Reduction of Voids in Solder Joints an Alternative to Vacuum Soldering

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Abstract
Voids in solder joints are representing one of the main problems especially for power electronics. A low and homogeneous thermal resistance of solder joints is demanded for a quick and uniform conduction of the heat loss from the power chip. The same applies for the electrical conductivity of solder joints. Enclosed voids can cause a displacement of electrical and thermal paths and a local concentration of power and heat. In addition, gas voids are anxious to form spheres in the solder gap, which could be a cause for tilting of chip components and a wedge-shaped solder gap. This is tightening the problem of patchy distribution of current or heat and is causing stress and cracks.

The amount of voids can be influenced by different measures, e. g. a good wettability of metallization, solder pastes with special adopted solvents and an adequate preheating profile. However, a special vacuum process step during soldering is demanded for absolutely void free solder joints. But this vacuum process is associated with some essential disadvantages. Besides of the technical expenses for vacuum pumps and additional locks, the vacuum process excludes the use of gas convection for heating and cooling. Apart from a special vapour phase–vacuum technology, most machines are using infrared radiation or heat conduction for soldering.

The same principles as used in vacuum soldering technology are applicable also for a higher pressure level. If the void in the solder joint is arising for an excess pressure, the normal atmosphere pressure could be sufficient for escaping of enclosed gas. Essential for this effect is the pressure difference between inside and outside of solder joint. A benefit of soldering with excess pressure is the possibility of gas convection for heat transfer. This allows the application of conventional components and the realization of the usual temperature distribution and profiles.

Introduction
By the progress of failure detection in solder joints by X-ray analysis or X-ray computer tomography, the issue of voids in solder joints is currently discussed very intensively. The increasing demands on homogeneity of joints for miniaturization and applications of high temperature electronics also made a contribution to this discussion. The specifications about the acceptable amount of voids in solder joints were further concretized in IPC-A-610D. The maximum amount of voids for plastic BGA solder joints as well as for thermal plane terminations (D-Pak) is less than 25% in an x-ray image area. Design induced voids, e. g. microvia in land, are excluded from this criteria and will need to be established between the manufacturer and user. Just for special technologies, like chip-on-board for power applications, a smaller threshold can be established. For the conduction of high electrical or thermal currents not only the electrical and thermal conductivity of the connection, but also the homogeneity of the solder joints are very important. Especially voids and enclosures can impair this homogeneity. The result can be “hot spots” on the chip, which limits the useable power or could damage the components.

However, voids often have another negative influence on large-area solder joints. Because of the ambition of gas bubbles and liquid enclosures to minimize their surface, they will contract in the solder gap depending on the size. In the ideal case small voids can contract in the gap as spheres. Larger voids can lift the components or the chips on discrete positions, because of the limited dimension of gap. Since the distribution of voids in the solder gap is rarely uniform or few small voids can cumulate to larger voids, a tilting of component is the result as a rule. A high tilt intensifies inevitably the inhomogeneity, the non-uniform distribution of currents and temperature and particularly the thermo-mechanical stress. The thickness of solder gap, especially in connection with very different materials, such as silicone and copper for FR4, is very important for the adaption of the unequal expansions to temperature changing. The deformation of solder joints will be increased with the length of components edges, the difference of temperatures and the difference of thermal expansion coefficients and can be decreased with the thickness of solder gap. Since the materials and joining areas are given by the component and substrate types, the thickness or height of solder gap is usually the only chance for soldering technology, to reduce the deformation and the affiliated stress for the unavoidable temperature cycles. An unregulated tilt of components or chips can lead to a local concentration of stress and therefore to additional weak spots of the solder joint, which will reduce the life time or reliability.

Indeed, voids in solder joints are nearly inevitable for common process conditions. The ingredients of the solder pastes, which are evaporating during the soldering process, cannot exhaust completely especially for plane solder joints and closed gaps and will be enclosed in the solder joints. With the introduction of lead-free solders with the well-known difficulties of poor wetting and smaller process windows the problem has become more acute. Therefore the acceptable or established maximum void content can exceed frequently. Improved materials and processes should produce relief for that.

Process Influences

Various studies and investigations were devoted to the finding of optimum process parameters for prevention of voids. So it is possible that solder joints made of the same materials and with the same components but manufactured with different soldering profiles can show outwardly perfect behaviours but nevertheless they will have a very different void content inside. Especially because of the use of lead-free solders with a higher melting point, it could be necessary to compensate the limited maximum of soldering temperature with an extension of soldering time (figure 1).

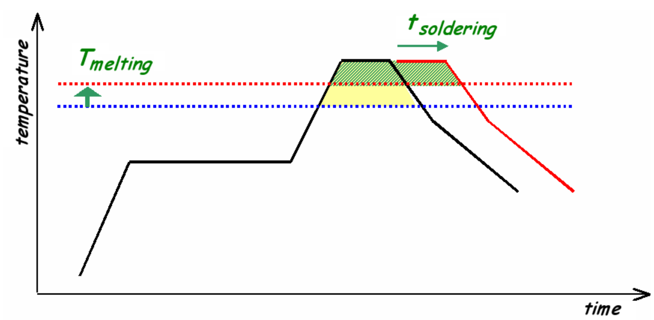

Figure 1 – Extended soldering time for compensation of a limited soldering temperature for higher melting lead-free solders

Even if the demanded adaptation of soldering profiles is able to transfer the same heat quantity and it is possible to realize the same visible result of wetting, the extended soldering process with lower temperatures will influence even so the speed and dynamics of soldering process. Because of the slower flow of solder and the higher viscosity of the melt for lower temperatures, flux residues can exhaust more poorly and form voids.

The Fraunhofer Institutes IZM and ISiT have investigated the forming and development of voids with more than 200 test boards in a joint research project [1]. Solder joints were observed by X-ray analysis also during the soldering process in this project. It was clearly visible that voids that have already been formed will never escape if keeping the soldering temperature. On the contrary, the apparent effect can be observed: the voids will be increased during holding of soldering temperature. But this is usually caused by the accumulation of several smaller voids, which are under the resolution limit themselves, into larger voids with clearly visible sizes. But there are also some cases, when voids can be formed by dewetting effects of component terminations or outgassing from PCB material during dwelling of soldering temperature.

Thus, a good and fast wetting is helpful for minimizing the amount of voids. A fast wetting which is able to transport the developing gases and residues out of the solder joints needs a certain minimum soldering temperature. This was shown clearly by systematic investigations with the wetting balance analysis. The interpretation of numerous wetting curves with different solder alloys and test temperatures results in a relation, shown in figure 2.

The desired fast soldering process requires a minimum soldering temperature of 10 % above melting point (based on Kelvin scale), independent from the solder alloy. That means that a preferred soldering temperature for SnPb alloy is 229°C, but for SnAgCu the soldering temperature is already 266°C. Such high temperatures are usually prohibited for assembly processes because of sensitive components and printed circuit board materials. Thus, problems with an increased amount of voids in solder joints are expected.

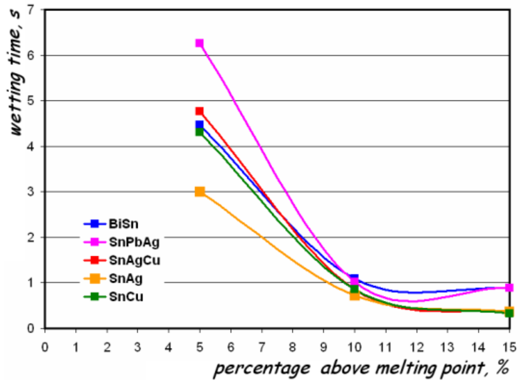

Figure 2 – Relation between wetting time and relative soldering test temperature for different solder alloys (percentage based on Kelvin scale)

Since the design of temperature profile and maximum soldering temperature is normally very restricted and the enclosed voids cannot be eliminated in a common soldering process, further improvements can be realized with appropriate preparation and treatment processes. With a pre-drying of the printed and assembled boards it should be possible in principle to reduce the amount of humidity of materials and volatile ingredients of solder pastes. Investigations have shown that for the optimized lead-containing solder pastes a pre-drying will effect rather a slight increase of void amount. However, figure 3 shows the evaluation of tests and, depending on manufacturer or flux type, also a considerable improvement of void content for SnAgCu solder pastes. At best it should be possible to achieve nearly the same low void amount as for SnPbAg solder pastes. One hour drying of assemblies above 100 °C also eliminates absorbed water, in contrast to storage at room temperature.

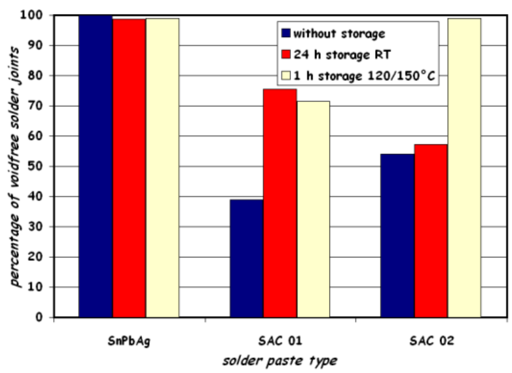

Figure 3 – Influence of pre-drying on number of void-free solder joints

Also the solder paste printing process itself could have an influence on the void content. Especially for components with plane terminations, often used for power electronics, escaping of flux residues is very problematic. A full area printing with solder paste is not advantageous from the printing point of view, nor it is for voiding. Different shapes of stencil openings were used for the manufacturing of chip on board solder joints. Afterwards they were investigated and evaluated by X-ray. The smallest amount of voids could be realized with shape type B, showed in figure 4. A directed flow of solder from inside to outside could be forced by the cross shaped printed solder paste, which enables the expulsion of enclosures and voids during soldering. Furthermore, a solder gap of at least 100 µm shows a positive effect to the void content, which demands a stencil thickness of 200 µm.

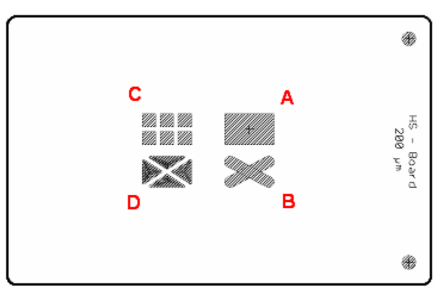

Figure 4 – Printing stencil for testing of different solder paste patterns

Material Influences
Beside of the process, the applied materials also have an influence on the amount of voids in solder joints. As already stated above, a fast solder wetting gives a positive contribution to a reduced void content because of the higher dynamic. Therefore, solder alloys, fluxes, and surface metallizations are preferred which abet a fast and good wetting. Figure 5 shows the comparison of the results from investigation of voids on different printed circuit board finishes, NiP/Au (ENIG), immersion tin and copper/OSP.

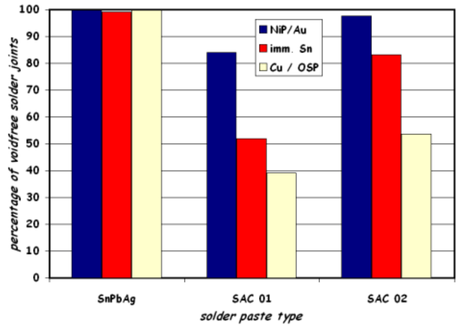

Figure 5 – Influence of surface metallization on amount of void-free solder joints

While SnPbAg solder shows a similar low void content on all three surface finishes, clear differences for both tested SnAgCu solder pastes were detected. The lowest void content will be obtained on NiP/Au surface finish, which is able – in conjunction with pastes showing good wetting behaviour – to realize similar good results like SnPbAg pastes.

Especially for reflow soldering of pre-soldered components such as BGA or CSP it is possible to minimize the amount of voids with a suitable combination of solder alloys [2].
If the solder paste is melting sooner than the alloy of the solder balls, the evaporating flux has a chance to escape from solder gap before the balls are melting. Because of that less gases and residues will be enclosed in the solder joints. These statements can be confirmed by experimental work. Figure 6 shows the result of these trials in an X-ray image.

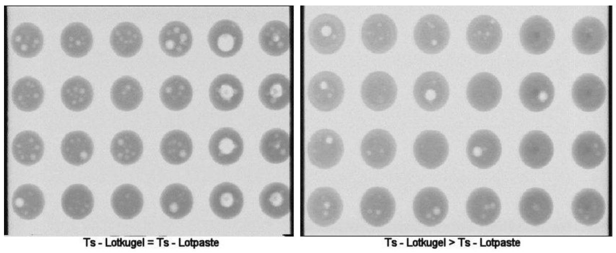

Figure 6 – Comparison of voids with different melting temperatures of solder balls and solder paste,
left Tm(paste) = Tm(ball) / right Tm(paste) < Tm(ball)

Special Processes
All measures of process and material adaption discussed so far can only give a contribution to minimize the number and size of voids. In this way a general elimination of voids is hardly possible.

The most effective measure against voids is the application of a vacuum process during soldering, which is able to suck off gases and flux residues from the joint, as long as the solder is molten. The effect is clearly visible when looking at the soldering results in X-ray images, shown in figure 7. By means of a vacuum process it is possible to eliminate the voids and enclosures almost completely.

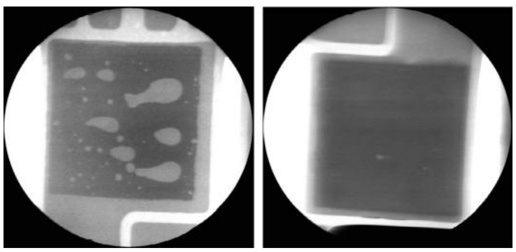

Figure 7 – Power chip soldered without (left) and with (right) vacuum process

The special demands of power electronics may sometimes legitimate the extraordinary efforts of a vacuum process. It is, however, advisable to select the solder materials especially for this vacuum process, since some flux ingredients incline to extreme foaming and blistering so that components can be replaced or uplift potentially. Apart from the choice of solder paste, the process can be adapted in such a way that the vacuum will not affect until the predominating part of the solvents is evaporated.

However, there are several disadvantages of a vacuum process. Printed circuit board materials and also some components are tending to excessive outgassing in vacuum. Therefore, the targeted vacuum pressure will be achieved very slowly. Also some electrolyte capacitors cannot tolerate the vacuum process because of the hermetically enclosed liquids. Another drawback is that heat cannot be transferred in the vacuum with the usual convection heating but only by means of infrared radiation or heat conduction. Both heating methods are not sufficient for the use on printed circuit boards. Some of the present soldering machines are using the fast and effective heating with vapour phase with a subsequent vacuum process [3]. The assemblies have to be heated sufficiently during this soldering process, so that the solder is still liquid in the following vacuum process. To ensure a minimum thermal exposure it is essential to achieve a fast transition from the soldering zone into the vacuum area which requires a powerful lock and pump system as well as optimum vacuum pressure.

Various experimental series were conducted to find the necessary pressure for the intended vacuum soldering process. A significant reduction of voids in solder joints was observed below 700 mbar. Obviously, voids in BGA and CSP solder joints are very intractable. Particularly removal of design related voids it is very difficult or even impossible. An example of a typical void in a BGA solder joint is shown in figure 8 which displays the geometrical relations.

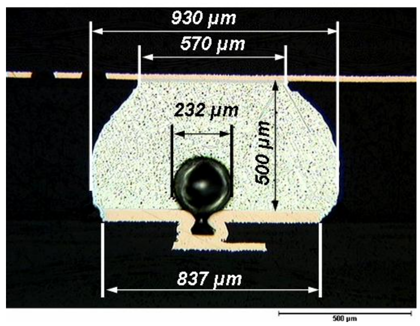

Figure 8 – Dimensions and relations of a typical void in a BGA solder joint

Following the Young-Laplace equation it is possible to calculate the pressure relations of such a void: $\Delta p > 2\ \sigma/r$

Apart from the measured radiuses the surface tension of the liquid solder (σ) is also important for the calculation. Own measurements of liquid solders (pending drop method) have resulted in a surface tension of 448 mN/m for SnPb and 548 mN/m for SnAgCu. Another reason for the higher amount of voids in lead-free solder joints or the difficulties to remove them is this significantly higher surface tension. With the data from the example above it is possible to calculate that a minimum of 100 mbar pressure difference between inside of void and its environment is necessary to remove this void. This means, that after soldering at normal pressure, the ambient pressure must decrease to 900 mbar or less in order to remove this void.

New considerations were proceeding on assumption that for the removal of voids it is not the absolute vacuum pressure that is important, but much more the difference of pressure between void and environment. This consideration leads to the inference that it should also be possible to remove a void at normal pressure if it was formed at excess pressure [4]. The advantage of this conception is obvious because a soldering process with overpressure allows heating of assemblies with forced gas convection, with similar thermal behaviour like standard reflow soldering and all its advantages, such as low temperature differences (delta T), good heat transfer and controlled heating process. Moreover, outgassing materials and leaking components are not likely to result from a soldering process with elevated pressure.

Due to the fact that the currently available soldering machines are technically not prepared to work with overpressure, a simple laboratory setup was improvised for the first principle tests. An espresso pot which is designed for a pressure of 2 bar was rebuild and used for these tests. The soldering samples were molten in this pot with overpressure and afterwards, in the liquid state of the solder joint, the atmosphere was released to normal pressure by opening an outlet. After first successful tests with heat conduction on a hot plate with DBC substrates and soldered Si chips, further lab setups were developed. This solution consisted of a greater pressure container which included a controlled heating, even a forced convection fan could have been installed (figure 9).

Figure 9 – Laboratory setup of pressure container with controlled heating

A standard FR 4 printed circuit board with large-area solder joints was selected for the first tests (figure 10).

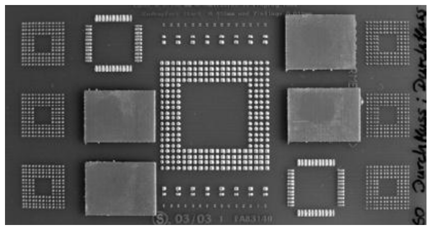

Figure 10 – Test board

Using the pressure container from the laboratory setup it was possible to vary the pressure conditions while temperature and other process parameters were kept on the same level. Figure 11 gives a small insight in possible temperature profiles and resulting solder connections with associated voids.

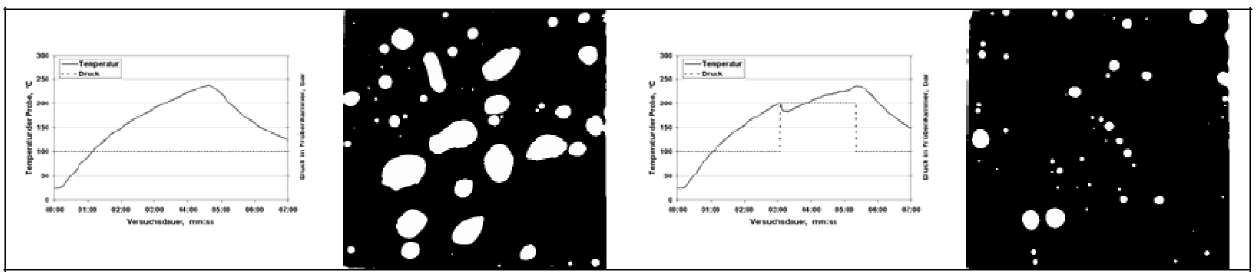

Figure 11 – Amount of voids at different pressure vs. time regimes

Based on these findings a reflow soldering system with convection preheating area and pressure chamber in the peak area was developed and introduced during Productronica 2011. The preheat area of this system completely corresponds to a regular reflow soldering system. The modified peak area consists of a specially designed pressure module in combination with a convection heating zone (figure 12). Compared to vacuum soldering, this solution provides the advantages of usual reflow soldering technologies. That means it is possible to heat the assemblies homogeneously and effectively by forced convection in either an ambient or nitrogen atmosphere.

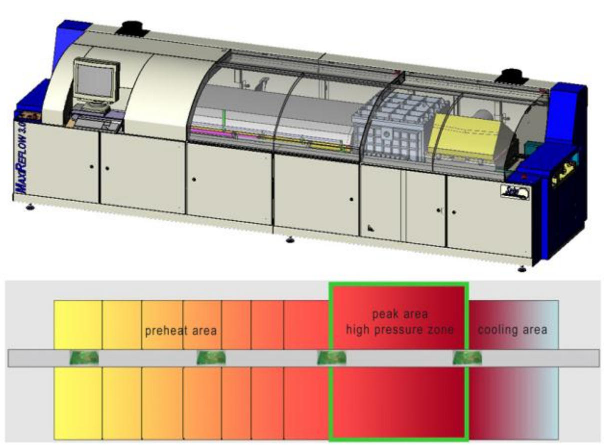

Figure 12 – High Pressure Reflow Soldering

First test series with this oven confirmed the positive approach of the laboratory tests. Overall, a high pressure zone provides a higher efficiency and more flexibility than a vacuum process. Whereas the pressure level for vacuum processes ranges between 1 bar (atmospherical pressure) and 0 bar, a high pressure zone allows a process range between 4 to 5 bar and 1 bar. Most noticeable, however, is the dynamics of pressure. As discussed earlier, a certain vacuum which would be able to remove voids only can be reached slowly and in addition this requires expensive pump technique. Less mechanical construction is needed to reach a high pressure range of 4 – 5 bar which can be released instantaneously to make voids leave the liquid solder depot (figure 13).

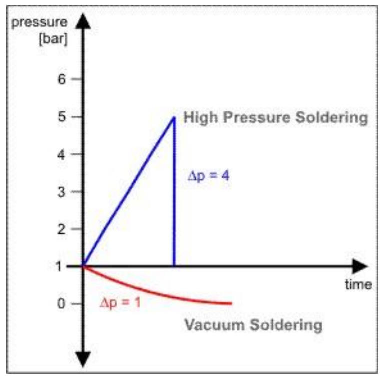

Figure 13 – Dynamics of pressure for high pressure soldering and vacuum soldering (schematic)

The following pictures and graphs demonstrate the test boards and results which could be obtained.

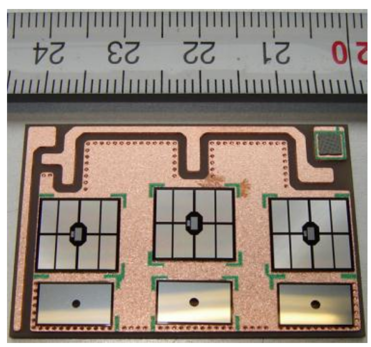

Figure 14 – Test board

surface: Cu; component: Bare Die; component metallization: Ag

solder paste: SnAg3.5Cu0.5; atmosphere: N_2

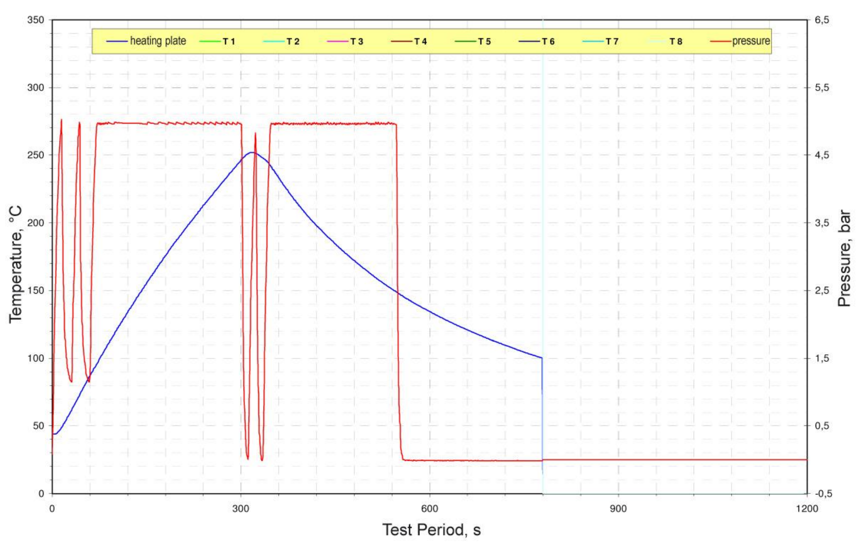

Figure 15 – Pressure / temperature profile

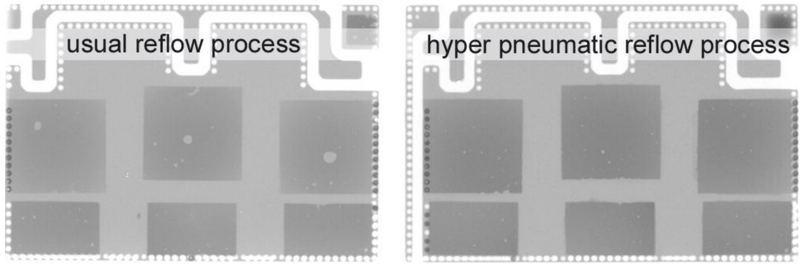

Figure 16

left: soldering results without high pressure technology, very often leaving one significant void under the warped bare die
right: soldering results with high pressure technology

Conclusions

The smaller process window for lead-free soldering does not allow much clearance for optimizing a void-free process. With best possible conditions including optimized fluxes and surfaces showing a good wetting behaviour, the amount of voids can be reduced.

A nearly void-free solder joint, often demanded for assembling of power electronics components, definitely only can be realized by variation of the atmospheric pressure. A variety of vacuum soldering processes were established in the past which use infrared radiation, heat conduction or the combination with vapour phase soldering for heating.

The same principle of pressure difference is used for soldering with elevated pressure and a sudden pressure release to normal level (hyper pneumatic soldering process). This new technology allows forced convection for heat transfer during the reflow process with all its well-known advantages.

References

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[3] Nowottnick, M.; Berek, H.; Bell, H.; Herwig, H.; Moschallski, A.: Condensation Heating Process for Lead-Free Soldering; SMTA International 2002, 22-26 Sep 2002, Chicago, USA

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Reduction of Voids in Solder Joints An Alternative to Vacuum Soldering

Presented by
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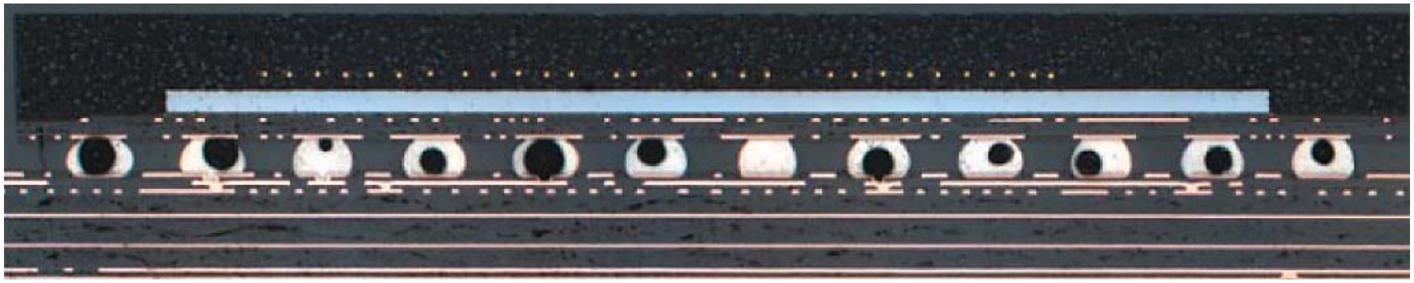
Voids



high number of voids

local concentration of power and heat
poor heat conduction
potential for tilting of components or wedge-shaped solder gap
increased failure probability
low reliability

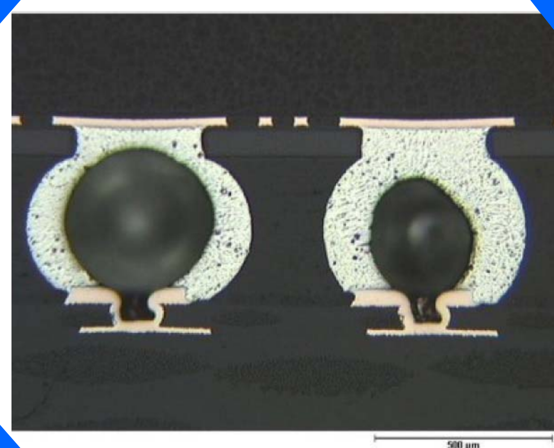
Voids: Influencing Factors

soldering process

- method
- temperature profile
- atmosphere
- soldering temperature
- time above liquidus

printed circuit board

- laminate (evaporation)
- surface metallization
- surface quality
- solder resist
- solder mask
- MicroVia



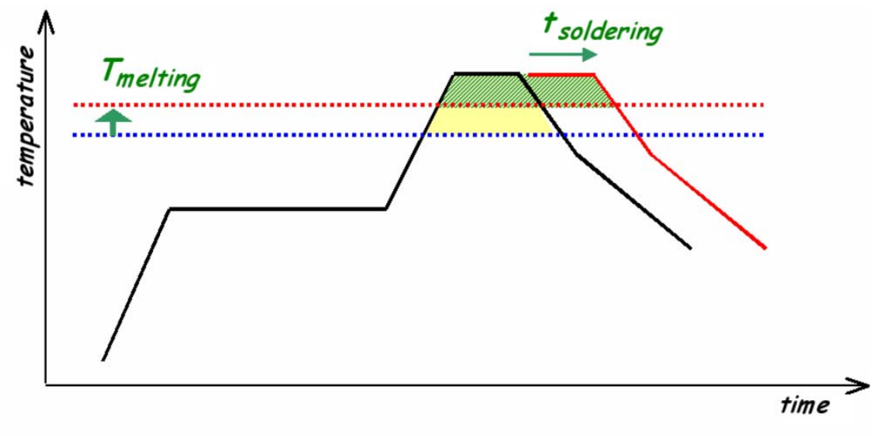
solder paste

- alloy composition
- powder quality
- powder size
- metal content
- flux composition

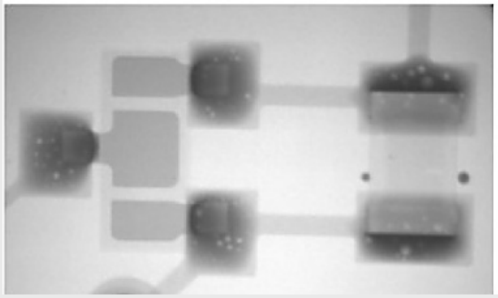
component

- surface metallization
- surface quality
- solder resist
- solder mask

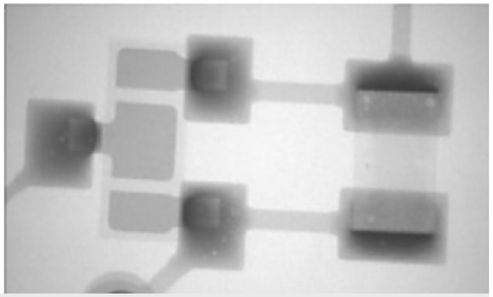
Process Influences



soldering temperature



237° C

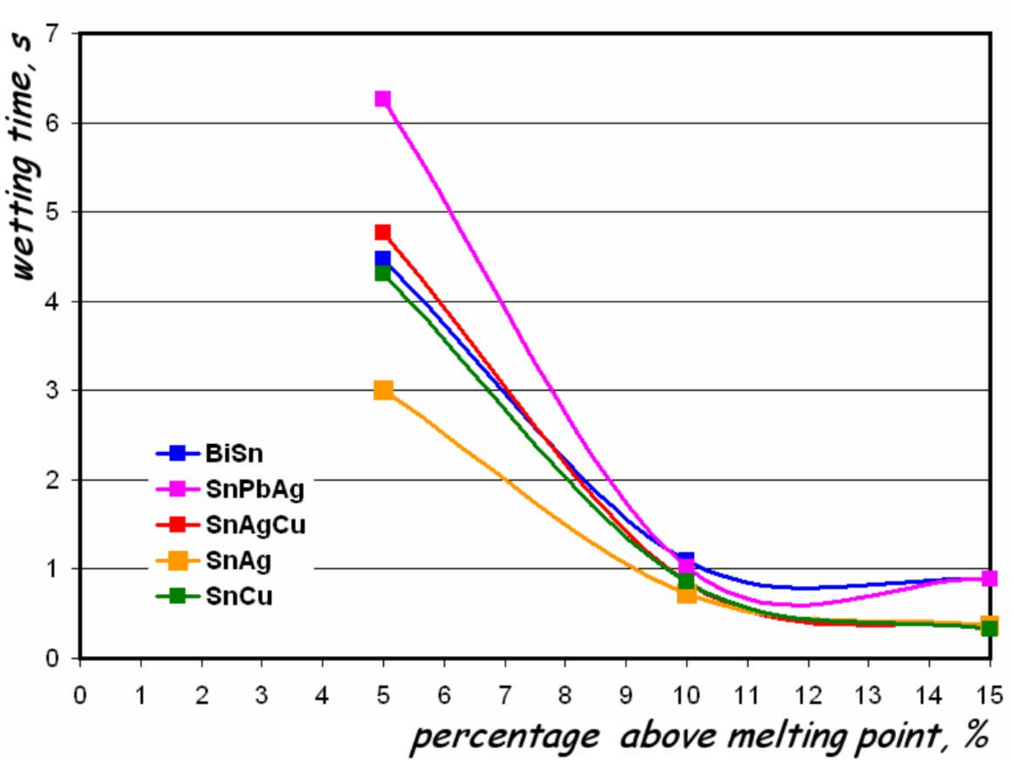


247° C

- extended soldering time for compensation of a limited soldering temperature for higher melting lead-free solders
- slower flow of solder and higher viscosity at lower temperatures
- flux residues can exhaust more poorly and form voids

Process Influences

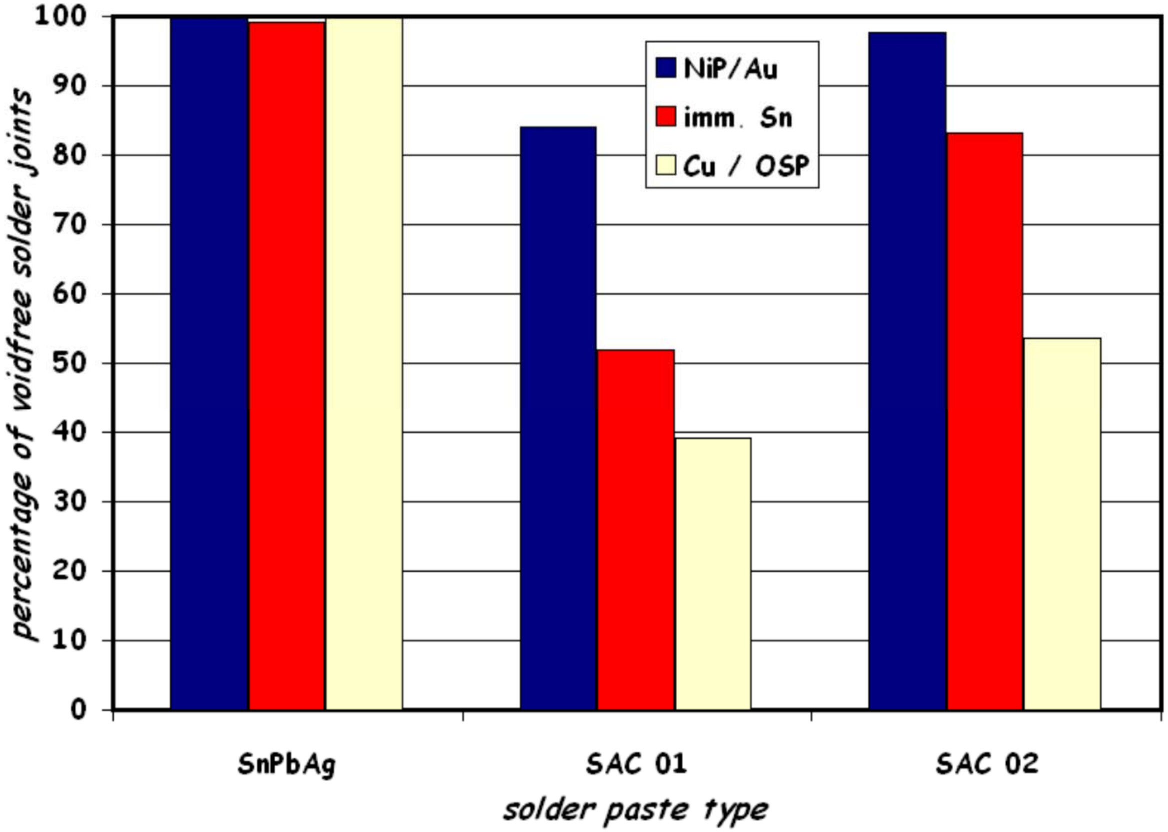
Target: optimum and fast wetting



fast soldering process requires min. soldering temperature of 10 % above melting point (based on Kelvin scale)

such high temperatures are usually prohibited because of sensitive materials

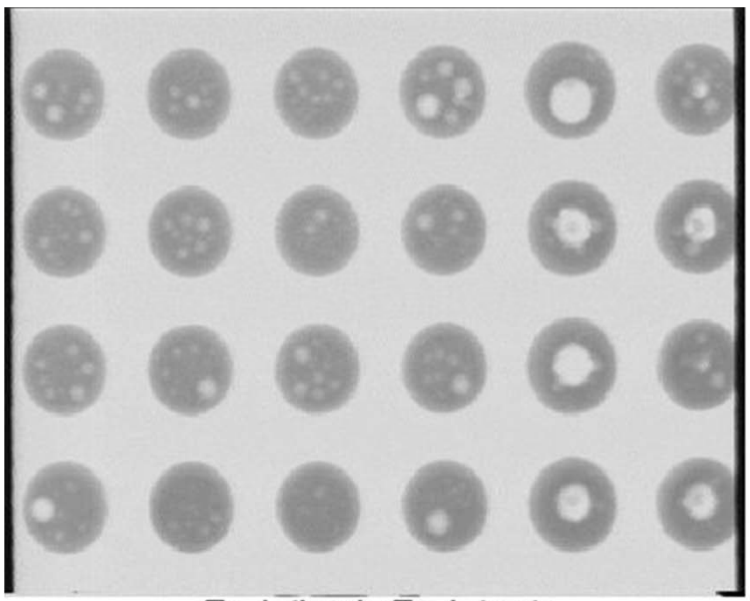
Material Influences



influence of surface metallization on amount of void-free solder joints

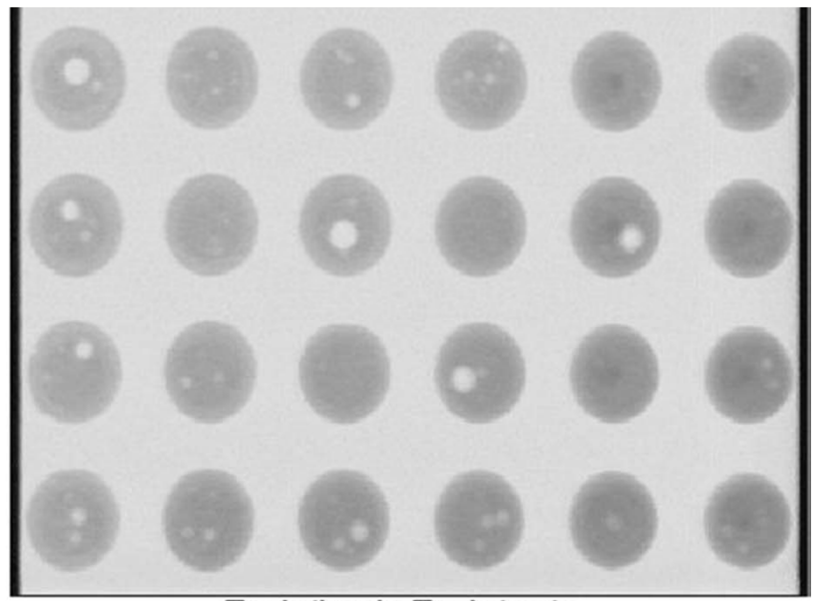
Material Influences

suitable combination of solder alloys reduces voids in BGA or CSP solder joints



Ts - Lotkugel = Ts - Lotpaste

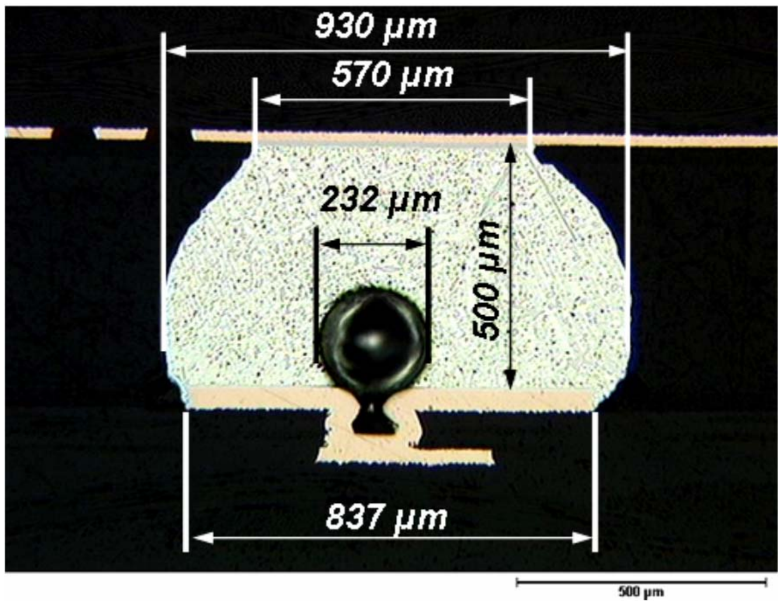
Tm(paste) = Tm(ball)



Ts - Lotkugel > Ts - Lotpaste

Tm(paste) < Tm(ball)

Typical Void in a BGA Solder Joint



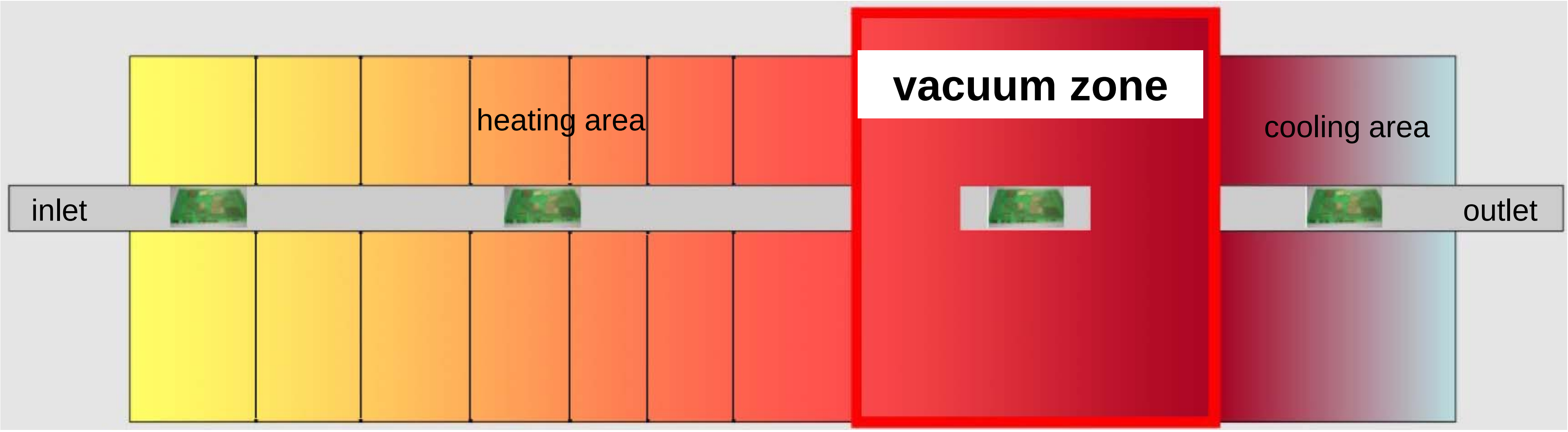
$\Delta p > 2\ \sigma/r$

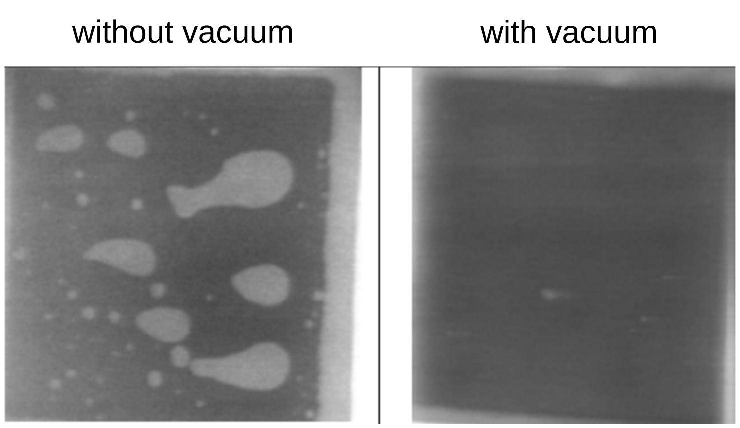
> 2 * 548 mN/m / 116 µm

> 9,450 Pa = 0.1 bar

result: a minimum of 100 mbar pressure difference between inside of void and its environment is necessary to remove this void

Technologies for Void-Free Soldering





Negatives:

- special solder pastes required
- not suitable for some components
- pass-through process remarkably interrupted
- no gas convection possible for energy transfer
- high mechanical effort required

Technologies for Void-Free Soldering

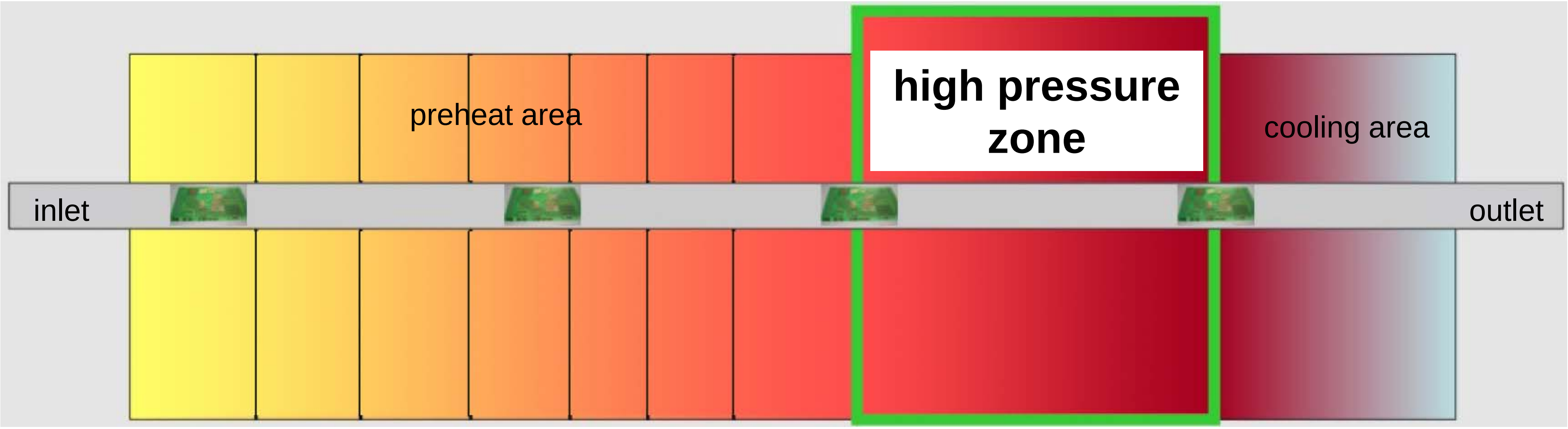
New Approach

not absolute pressure, but difference pressure is important for removal of voids

instead of producing a vacuum to remove voids:

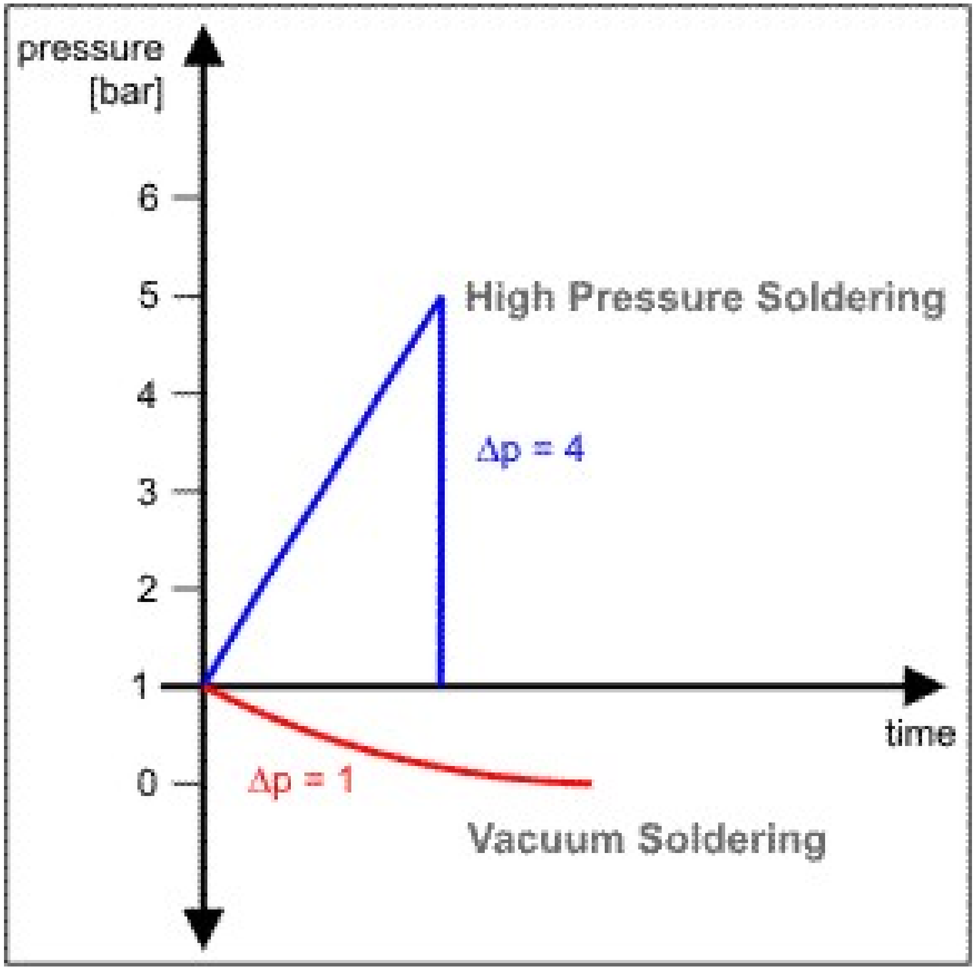
remove voids at normal pressure if they were formed at high pressure

Technologies for Void-Free Soldering



- **convection** as heat transfer mechanism
- required pressure easier to achieve than vacuum
- high pressure zone requires less tightness compared to vacuum
- pressure range allows **higher efficiency**:
  pressure levels: vacuum 1 – 0 bar I HP 5 – 1 bar (or more)
  dynamics of the pressure
- **no solder splashes**

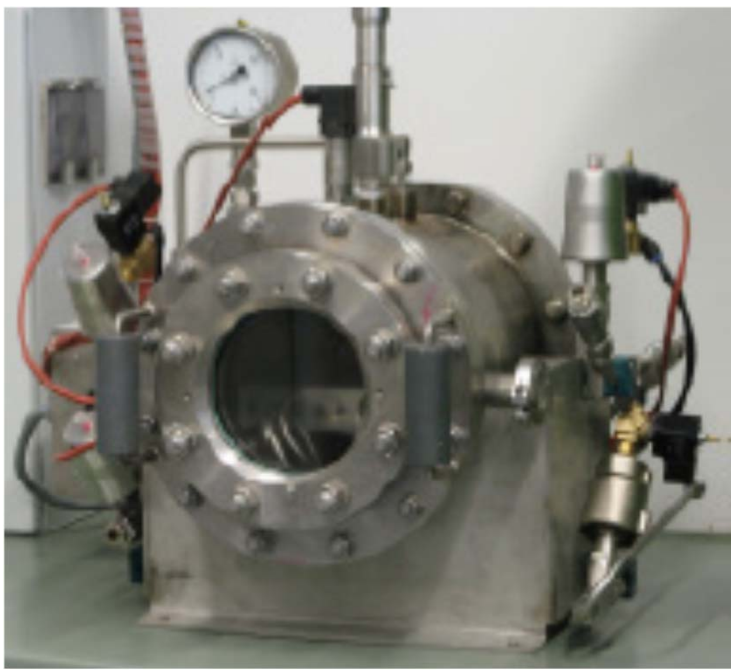
Technologies for Void-Free Soldering



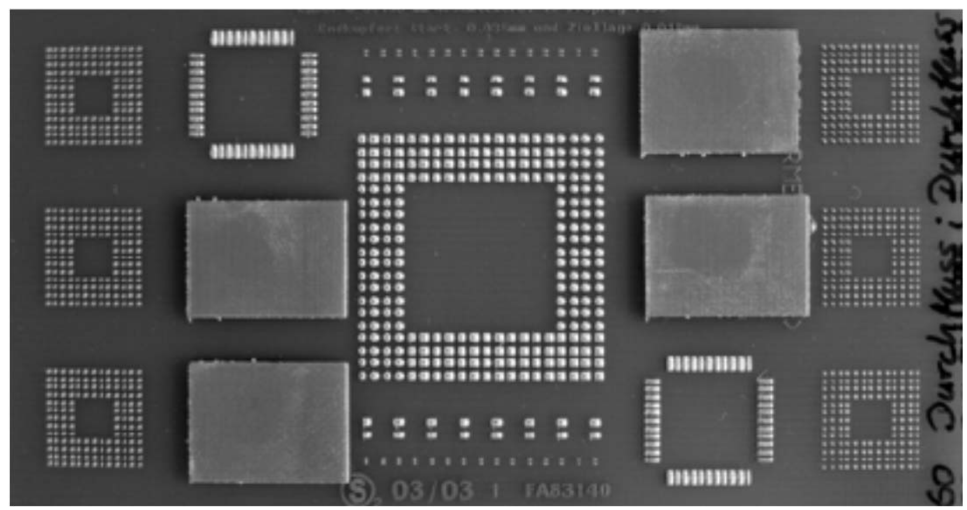
Vacuum vs. High Pressure Soldering

Technologies for Void-Free Soldering

laboratory setup



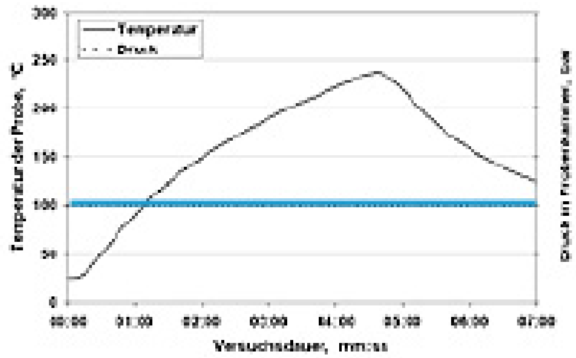
test board

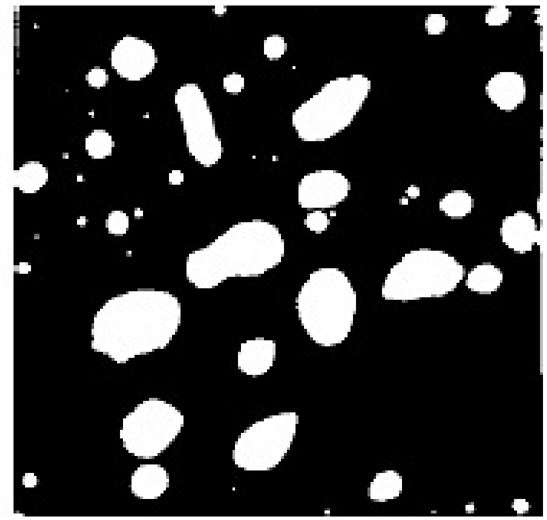


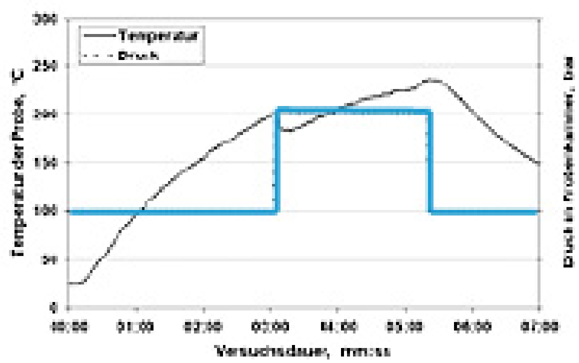
FR 4 with large-area solder joints

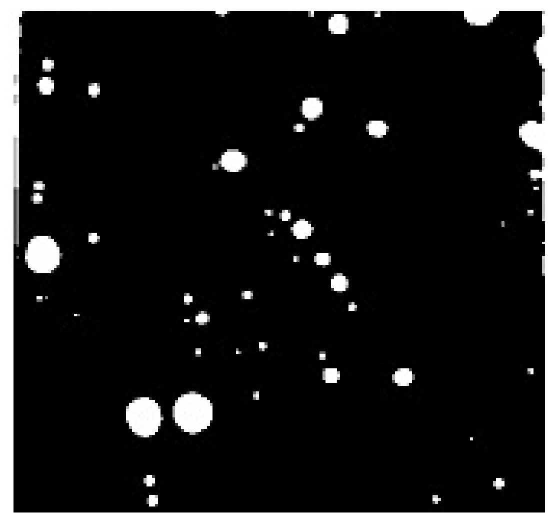
Technologies for Void-Free Soldering

Results



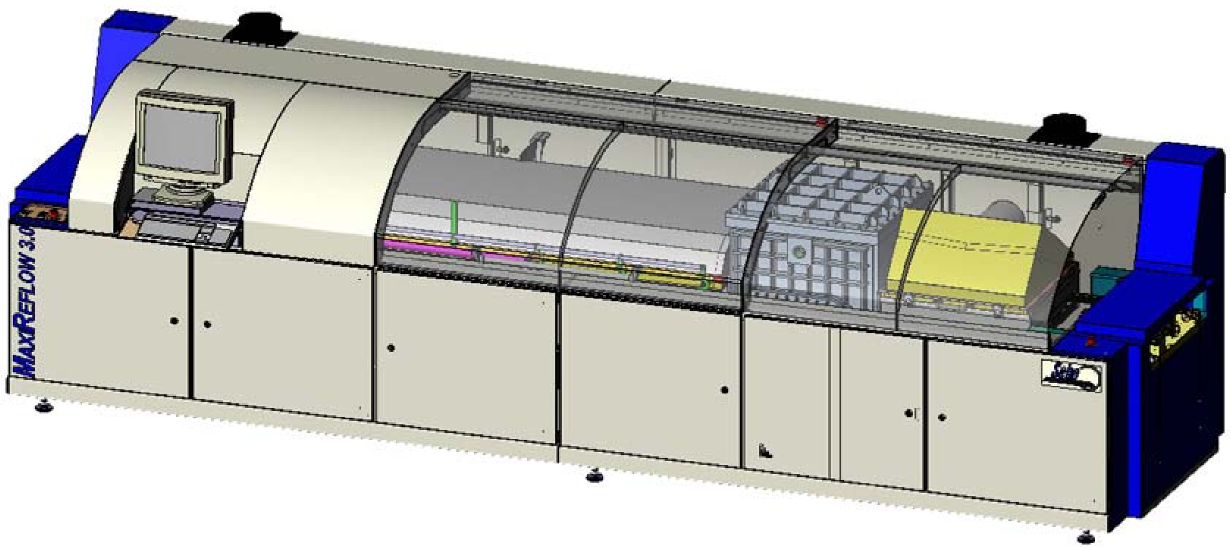


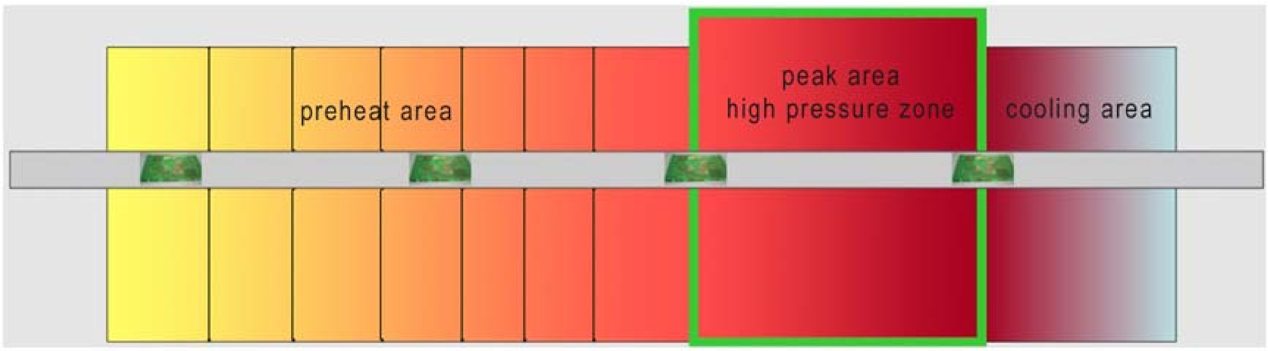




Technologies for Void-Free Soldering

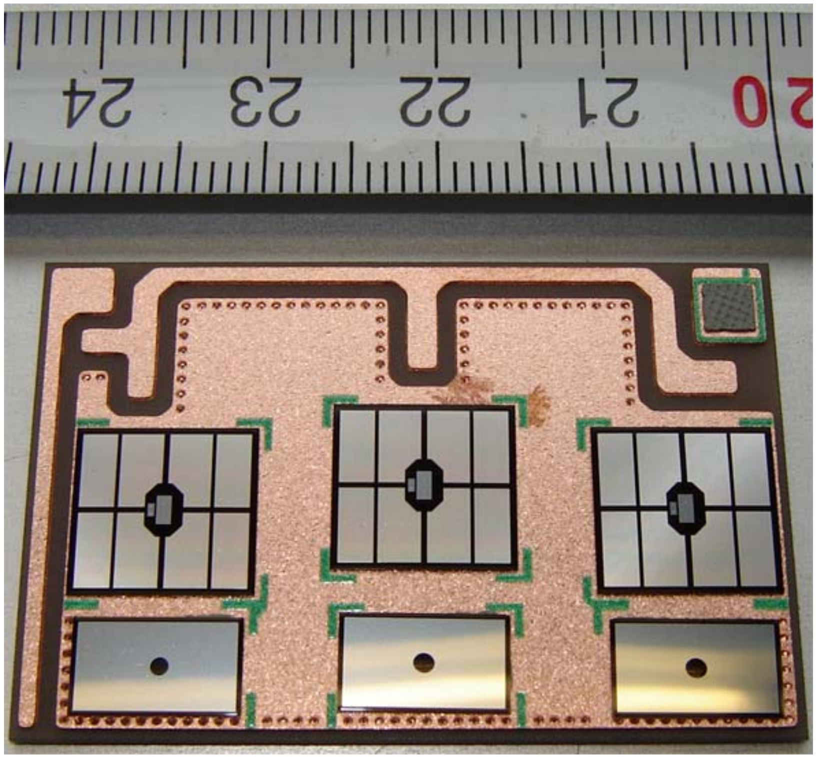
Development of a pass-through reflow system with high pressure zone in the peak area for first field tests





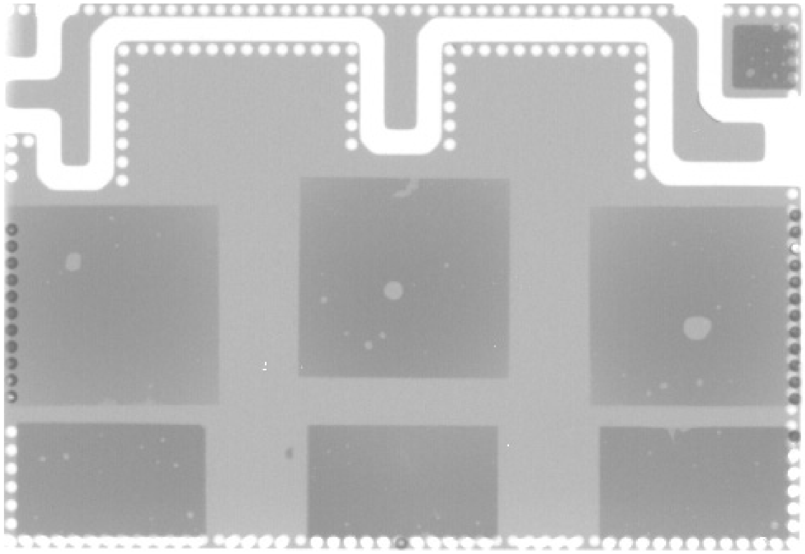
Technologies for Void-Free Soldering

test board

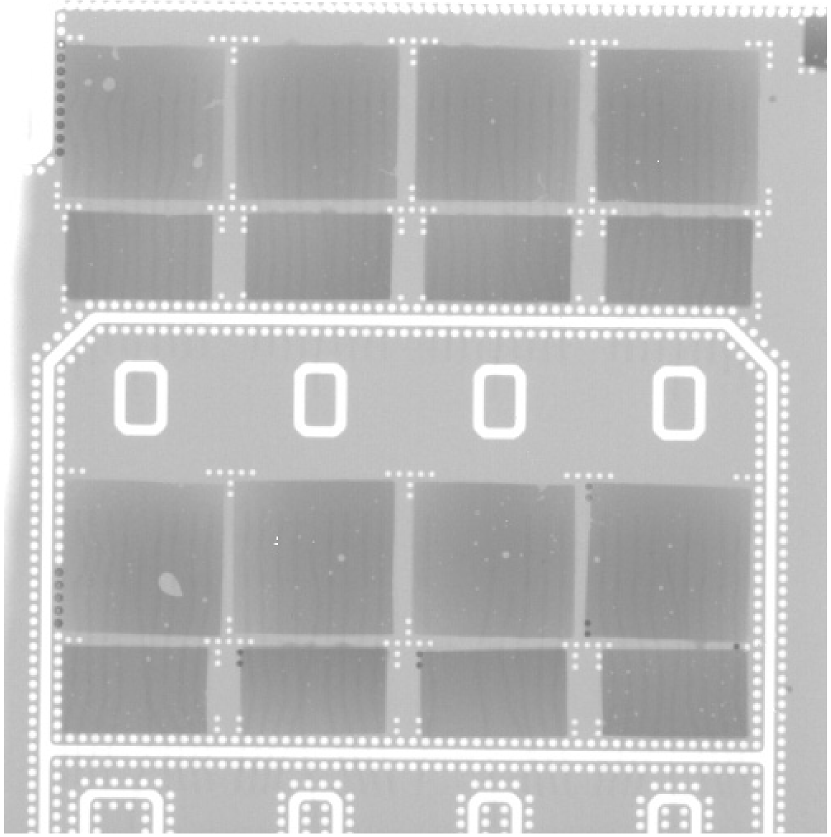


surface:	Cu
component:	Bare Die
component metallization:	Ag
solder paste:	SnAg3.5Cu0.5
atmosphere:	N_2

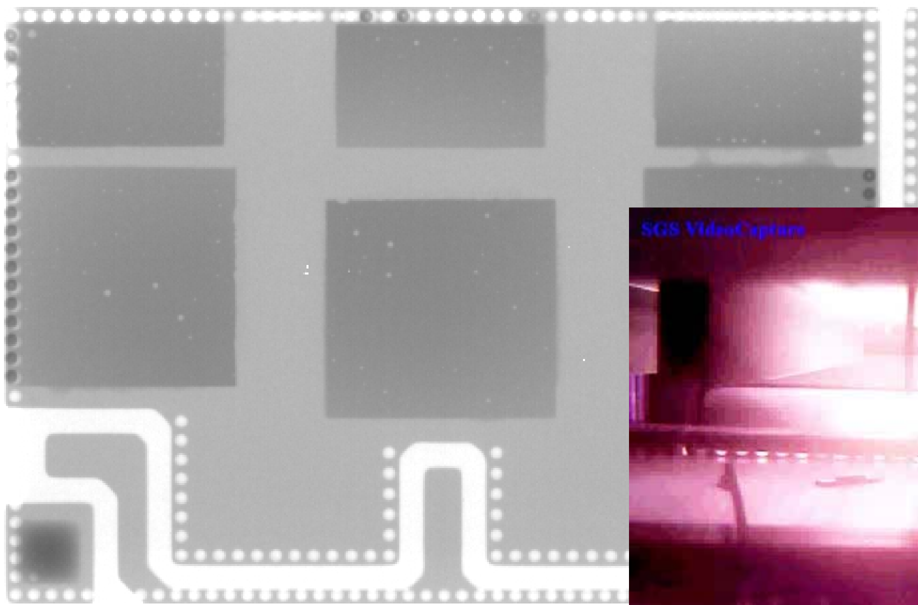
Technologies for Void-Free Soldering



Soldering Process **without** HP Technology

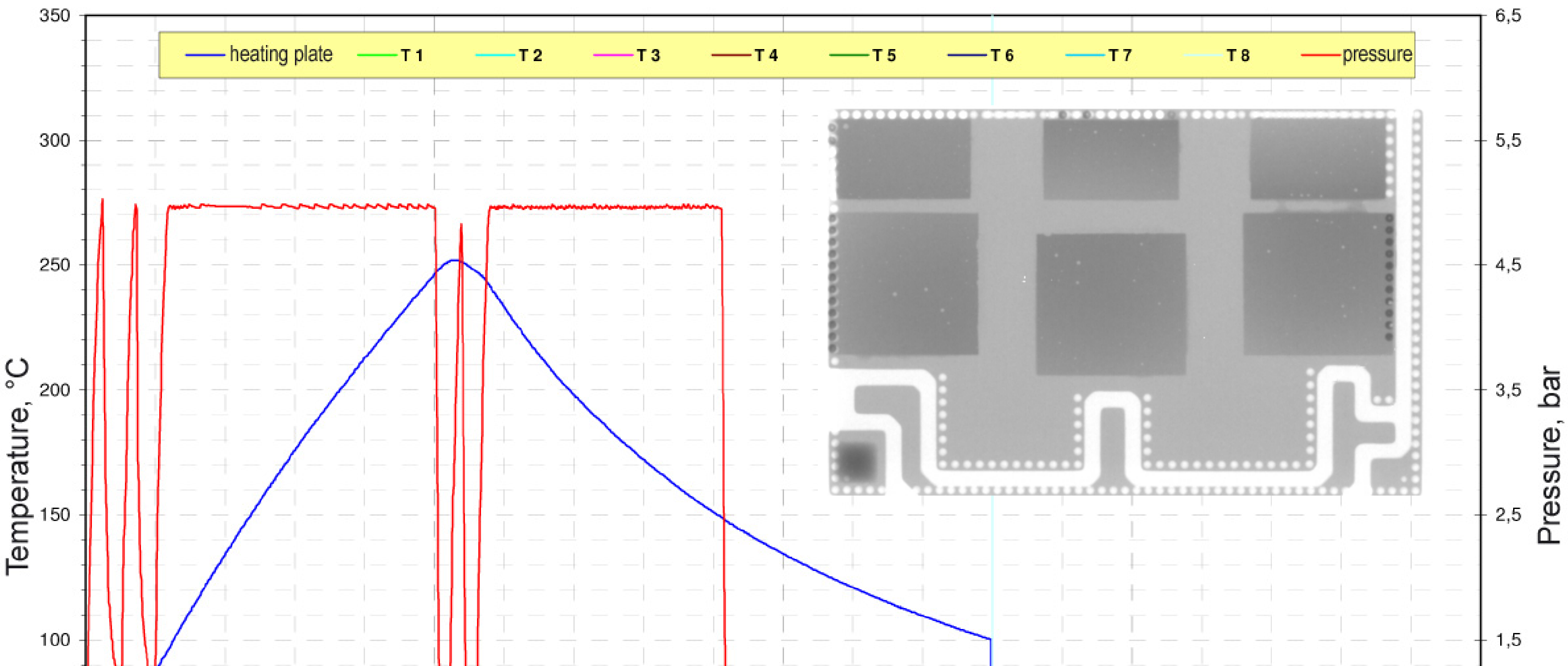


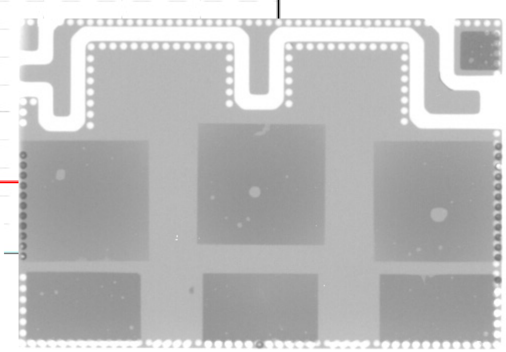
Technologies for Void-Free Soldering



Soldering Process **with**
HP Technology

Technologies for Void-Free Soldering





reference board without HP technology

Thank You!

Questions?