Mechanical Stress and Deformation of SMT Components During Temperature Cycling and PCB Bending

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Keywords
Bending behavior, Components, Printed circuit boards, Stress, Temperature cycling

Abstract
A very common method to predict the reliability of components soldered on printed circuit board (PCB) or substrates is by bending tests and temperature cycle tests, for instance between - 55 °C and 125 °C (up to 2000 cycles at 1 h cycle period). Sensitive SMD constructions such as chips with ball grid array mounting or multilayer chip capacitors (MLCC) are often a major issue due to their “flex cracking” problems. This paper describes the real behavior of deformation at temperature cycling and PCB bending of chip components (body size 0603). By using the piezoresistive effect in thick film resistors the effects of stress on the alumina body can be determined and described for the whole temperature range of interest. The complete system of component, PCB/substrate and solder joint will be discussed and different influences will be isolated. It will be shown that CTE-matching of the component and substrate does not lead to an optimum situation. The influence of the solder joint plays an important part. Optimization potentials and design rules for the whole system will be given. The basis of this paper is a quite unusual “measurement tool”, the effect of piezoresistivity. The investigation into that phenomenon will be described very thoroughly first.

Special thanks to Maren Steffen who carried out most of the measurements, to my colleague Joachim Aurich for fruitful discussions (he was the first in our company who had discovered and observed the piezoresistive effect on discrete resistors), and Reimer Hinrichs who made most of the drawings.

THE PHENOMENON OF PIEZORESISTIVITY

In the Beyschlag laboratory the piezoresistive effect was not relevant when dealing with cylindrical thin film components; leaded resistors and SMT components in MELF form. However, further miniaturization of components down to case sizes of 0603 and 0402 has necessitated a move to a flat chip design. The objective was to develop a universally applicable resistor with a high-end specification and a competitive price. To determine the optimal component construction (Kühl, 1996), detailed studies of areas such as film design and contact design have had to be undertaken.

A surprising piezoresistive phenomenon was observed when measuring thick film components with tolerances ≤ 1 %. Measurements were carried out using a reliable device from a well-known manufacturer. Standard practice in resistor manufacture is to use two ohmic measuring stations for component verification (tolerance of ohmic value) before taping and reel packaging. A higher level of verification has been implemented at Beyschlag’s production facilities for many years. In addition to the standard measurements, the component undergoes pulse loading, or measurement of non-linearity. The two release algorithms described below, together with the two ohmic tolerance measurements, enable a comparison which gives us important additional information regarding the resistor’s specification:

(1) Tolerance measurement 1 and tolerance measurement 2 have to be lower than a quoted tolerance, e. g. < ± 1 %. This is state of technology for releasing chip resistors world-wide.

(2) Tolerance measurement 1 minus tolerance measurement 2 have to be lower than a quoted deviation. This is our extended release algorithm.

This extended algorithm ensures that calibration of the measurement equipment is correct, and identifies “weak” components, which would otherwise pass the release criteria. This is in accordance with Beyschlag’s 0.05 ppm-quality targets and zero defect philosophy.

These successful new features were also incorporated in the measuring stations for flat chip production. When production commenced, a component reject rate was observed for thick film resistors of almost 100 % due to failure to meet the second criteria - even the pulse load screening between the two tolerance measurements was omitted. A detailed investigation into the phenomenon identified the cause: piezoresistivity.

The problem resulted from a slight difference in the mechanical design of the glass stopper plate used in the first and second measurements as known in Figure 1. The different bending moments experienced by a component at the two stations caused resistance value to shift by approximately 0.15 %.

Another curious observation was made during bending tests in accordance with CECC standards (CECC 40 000).

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This test is designed to determine the resistance of the contacts to cracking under conditions of PCB bending. Our comparative studies showed an astonishing difference between thick film and thin film resistor. A piezoresistive effect occurs due to the type of resistive-layer system and the bending of the PCB (Kühl, 1996).

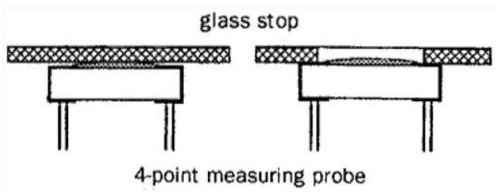


Fig. 1 - Two slightly differing constructions in the measuring station

The discovery of these two phenomena resulting from the component's piezoresistivity made it necessary to launch a research program to explore the issue thoroughly.

PIEZORESISTIVITY OF DISCRETE RESISTOR CHIPS MOUNTED ON PCB

To determine what happens to the components, ten size 0603 resistors were mounted by reflow soldering (Sn60 Pb36 Ag2) on a test PCB (size 100 mm x 70 mm x 1.6 mm; fillet width 1.0 mm) of FR4 material.

A bending procedure in accordance with CECC 0082, which is equivalent to EIA PN-3333, was used, but with additional dynamic resistor measurements (Figure 2). The bending of the PCB was carried out in 0.5 mm steps, with the resistance value being taken 15 s after each new bending position was reached. When the maximum bending displacement of 4 mm was reached the PCB was returned to zero displacement in 0.5 mm steps and bending was then repeated.

The test conditions are given in Figure 3.

The average resistance change of each of the ten resistors was taken for analysis.

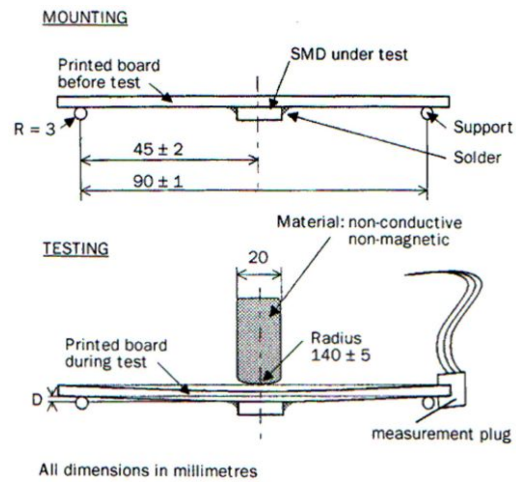
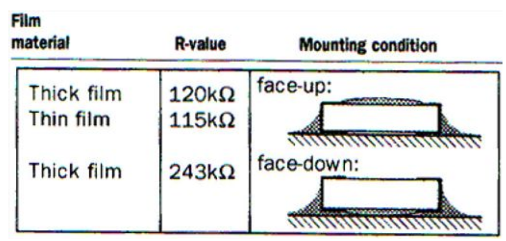


Fig. 2 - Bending test with dynamic resistor measurement



Film material	R-value	Mounting condition
Thick film	120kΩ	face-up:
Thin film	115kΩ	
Thick film	243kΩ	face-down:

Fig. 3 - Test conditions for PCB bending

Face up mounting results

The results for face-up mounted devices are shown in Figure 4.

- While thick film chip resistors show a significant deviation in ohmic value, thin metal film chip resistors show no significant change in resistance at all.
- Bending from the rest position results in a reduction of resistance. The maximum deviation of ohmic value was obtained at no more than 2.5 mm to 3 mm bending displacement.
- When bending was reduced back towards the rest position, the characteristic of resistance change was quite different from the behaviour when the degree of bending is being increased, with the resistance value immediately getting higher.
- When returned to zero bending, a resistance offset was observed, i.e. the resistance was higher than that observed initially on the unbent PCB.
- When bending again, hysteresis in the resistance change became apparent.

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This effect is non-critical for metal film chip resistors and these results make clear that further studies on the effect of piezoresistivity should focus on thick film chip resistors.

To gain further insight into the chip/PCB system, the incremental bending test was extended to different maximum bending displacements of the PCB with resistors mounted in the face-down orientation.

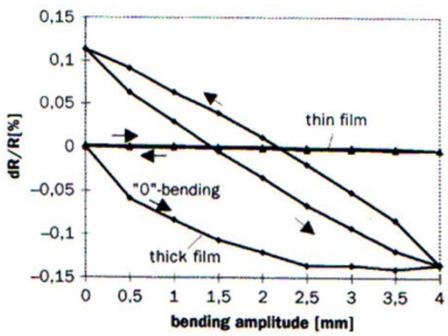

Fig. 4 - Effect of bending of face-up mounted thick and thin film resistors

Face-down mounting results

The results for face-down mounted devices are shown in Figure 5.

- The placement orientation, that is face-up or face-down, affects both the direction of resistance change, and its magnitude, the change for face-down devices being approximately twice of those face-up.
- The initial $\Delta R/R$ characteristics up to the respective maximum displacements are the same and independent from bending amplitude.
- At a bending displacement greater than 3 mm the rate of change in resistance decreases again. It will be shown later that this is a feature linked to stress and strain of the tin/lead solder joint.
- The offsets of the change in resistance after bending of PCB and the hysteresis are significantly dependent on the bending displacement. The effects of subsequent bending lead to a similar hysteresis with a "memory effect" related to the bending displacement.

It becomes obvious that the effects which occur in the PCB assemblies can not be attributed to piezoresistivity alone. Literature shows that the effect should be linear (Zerbst, 1963). In addition to this effect, a permanent deformation of the solder joint also occurs, according to the results of the bending test. The higher resistance offsets and the bigger hysteresis with increasing bending displacement give clear indication of this. The evidence will be shown in the following sections.

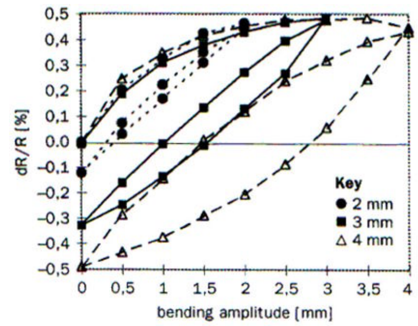

Fig. 5 - Influence of different bending displacement (face-down mounting) 2 mm (●), 3 mm (■), and 4 mm (Δ)

INVESTIGATIONS INTO THE PIEZORESISTIVE EFFECT

To isolate the piezoresistive effects a thick-film resistor paste of 100 kΩ per square was printed directly onto an alumina substrate (size 50 mm x 50 mm x 0.63 mm) and fired, as in hybrid technology. To measure the ohmic deviations when bending these substrates a special bending apparatus was constructed with a precision micrometer for measuring the exact bending displacement, as shown in Figure 6.

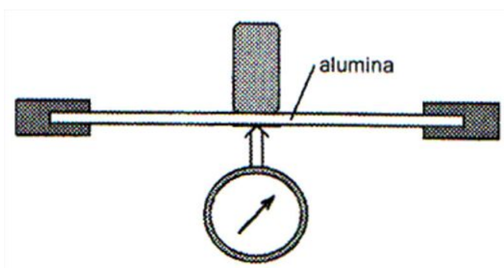

Fig. 6 - Bending apparatus with micrometer for precision measurement on alumina substrates

For these thick film resistors on alumina substrates a pure, nearly perfect linear piezoresistive effect was achieved (Figure 7).

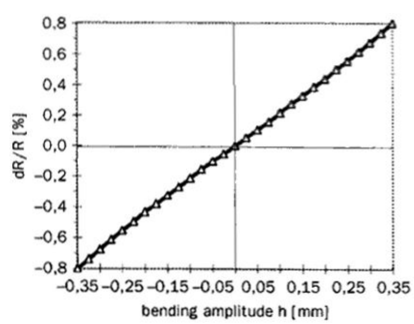

Fig. 7 - Effect of bending on hybrid-style thick film resistor

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The piezoresistive effect is defined by Zerbst (1963):

$$\frac{dR}{R} = \left(1 + \upsilon_K + \upsilon_R + \frac{(dp)/p}{\varepsilon}\right)\varepsilon = \underline{k} \times \varepsilon$$

Where:
υ_K is the Poisson ratio (ceramic);
υ_R is the Poisson ratio (R-layer);
p is the specific resistance; and
ε is the relative strain (relative change of length)

The *k*-factor gives the magnitude of the piezoresistive effect:

$$k = \frac{dR}{R} \times \frac{1}{\varepsilon}$$

The change of length Δ1/1 is easily calculated by simple geometric functions. The alumina substrate's deformation was assumed to be a homogeneous segment as shown in Figure 8.

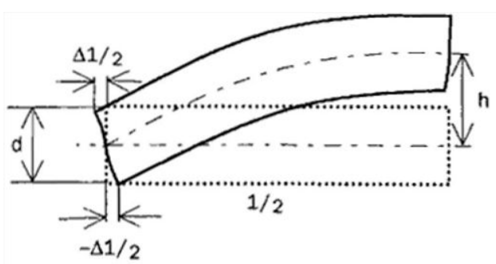

Fig. 8 - Calculation model for the strain. Δ1/1 of the alumina substrate during the bending procedure: where 1 is length, d is thickness, and h is the bending amplitude of the substrate.

So the piezoresistive change in ohmic value is a direct and linear function on tensile or compressive strain (upset) experienced by the resistive layer (Figure 9).

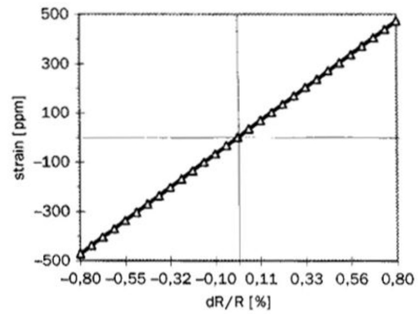

Fig. 9 - Relative change of length e in relation to piezoresistive change of ohmic value

The k-factors of the test substrate were reproducibly between 18 and 20 with resistor pastes of 100 Ω per square with different print geometries and a paste system with a rated TCR of ≤ 100 ppm/K.

INVESTIGATIONS INTO THE TEMPERATURE CHARACTERISTICS OF THE PIEZORESISTIVE EFFECT

To determine whether the piezoresistive effect is temperature dependent another test was necessary in which PCB and component were subjected to high and low temperatures at a constant bending radius (Figure 10).

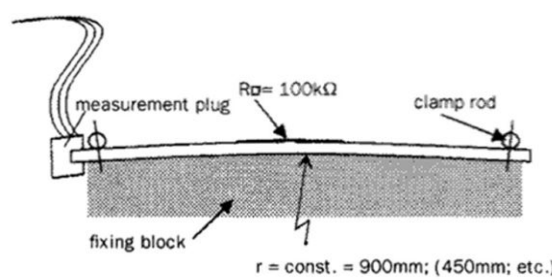

Fig. 10 - Bending block for measurement in temperature chamber

Test method

Printed resistors on alumina ceramic substrates were bent in the tensile and compressive strain direction respectively and tested over the temperature range of - 55 °C to + 155 °C, in which electronic components are commonly designed to operate. Measurements were taken in 25 °C steps downwards starting at 155 °C, 15 min after reaching each temperature.

Again the mean values of ten measurements were used for the evaluation. The results show (Figure 11):

- The piezoresistive effect and the k-factor of the resistive layer do not depend on temperature

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- Changes of temperature result in a nearly constant offset (change) in the value of resistance which is symmetric for strain or compressive strain throughout the whole temperature range
- According to the results the conductivity change must be caused by the tunnelling effect only. This is the only conductivity principle which is widely independent from temperature and only dependent on the tunnel distance and voltage (Heywang and Pötzl, 1991)

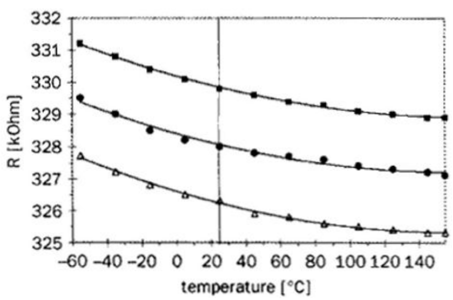

Fig. 11 - Temperature characteristics of bent and unbent resistors directly printed on alumina substrates

TEMPERATURE CHARACTERISTICS OF DISCRETE COMPONENTS ON PCB AND ALUMINA

As shown earlier, discrete components do not demonstrate linear resistance change characteristics, as a pure piezoresistive effect would lead us to expect. So we have to examine the system of PCB (or alumina substrate), solder joint and SMT-component, in more detail. Up to now the investigations have dealt with mechanical forces on PCB and substrate. A further investigation was necessary to determine whether piezoresistive effects occur under the influence of temperature cycles.

The system involves materials with quite different coefficient of thermal expansion (CTE), as shown in table below.

MATERIAL	CTE (ppm/K)
Tin (component's contact)	27
Tin/lead eutectic (solder)	24
FR4	16 ... 20
Alumina (component body and substrate)	5.7

Test 1

Measurement over the whole category temperature range of 0603 size discrete thick film resistors R = 243K, face-up and face-down on FR4 PCB

Test 2

Measuring temperature characteristics with wire connection (the only stress-free condition for component - see Figure 12)

Again, the analysis is based upon the average measurements of ten resistors.

Results

- In contrast to hybrid technology (Figure 11), the temperature characteristics of discrete thick film resistors change due to stress on the component, when heating the system up or cooling it down (Figure 13)

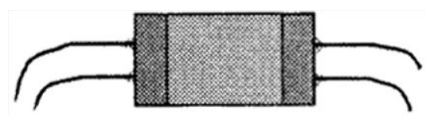

Fig. 12 - Thick film chip resistor equipment with wire contacts to achieve stress-free test conditions

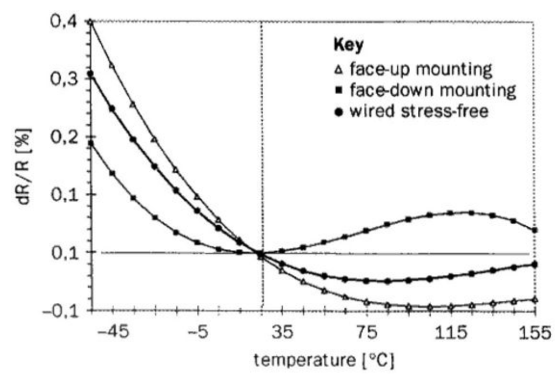

Fig. 13 - Temperature characteristics of discrete thick film resistors PCB in face-up and face-down mounting compared with wired stress-free resistors

Test 3

When making the same measurement with discrete chip components mounted on alumina substrate (substrate and chip body have some coefficient of thermal expansion), the results are remarkably different, see Figure 14.

As we have seen, the piezoresistive effect is independent from temperature and very linearly dependent on mechanical deformation. When the stress-free temperature characteristic (leaded R-chip) is subtracted from the stress-affected (chip mounted on FR4 PCB or alumina substrate) the effects (influence) of the solder joint and PCB can be isolated:

- Temperature characteristics of discrete resistor on PCB (FR4)
  → Effect of PCB plus solder
- Temperature characteristic of discrete resistor on alumina
  → Effect of solder only, caused by the CTE-matching of component and substrate
- Result on PCB minus result on alumina →
  → Effect of PCB only (PCB plus solder minus solder)

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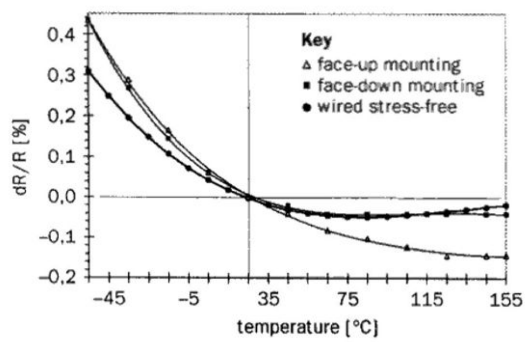

Fig. 14 - Temperature characteristics of discrete thick film on alumina in face-up and face-down mounting compared with wired stress-free resistors

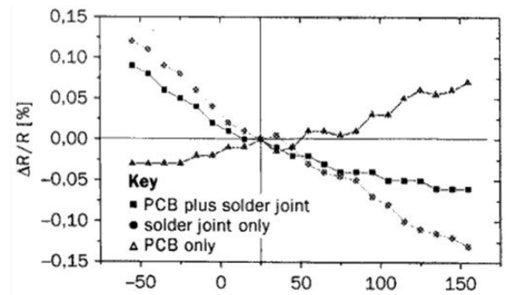

Fig. 15 - Temperature characteristic changes due to mechanical deformation of face-up mounted discrete chip component caused by influence of system
→ PCB plus solder joint (■); → Solder joint only (●); → PCB only (Δ)

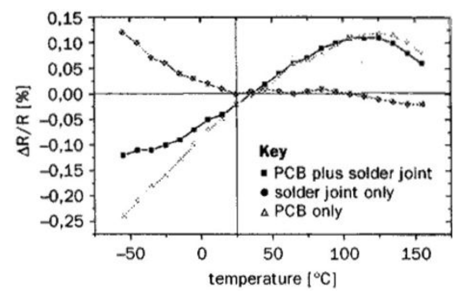

Fig. 16 - Temperature characteristic changes due to mechanical deformation of face-down mounted discrete chip component caused by influences of system
→ PCB plus solder joint (■); → Solder joint only (●); → PCB only (Δ)

Results

- *Face-up mounting:* In addition to the changes in resistive value caused by mechanical stress due to PCB bending, the different coefficients of thermal expansion of the PCB, solder joint and component result in piezoresistive effects in the thick film resistors, which changes temperature characteristics of resistive value in excess of ± 0.15 % (Figure 15).
- *Face-down mounting:* The lacquer covering the resistive layer results in a gap of 30 µm to 40 µm between component's contact and the substrate or PCB. Due to the bigger solder deposit underneath the component at that place, the piezoresistive effects are not significantly higher than was the case with the mechanical bending tests. The softening of solder at higher temperatures is clearly seen in the results associated with the PCB. At lower temperatures the effect is again more marked. It may change the temperature characteristics of resistive value in excess of 0.25 % (Figure 16).
- The stress in the component in CTE-matched SMT systems (chip components with alumina body on alumina substrate) is higher. The high CTE of solder joint affects the system more than "mis-matched" combinations like alumina chip and FR4 PCB. On the contrary, a substrate CTE in between that of the component and the solder joint seems to compensate the stress in the SMT-system significantly

INTERPRETATION OF THE SYSTEM CHIP COMPONENT ON PCB OR ALUMINA SUBSTRATE

From the very clear results of the piezoresistive effects of hybrid-style resistors on alumina subtrate during bending or temperature cycling, we can postulate that all of the resistance changes observed are caused by the piezoresistivity of the resistive layer. When utilizing this very defined effects as a sensor, the tensile and compressive strain caused by bending or temperature changes could be calculated when using the method shown in Figure 8 and the data on strain Figure 9.

It is therefore possible to suggest clearly what occurs in the complex system of PCB, solder joint, and components. These effects are transferable in their general behaviour to all discrete chip components (capacitor, inductors, silicon, chips, etc.) on a PCB or any other substrate.

The effects examined are true for all chip component sizes. The stated numerical quantities apply only to case size 0603 (component body 96 % alumina), solder joint Sn60 Pb38 Ag2, PCB of FR4 material, and alumina substrate (96 %, thickness 0.6 mm) respectively.

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Deformation of surface mounted chip components due to mechanical bending of the PCB

Calculation results

Example 1

Bending PCB h = 2 mm, length 85 mm; size 0603; face-up mounting is shown in Figure 17

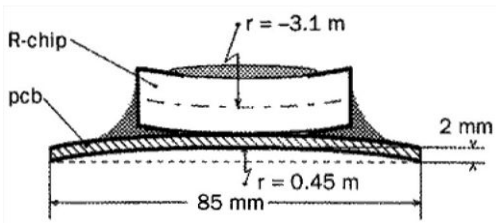

Fig. 17 - Bending of PCB; face-up mounting

Example 2

Bending PCB h = 2 mm length 85 mm; size 0603; face-down mounting is shown in Figure 18.

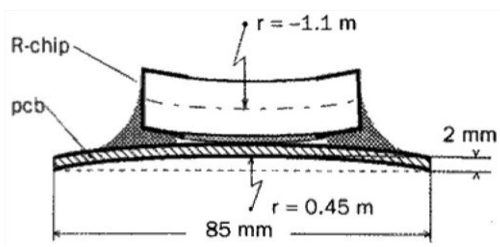

Fig. 18 - Bending of PCB; face-down mounting

Results

- A convex bending of the PCB results in a concave flexion of the component
- Under the same PCB conditions, the face-down component has a smaller flexion radius, which means a much higher strain than the strain in the resistive layer in face-up mounting

Deformation of chip components mounted on PCB or alumina due to temperature cycle conditions

As seen before, all changes of resistive value during temperature cycle are caused by piezoresistivity, e.g. strain or compressive strain are exposed to resistive layers. According to stress-affected piezoresistive changes of resistance value (Figure 14 and 15) the deformation of chip components could be calculated over the whole temperature range. The results for face-up mounting are shown in Figure 19 and for face-down mounting in Figure 21.

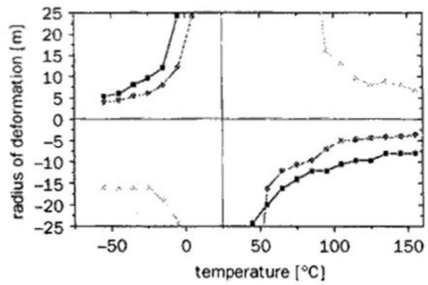

Fig. 19 - Calculation of deformations on discrete 0603 alumina body alumina and PCB over category temperature (face-up mounting). Influences on component's deformation

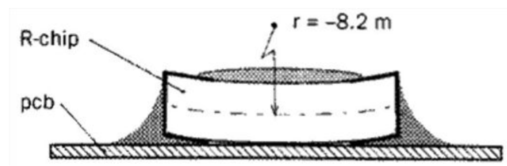

Fig. 20 - Upper category temperature, face-up mounting

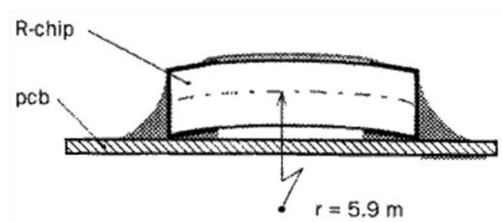

Fig. 21 - Lower category temperature, face-up mounting

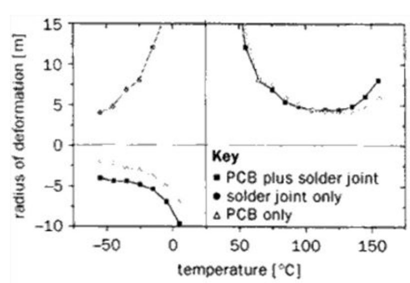

Fig. 22 - Calculation of deformations on 0603 alumina body over category temperature (face-down mounting). Influences on component's deformation

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Examples for face-down mounting
Unbent PCB, heated up to surface temperatures of 115 °C to 125 °C is shown in Figure 23.

Unbent PCB, cooled down to - 55 °C is shown in Figure 24.
Remark: The deformations of solder joint and PCB are not considered in the drawings.

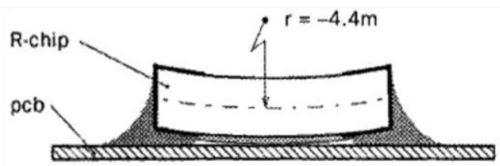

Fig. 23 - Upper category temperature, face-down mounting

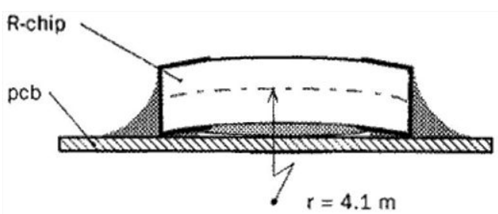

Fig. 24 - Lower category temperature, face-down mounting

Discussion of results

- At high temperatures the component bends into a concave position due to the higher coefficient of thermal expansion of tin in the solder joint
- At low temperatures we observe the opposite effect: A convex bend of the component occurs.
- Between these two situations the solder meniscus has to follow strain and compressive strain. Additionally, the component endures a lot of tension at the center of stress, at the end of the lower solder joint
- The results on the component's behaviour on PCB (Figure 17 and 18) could be verified and simulated by using the method of finite elements

RELEVANCE OF RESULTS FOR SMT APPLICATION

When carrying out temperature cycling, for instance with sensitive components like MLCC's there are recognized weak points in both component and solder joint where cracks may occur (Bergenthal, 1998). The components are subject to remendous forces. The experimental results make very clear now, where and why this happens (Figures 25 and 26).

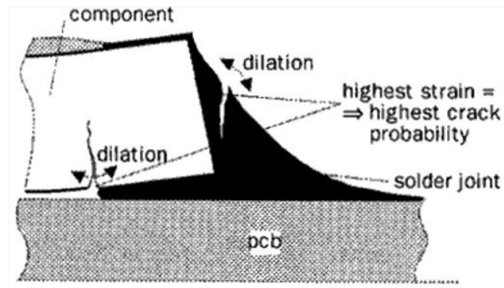

Fig. 25 - Stress on component and solder joint during temperature cycling: Cracking of component and solder joint. Situation is true for upper cycle temperature or a convex bending of PCB

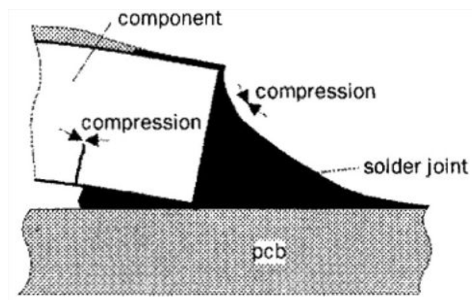

Fig. 26 - Stress on component and solder joint: Situation is true for lower cycle temperature or a concave bending of PCB

CONCLUSIONS

- The piezoresistive effect can cause significant resistance changes to thick film chip resistors, especially when the PCB bends, temperature changes occur, or the components experience stress when they are embedded or molded. The component's TCR will be also affected.
- These effects are not seen in thin metal film chip resistors.
- Thick film resistors can be used as sensors for mechanical stress investigations on printed circuit boards and ceramic substrates. Solder and pad properties can also be investigated and optimized by this method.
- Even when using a solid chip body of alumina a large deformation of the component can be measured. Components made from weaker materials such as MLCC will suffer much higher deformations within their body. The root causes of cracking problems of special chip component construction in SMT have become quite clear.
- What really happens to the component is dependent on the whole system of solder joint, PCB, and component. It is always the question of which part of this system takes on which amount of the distortion work. The highest amount always takes the weakest part.

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- Attempting to combine a discrete component with an alumina substrate (CTE-matching) in order to achieve lower stress on the component is labour in vain. The high coefficient of thermal expansion of tin in the solder joint is the critical factor. Mounting a discrete component on a PCB with CTE-value between those of the component and the solder leads to less stress and therefore has better results under conditions of temperature cycling. Optimum stability is consequently achieved by optimized CTE-matching of the solder contact and PCB.

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