Void Reduction in Reflow Soldering Processes by Sweep Stimulation of PCB Substrate

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Abstract

Due to the ongoing trend towards miniaturization of power components, the need for increased thermal conductivity of solder joints in SMT processes gains more and more importance. Therefore, the role of void free solder joints in power electronics becomes more central. Voids developed during soldering reduce the actual thermal transfer and can cause thermal damage of the power components up to their failure. For this reason, the company has developed a new technique to minimize the formation of these voids during the soldering process.

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 µm 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 (e.g. 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 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.

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 was 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 µm) 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 positions of the measuring points were 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

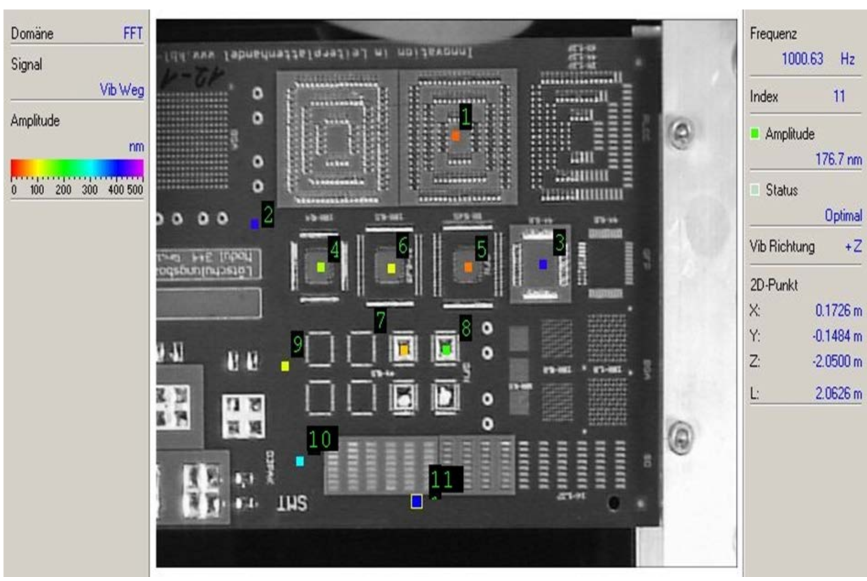

Figure 1 – Measuring Points for the Laser Vibrometer

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.

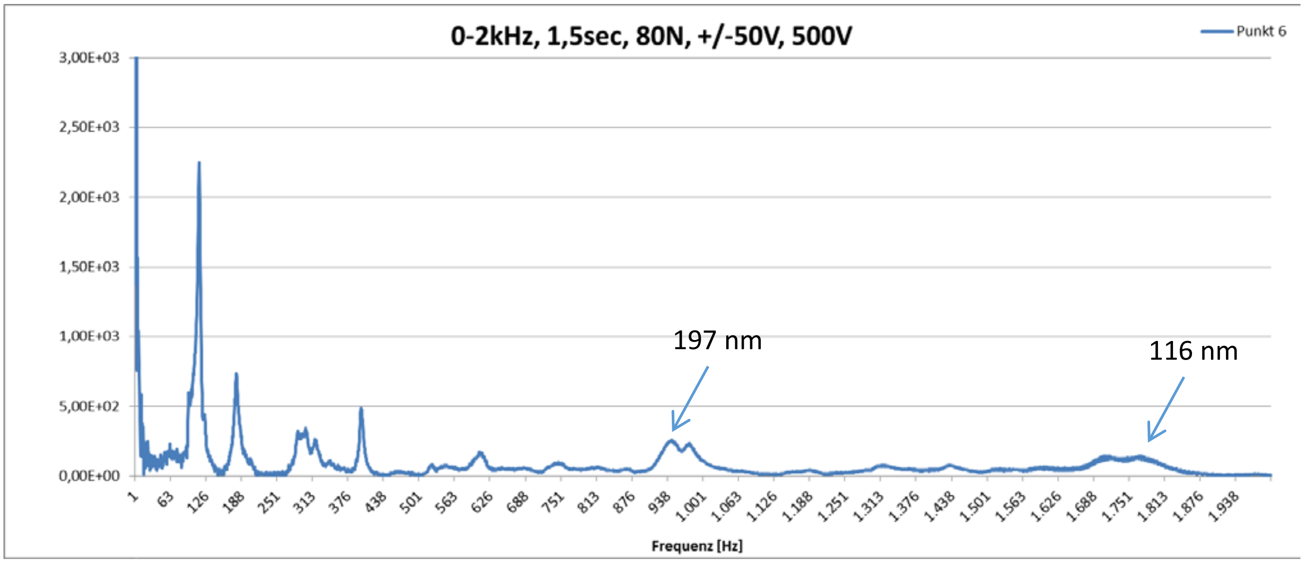

Figure 2 – Oscillation Profile of the PCB in Measuring Point 6 as Detected by Laser Vibrometer

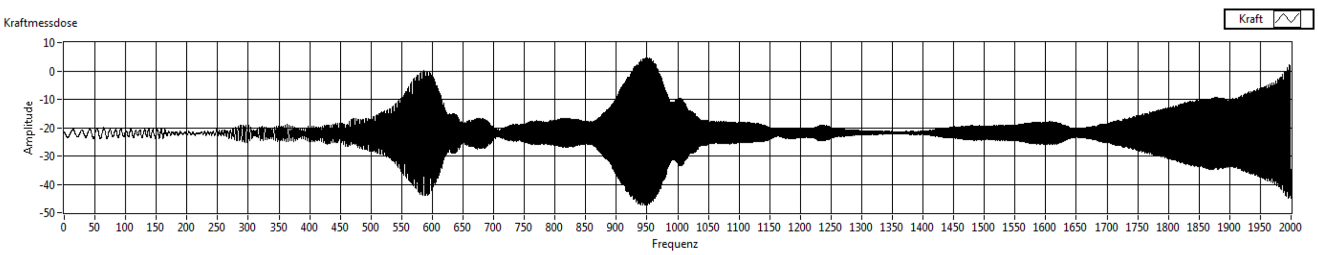

Figure 3 – Spectrum of Forces as Detected During a 0 – 2 kHz Sweep by the Measuring Box

Figures 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.

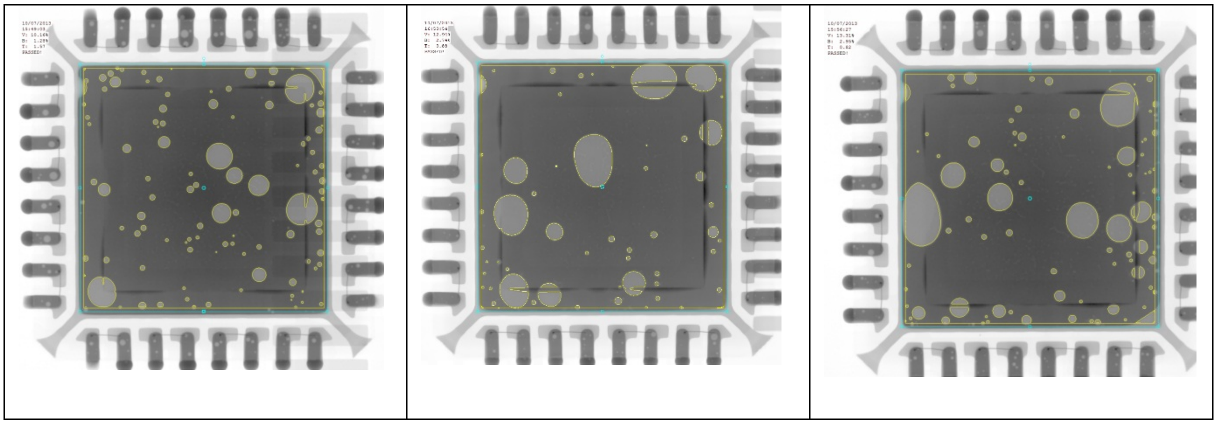

Figure 4 – Reference Sample X-ray Images

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 9.09% and the average size of the voids is 2.00 % of the soldered area.

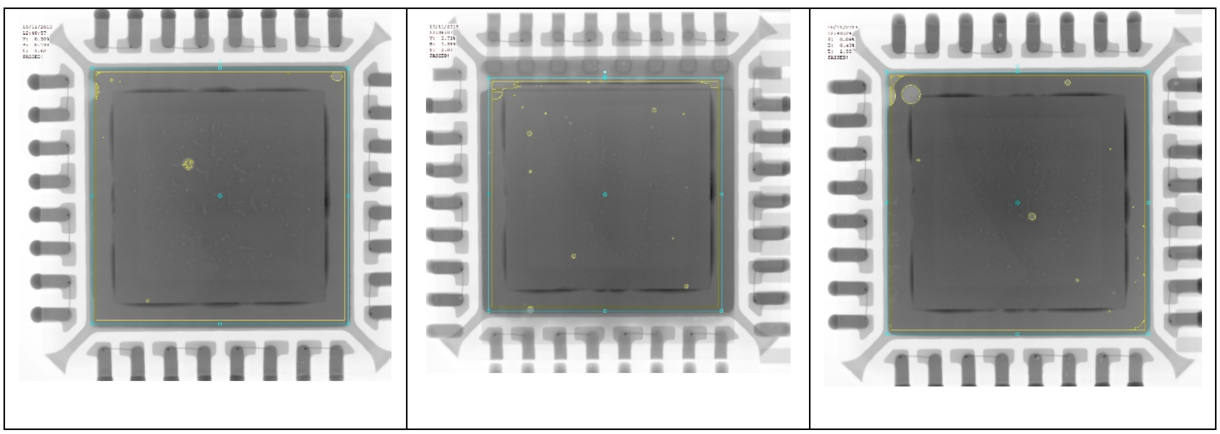

Figure 5 – Test Setting No 16

The analysis of the x-ray images of Figure 5 show a significant improvement in the average void rate of the soldered areas, which is 1.83 %compared to 9.09% in the reference PCBs soldered without actuation (over 80% reduction in average void rate). The remaining voids have a smaller diameter and are spread homogeneously over the large soldered area of the QFN component. Most of the gaseous inclusions in the actuated components are located outside of the soldered area underneath the component.

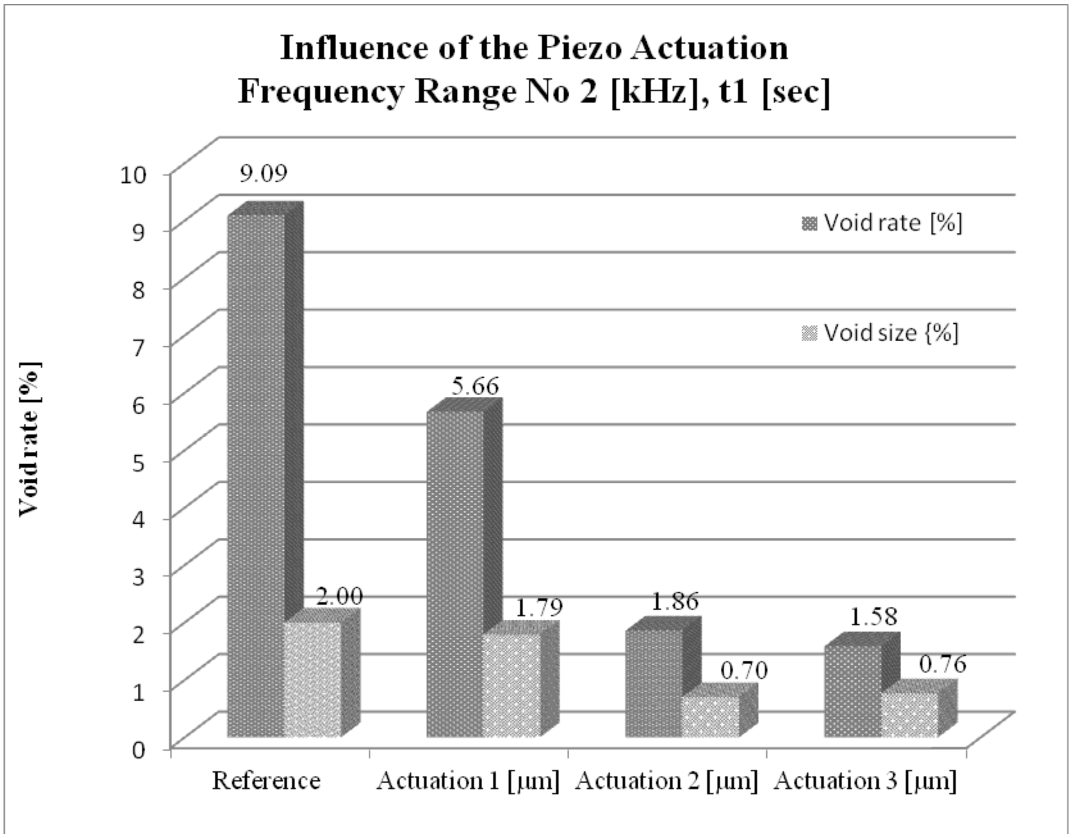

Figure 6 - Influence of the Piezo Actuation on Void Formation and Size

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 a reduction in average void rate 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 %.

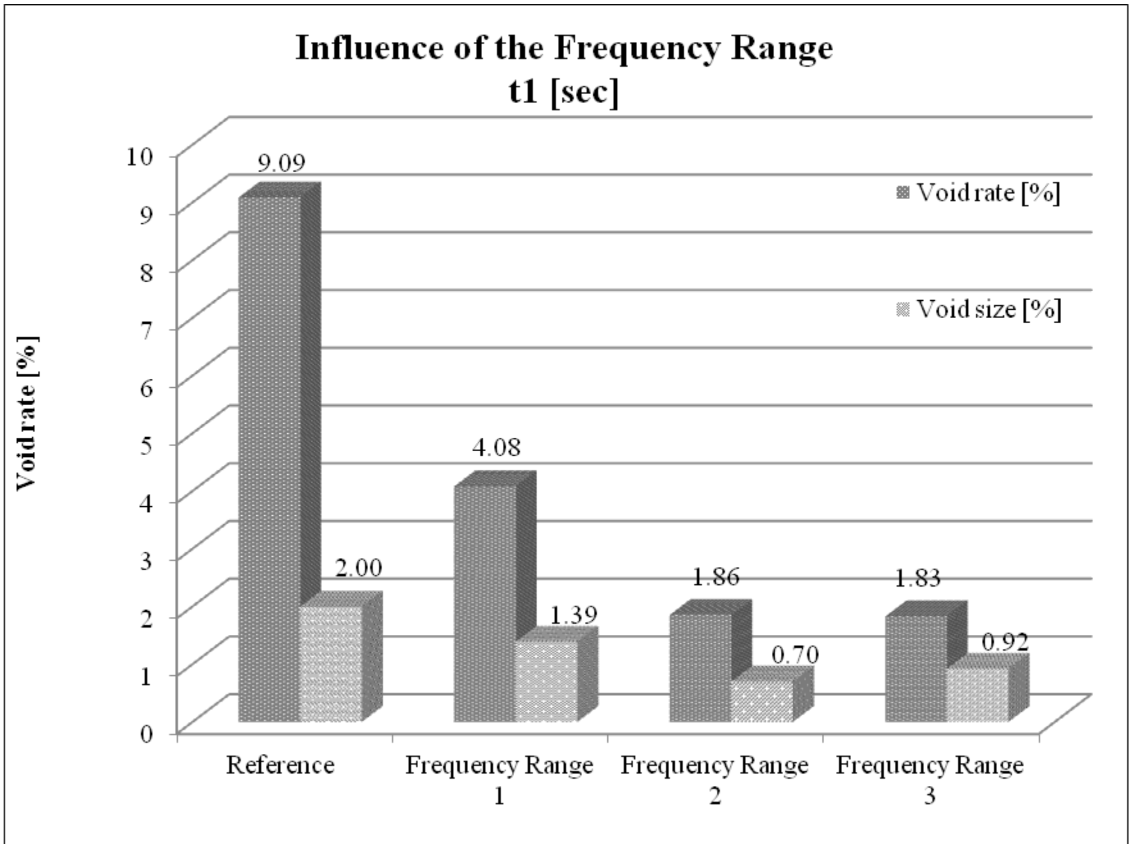

Figure 7 - Influence of the Frequency Range During Actuation 2

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% for the reference 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.

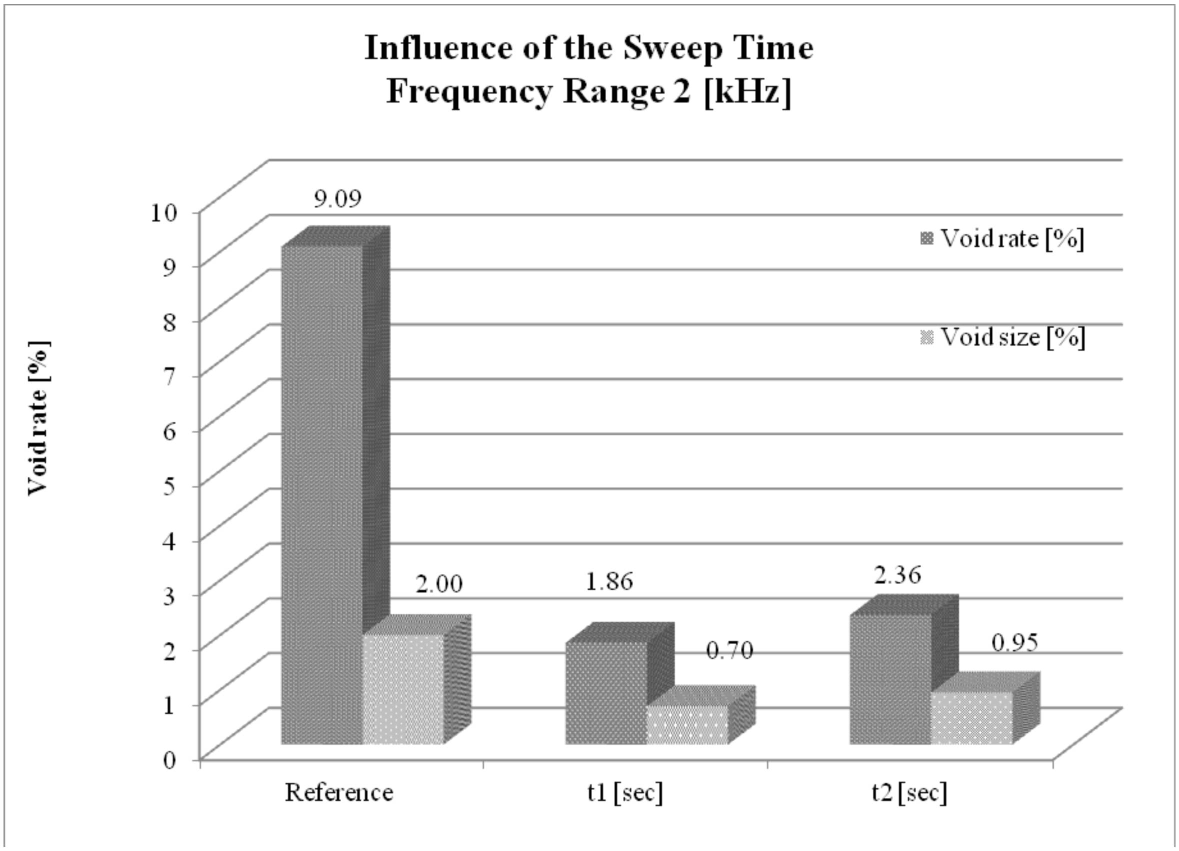

Figure 8 - Influence of the Sweep Time for Frequency Range 2

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.

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 amplitude of the actuation 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 average void rate of about 83% from the reference PCB to the actuated PCB. 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 amplitude of the actuator has a positive influence on the reduction of voids.

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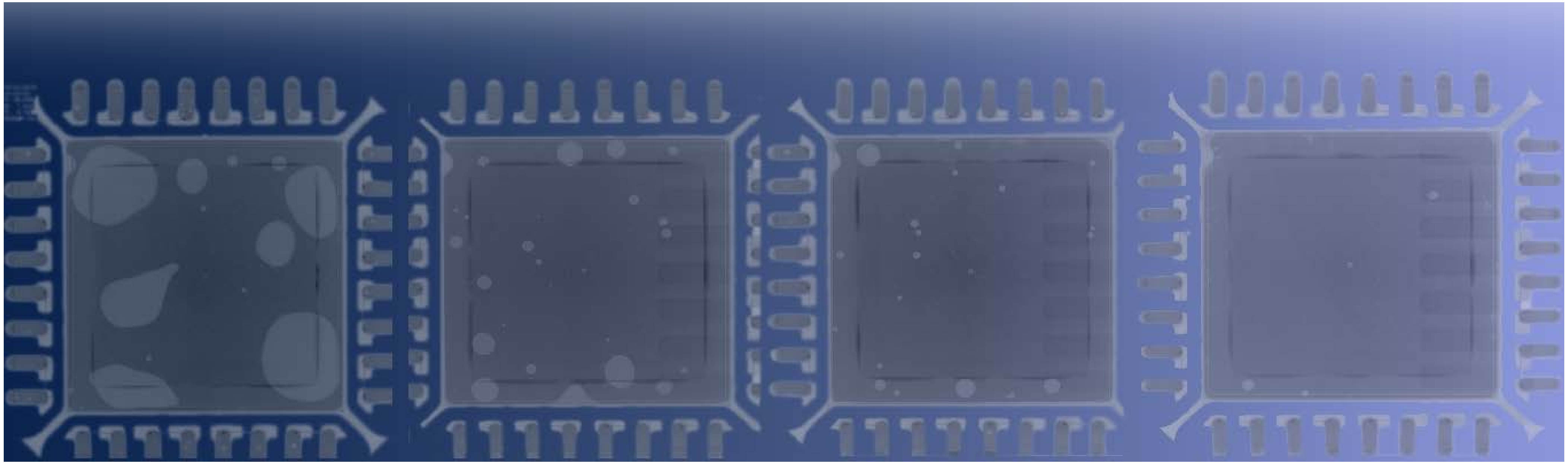
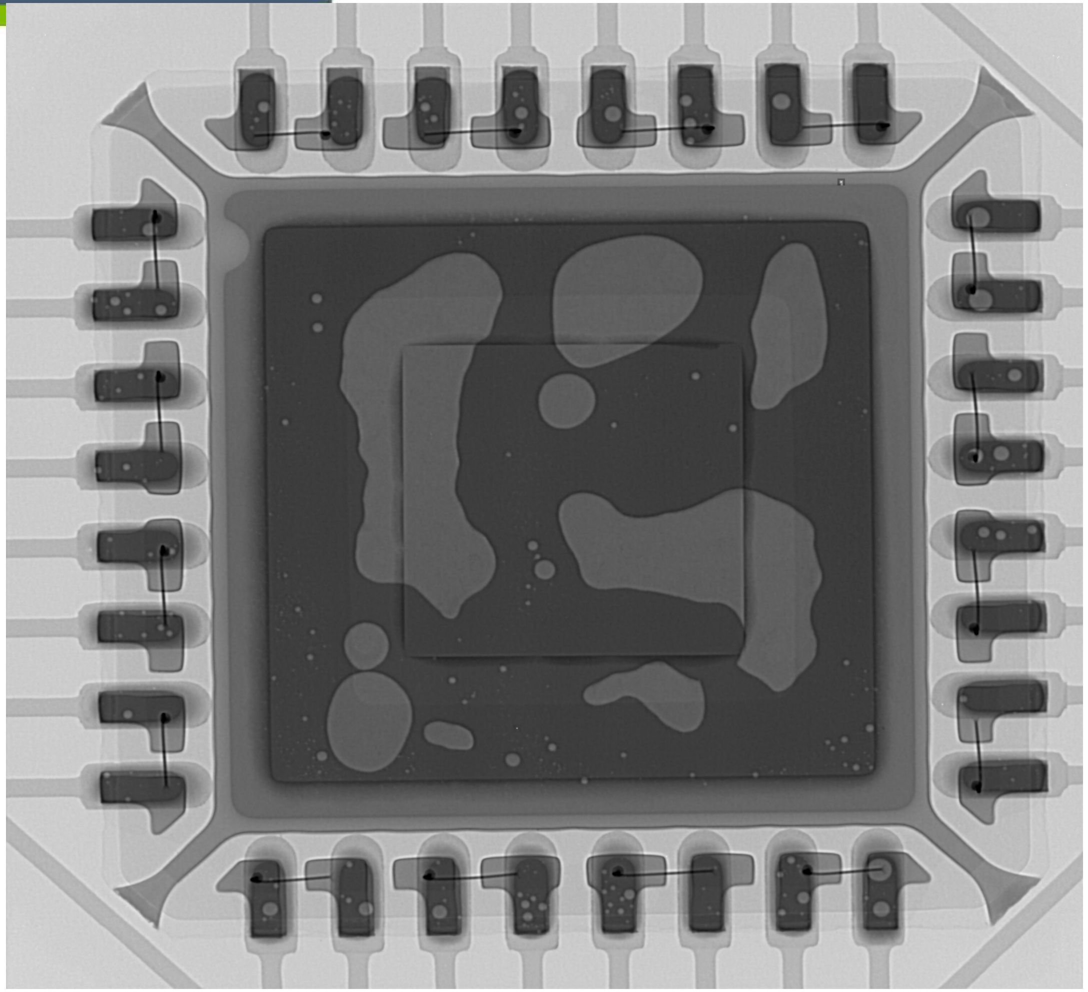
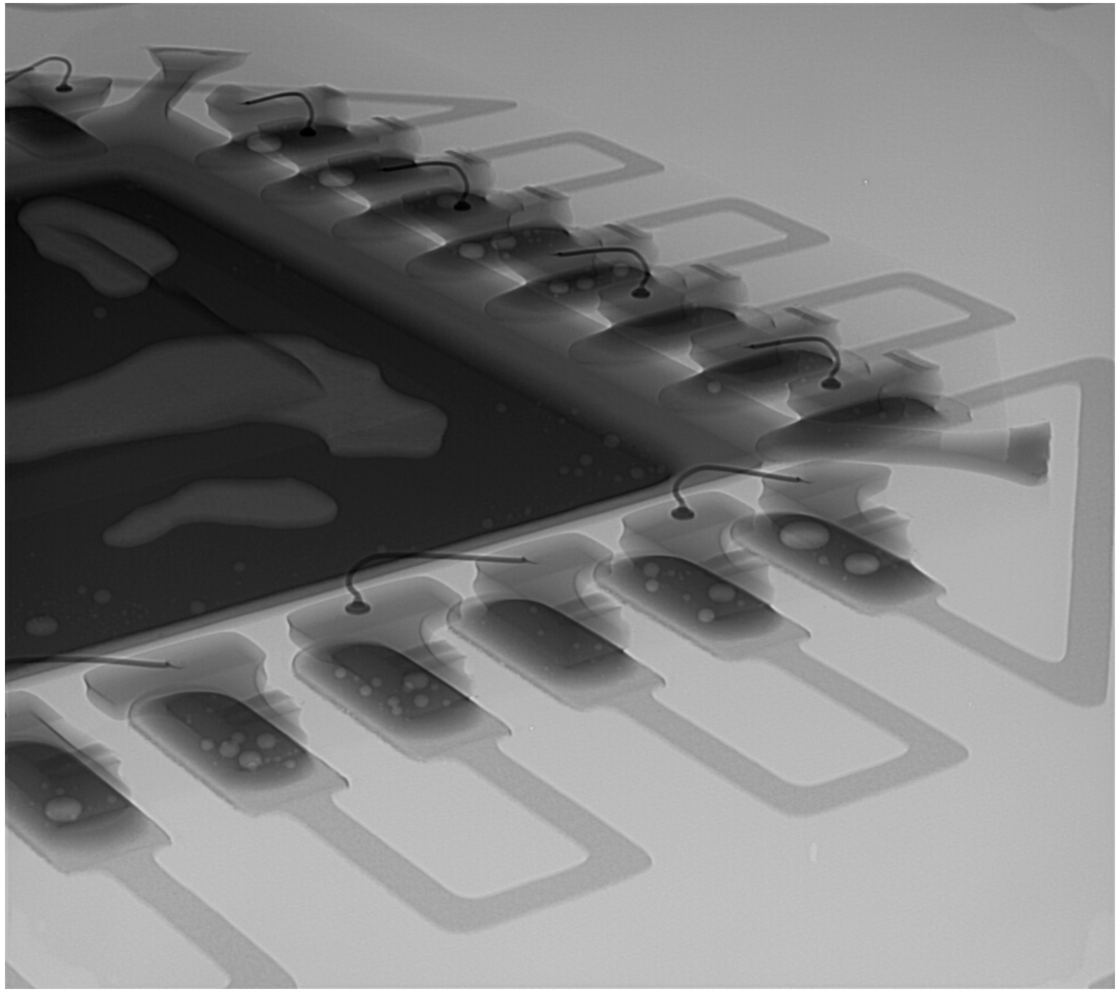
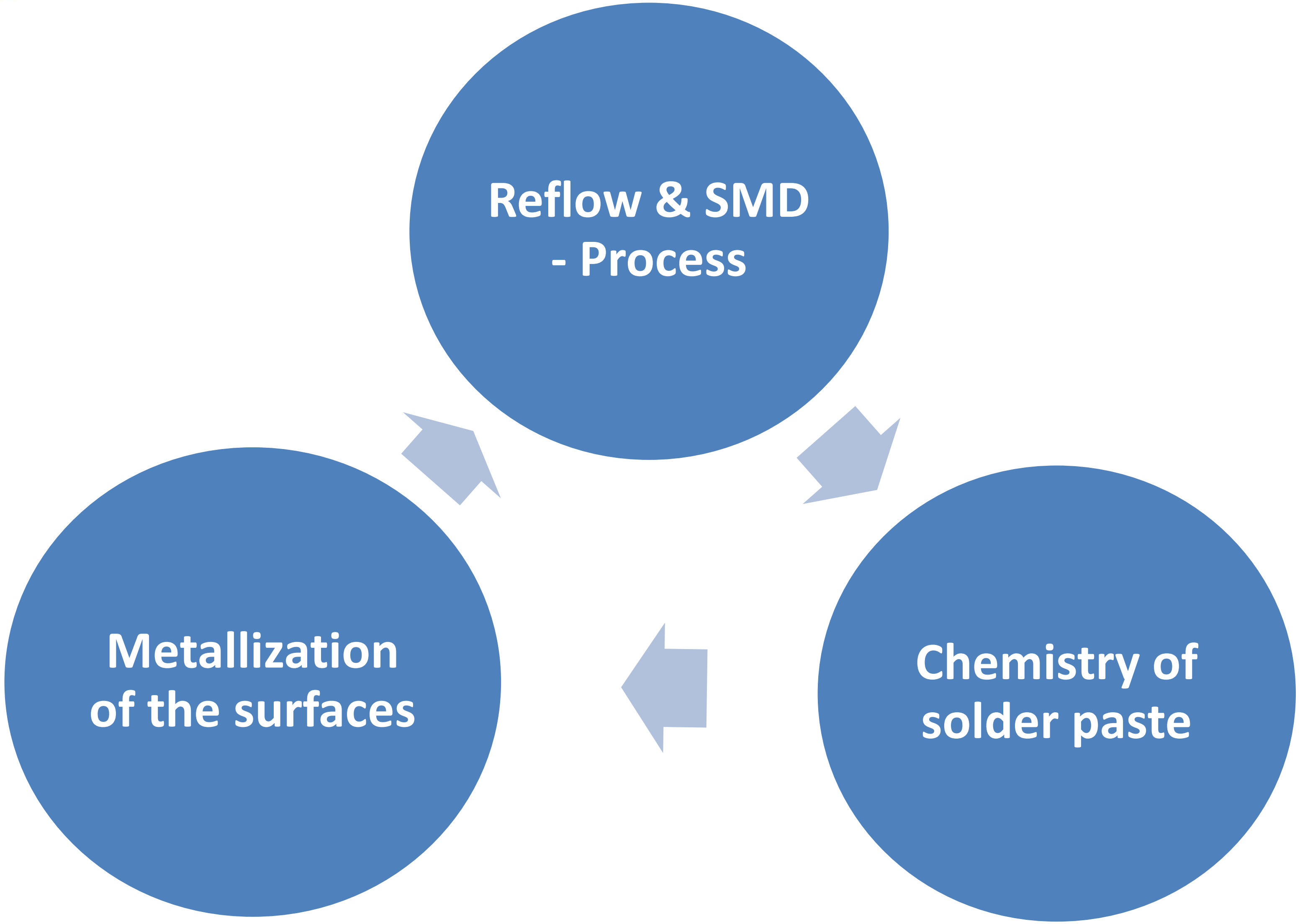


Void Formation During Soldering Processes

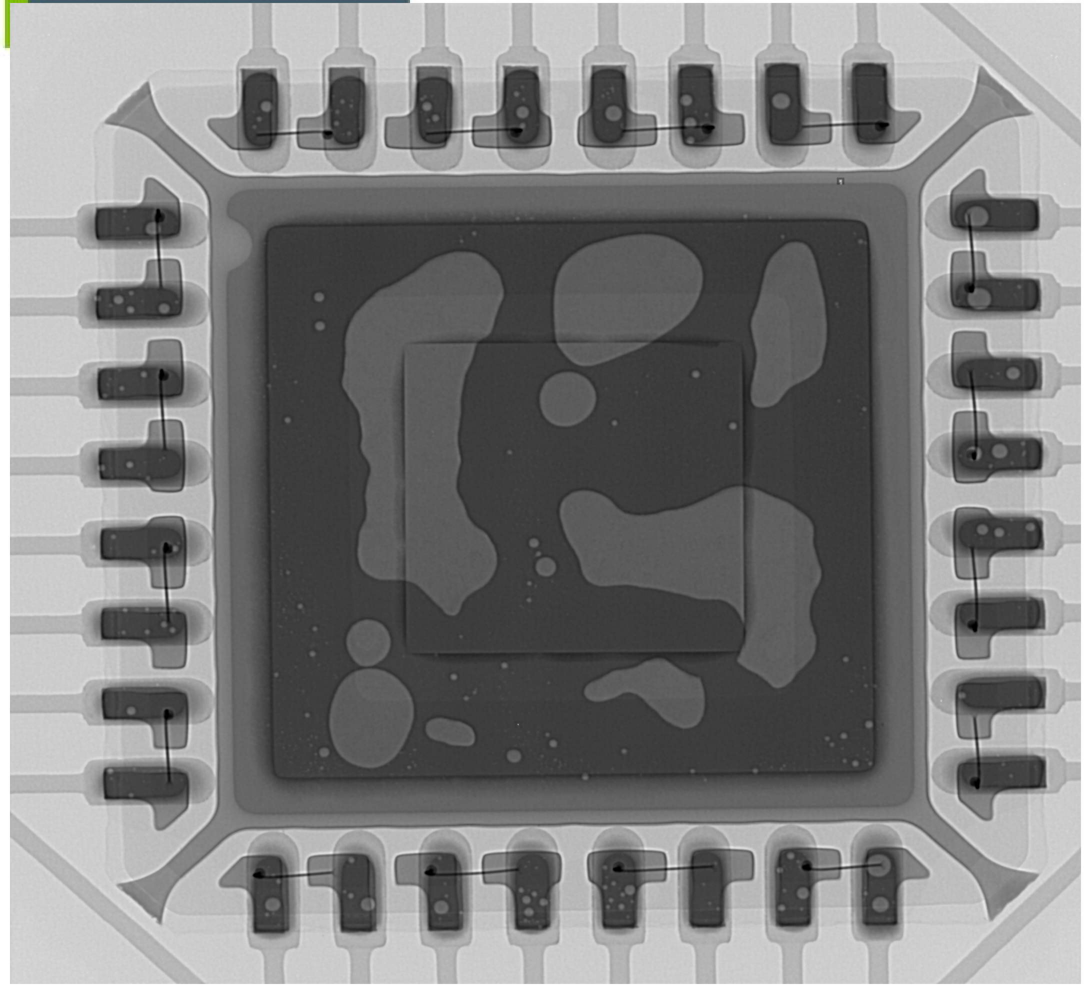




Parameters – Void Formation During Soldering Processes



Void Formation During Soldering Processes



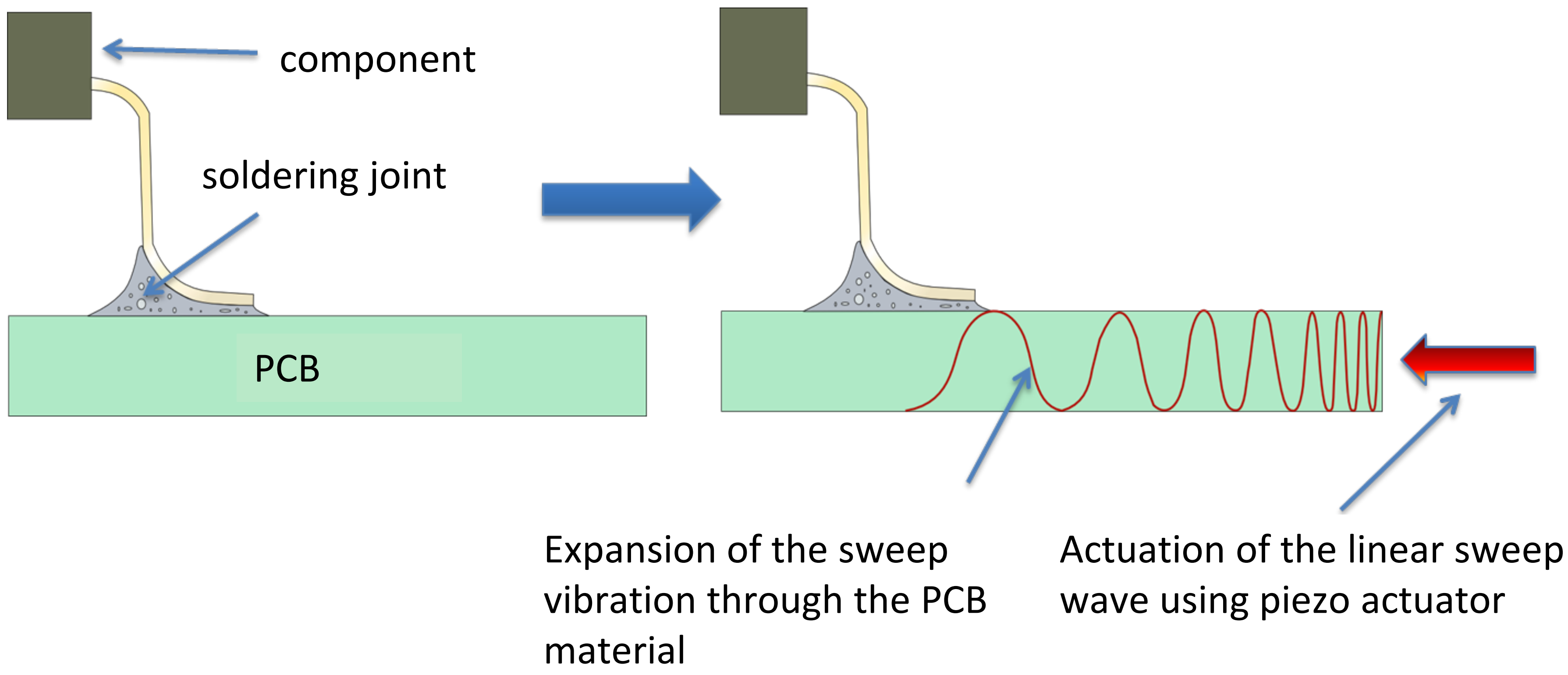
Void cause:

- Increase in contact resistance, for example at QFNs
- Reduction of heat conductivity between component and PCB
- Excessive component heat up due to the reduction of the heat conductivity in power electronics assemblies

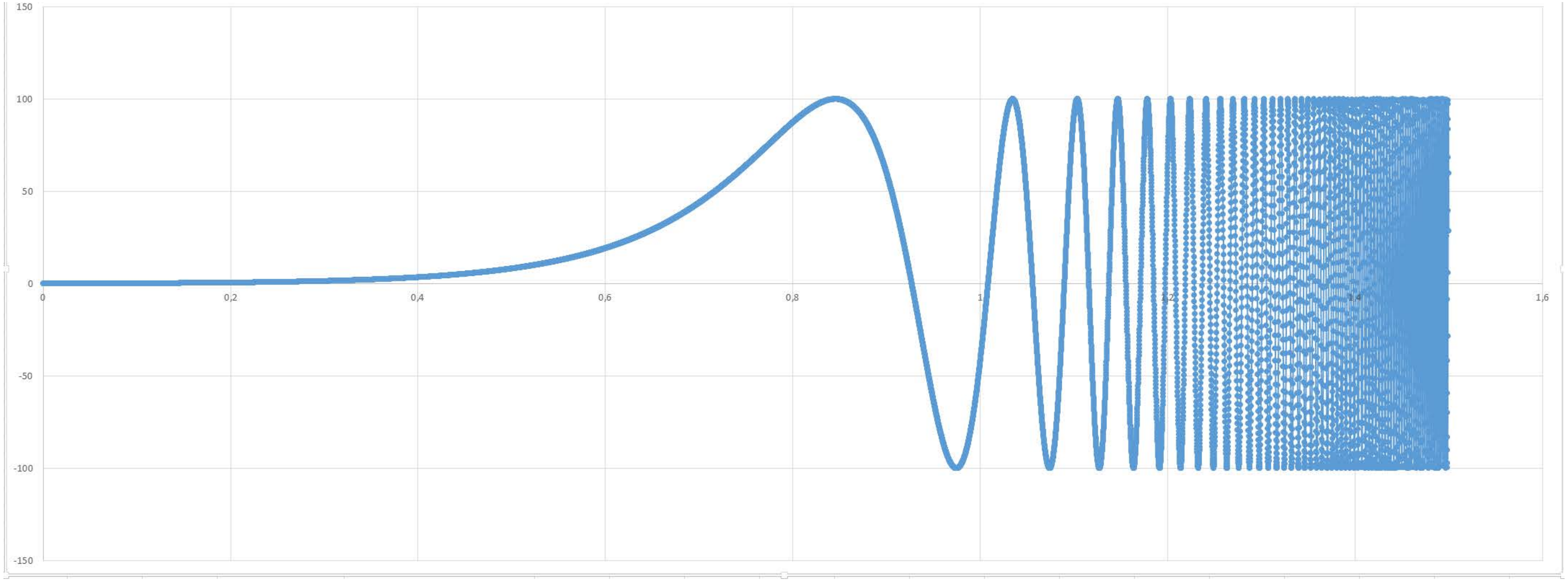
Solution Approach Void Reduction

Reduction of void formation by applying sinusoidal linear/logarithmic sweep movements

using piezoelectric actuator with a small amplitude.



Sweep Actuation – Linear or Logarithmic Frequency Increase

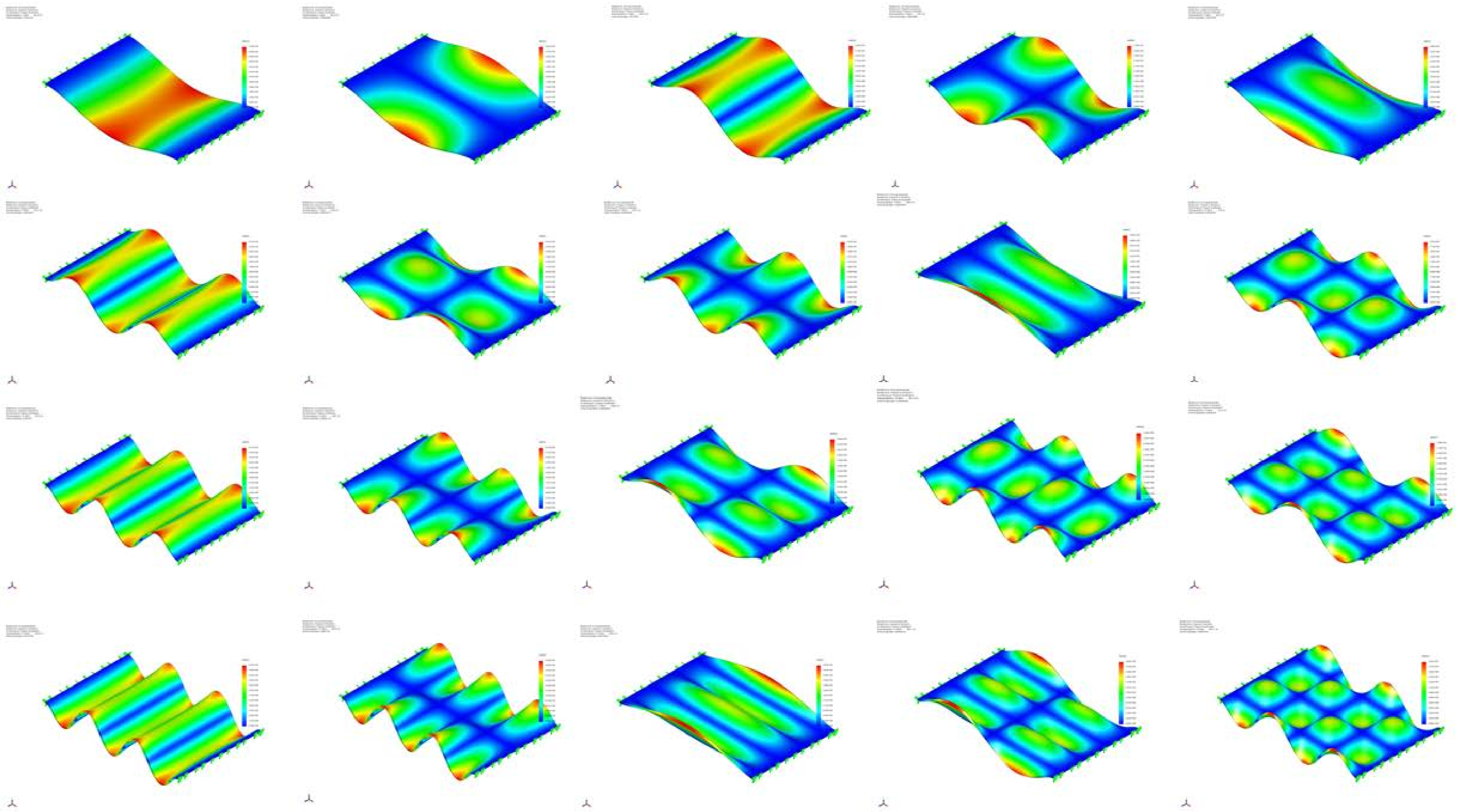


➔ Change of the frequency from a start to a final value in a defined time.

Reasons to Use Sweep Actuation:

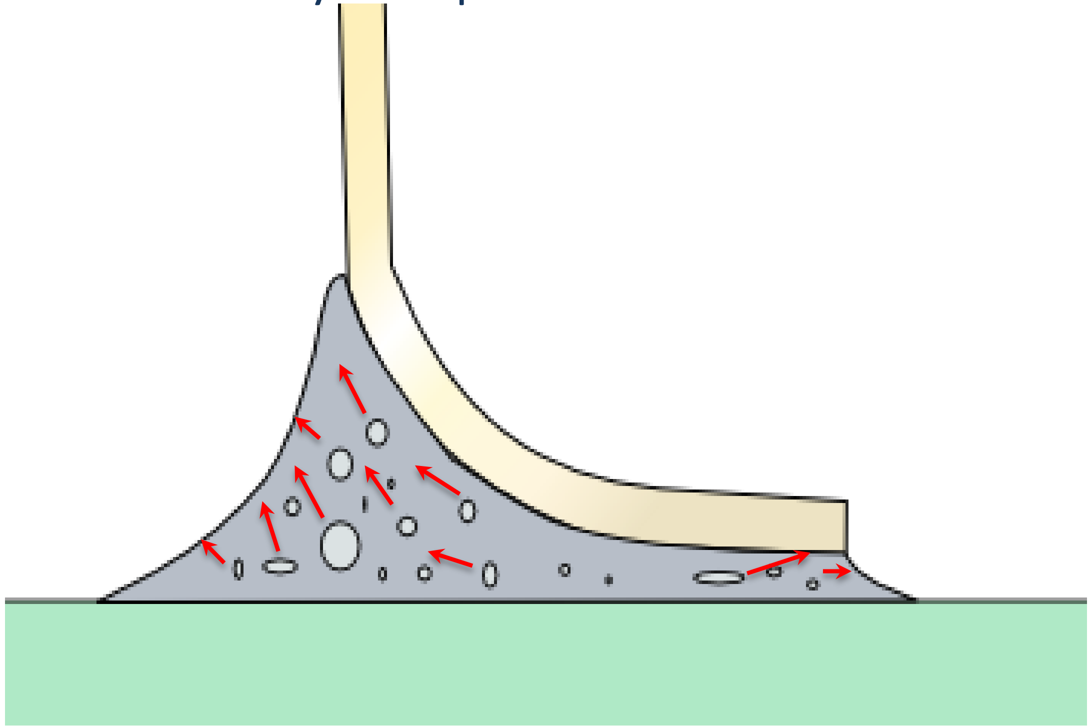
- Starting the actuation with a low frequency of the piezo actuator is better for the mechanical parts of the soldering machine
  - ➔ Long life time
- A slow vibration transmission at the start of the actuation causes a homogeneous vibration expansion in the PCB substrate. In this case all molecular structures are set in motion slowly.
  - ➔ Lower starting energy
- A vibration acceleration reaches multiple resonance frequencies of the PCB - independent of their geometry.
  - ➔ All PCBs are forced into effective self-resonances and transmit the vibration to the liquid solder

Multiple Resonance Frequencies of the PCB – Surface Movement



Sweep Actuation of the PCB:

- Transmit a longitudinal and a transversal wave into the PCB
- The complex structure of the long epoxide resin molecules of the PCB are moved softly
- Increasing the frequency causes a higher stiffness of the PCB and better transfer of the vibration, because of the lower damping
- In liquid solder the voids are moved to the outer areas by sweep vibration



Test Setup

Display load cell

Frequency generator

Voltage amplifier

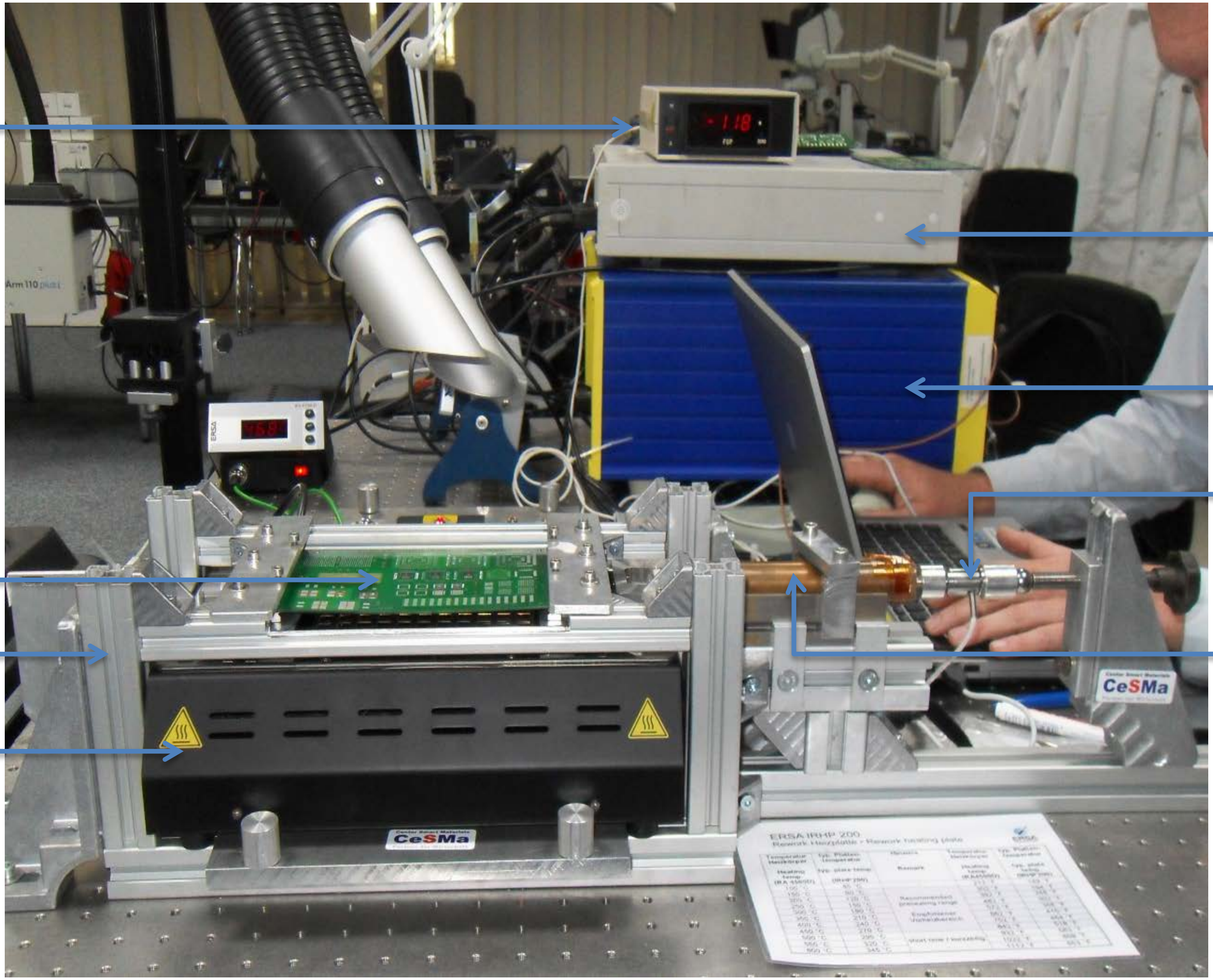
PCB

Load cell

Test setup

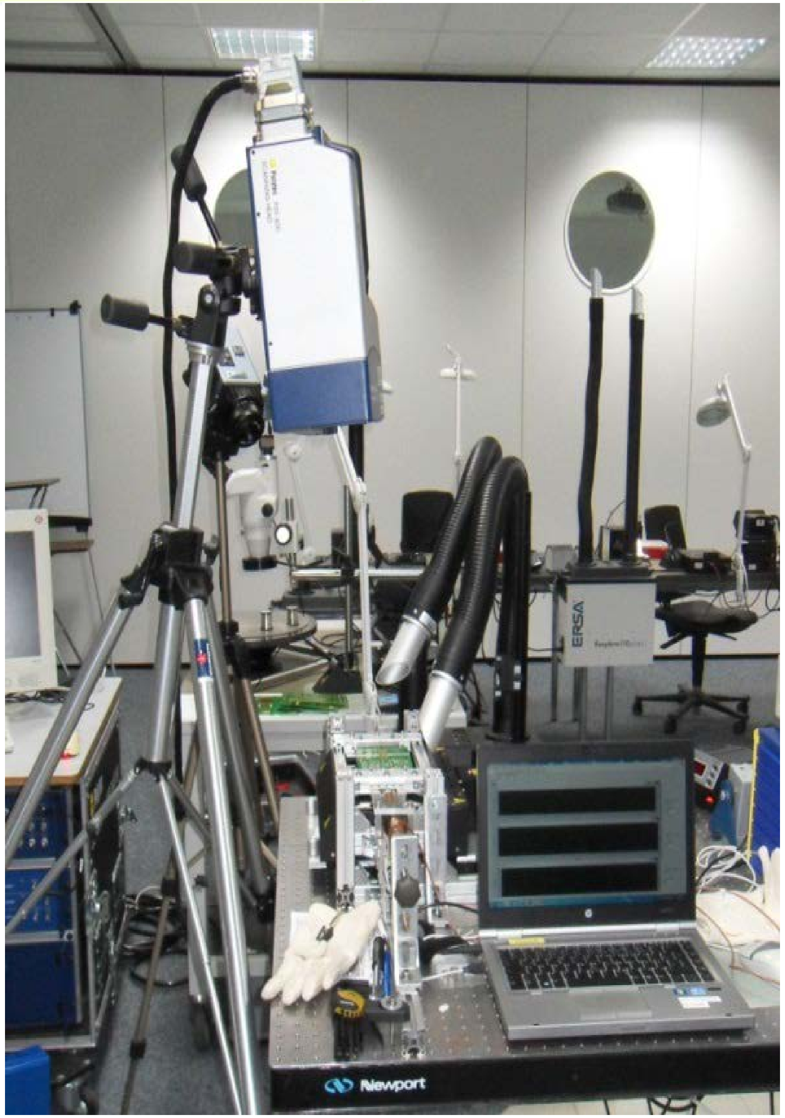
Piezo actuator

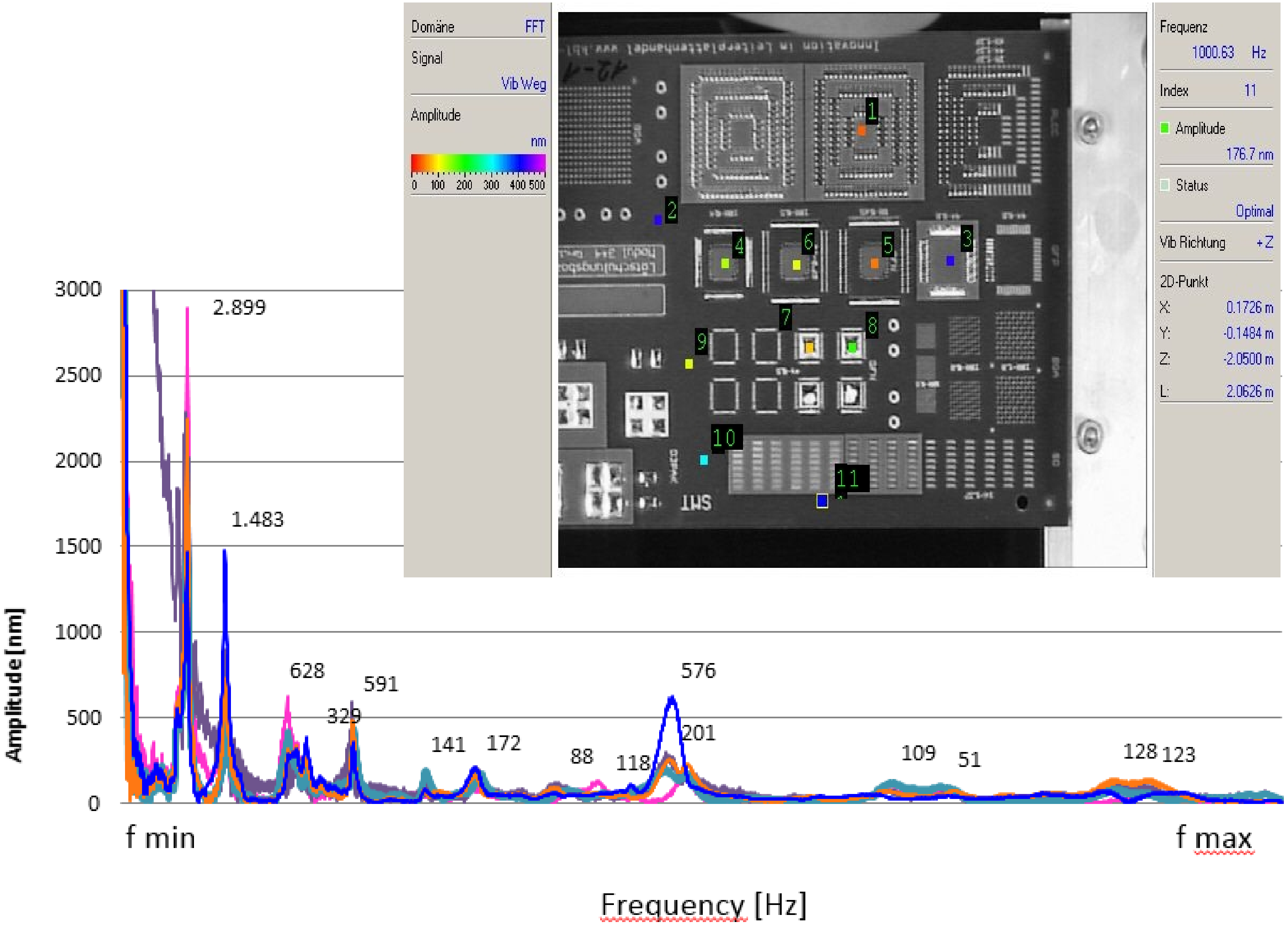
IR Heater



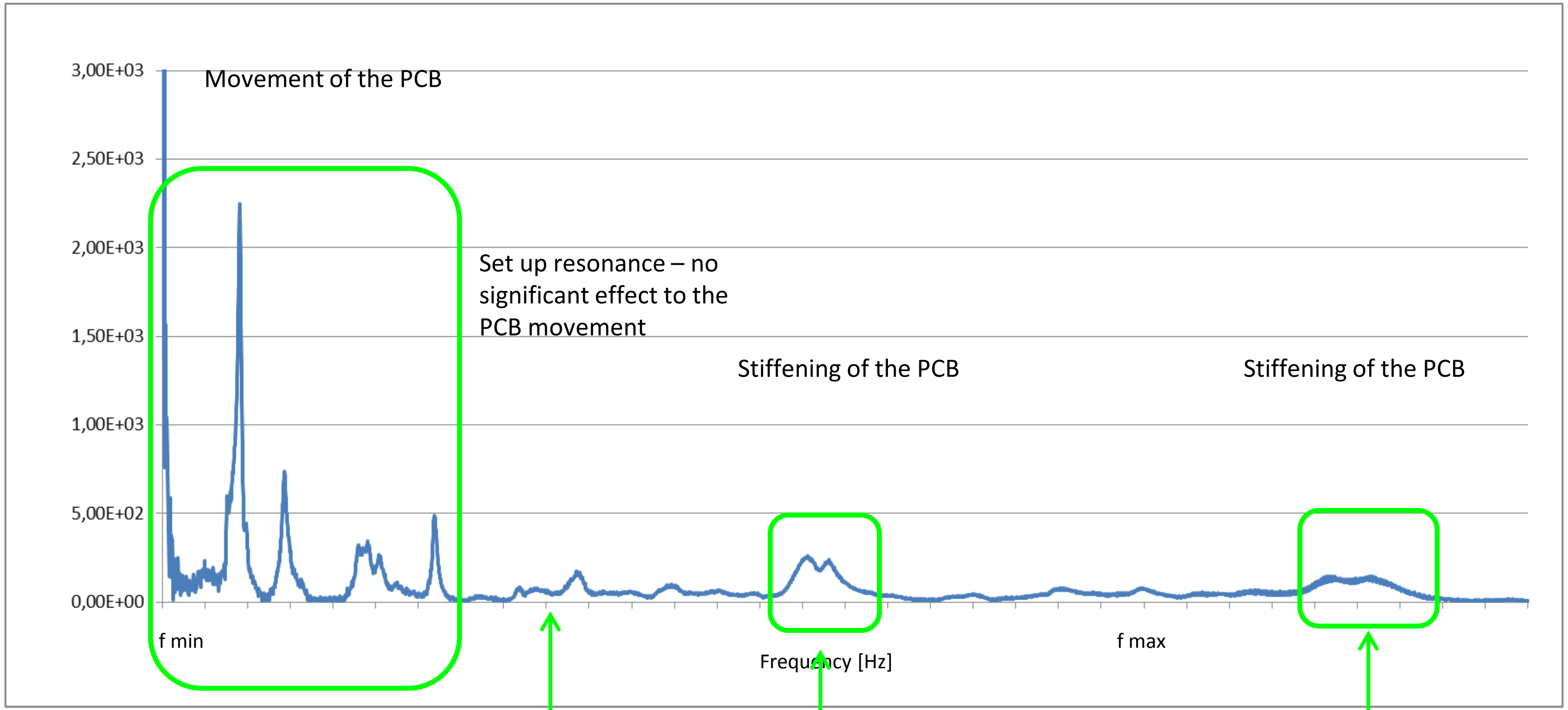
Measuring Points of the Laser Vibrometer on the Surface of the PCB

Laser vibrometer

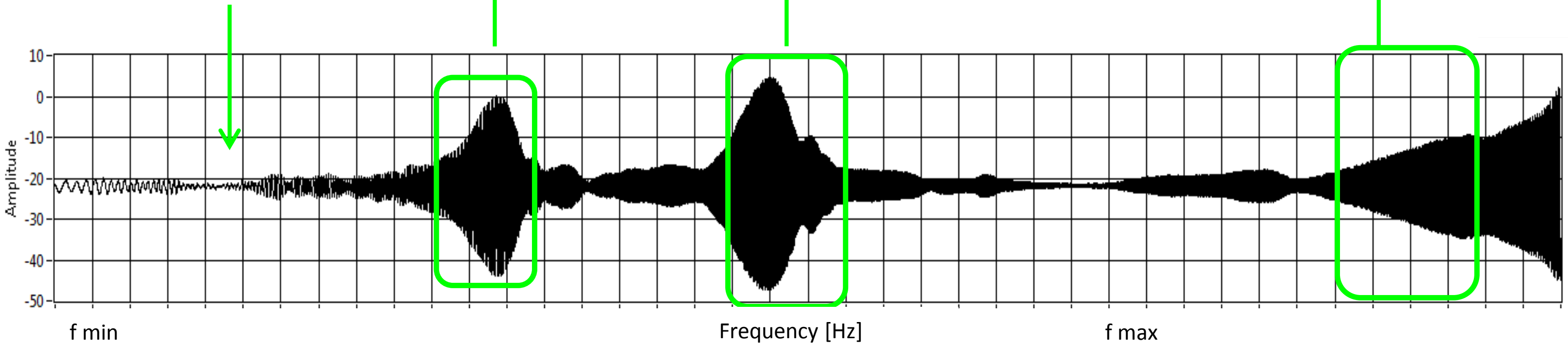




Results: PCB Surface



Signal of the laser vibrometer



Signal of the load cell

Before Void Reduction:

No recognizable trend of the void size and their allocation

Average void rate [%]	Average void size [%]
8,99	**1,54**
8,09	**1,90**
10,19	**2,55**
9,09	**2,00**

Reference PCB No 1

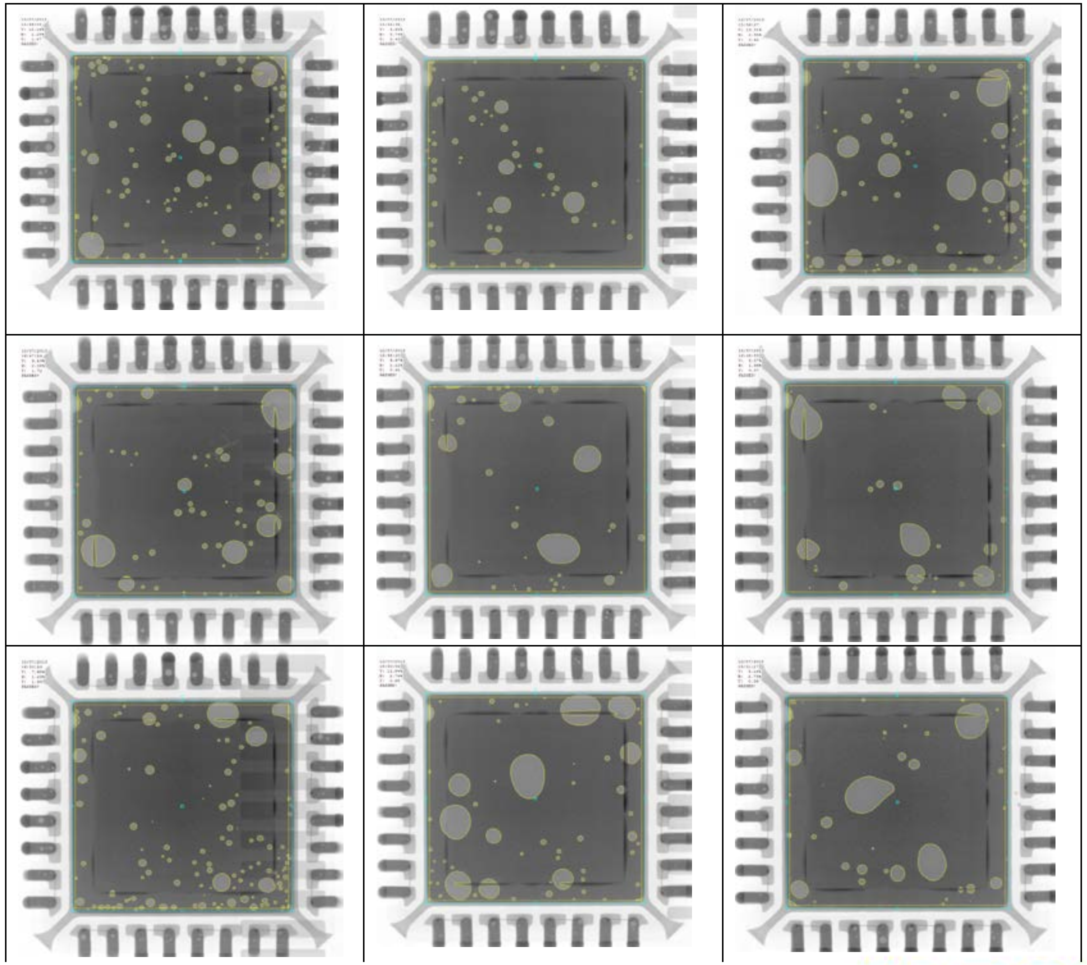
Component	Void [%]	Max.Void [%]
1	10,16	1,28
2	4,65	0,74
3	13,31	2,95
Average	**9,37**	**1,66**

Reference PCB No 2

Component	Void [%]	Max.Void [%]
	9,13	2,08
2	6,67	2,22
3	8,07	1,96
Average	**7,96**	**2,09**

Reference PCB No 3

Component	Void [%]	Max.Void [%]
1	7,68	1,26
2	12,94	2,74
3	9,18	2,75
Average	**9,93**	**2,25**



After Void Reduction Parameter 1:

Reducing the void percentage to 1,58 %

Average void rate [%]	Average void size [%]
1,38	0,56
1,72	0,95
1,65	0,78
1,58	0,76

PCB No 1

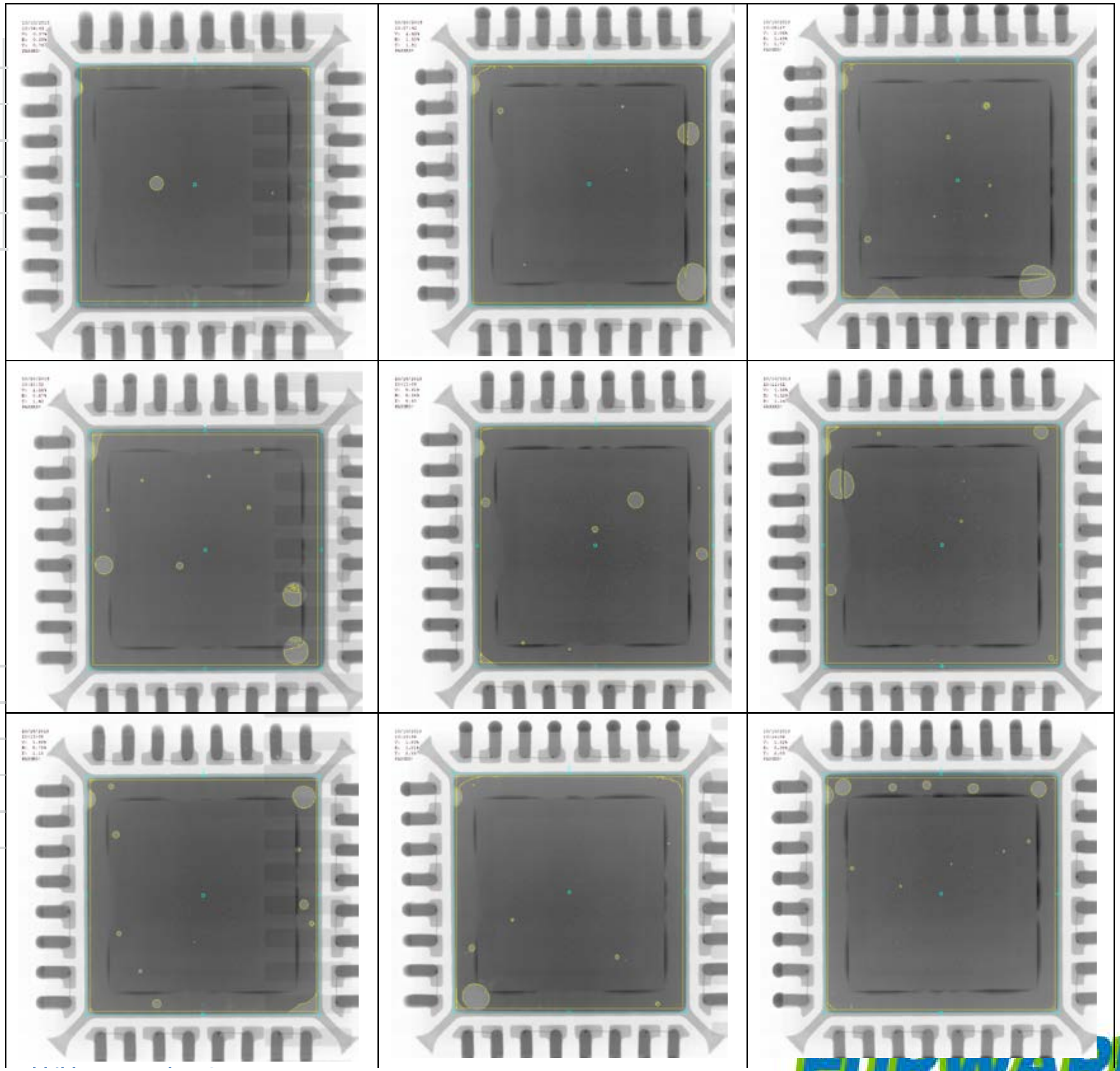
Component	Void [%]	Max.Void [%]
1	0,37	0,28
2	2,43	1,5
3	2,06	1,43
Average	**1,62**	**1,07**

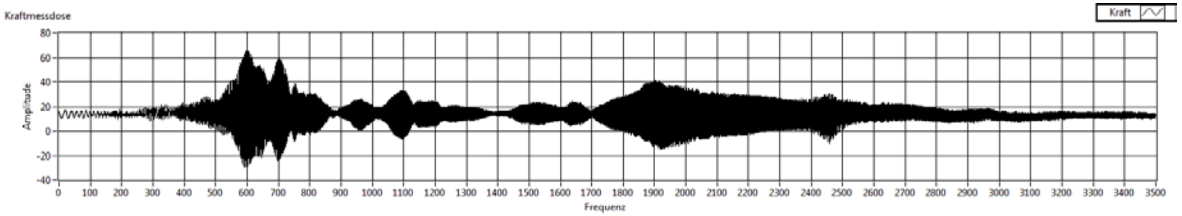
PCB No 2

Component	Void [%]	Max.Void [%]
1	2,08	0,67
2	0,91	0,34
3	1,56	0,52
Average	**1,52**	**0,51**

PCB No 3

Component	Void [%]	Max.Void [%]
1	1,69	0,73
2	1,83	1,01
3	1,32	0,38
Average	**1,61**	**0,71**





After Void Reduction Parameter 2:

Reducing the void percentage to 1,83 %

Average void rate [%]	Average void size [%]
2,71	**1,10**
1,31	**0,90**
1,48	**0,77**
1,83	**0,92**

PCB No 1

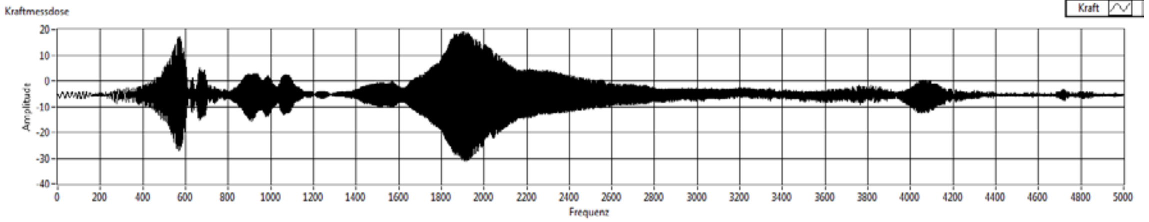
Component	Void [%]	Max.Void [%]
1	3,64	1,44
2	2,25	1,91
3	2,23	1,44
Average	**2,71**	**1,60**

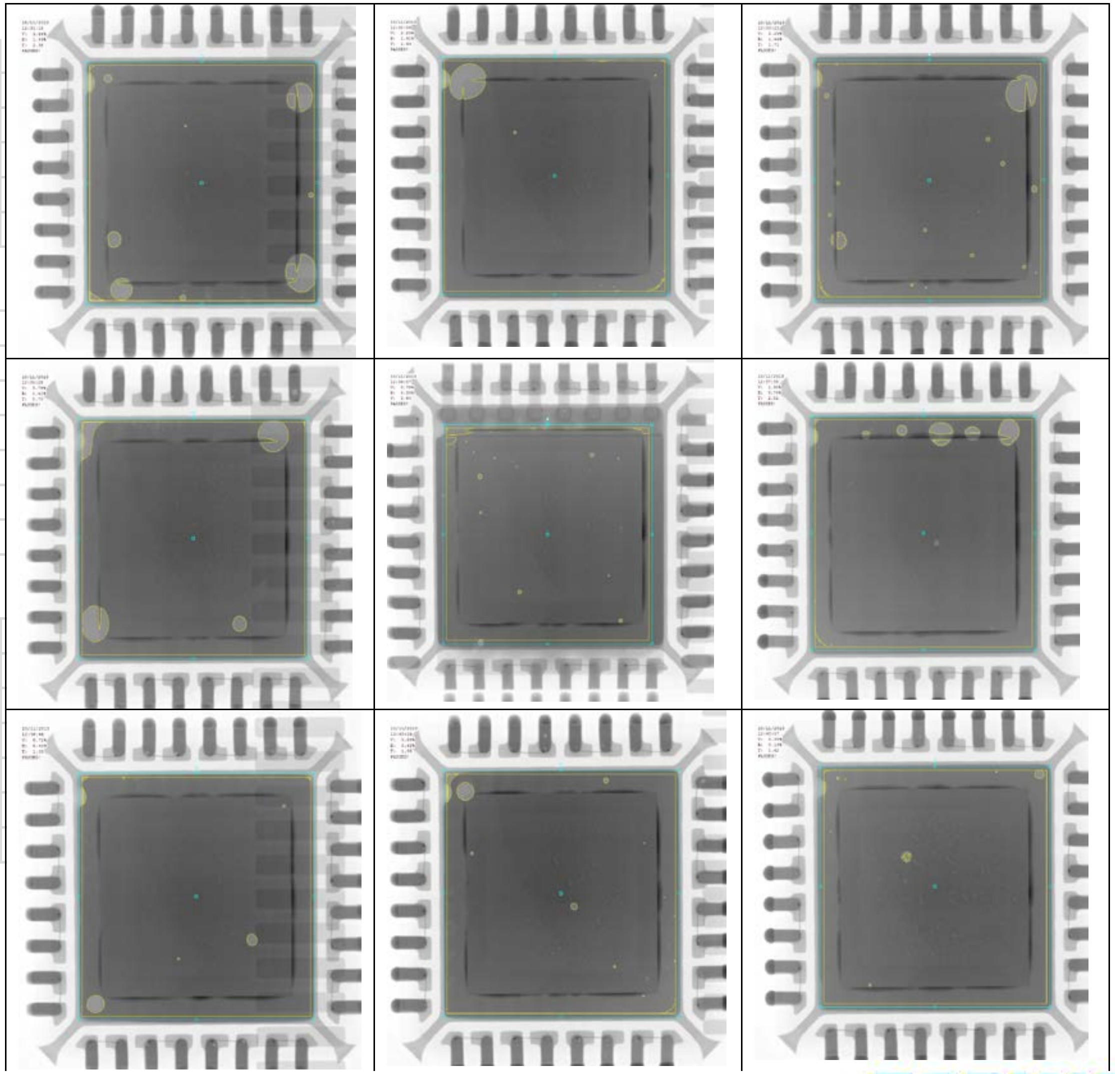
PCB No 2

Component	Void [%]	Max.Void [%]
1	3,76	1,41
2	0,78	0,35
3	1,9	0,74
Average	**2,15**	**0,83**

PCB No 3

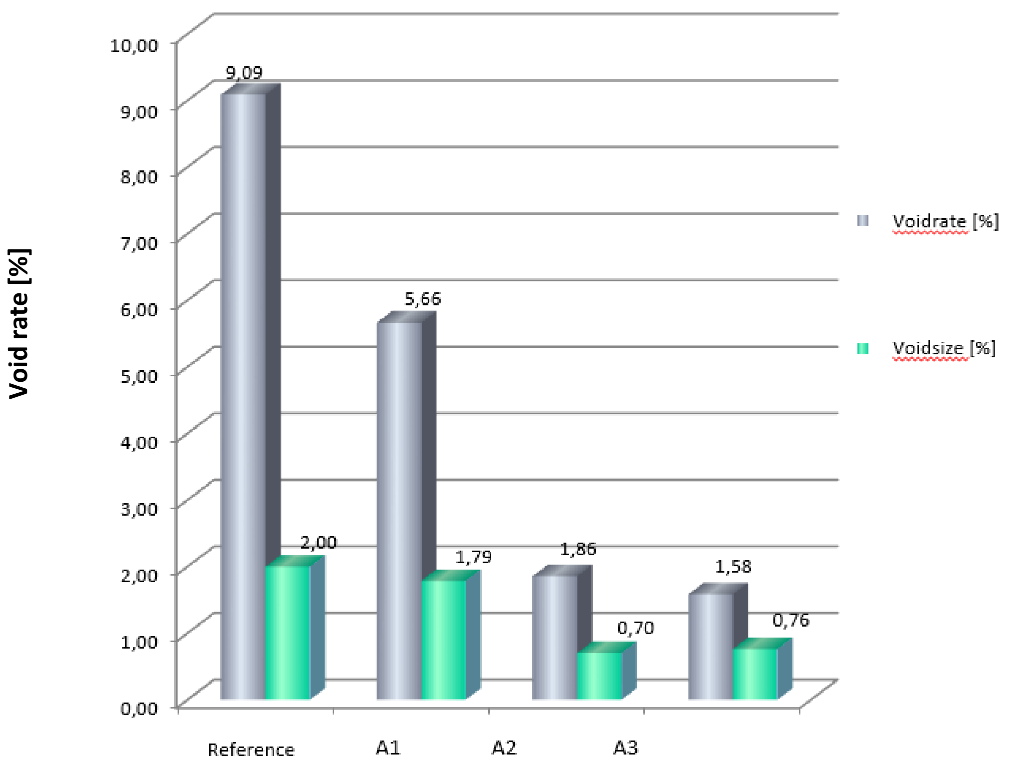
Component	Void [%]	Max.Void [%]
1	0,72	0,44
2	0,89	0,43
3	0,3	0,13
Average	**0,64**	**0,33**



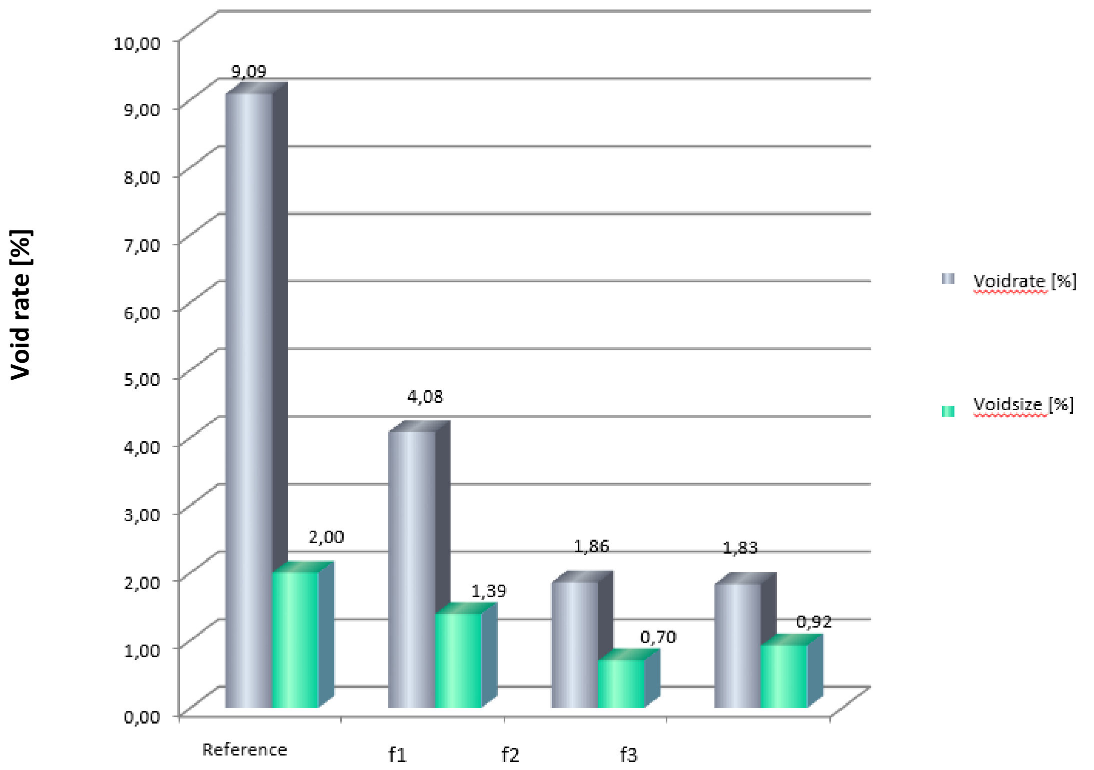


Results – Influence of the Setting Parameters on Void Reduction

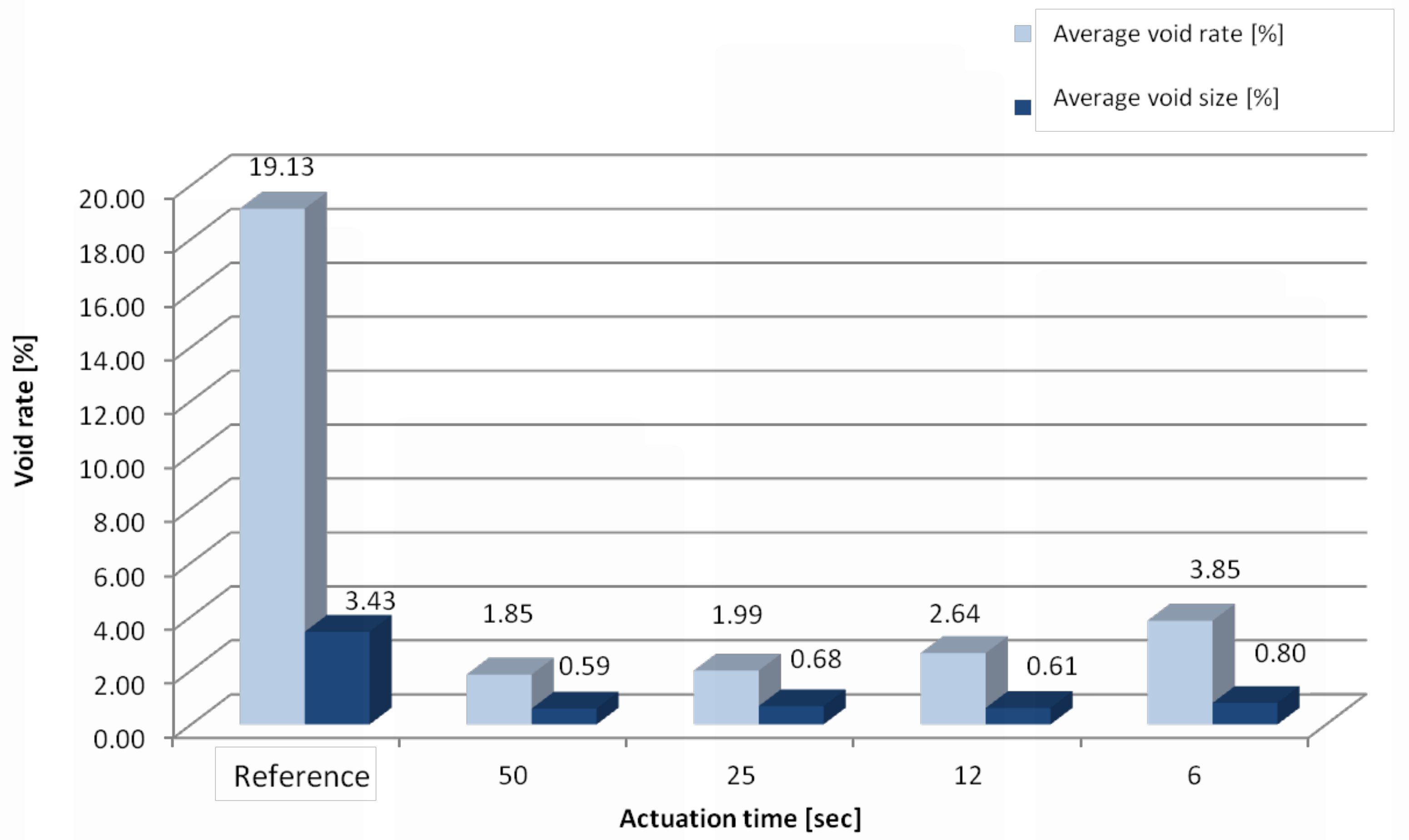
Effect of the actuator elongation



Effect of the sweep range



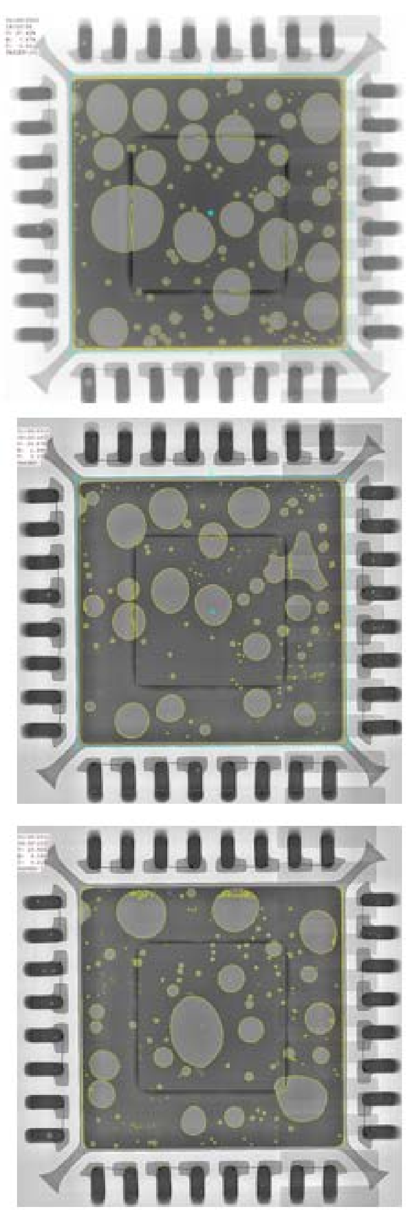
Influence of the Actuation Time to the Void Rate



Actuation time [sec]	Void rate [%]	Improvement compared to reference PCBs
50	1,85	90,32 %
25	1,99	89,58 %
12	2,64	86,17 %
6	3,85	79,88 %

Influence of the Actuation Time

Non-vibrated reference PCBs



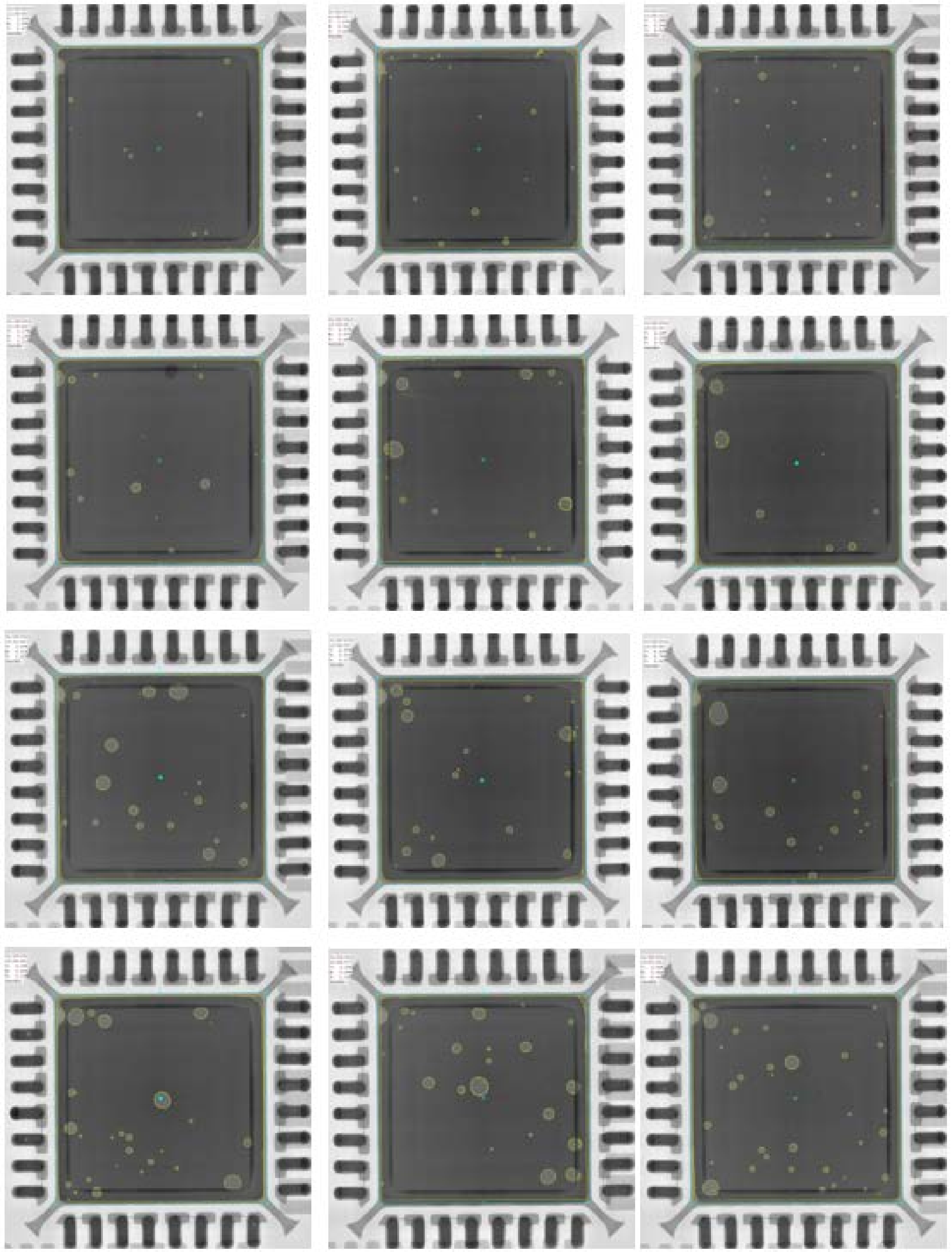
Actuation time [sec]

50sec

25sec

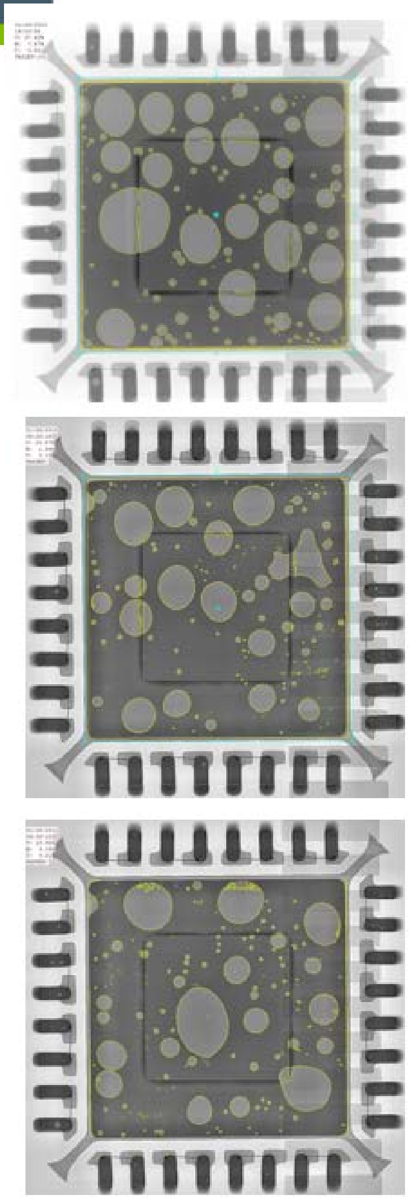
12sec

6sec



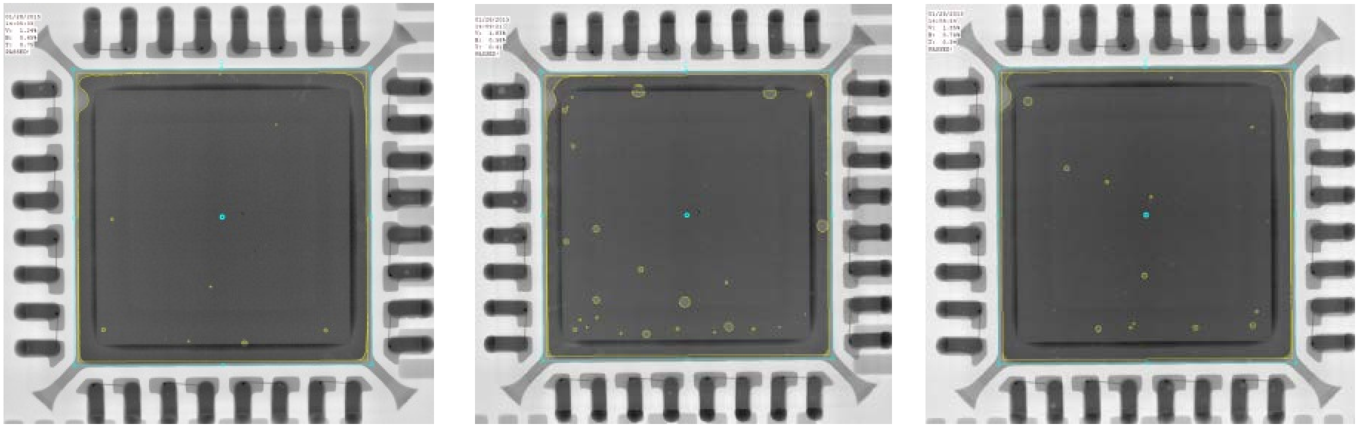
Influence of the Reapplied Soldering Process

Non-vibrated reference PCBs

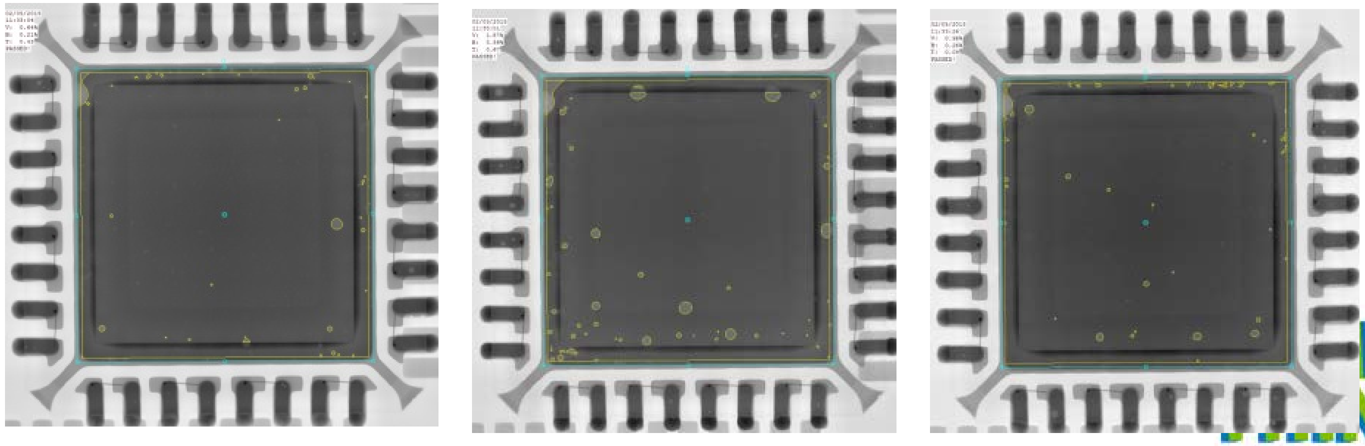


Test settings No 3

After void reduction process



After reapplied soldering process without void reduction

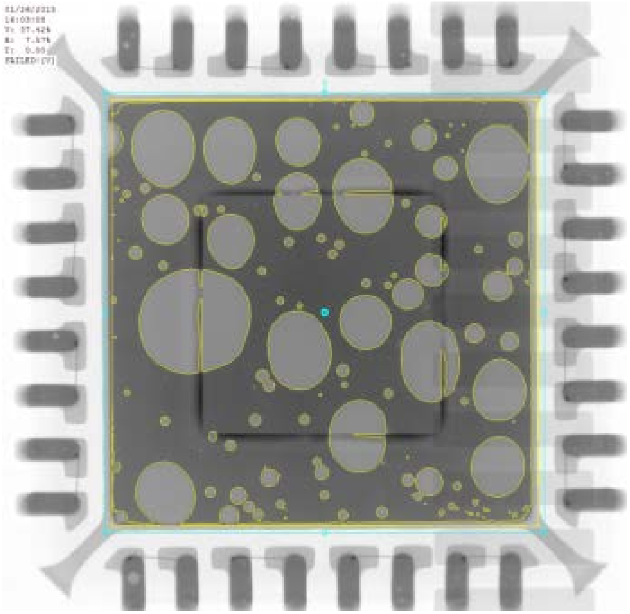


Summary

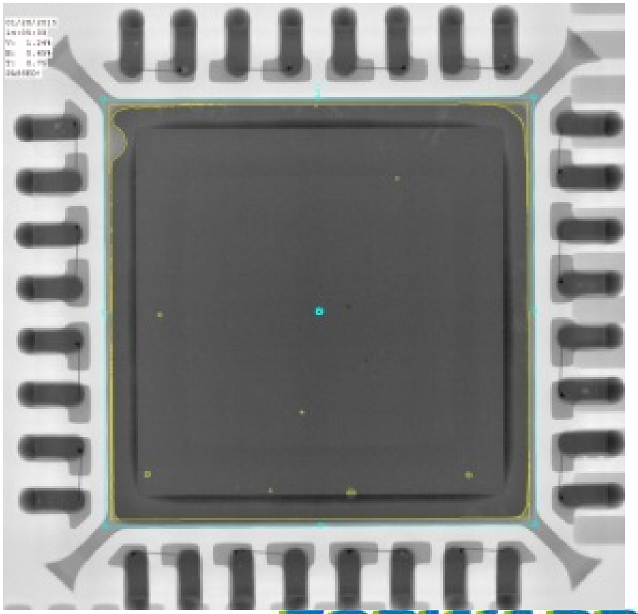
Results of the proof of concept are positive

1. 60 PCBs with identical geometries and three identical components on it have been researched.
2. Analysis of the sweep time, sweep range and actuator voltage.
3. We have succeeded in the course of the study to achieve a reduction of the average void rate of 9.09% to 1.58% of the reference sample.

➔ Equivalent to an average void reduction rate of 83%



➔



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Thank you for your attention!