid and therefore has a higher thermal conductivity which in turn has a positive effect on the component performance and life.

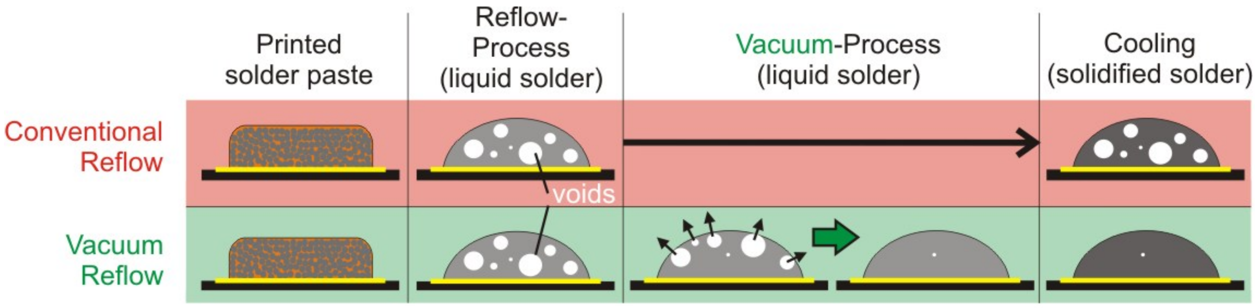

Figure 2: Schematic comparison of the conventional (red) and the vacuum reflow process (green). In the vacuum reflow process, the vacuum stage which removes the pores from the liquid solder follows the actual melting process. The assembly is then cooled.

Description of the vacuum reflow process

Figure 3a shows the vacuum soldering system developed by SMT Wertheim. Two edges of the assembly lie on a chain (3 mm or 5 mm edge contact) which transports it through the machine from left to right. The left-hand part of the soldering system shown in white comprises the pre-heating zone and the peak zone in the top and bottom part of the heating chamber (Quattro-Peak®).

The vacuum module is on the right of the heating chamber and is shown dark in Figure 3a. It has an additional peak zone to enable the overall temperature profile of the soldering process to be adjusted more flexibly. In this overall heating zone, the assembly is heated by convection using air or nitrogen until the solder melts.

The assembly with the liquid solder is transported out of the convection zone into the vacuum chamber in which the actual vacuum process takes place. After this vacuum process, the assembly is transported to the cooling zone (right-hand white area in Figure 3a) where it is cooled to the required temperature using air or nitrogen.

The length of the heating zone and the cooling zone can be chosen individually and matched to the printed circuit board throughput. The type of vacuum chamber chosen here accommodates printed circuit board sizes up to 510 mm x 320 mm. Other types of chamber for printed circuit board sizes up to 600 mm x 450 mm are available.

Figure 3b shows the temperature profile of the bare dies measured by means of a temperature recorder as a function of the overall process time. At time t = 0 s the assembly is at the start of the first pre-heating zone. At t = 118 s the assembly has been transported to the peak zone. The melting temperature (liquidus) of the solder is 219 °C. The temperature profile of the actual vacuum process is shown in Figure 3b by a dark bar. The vacuum chamber is heated so that the assembly and the chamber have the same process temperatures. The heat radiation balance between chamber and assembly guarantees that the temperature of the assembly is constant even in vacuum, and the solder remains liquid.

Figure 3c shows the pressure profile of the vacuum process during part of the overall process time. To simplify comparison between Figures 3b and 3c, the time periods for the vacuum process are shown with a dark background. The start and finish times of the vacuum process are indicated by arrows. The assembly with the liquid solder is transported into the vacuum chamber and the chamber closes (left-hand "white" area in Figure 3c).

In the next process steps, the chamber is evacuated, the vacuum is maintained and the chamber is subsequently filled with air or nitrogen (dark area in Figure 3b and 3c). The evacuation time, the final pressure, the vacuum retention time and the filling time can be set individually. Chamber pressures down to 5 mbar are possible. The pores are effectively removed from the soldered joint as was shown in the schematic representation in Figure 2.

After the vacuum process, the chamber opens and the assembly with the liquid solder moves into the cooling zone. Here, the solder is solidified by blowing cold air or nitrogen onto the assembly.

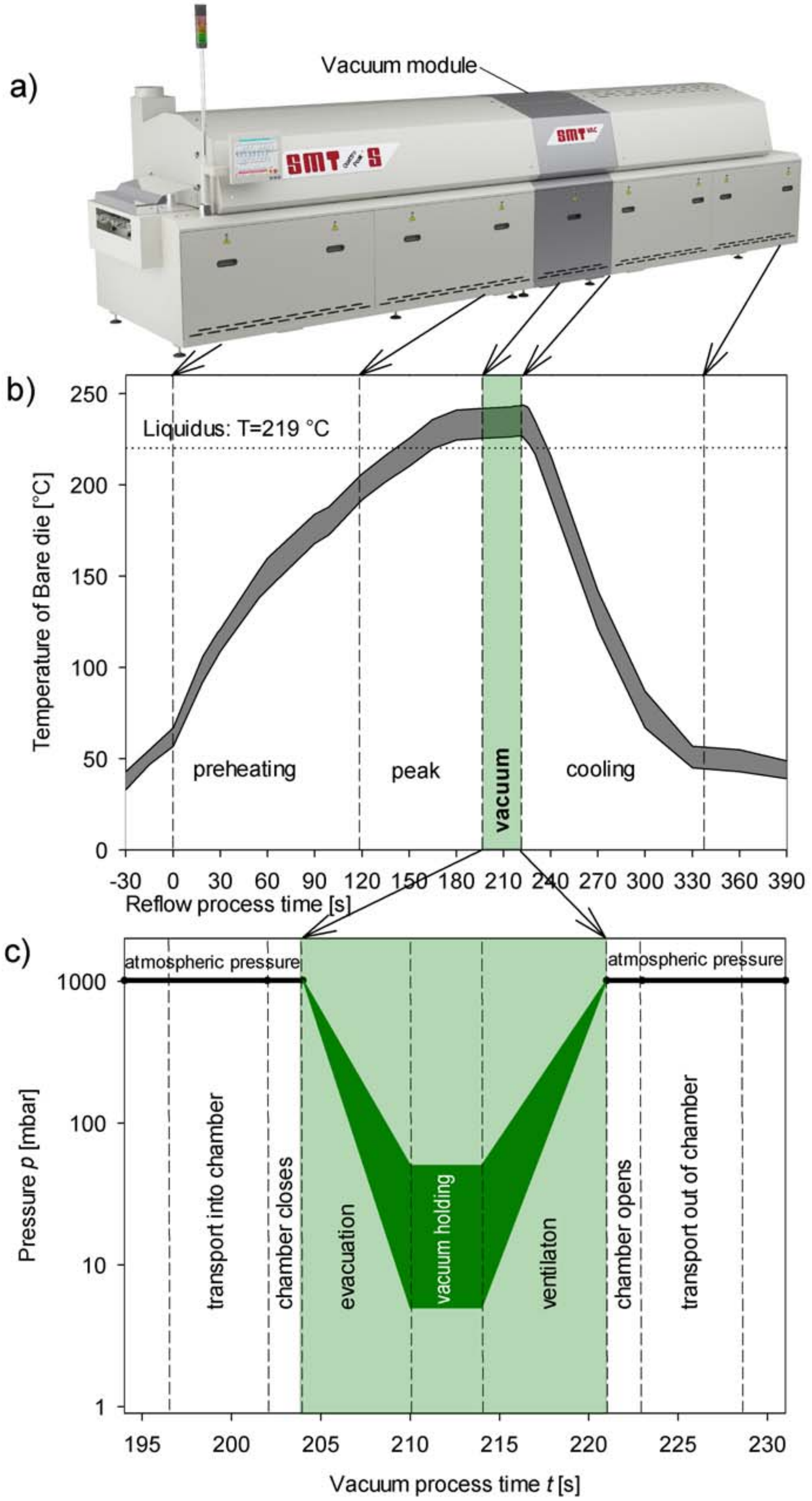

Figure 3: a) Photo of the SMT QP S Vac reflow soldering system. The vacuum module (dark) is located between the active convection zone (= pre-heating zone + peak zone, left) and the cooling zone (right). b) Measured temperature profile of the bare die as a function of time. The actual time of the vacuum process is shown with a dark background. c) Vacuum-pressure profile as a function of time. The time period with a dark background is the same as that shown in Figure 3b.

Statistical evaluation of the number of pores in the soldered joint

The specification defined with the customer states that pores must cover less than 10% of the area of the soldered joint between the bare die and the DCB surface. The data presented below were obtained from Continental in Nuremberg and subsequently evaluated.

In order to be able to assess the effectiveness of the vacuum reflow process compared with conventional reflow soldering, assemblies were soldered using the conventional and the vacuum process.

The conventional reflow process had a similar temperature profile to that of the vacuum process. The absence of the vacuum chamber in the conventional process was compensated for by a lower throughput speed. As a result, the assembly was in the peak zone for the same length of time and the time above the liquidus temperature was also the same.

119 soldered joints were x-rayed for the conventional reflow process, and 1806 soldered joints for the vacuum reflow process.

Figure 4 shows the percentage of pores in the area of the soldered joint as a function of the measured frequency. The bars designate measurements; the black curves are Gaussian normal distributions[4] which have been fitted to the measurements.

For the conventional reflow process (red bar in Figure 4), the average percentage of pores in the soldered joint is 7.9%. The "width" of the normal distribution is defined by the so-called standard deviation σ and in the conventional process is 2.1%. The process capability value (C_{pK} value[5]) resulting from this distribution and the desired target value of less than 10% pores in the soldered joint is only 0.3. This is a very much smaller and poorer value compared with a required C_{pK} value of at least 1.7. Figure 4 shows this situation graphically. A larger proportion of the conventionally treated soldered joints (red bar) has a pore frequency of greater than 10%. These joints and the corresponding assemblies would have to be rejected. As every assembly has 7 bare dies, the proportion of assemblies with a percentage of pores greater than or equal to 10% is seven times greater than for the soldered joints. The process capability of the conventional reflow process is therefore not achieved with the defined requirements.

As a result of the vacuum reflow process, the average percentage of pores in the soldered joint is reduced to a mean value of 0.63% (green bar in Figure 4). The standard deviation is still only 0.39%. This results in a larger C_{pK} value of 8.0. The distance between the mean value and the upper tolerance limit of 10% pore content is 24 times the standard deviation. The quality number of 6 standard deviations (6 σ) which is frequently aspired to is therefore clearly achieved, and the process capability is fully guaranteed. The high demands on the percentage of pores in the soldered joint can be fully guaranteed with the vacuum reflow process.

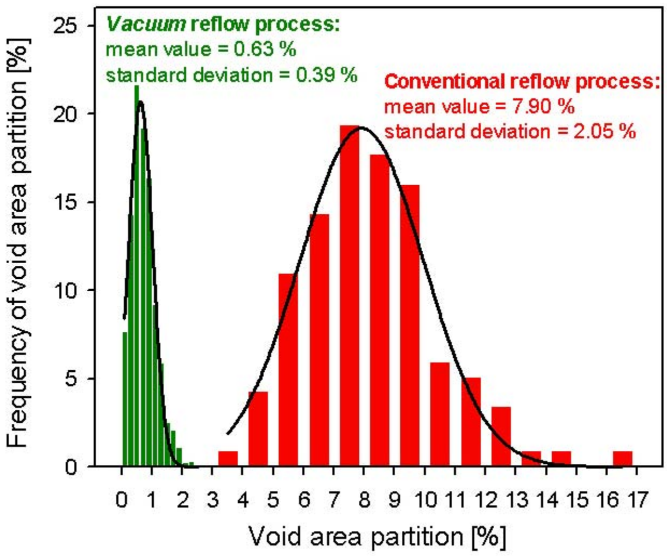

Figure 4: Frequency of the relative total pore areas as a function of the measured relative pore area of the soldered joint. Integration of the vacuum (green) shifts the overall pore area to values of less than 1%. The conventional process is unable to satisfy the stringent demand of less than 10% pores.

As well as the total surface percentage of all pores, the surface percentage of the largest pore is also important. The largest pore to a great extent determines the thermal conductivity in the appropriate region beneath the bare die. Here too, the smaller the largest pore, the better the thermal conductivity in the soldered joint. Figure 5 shows the frequency of the largest pores as a function of their percentage area in the soldered joint. The same soldered joints as in the previous evaluation were investigated. In the conventional process (red bar in Figure 5), the mean value was 0.37% and the standard deviation 0.06%. The largest pores take up more than 1% of the soldered joint, as can be seen from the right-hand red bar in Figure 5. The size of the remaining pores is reduced by the vacuum process. The distribution of the pore area (green bar in Figure 5) is shifted to smaller values with a mean value of 0.2% and a standard deviation of 0.07%. Here too, it can be seen that the vacuum process enables the critical parameter of the largest single pore in the soldered joint to be greatly reduced and the quality of the soldered joint to be increased.

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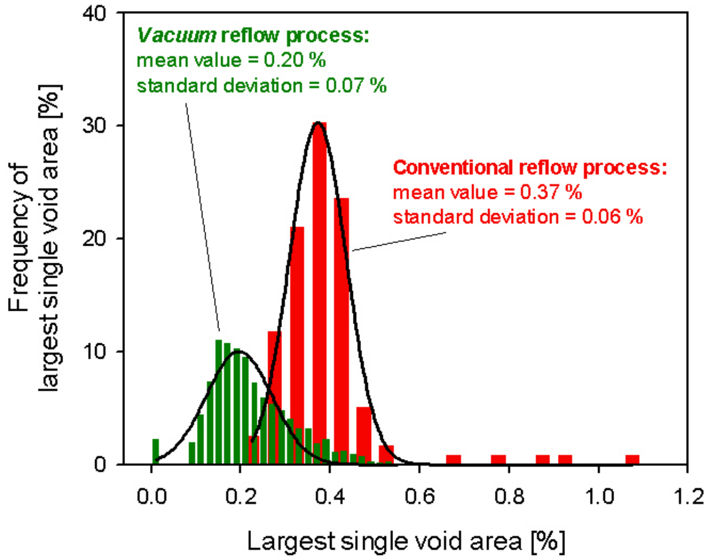

Figure 5: Frequency of the largest single pore in the soldered joint as a function of the measured largest single pore area. Integration of the vacuum (green) rules out individual pores with a relative area of greater than 0.6%. With conventional soldering (red), the largest single pore area is greater than 1%.

Summary

The vacuum reflow soldering system newly developed by SMT in Wertheim combines the advantages of proven conventional reflow soldering with a simple vacuum process which leads to increased process capability. The percentage of pores in the soldered joint are reduced to less than 1% by the vacuum reflow process. The result satisfies the stringent demands on the degree to which the soldered joint is free from pores. This enables results to be achieved even in the automotive sector which exceed the end customers' expectations. The statistical evaluations discussed show that process capabilities of greater than 6-sigma can be achieved.

References

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[2] *N. Zhu, Thermal impact of solder voids in the electronic packaging of power devices, Semiconductor Thermal Measurement and Management Symposium, p. 22-29, Fifteenth Annual IEEE, 1999.*

[3] S.T. Nurmi, J.J. Sundelin, E.O. Ristolainen, T. Lepistö, (2003) "The influence of multiple reflow cycles on solder joint voids for lead-free PBGAs", Soldering & Surface Mount Technology, Vol. 15 Iss: 1, pp.31 – 38.

[4] *Gaussian normal distribution*

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-0.5\left(\frac{x-\mu}{\sigma}\right)^2\right)$$

, where σ is the standard deviation, μ is the mean value and x is the measured data.

[5] *Process capability value:*

$$C_{pK}=\frac{x_O-\mu}{3\sigma}$$

, where x_O is the defined upper limit (in this case 10% pores), μ is the mean value, and σ is the standard deviation.