

Online-TCT: New Measurement Technique for Precise Results at Accelerated Lifetime Tests for PCBs

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Abstract:

There are two common techniques for testing the lifetime of printed circuit boards (PCBs) under environmental thermal stress: the well established thermal cycling test (TCT, e.g. IEC 68, JESD22-A104-B), also called thermal shock test (e.g. MIL-P-55110 E, IPC-TM-650 2.6.7) and the interconnect stress test (IST, IPC-TM-6502.6.26). While for the TCT - when carried out classically with microsections after finishing the test - the failure analysis is neither statistically significant nor correlated to the function of the PCB, the fast IST detects the failures in a statistically more significant way by a functional criterion (resistance increase). However, the TCT is widely accepted - especially in the automotive industry - whereas for the IST temperature cycling happens in a physically different way. Thus up to now little is known about its correlation to the TCT and so its acceptance is still low. The TCT with real-time resistance measurement at daisy chains (Online-TCT) combines the advantages of both methods: the wide acceptance of the test method and the statistically significant way of failure detection by a functional criterion. The authors discuss its potential at the example of their own realization of an online-TCT.

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Introduction

In many fields of application of printed circuit boards (PCBs), e.g. in automotive electronics, their reliability under difficult conditions over many years is of great importance.

Keeping to the example of automobiles: complex electronic components are used at more and more places in a car and for an increasing number of functions. On their faultless function depend the safety (e.g. antilock brake system, electronic stability program), the comfort (e.g. navigation systems, air-condition), or simply the roadworthiness (e.g. engine, brakes). These electronic components are subject to large temperature variations; due to the big mismatch between the thermal expansion coefficients of base material and copper this leads to strong (cyclic) mechanical stress, which can lead to malfunctions or defect of the electronic component. At the same time, the automotive industry wants to extend the warranty on the cars. Of course, the long-term reliability of the electronic components must be proven prior to serial production. As the necessary tests cannot be performed in real-time, accelerated test methods for thermo-mechanical reliability are used.

Accelerated test methods for PCBs

There are many thermo-mechanical stress tests in use for PCBs, the most common are the solder shock test, the sand bath test, the thermal cycling test (TCT, also known as thermal shock test), and the interconnect stress test (IST) [1].

The TCT is established to simulate long-term environmental thermal stress. This test is used worldwide in different branches of the PCB industry; and there are a lot of standards available, a small selection is given in Refs. [2–6]. These standards have in common that PCBs or parts from PCBs – either from normal production or with a special test design – are subject to high and low temperatures in special climate chambers. Usually the test is performed in air [2–5], but there are also test chambers with special liquids in use [6]. The changes between high and low

temperature can be abrupt (a few seconds transfer time between hot and cold chamber, thus the name thermal shock test) or with a defined heating/cooling rate.

In Germany PCBs for automotive electronics are usually tested with abrupt changes (3–10 s) between the cold (–40 °C) and the hot (+125 °C) chamber with 30 min dwell time in each chamber. In future electronic components will be mounted closer to hot parts of the car (e.g. engine, brakes), thus the temperature range will be extended for some quality classes (e.g. –40 °C / +150 °C or –65 °C / +150 °C). According to the quality class the number of cycles to be passed is typically between 200 and 500 (up to 1000); in future 500 up to several thousand cycles will be required.

After the thermal cycle test failure analysis is performed by metallographic sample preparation and optical microscopy with the following disadvantages:

- a) Samples are taken more or less randomly. When the first failures occur they can only be found by chance. Resistance measurements at room temperature to locate a failure have mostly no success.¹
- b) It is only possible to find out that a failure occurred (with some scope for interpretation), but not when it occurred. Therefore it is common during long running tests to take out a sample for examination e.g. each 100 cycles. So with increased effort it is possible to delimit the time the failure occurred.
- c) It is not possible to give clear statements about functional deterioration based on microsection images alone. Beginning barrel cracks or interconnection defects (ICDs) seldom affect the whole circumference of a through-hole, so that only the resistance increases without causing malfunction or defect. Some standards for TCT already mention resistance measurements at maximum temperature for functional assessment [3, 4], but they give no hints how to do it in praxis.
- d) A fourth disadvantage of the TCT is the long test time (up to 1 h per cycle) which is, however, inherent in the system.

IST, an alternative to TCT?

The IST avoids the disadvantages of TCT discussed above by another test method [7–9]. Test PCBs with a special layout have to be used; they have two daisy chain circuits (called “power” and “sensor”). Through the power circuit a high current (several amps) is passed in such a way that the test coupon is heated up from room temperature to 150 °C within three minutes; then it is cooled down again with fans. Thus one cycle needs only five minutes. The resistance of both circuits is measured accurately with the four-point method throughout the test time; according to Eq. (1) the temperature is calculated from the resistance.

$$R(T) = R(T_0) \times [1 + \alpha(T - T_0)] \quad (1)$$

Small cracks or ICDs cause remarkable increase in the resistance of the daisy chain in the warm state, whereas the resistance change at room temperature is negligible; thus the failure criterion is usually 10 % increase in warm state resistance with respect to the reference value [9] (Fig. 1). IST determines the reference value of the warm state resistance at the end of the heating phase of the third cycle. Each test coupon is cycled until either the failure criterion or the specified maximum number of cycles is reached. The system automatically generates report and protocol files.

Failure analysis on failed test coupons is made easy by heating the defective daisy chain once again such that the hottest spot – i.e. the point with the highest resistance (e.g. crack) – can be localized under an IR camera.

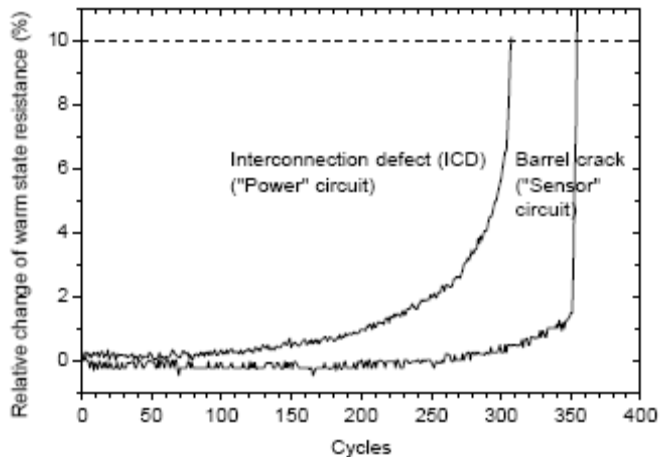


Fig. 1: Warm state resistance as a function of IST cycles¹[1].

The advantages of IST over the TCT as described above are the following:

- Shorter test times.
- Real-time failure detection.
- Objective assessment of failures with a functional criterion (resistance of a daisy chain).
- Secure sampling for a subsequent analysis of a microsection in an optical microscope.

Despite these advantages of IST, the TCT is still the predominant method for testing long-term reliability of PCBs. Possible reasons are:

- The method to heat up the PCBs is entirely different for IST and TCT. During TCT only minor temperature differences occur between different points on a PCB, while during IST differences of more than 10 % of the final temperature are possible between the middle and outer areas of the test coupon.
- IST cannot test in the range of low temperatures (contraction of the PCB).
- The final temperatures between IST and TCT programs are often different.
- Temperature measurement at IST does not work as precise as with a Pt-100 or a thermocouple; furthermore, it cannot be checked or calibrated by the user.

Because of these differences only little is known up to now about correlations between IST and TCT (see citations in Ref. [7]). For useful correlation studies it is necessary to design the temperature programs such that the same total strain is reached [10] and that the glass transition temperature of the base material is exceeded either in both cases or in neither of them.

Online-TCT

Because of the difficulties comparing IST and TCT described above it seems unlikely that IST will supplant TCT soon. Thus it is advisable to eliminate TCT's disadvantages (a)–(c) described above. This is done by using PCBs with daisy chains at which four-point resistance measurements are performed continuously throughout the whole test (Online-TCT) [1]. In contrast to IST it is not mandatory to follow special design rules; of course, the design of the test boards must be suited for the desired information. It is obviously possible to use IST test coupons for the Online-TCT.

With the Online-TCT an objective and real-time failure detection based on a functional criterion is possible similar to IST; furthermore, the well-known advantages of TCT are kept. Failures on failed test coupons can be localized with heating current and IR camera similar to IST.

¹ "Switch effect": tiny cracks are only "open" at high temperatures with high mechanical stress whereas they cause a negligible resistance increase at room temperature.

TCT-COMFORT 40

Presently, there are only little commercial offers for Online-TCT, thus the authors have developed a system on their own. Its name TCT-COMFORT 40 is an abbreviation for „Thermal Cycle Test with Control Measurements: Four-point Resistance and Temperature with up to 40 Channels“. The name describes also the properties of the system: it is compact, it can be attached to existing TCT equipment, and it is designed for a comfortable routine use in a PCB testing lab. In the following details of the Online-TCT are discussed at the example of TCTCOMFORT 40.

Hardware (Fig. 2):

A common TCT machine with two vertically aligned temperature chambers is used; the lower and the upper one are used for the low and high temperatures, respectively. The samples are placed in a basket that can be moved within a few seconds between the two chambers. Loading and unloading is performed in the upper chamber.²

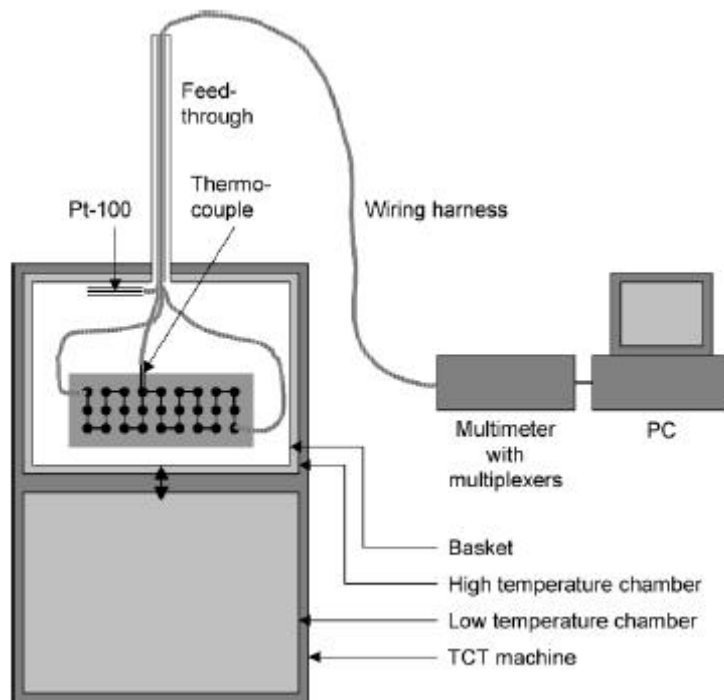


Fig. 2: Sketch of an Online-TCT setup.

The cables being necessary for the Online-TCT are introduced via a rod into the basket. The rod is mounted on the top side of the basket and reaches out of the TCT machine at all time. At this rod the cable harness from silicone insulated copper wire (operation range $-50\text{ }^{\circ}\text{C}$ to $+180\text{ }^{\circ}\text{C}$) is fixed such that it does not move the samples when the basket is moved.

Outside the machine the cables are lead to a multimeter with two multiplexer cards. Each of the multiplexers can handle 20 channels for four-point resistance measurement (resolution $< 1\text{ mW}$ at 1 kW range) or temperature measurement with a Pt-100; one of them can also handle thermocouples. One Pt-100 is used to monitor the air temperature within the basket; thermocouples can be used to monitor the temperature of the samples (e.g. in a through-hole of a PCB). At least one temperature channel is mandatory for the operation of TCT-COMFORT 40 (see below).

² An alternative construction uses two horizontally adjacent temperature chambers; the basket with the samples is turned between them [1].

Within the basket each channel (four cables) is labeled. They are connected to the daisy chains with plugs, solder joints, or ceramic luster terminals. The multimeter with the multiplexers is controlled by a PC, which records the data and evaluates them in real-time.³

Software:

The software recording and evaluating the Online-TCT data is independent from the TCT machine control. The operator defines all important parameters before starting a measurement:

- Active channels N_a with individual labels and function (resistance, Pt-100, thermocouple).
- Range for resistance measurement (typically 1 k Ω).
- Delay t_w between switching of the relays in the multiplexer and recording of the data for the respective channel (typically 200–500 ms).
- Integration time t_i for determining one resistance or temperature value (typically 40 ms or 100 ms).
- Type of thermocouple (e.g. NiCr/Ni).
- Sampling time interval Δt [e.g. 20 s; minimum $\Delta t = N_a \cdot (t_s + t_w + t_i)$ for t_s being the relays' switching time].
- Temperature channel for the internal cycle counter.
- Threshold for the increase in warm state resistance (e.g. 3 %).

During the measurement all actual values, real-time evaluations, and status messages are displayed in an easy to survey matrix on the screen; furthermore, they are written into two files (raw data, warm state resistance and maximum temperature as a function of cycles⁴ with status) on the hard disk.

The system determines the actual cycle from the measured temperature as a function of time. During each warm half cycle the measured resistance is analyzed for each channel and the highest value is logged as warm state resistance of the actual cycle. The reference value for the warm state resistance of each channel is determined during the third cycle to ensure stabilized operation conditions of the TCT machine. Afterwards, the warm state resistance trend including the threshold for each channel and the temperature drift can be displayed graphically.

As soon as the warm state resistance of a channel is larger than the respective threshold the channel is marked as failed (the raw data recording continues) and the cycle in which the failure happened is shown.

Intermediate and final reports with the viewgraphs can be generated and printed.

The operator might wish to remove a failed PCB from the TCT machine shortly after the failure was detected (e.g. if failure analysis at a microsection should be performed at a certain warm state resistance increase). For this purpose it is advisable to interrupt the measurement and the program of the TCT machine just after the transfer from the cold to the hot chamber, to take out the PCB, and to continue the machine program and the measurement immediately. If desired, the channel of the removed PCB can be deactivated.

After a failure of the hardware or the software a discontinued measurement can be resumed; of course, there will be a gap in the logged data.

³ An alternative construction uses ribbon cable with unambiguously assigned pins in the feed through. So more than 320 channels can be realised [1], but the electronics is expensive and the cables have a smaller temperature range than those with silicone insulation.

⁴ The maximum temperature in the hot chamber is not exactly equal for each cycle. At the time of determining the warm state resistance also the maximum temperature is logged. The maximum temperature as a function of cycles is called "temperature drift" in this paper.

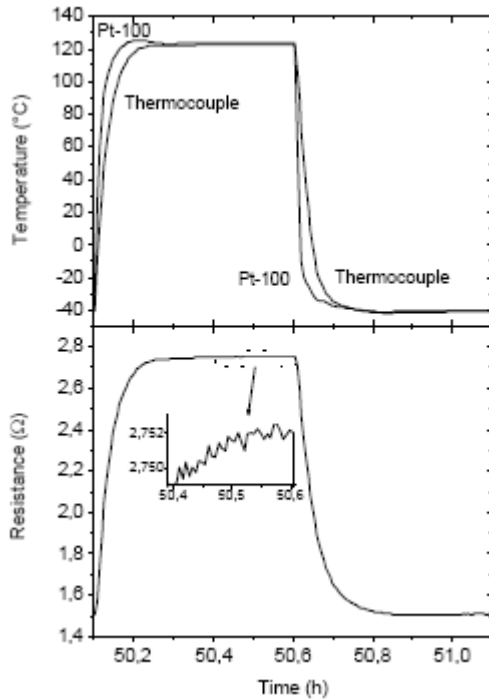


Fig. 3: Extract from temperature and resistance as a function of time from an Online-TCT measurement. The temperature inside a plated through-hole (thermocouple) follows the air temperature (Pt-100) with a short time lag.

First practical experience

The resistance measurement works accurately and with low noise (approx. 1 mW); as expected, the resistance follows the temperature in the basket (Fig. 3).

For low load of the basket the temperature of the PCBs follows the air temperature with a short time lag (Fig. 3).

Temperature drift is mirrored in the trend of warm state resistance; it is responsible for a major part of the noise in the trend of warm state resistance (Fig. 4). It is possible to correct the trend of warm state resistance after the measurement with Eq. (1), because temperature drift is recorded at the same time (Fig. 4).

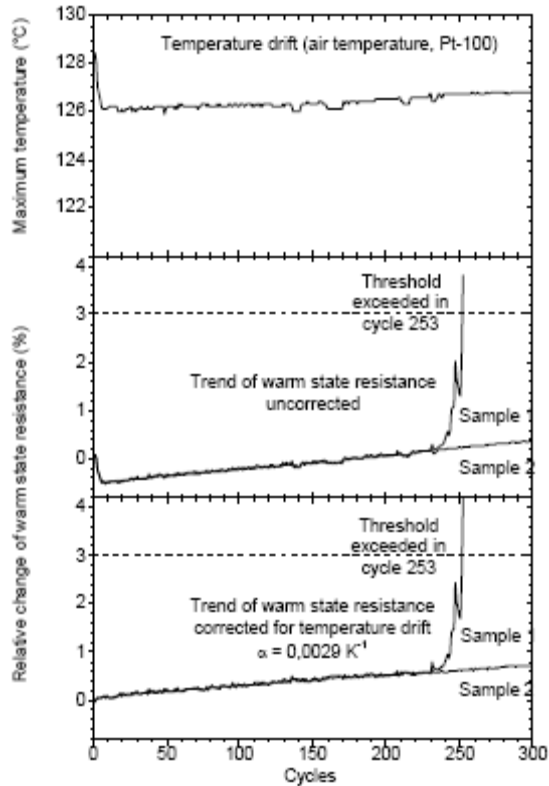


Fig. 4: Temperature drift (top) and trend of warm state resistance (middle uncorrected, bottom with correction of the temperature drift) from an Online-TCT measurement.

Now the following question gets interesting: which increase in warm state resistance corresponds to which strength of cracks, especially is it possible to detect the first beginning of cracks with an electrical method alone?

- From experience the cracks at 10 % increase in warm state resistance are already quite strong both for standard IST and for Online-TCT (Fig. 5); thus this threshold seems too high for detecting the beginning of cracks.
- Although it is possible to find cracks like those shown in Fig. 7 at 3–5 % increase in warm state resistance (Fig. 6), the more typical cracks look like in Fig. 8. The cracks appear finer than for 10 % and seldom extend through the complete copper layer, but usually several of them are found within one microsection.
- Even for approx. 1 % increase in warm state resistance the cracks look similar, but usually they are less and smaller (Fig. 9).

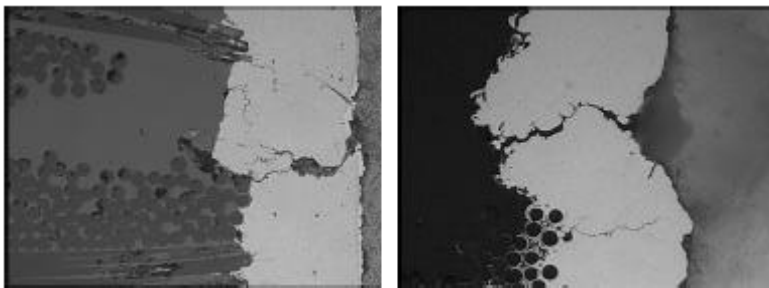


Fig. 5: Cracks at approx. 10 % increase in warm state resistance for IST (left) and Online-TCT (right).

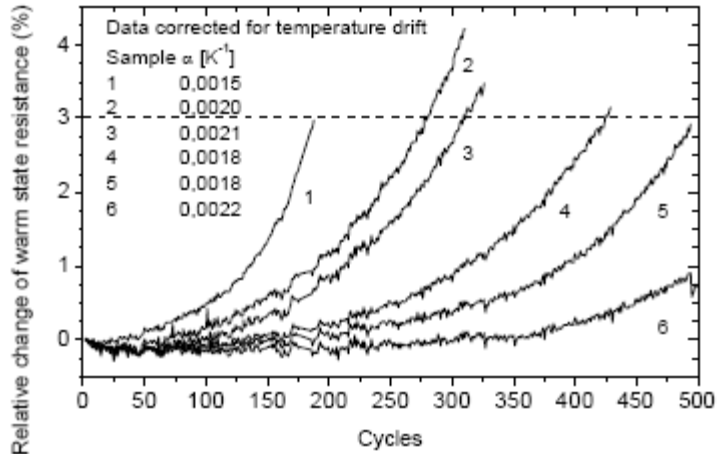


Fig. 6: Trend of warm state resistance (corrected for temperature drift) from an Online-TCT; each PCB was removed from the TCT machine after 3–5 % increase in its warm state resistance.

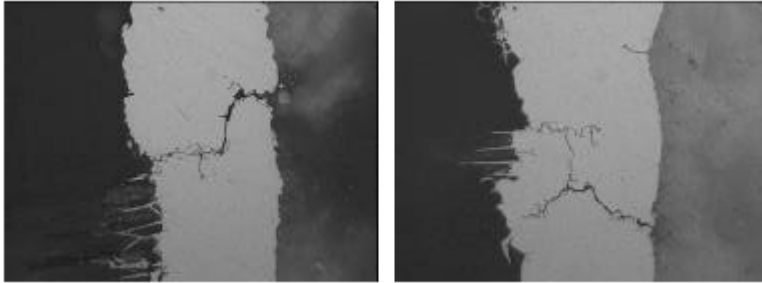


Fig. 7: Strong cracks observed at samples from the same experiment as shown in Fig. 6 (3–5 % increase in warm state resistance).

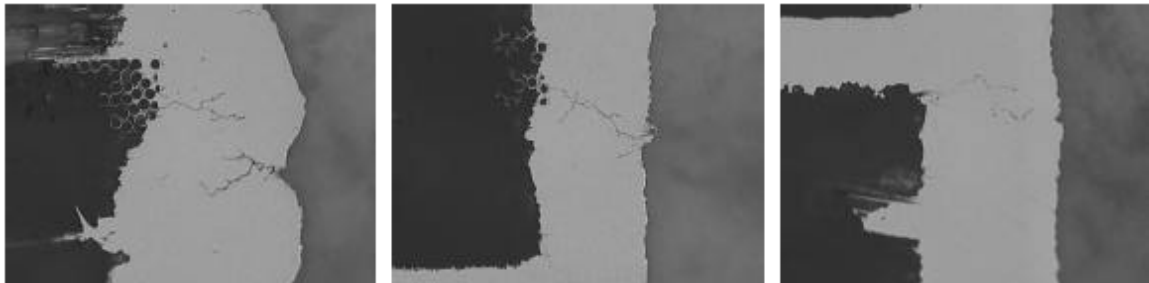


Fig. 8: Typical cracks observed at samples from the same experiment as shown in Fig. 6 (3–5 % increase in warm state resistance).



Fig. 9: Cracks which can be found at approx. 1 % increase in warm state resistance (from the same experiment as shown in Fig. 6).

To really detect the beginning of first cracks the threshold would have to be less than 1 % increase in warm state resistance. The resolution of TCT-COMFORT 40 is in principle good enough; but the temperature drift cannot be corrected in real-time – α is not known in advance. A fixed value for α would just manipulate the data, but it cannot be guaranteed that resistance peaks due to temperature drift are corrected in a sensible way.⁵ Without correction for temperature drift resistance fluctuations are in the range of some tenths of a percent (Fig. 4).⁶ However, the threshold for failure should be significantly higher than the noise level. Furthermore, sometimes artifacts happen during resistance measurement – the worse the quality of the electrical contacts, and the shorter t_w and t_i the more likely they are. Although the TCT-COMFORT 40 software features routines to recognize and suppress artifacts, premature failure messages cannot be excluded.^{7, 8} The lower the threshold the more likely an artifact can cause a premature failure message. For these reasons thresholds around 1 % are not suitable for a reliable life-time assessment, neither for Online-TCT nor for IST. Presently, experiments for the verification of PCB damage models are conducted at Atotech with 3 % threshold for Online-TCT as well as for IST.

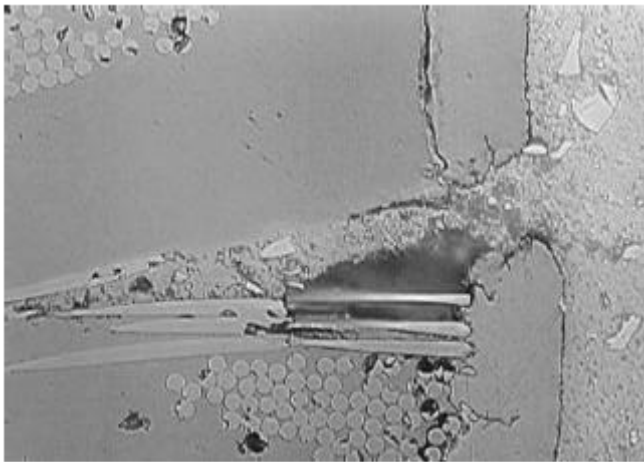


Fig. 10 Delamination of the base material caused a strong barrel crack during IST. (Above the glass fiber bundle the delamination caused a wedge-like gap, which is – with the exemption of an air bubble – filled with mounting resin.) Such a failure image corresponds to more than 10 % resistance increase.

One can note that many of the barrel cracks shown in Figs. 5 and 7–9 start at glass fibers reaching into the copper layer or at necking in the copper layer. At glass fibers and other edges the local stress is much higher than the average stress in the copper layer such that they act as predetermined breaking points. Necking in the copper layer (Fig. 7 right, Fig. 8 left, Fig. 9 right) can be accompanied in their direct neighborhood by a gemmiform crystal structure with pronounced grain boundaries perpendicular to the layer, so they are mechanically weak points and can cause premature cracking. Furthermore, the properties and the behavior of the base material, e.g. delamination (Fig. 10), can cause premature barrel cracks.

⁵ For correcting resistance peaks which are caused by temperature drift α must be “fitted” and smaller than its literature value for copper. If α is too large “overcorrection” happens, if α is too small the peaks are not fully suppressed. In Figs. 5 and 7 the used values for α are given.

⁶ From experience the noise during IST is of the same magnitude (Fig. 1). If the ambient temperature of the machine is not constant the measurements can even become useless. IST data cannot be corrected for temperature drift.

⁷ Due to the ongoing raw data logging it is possible to determine the true time of failure afterwards.

⁸ Premature failure messages due to artefacts are also known for IST. However, the measurement is then terminated completely.

Summary and outlook

Presently, the still new method of Online-TCT, e.g. in its realization by TCTCOMFORT 40, proves its suitability for daily use. The warm state resistance of daisy chains in the tested PCBs can be measured precisely such that in analogy to IST failures are determined in a statistically secure way based on a functional criterion. Thus the Online-TCT is better suited for meaningful TCT-IST correlation studies than the classical TCT [1].

Acknowledgements

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