COMPARISON OF ACTIVE AND PASSIVE TEMPERATURE CYCLING

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ABSTRACT
Electronic assemblies should have longer and longer service life. Today there are partially demanded 20 years of functional capability for electronics for automotive application. On the other hand, smaller components, such as resistors of size 0201, are able to endure an increasing number of thermal cycles until fail of solder joints, so these are tested sometimes up to 4000 cycles. But testing until the end of life is essential for the determination of failure rates and the prognosis of reliability. Such tests require a lot of time, but this is often not available in developing of new modules. A further acceleration by higher cycle temperatures is usually not possible, because the materials are already operated at the upper limit of the load. However, the duration can be shortened by the use of liquids for passive tests, which allow faster temperature changes and shorter dwell times because of better heat transfer compared to air. The question is whether such tests lead to comparable results and what failure mechanisms are becoming effective. The same goes for active temperature cycles, in which the components itself are heated from inside and the substrate remains comparatively cold. This paper describes the various accelerated temperature cycling tests, compares and evaluates the related degradation of solder joints.

Key words: reliability, testing, temperature cycling, power cycles

INTRODUCTION
The service life of technical systems follows usually the typical bathtub curve. After a short period of early failures, which are mainly due to the production process, is following a longer period of random failures with a failure rate as low as possible. Especially the rising failure rate due to the fatigue of the system is critical, which should happen only after the end of the planned service life. But this is exactly the problem for the design and development of new products, because the end of life is usually far in the future and testing under real conditions until release cannot wait as long, of course. Especially technical systems for safety-related products will be projected with a high safety factor because of this, but that boosts the cost unfortunately. The best possible prediction of the reliability, which is the change in quality over time, requires a good life time model and/or a testing method, which causes a drastic and predictable acceleration of aging of the system. The accelerated aging test should provide a result after a few weeks or days, which only occurs in the application after a few years. During the development and testing of new technologies it is particularly important because at this stage multiple test passes are usually required until the optimal result is achieved. On the other hand the more stringent test conditions should not show errors, which are completely irrelevant for this application. The accelerated aging tests commonly used today meet this requirement only partially, what will be examined and discussed in the following study.

AGING OF SOLDER JOINTS
Electronic devices and systems consist of many components and materials, whose lifetime is limited to a variety of ways. While the aging of pure materials is typically caused by oxidation, corrosion and migration, but also by grain growth or polymerization under the influence of temperature, field strength, time and humidity, for material connections plays especially the interaction of materials an important role in aging. Different Young's modulus or coefficients of thermal expansion can lead to mechanical stresses or different concentrations can cause material diffusion and phase growth. Therefore an accelerated aging test cannot consider all aging mechanisms in equal measure in such a complex system. It is important to know what a failure mechanism is dominating and by which influences this mechanism is accelerated to what degree precisely. For electronic appliances and systems it is often assumed that the service life is limited mainly by the aging of the solder joints. In simple terms these solder joints are representing the interface between an electronic component and the substrate (= printed circuit board) (see Fig. 1).

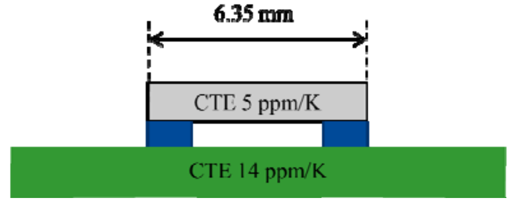


Figure 1. Simplified schematic of of the connection between a chip resistor CR2512 and a printed circuit board by two solder joints (at room temperature)

Even if the operating temperature of the assembly is limited by the melting temperature of the solder joints, not the temperature is the major influence in the aging of solder joints. Crucial is the mechanical load on the connections due to temperature changes caused by the different coefficients of thermal expansion.

If the assembly is heated from room temperature to 125°C for example, the materials expand differently, which leads to a difference in length between the component and printed circuit board (see Fig. 2).

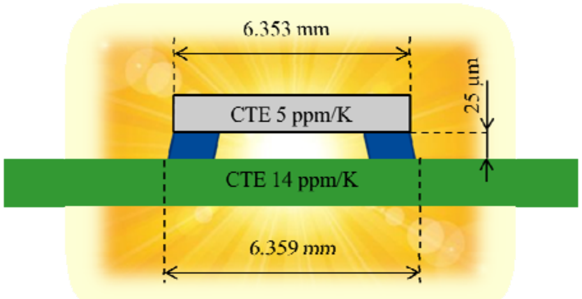


Figure 2. Connection between a chip resistor CR2512 and a printed circuit board after heating up to 125°C

This difference in length depends on the materials involved (here ceramic and FR4) and the initial length of the component (here CR2512). In the example the difference is 6 microns based on the total length of the component of 6.3 mm. The resulting mechanical stress have to be degraded by deformation by the two solder joints (in the best case, both uniformly, respectively 3 microns each; see Fig. 3).

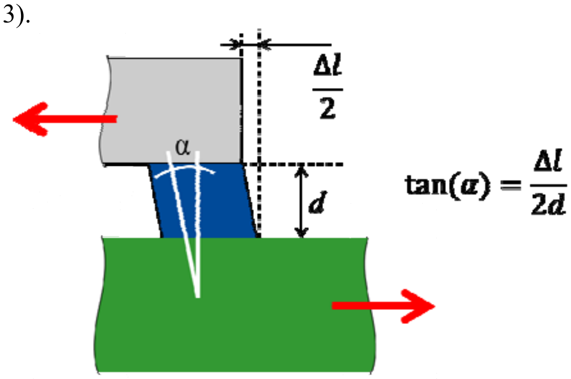


Figure 3. Plastic deformation of a solder joint as a result of temperature change

Solder joints have hardly any elasticity, so that the deformation takes place plastically by creeping until the entire stress is relaxed. At each temperature change, this plastic deformation is repeating with alternating signs, until the connection fatigues, the structure forms cracks and finally breaks. Heating and cooling can be caused by the changing heat loss of the components when switching on and off, but also by the environment, for example, in the engine compartment of cars. The aging of the solder joints is accelerated typically by using the on-off-cycles of the entire operating period, 3 years for example, sequentially reproduced by passive heating and cooling in a climate chamber. The decreasing stability of the solder joints can be determined by destructive testing by shear test, as in the example in Fig. 4 for 1000 cycles a chip resistor CR1206 in a single-chamber test [4].

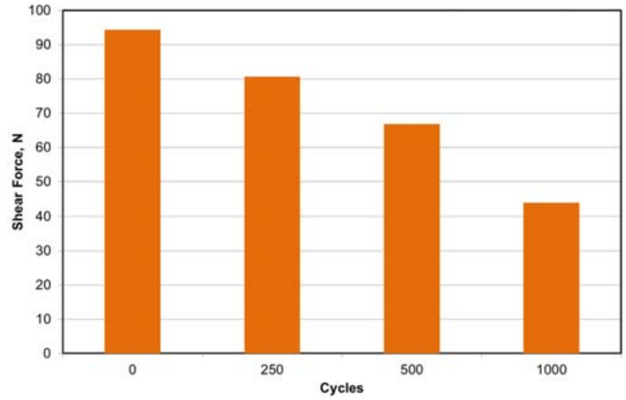
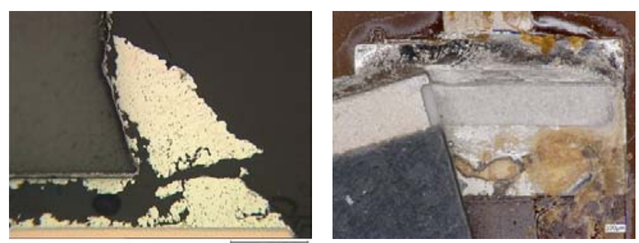


Figure 4. Shear forces of 1206 chip resistors (SnCu0.7 on Cu/OSP) after slow temperature cycles (1 chamber / cycle = 90 min)

The test chamber requires for the change between -20°C and +150°C 45 minutes for the tested assembly, so that a complete cycle lasts 90 minutes and the required 1000 cycles need 2 Months accordingly. While that is significantly shorter than the planned service life, but still relatively long to provide the reliability verification of an assembly in development. The cracks and structural changes in the solder joints can be seen clearly in Fig. 5 after 500 thermal shock cycles.



growing cracks after shear test

Figure 5. Changing structure and strength of chip resistor CR1206 after 500 temperature cycles

POSSIBILITIES OF ACCELERATED AGING

In order to shorten the test time even further, there are various ways of acceleration. Due to the extension of the tested temperature range the elongation increases, according to the Coffin-Manson relation, and thus the aging will be accelerated, so that the damage can be done by less temperature cycles. However, this type of acceleration has its limits. The temperature range cannot be expanded up significantly, because the temperature limits of other materials, e.g. the glass transition temperature of the printed circuit board, may not be exceeded. For FR4 this is usually between 130°C and 150°C. Above this temperature completely different failure mechanisms would act which are not comparable with the real loading. Especially for applications in the automotive and power electronics, this temperature range is already maxed out in application, so that hardly exist any possibilities of increase [2].

The same applies in principle for the lower temperature limit. Below 0.4 homologous temperature (40% of the

absolute melting temperature) solders behave as brazing alloys and no plastic deformation occurs by creeping. The failure mechanism is changing so that brittle fractures are dominating. For SnAgCu solder, this temperature is about -77°C, but for military applications already temperatures down to -55°C are commonly used. Again, a further acceleration by dropping below this temperature is limited.
Faster temperature changes can also shorten the test time. Bicameral test chambers are usual today with a mobile container, so that the heating and cooling times practically depend only on the heat capacity of the module and the heat transfer coefficient between air and assembly. In this case are 15 minutes for the equalizing of the temperatures realistic, depending on the mass of the assembly and differential temperature, so that a minimum duration of 30 min for one cycle can hardly be undercut (Fig. 6). For 1000 cycles 3 weeks are needed at least.

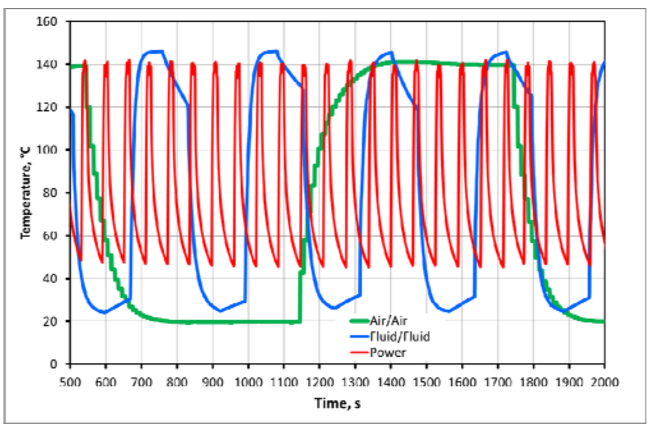


Figure 6. Comparison of different temperature cycling methods: air/air (green), fluid/fluid (blue), power cycle (red)

Obviously there is a potential for further reduction of testing time by increasing the heat transfer coefficient by a suitable test medium. This can be done either by forced convection or by a liquid medium. Such fluid must also be thermally stable itself and should behave preferably chemically inert to the assembly. Vapor-phase media are here a suitable, even though relatively expensive fluid. The test time could be shortened with the same selected test assemblies in a two-chamber fluid testing system to about 5 minutes per cycle. This corresponds to a total time of 4 days for 1000 cycles (also Fig. 6).

For even quicker heating it could be suitable to use an active warming by current or power loss, which can be realized effectively especially with resistor components. Fig. 7 shows the test setup with the specially developed driving and temperature control circuit for active temperature cycle testing [3].

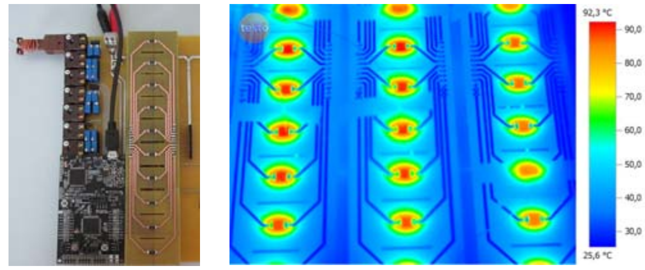


Figure 7. Active heating (+150°C / room temperature) of chip resistors CR2512 on a test board

The heating can be carried out extremely quick in this way, but the temperature of the resistive layer is about 5 ... 10 K higher than that of the solder joints. However, the cooling down to room temperature in air is relatively slow. Therefore the cycle was limited downwards at 45°C for the selected test assembly, because the cooling curve runs much flatter beneath. At 70 second cycle time, the test period for 1000 cycles is only a total of 20 hours (also Fig. 6).

As an active cooling of the components is hardly possible, a further optimization potential is in the choice of the ambient temperature in relation to the lower test temperature. Referring to Fig. 8, the cooling curve at room temperature in air is logically flatter than the cooling in a cooling chamber at -40 ° C, because of the lower temperature difference. This is a passive cooling in air in both cases. Taking this steeper cooling curve but stopping this at 20°C by active warming against the cooled environment, the fast cycle of 70 seconds can also be done between room temperature and +140°C.

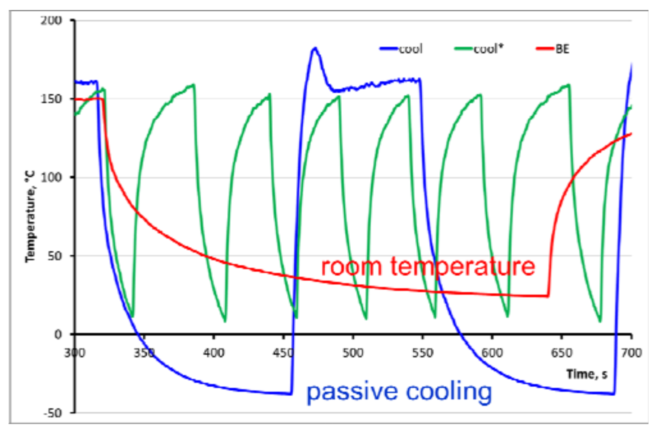


Figure 8. Cooling after active heating with different ambient temperatures

EVALUATION OF TEST RESULTS

Now that the fastest method of heating and cooling has been found, the question arises whether the results are comparable. For evaluation the shear strength of soldered CR2512 resistor components was measured over a period of a total of 4000 cycles. Because this is a destructive test, every 500 cycles 10 components were tested and the mean was calculated. Fig. 9 shows the comparison of the development of the shear forces for the different accelerated aging tests. Because additional data were depicted in the chart from a previous study with slow temperature cycles and CR1206 size components, a normalization of shear forces was used (initial state = 100%). The other absolute values behave otherwise equally.

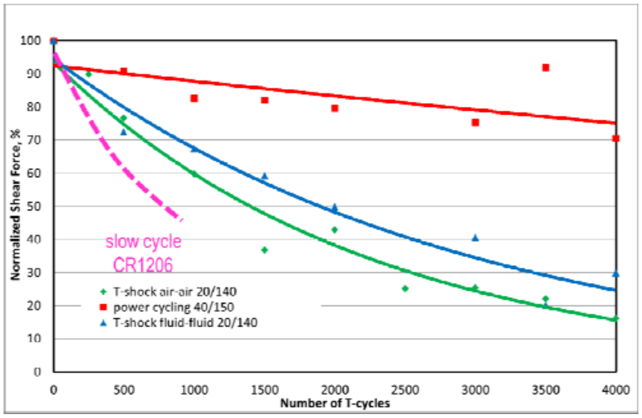


Figure 9. Normalized shear forces over cycle number for different test procedures

Most notable in the evaluation in Fig. 9 is that the active (rapid) thermal shock cycles have the smallest decrease in shear forces by far. A more detailed analysis of the temperature changes shows, that is due less to the speed but by the temperature distribution [5]. While the solder joints warm about 10 Kelvin less than the resistive layer, the printed circuit board is even 40 Kelvin colder. This shows the measurement in Fig. 10.

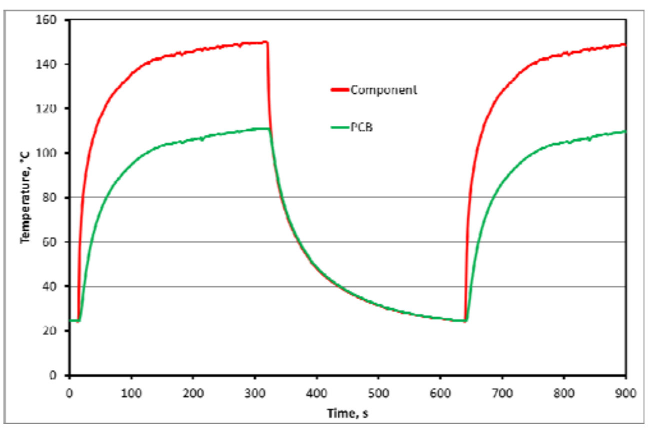


Figure 10. Temperature differences between component and PCB for active cycles

The problem with non-uniform temperature distribution by active heating is that the material with the greater expansion coefficient (the printed circuit board with 14 ppm/K) has the lower temperature and the material having the smaller expansion coefficient (ceramics with 5 ppm/K) has the higher temperature. Thereby the expansions of both are almost repealing. Therefore, the active cycles produce in the solder joints hardly any stress, which explains the slight decrease of shear forces over 4000 cycles. Favorable would be an active heating of the printed circuit board (with the higher expansion coefficient) which would be technically very difficult to implement.

However, these temperature differences do not explain the trends of the remaining thermal shock cycles. The fluid/fluid temperature cycles also result in a slightly lower decrease in shear forces than the slower air/air cycles. This means that in addition to the temperature difference and the number of cycles the holding time needs to have an influence on the aging or damage of solder joints too. Even more significant is that, if the slow cycles of the single-chamber test will be included in this comparison (Fig. 9). Although smaller resistors with a lower absolute difference in length were used, the decrease in shear forces is significantly steeper already at 1000 cycles.

Also this effect can be explained by the closer examination of the processes during the temperature cycling. The creep rate depends on both the mechanical stress as well as on temperature. From literature data [1] the creeping rates of SnAgCu solder for 15 MPa were plotted in the diagram in Fig. 11. The graph shows that with an increase in temperature of 30 K the creep rate increases by an order of magnitude.

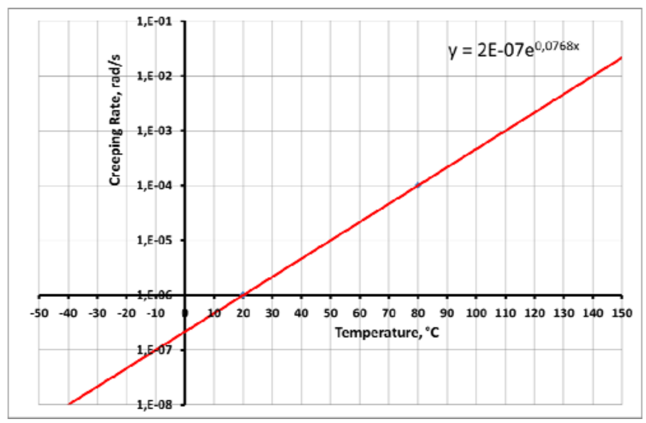


Figure 11. Creeping rate of SnAgCu solder joints for 15 Pa depending on temperature

This strong effect of temperature on the creep rate has the consequence that the plastic deformation at a low temperature takes a lot longer than at high temperatures. However, this deformation is necessary in order to accelerate the fatigue of the solder joints. This means that if the holding time is too short, although the mechanical stress builds up, but without operating the intended degradation. Of course, this issue of necessary holding times is relevant especially at low temperatures.

The diagram in Figure 12 shows how a compromise between the deformation resulting from temperature change and the attainable deformation within 15 minutes can be found. This is just an example that cannot be transferred to any components, but it is intended to illustrate the tendency. In the chosen example, a lower holding temperature of 75°C would be optimal in order to achieve the maximum deformation within 15 min. Any further reduction in temperature would increase the stress indeed, but without causing an additional plastic deformation. In the worst case, the assembly breaks at a different location, which would be not comparable as a failure in the application.

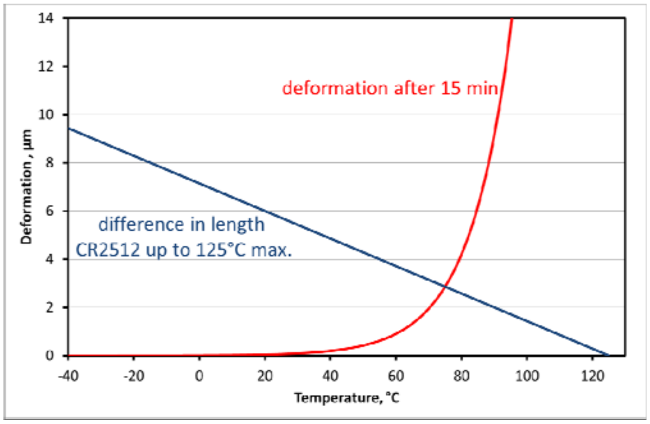


Figure 12. Deformation during accelerated aging with a dwell time of 15 minutes (example)

For the same assumed deformation of 3 µm difference in length a dwell time of only less than one second would be needed at 125°C. At room temperature, a dwell time of 5 min is required, at -25°C it is already 2.5 hours und at -40°C it is necessary to hold at least 8 hours. However, this means that all the usual accelerated aging tests today are not optimal. Therefore an optimized aging in terms of the shortest possible duration of the test with comparable damage of solder joints must be asymmetrically and separately adjusted for upper and lower test temperature.

Of course, the number of cycles and their effect on the damage to the solder joints is not the only criterion for optimizing the accelerated aging. Finally, the goal is to cause damages in the shortest possible test time, which can be converted into a real stress. It could be interesting to evaluate the already shown shear forces not on the number of cycles, but on the absolute test time. Figure 13 illustrates this relationship with the same data from Figure 9.

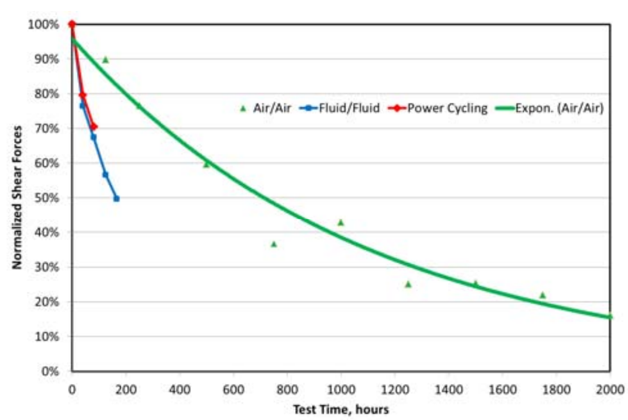


Figure 13. Normalized shear forces over absolute time for different test procedures

Here, suddenly a very different picture emerges. The fluid/fluid test achieves in this view the most rapidly significant decrease of the shear forces, even though at a much higher number of cycles. But even the inefficient active power cycle results in a similar short time to comparable results. For this purpose, however, a multiple number of the tested 4000 cycles have to run. The verification whether the type of damage in achieving of similar shear forces is still comparable, is still pending. For that purpose metallographic investigation by cross sections are planned.

CONCLUSION

As mentioned in the evaluation, for the thermal shock cycle test the upper and lower temperature limits should be optimized separately. The utilization of maximum deformation by the application of full temperature range, e.g. from -40°C to +125°C, is obviously inefficient, because this will take effect for several hours dwell time. It has to find a compromise between the maximum usable temperature difference and the shortest possible dwell time at the lower temperature limit. Fig. 14 illustrates this compromise schematically.

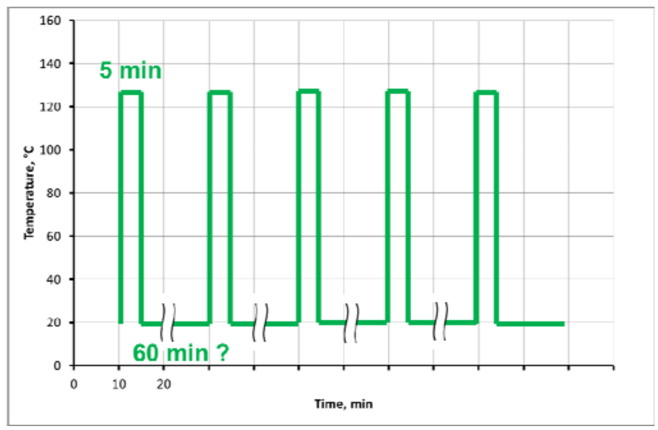


Figure 14. Suggestion for optimized accelerated aging by temperature cycling

In addition to adjusting the temperature limits and dwell times, there is still some potential for improvement in the reduction of the warm-up and cool-down times. For small and low-mass assemblies is the heat transfer by convection sufficiently effective. For heavy assemblies, it may be useful to improve the transfer of heat by a fluid. However, the experiments have also shown that active heating of components by current does not cause the desired aging of solder joints. What certainly is a positive effect for the practical application of assemblies, affects the accelerated aging tests unfavorable.

The optimization of temperature limits, dwell times and heat transfer should be further investigated and evaluated in future studies. It has to be considered that the optimum for different components and materials may require different parameters. The possibility of active heating of the substrates would be also interesting, as already explained above. With standard printed circuit board that is certainly almost impossible. Nevertheless, even this approach should be pursued in research by alternative heating methods, for example by electromagnetic fields. It is also planned to analyze the evaluation of aged solder joints additionally by metallographic investigations of structural changes.

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