

# Void Reduction in Reflow Soldering Processes by Sweep Stimulation of PCB Substrate– Process Integration in Industrial Production

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## Abstract

Due to the ongoing trend towards miniaturization of power components, the lossless thermal conductivity of solder joints in SMT-processes gains more and more importance. Therefore, the role of voidfree solder joints in power electronics becomes more central. Voids developing during soldering reduce the actual thermal transfer and can cause thermal damage of the power components up to their failure. For this reason, Ersa GmbH has developed a new technique to minimize the formation of those voids during the soldering process and has tested its practicability in industrial soldering processes as well as its influence on process time.

The result of this development is a universal technique to reduce voids in the liquid solder between component and PCB by applying a mechanic sinusoidal actuation. Primarily the PCB is stimulated by a longitudinal wave with an amplitude of less than 10  $\mu\text{m}$  on the PCB level. During this sinusoidal actuation of the PCB in a defined frequency range, the self-resonances of this area are stimulated regardless of the PCB layout. The low starting frequency of the sweep stimulation ensures a gentle, homogeneous propagation of the vibrations in the PCB, without damaging the molecule chains (f.e. in FR-4). The intensification of the frequency causes a stiffening of the PCB substrate, an increase in the elastic modulus and, because of the reduced damping factor, an improved energy transmission of the liquid solder. Thereby areas with a low density, so-called voids are moved out of the solder joint by the vibration. Since a sinusoidal actuation of the PCB in a defined frequency range is actuated over the complete spectrum of this range, all the self-resonances of the PCB in this frequency range are stimulated, too. By this, the liquid solder is stimulated repeatedly by the vibration propagation in a relative shearing motion leading to a reduction of voids in the solder joint. The sweep stimulation onto the components is absorbed mostly by the liquid solder, which protects the components from damage caused by vibration transfer. Positive side effects of the sweep stimulation are the centering of the components on the pad and an optimized spreading of the solder on the pad. The process of void minimization takes place within seconds, without causing any significant increase in cycle time.

The insights of the feasibility study were the basis for the integration of the voidless technique into an industrial production process. The quality of the solder joint concerning the voidrate is strongly influenced by the duration of the voidless process. Therefore multifold tests were made, contrasting the influence of the process duration as well as the as the influence of the different types of sweeps.

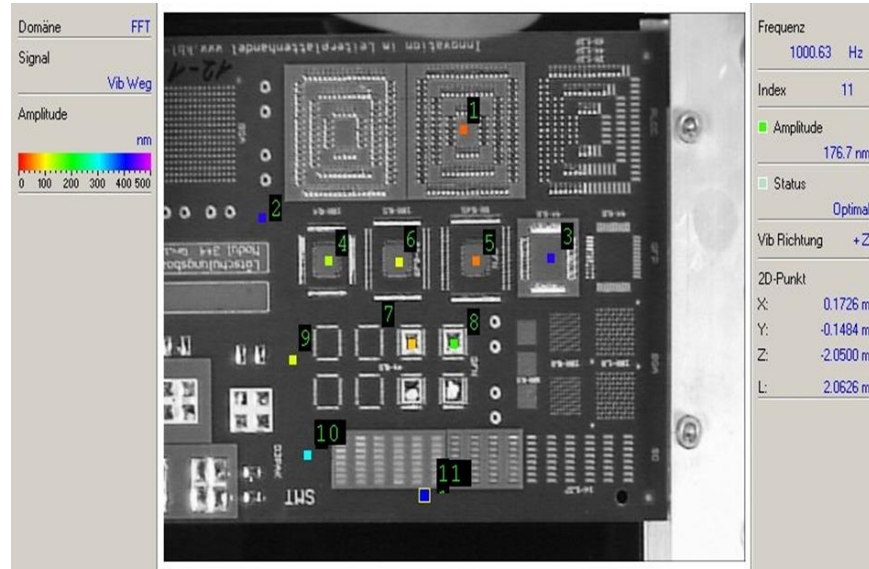
## Introduction

The goal of this research project was the investigation of a technique for the reduction of voids in soldering joints without the disadvantages that current state-of-the-art methods suffer from. For this a concept was adapted that is normally used in measuring low-level signals of piezo actuators. In the process, a defined sinusoidal sweep actuation and a stimulation amplitude on a relatively low-level are used to stimulate the frequency range of the piezo actuator to detect the resonance frequencies.

This technique is used in order to characterize the piezo-electric properties of the transducer. The project was based on the idea to transfer this principle to use it for the actuation of a PCB in the pre-defined frequency range. By this, every self-resonance of the PCB within this frequency range is stimulated, independent of the PCB layout or its material properties. The sinusoidal actuation of the PCB causes the propagation of transversal and longitudinal waves which overlap within the frequency range and transfer their kinetic energy on a medium with lower density (here: gaseous inclusions in liquid solder). A starting sweep actuation with a frequency of almost 0 Hz on the one hand has a low impact on the piezo actuator and the system components, and on the other hand enables the homogeneous propagation of the polymer chains in the FR-4 substrate. As characteristically for all plastics, an increase in the frequency causes an increase of the elastic modulus of the PCB substrate. The polymer chains have no time to adapt to the increasing and changing stress thus, they stiffen in the process, which leads to an increase of the elastic modulus. In this state, the transmission of the oscillation through the PCB in the liquid solder is ideal. The energy induced in the PCB is partly absorbed and partly transformed into kinetic energy.

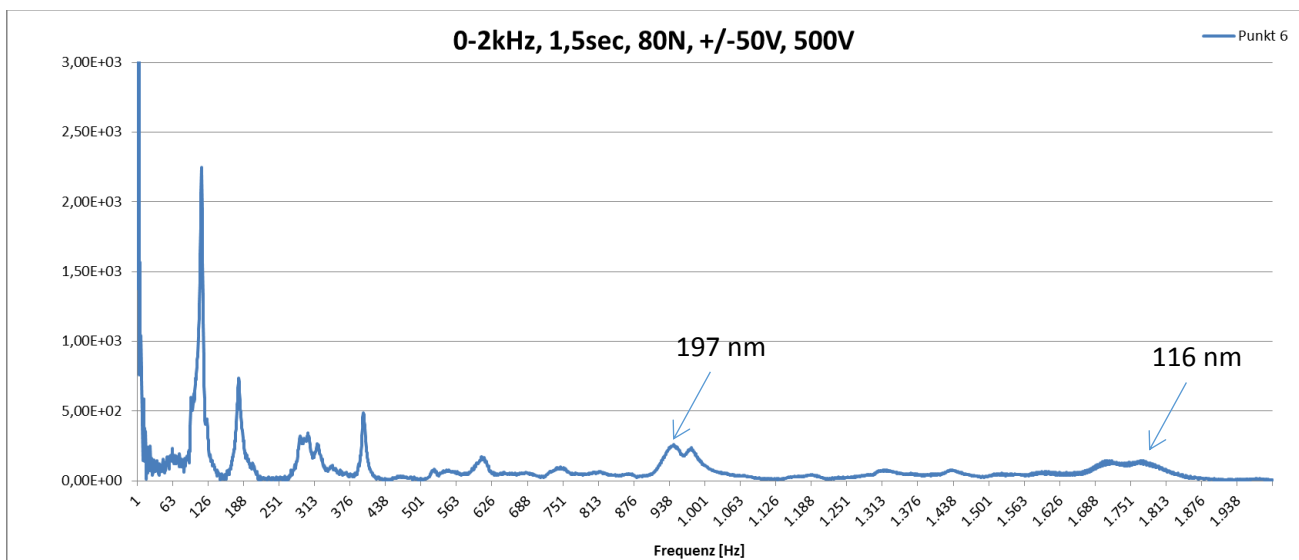
In the context of the feasibility study, the influence of those sinusoidal sweep actuations on the rate of voids in solder joints where tested. For this, FR-4 PCBs were placed in a specially designed test rig and heated up by suitable heater with a temperature profile corresponding to those used in inline reflow soldering systems. The sinusoidal sweep actuation was transferred directly into the PCB substrate by a piezo stack. The longitudinal actuation on PCB level caused a compression of the FR-4 substrate. Because of the minimal amplitude of the stimulation (only few  $\mu\text{m}$ ) the substrate of the FR-4 PCB remains in the linear viscoelastic range which leads to the resilience of the material. The movement on the surface of the PCB, which is caused by the transversal wave, a side effect of the sweep actuation, was measured at a defined point on the PCB with a laser vibrometer. The position of the measuring points was chosen such that all relevant areas on the PCB surface could be examined. For this, one measuring point for each frequency sweep on the PCB was analyzed. In order to be able to analyze the response signal of the elastic modulus of the PCB substrate the counteracting force generated during the actuation was detected by a load cell.

## Results

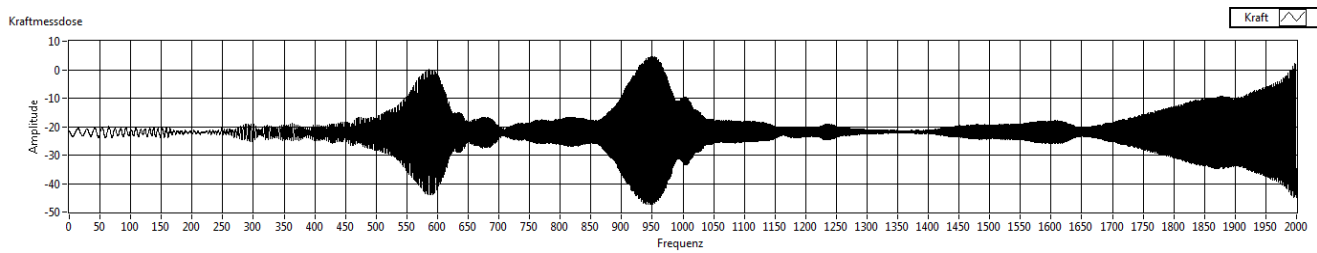


**Figure 1 – Measuring Points for the Laser Vibrometer**

The measuring points 4, 5 and 6 are located on the top of components (see Figure 1) and allow conclusions about the vibration behavior of the solder underneath the components. The PCB was actuated with a sweep for every measuring point to analyze the vibration behavior on the surface of the substrate.



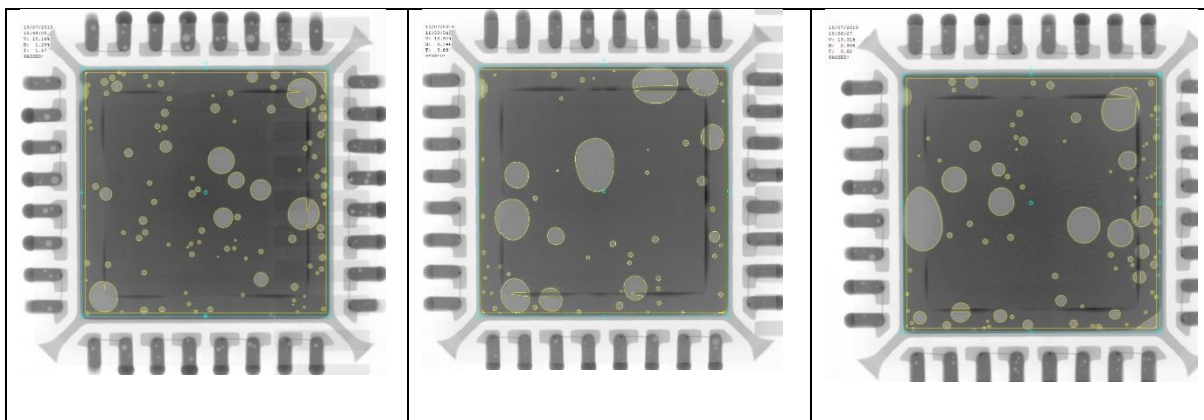
**Figure 2 – Oscillation Profile of the PCB in Measuring Point 6 as Detected by Laser Vibrometer**



**Figure 3 – Spectrum of Forces as Detected During a 0 – 2 kHz Sweep by the Measuring Box**

Figure 2 and 3 show the oscillation of the PCB in measuring point 6 which were detected by the laser vibrometer in correlation with the signals of the measuring box. The higher amplitudes of the laser vibrometer signal in the frequency range below 600 Hz result from the movement of the PCB. The corresponding signal of the measuring box shows no significant raise in force up to a frequency of 600 Hz. In this frequency range the actuation energy coupled into the PCB is almost totally converted in the elastic deformation of the PCB. Figure 2 shows that the first resonance at about 600 Hz is caused by the construction of the test rig and has no influence on the behavior of the PCB (no significant amplitude raise at 600 Hz in measuring point 6). When higher frequencies above 870 Hz are reached the PCB reinforces caused by the raised elastic modulus. The change in the elastic modulus causes a better energy transmission on the solder. The rise of the amplitude up to 197nm at about 940 Hz and the further raise up to 119 nm in the frequency range from 1700 to 1800 Hz clearly shows this (compare figure 2). The detected amplitudes shown during the reinforcement of the PCB in the higher frequency ranges are not only PCB movement but also the movements of the solder and the components placed on it.

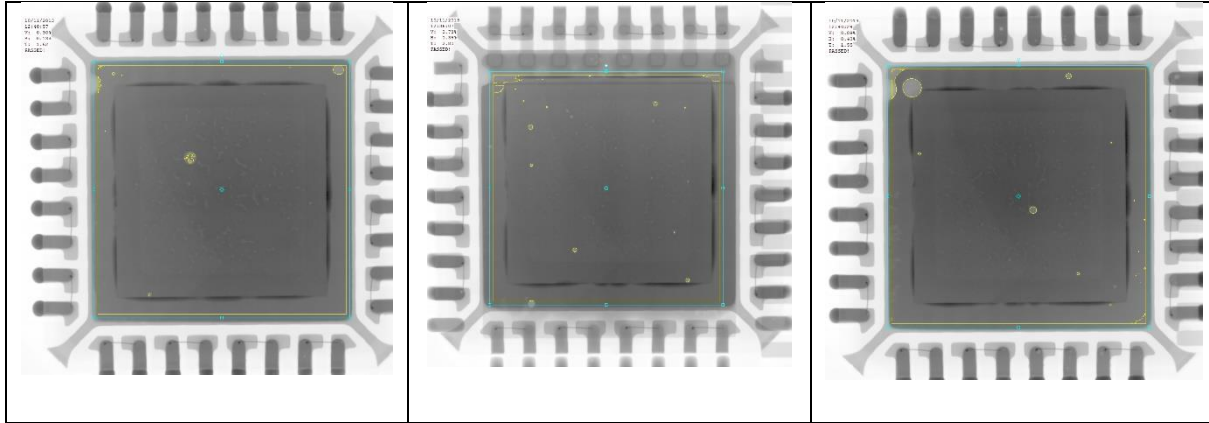
In order to be able to analyze the influence of the variation of the parameters on the formation of voids and their dimensions three identical PCBs with identical components were used for each set parameter. During the analysis of the test results the median of the void ratio in nine solder joints was formed. For those tests, the PCBs were fixed in the test rig with a low mechanical tension. The infrared heating underneath the PCB was set to a temperature profile corresponding to that of a reflow soldering system. After the melting temperature was reached, a sinusoidal sweep was actuated for a predefined time. Afterwards an x-ray analysis of the soldered PCB was performed to identify the rate of voids in relation to the size of the soldered area and the size of the largest void in the soldering joint.



**Figure 4 – Reference**

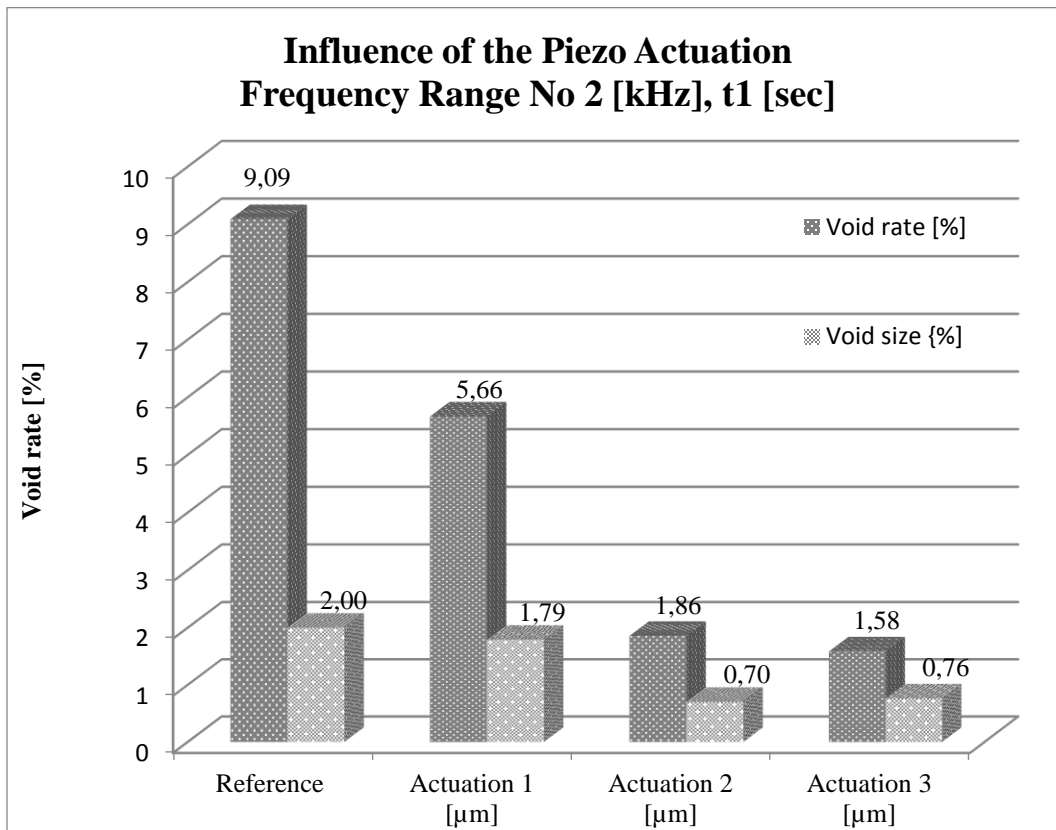
Figure 4 shows the x-rays of three components of the reference sample which were soldered without the influence of the oscillation. The high amount of gaseous inclusions (voids) is obvious. The spreading of the voids shows no significant

tendency, since larger as well as smaller voids in different amounts can be seen. The afterwards analysis shows the void rate in percent for each component as well as the percentage of void size in comparison to the soldered area. The average void rate in the reference PCBs is about 9% and the average size of the voids is 2.00 % of the soldered area.



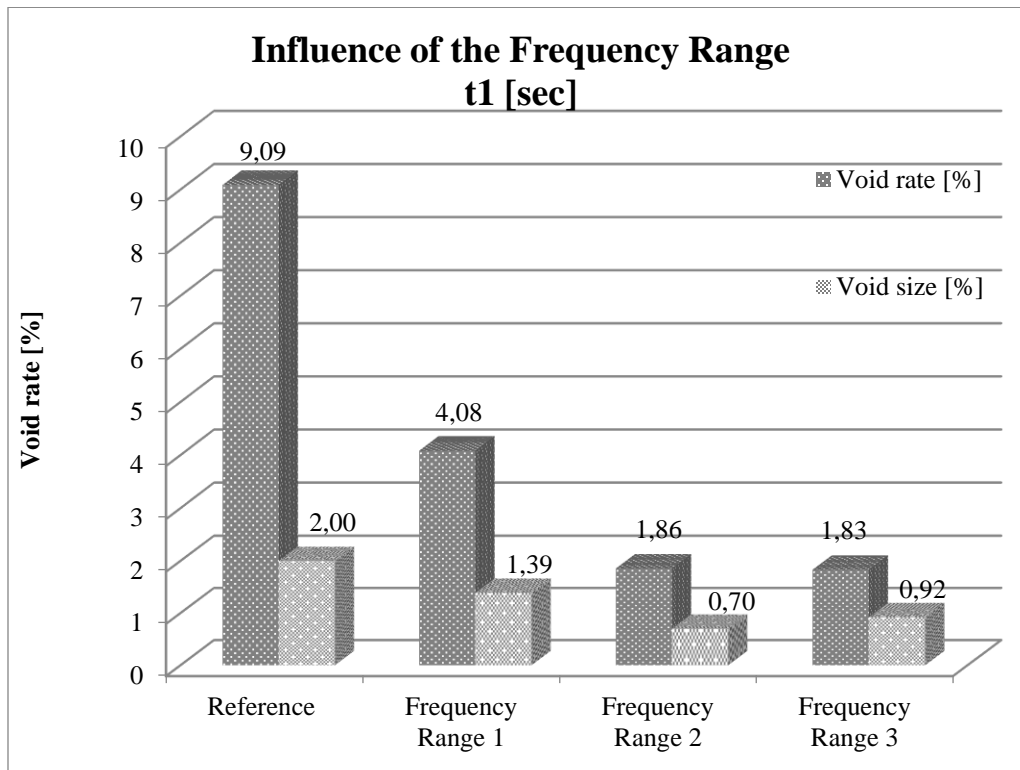
**Figure 5 – Test Setting No 16**

The analysis of the x-rays of figure 5 show a significant improvement in the average void rate of the soldered areas, which is 1.83 % compared to above 80% in the reference PCBs soldered without actuation. The remaining voids have a smaller diameter and are spread homogeneously over the soldered area. Most of the gaseous inclusions in the actuated components are located outside of the soldered area underneath the component.



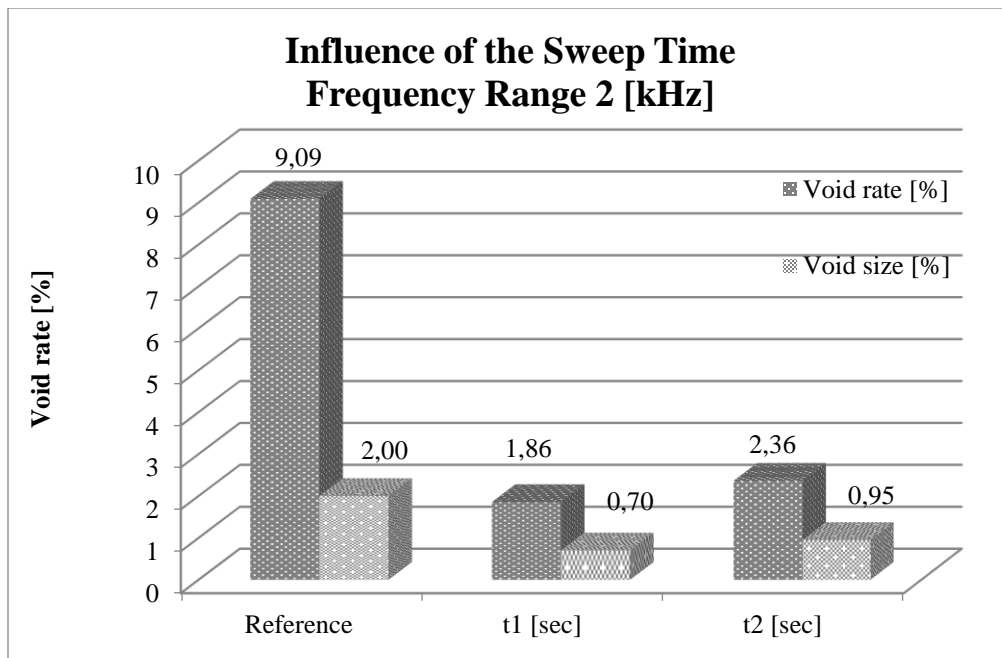
**Figure 6 - Influence of the Piezo Actuation on Void Formation and Size**

Figure 6 shows the influence of the amplitude of the actuation on void size and void formation. A higher amplitude of the actuation causes a significant decrease in the void rate. Actuation 1 already realizes a reduction of the void rate from 9.09 % (reference) to 5.66 %. A further raise of the actuation amplitude (actuation 2) causes a further reduction to 1.86 %. The amplitude set of actuation 3 finally realizes a void rate of less than 1.58 %. This is an improvement in comparison to the reference test of 82.6 %. The average percentage of larger voids is also decreasing with the raising of the amplitude. While the reference test shows 2.0 % of larger voids this amount decreases in actuation 2 to 0.7 %.



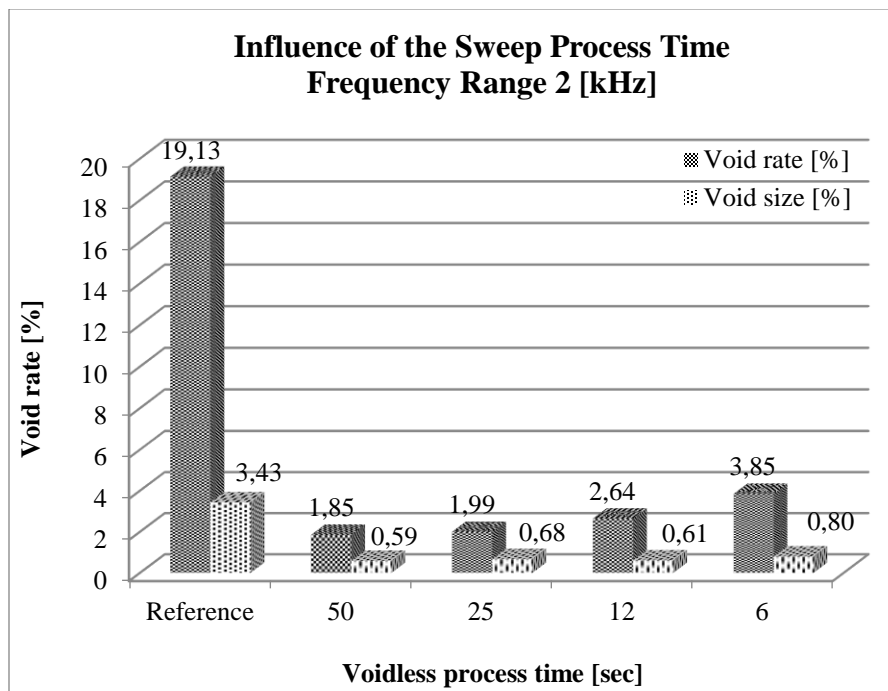
**Figure 7 - Influence of the Frequency Range**

Figure 7 shows the influence of the frequency range on the void reduction during actuation 2. The reduction of voids in comparison to the chosen frequency range shows a non-linear development. The average void rate already decreases in frequency range 1 from 9.09% to only 4.08 %. A further significant decrease of the void rate results from the frequency range 2 where 1.86 % of residual voids are realized. A further raise of the frequency range does not cause significant improvements in the average void rate. Frequency range 3 shows 1.83% of voids, which is only a decrease of 0.03% in comparison to frequency range 2.



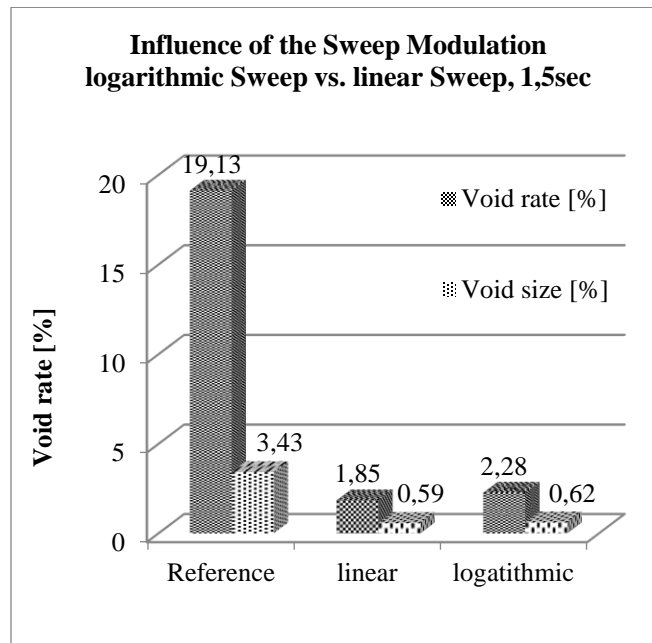
**Figure 8 - Influence of the Sweep Time**

Figure 8 shows the correlation of the decrease of voids and the sweep duration for frequency range 2. In this context, the influence of the sweep width on the decrease of the average void rate is obvious. For a sweep duration t1 it is 1.86%. In the context of the research project, it was shown that the sweep width has a positive influence on the decrease of voids. On the other hand, the average void rate rises with a raise of the sweep duration from 1.86 % in t1 to 2.36 % in t2.



**Figure 9 - Influence of the Voidless Process Time**

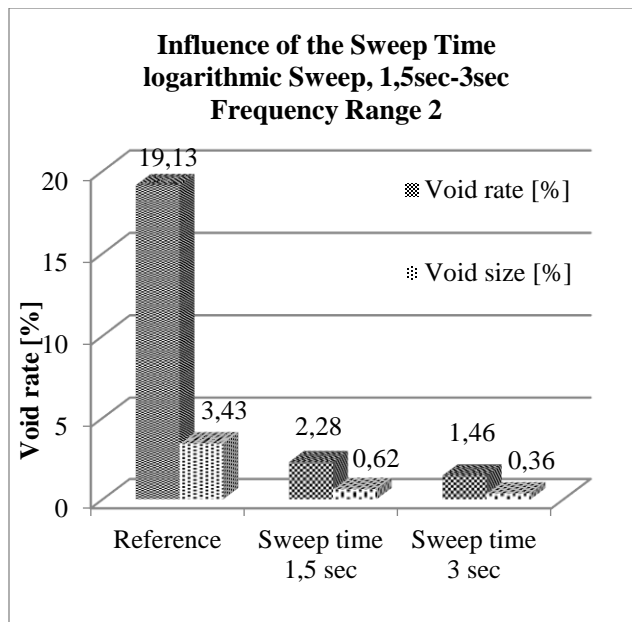
A continuous examination of the process is vital for its integration in the industrial soldering process, since the process time influences the production output. This was part of further examinations. Figure 9 shows how time influences the rate of residual voids in the solder joint during the voidless process. The overall time of 50 seconds for the voidless process results in an average void rate of 1.85%. With half the process time, the rate of residual voids reaches 1.99%. With a reduced voidless process time of 6 seconds an average rate of 3.85% per solder joint is reached.



**Figure 10 - Influence of the Sweep Modulation**

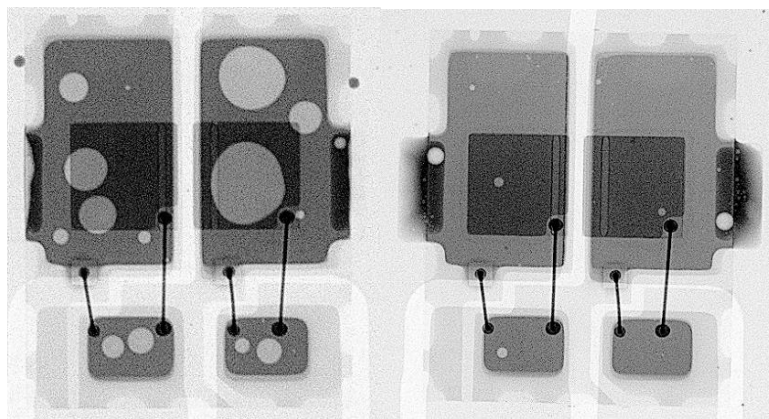
Likewise examinations of the influence of logarithmic and linear sweep modulations on the reduction of voids in the liquid solder joints were made and compared to each other as shown in figure 10. It becomes visible that a linear sweep with a length of 1.5 seconds of PCB substrate results in a residual void rate of 1.85%. A logarithmic sweep with identical parameters results in a higher residual void rate of 2.28%. The reason for this is the density of electromagnetic energy per time brought into the solder joint. If the relation of both factors is too large, because either the density of electromagnetic energy is too high or the sweep time is too short, this can influence the voidless process negatively. Further tests were made to analyze the influence of the sweep duration in combination with a logarithmic sweep modulation.





**Figure 11 - Influence of the Sweep Time using logarithmic Sweep Actuation**

Figure 11 shows the influence of a logarithmic sweep modulation on the quality of the solder joints. It becomes obvious that the duration of the sweep has an important influence on the void rate. With a logarithmic sweep in the voidless process, a longer sweep duration is needed to gain better results. The reason of this is the amount of density of energy brought into the solder joint during a sweep actuation. With a larger sweep width, a longer sweep duration is needed to reach a higher degree of voidlessness. A practical example is shown in figure 12, which shows radiographs of a 18 mg LED-component. This shows that with an unfavorable relation of the component weight to the soldered area a logarithmic sweep actuation with a higher width is recommended because a higher amount of self resonance of the PCB substrate must be reached in relation to the relative movement of the solder. Due to the low component weight the usage of a linear sweep is not recommended because when the PCB is actuated already at the beginning of the process  $t$  with a constant linear speed no sufficient relative movement of the liquid solder depot is reached.



**Figure 12 - Influence of the Void rate using logarithmic Sweep Actuation**

## Summary

It was shown that the influence of the oscillation on the PCB during the soldering process dependent on the test parameter caused a significant improvement in the void rate of the soldering joints. The research project showed positive results concerning the influence of a sinusoidal sweep actuation on the minimization of the void rate. In the project, 60 identical PCBs with three identical components were analyzed. The influence of different parameters like sweep duration, width, and the influence of the tension of the actuation could be analyzed. It was possible during the research project to reduce the rate of residual voids from 9.09% in the reference PCB to 1.86% using the right actuation parameters. This is a decrease in the void rate of about 83%. Further valuable findings during the research project: A shorter sweep duration causes the formation of smaller voids in the soldered area. A longer sweep duration causes the formation of few bigger voids that gather on the edge of the component. A larger sweep width causes a decrease in the void rate in the soldering joints. An increase in the tension of the actuator has a positive influence on the reduction of voids.

The results of the feasibility study were the basis of the integration of the voidless process into a industrial soldering process. The influence of the process time on the residual void rate of the liquid solder joint plays a major role for the integration into an industrial process. Equally important is the choice of the right sweep modulation. Components with a low weight and a relatively large soldering area the voidless process with a logarithmic sweep actuation has proven to be favorable. This kind of modulation reaches a sufficient relative movement of the liquid solder, which causes an effective reduction of the residual void rate.