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Reliability aspects of electronic devices for advanced requirements

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Abstract

Purpose – This paper aims to detail the qualification of alternative substrate materials and reliability aspects for quad flat no lead (QFN) packages for highly stressed electronic devices, e.g. for use in automotive applications.

Design/methodology/approach – Detailed information is given on the advanced climatic and mechanical requirements that electronic devices have to withstand during life cycle testing to qualify for the automotive industry. Studies on the suitability of high-temperature thermoplastics as substrate materials for printed circuit boards and the qualification of QFN packages for advanced requirements are described. In addition, information on cause-effect relationships between thermal and vibration testing are given.

Findings – With respect to adhesion of metallization on high-temperature thermoplastics and the long-term stability of the solder joints, these substrate materials offer potential for use in electronic devices for advanced requirements. In addition, the long-term stability of the solder joints of QFN packages depends on the design of the landings on the PCB and the separation process of the components during manufacturing.

Research limitations/implications – The paper covers only a selection of possible high-temperature thermoplastic materials that can be used in electronics production. Also, this paper has a focus on the new packaging type, QFN, in the context of qualification and automotive standards.

Originality/value – The paper details the requirements electronic devices have to meet to be qualified for the automotive industry. Therefore, this contribution has its value in giving information on possible substrate alternatives and the suitability for the usage of QFN components for highly stressed electronic devices.

Keywords Electronics industry, Automotive industry, Soldering, Tests and testing

Paper type General review

Introduction

In recent years the automotive industry has been responsible for a constant technology push in the development of innovative components and materials for electronic devices (Schöner, 2004). This is due to the fact that a value percentage of electronics in automobiles up to 35 per cent is predicted for the next few years (Krapp *et al.*, 2003). The fields of application such as sensors, motor and gear control or safety systems are especially challenging for interconnection technology in shorter development cycles. Apart from that, electronics are more and more integrated in actual mechanical fields, e.g. braking and exhaust systems. According to this development, components of electronic devices like printed circuit boards, interconnection materials and electronic elements themselves have to be qualified and optimized for use in automobiles or alternative components have to be found.

In this context, moulded interconnect devices (MID) offer great potential, by opening up the possibility to integrate mechanical and electrical functions in one device with the addition of freedom in design. However, the adhesiveness of metallization on thermoplastics and the influence of thermal tension due to the higher coefficient of thermal expansion (CTE) of these materials are critical factors for the long-term stability of MIDs. Nevertheless, the glass transition temperature and the melting temperature of the thermoplastics have to be equal with the operating temperature of the electronic device. Because of this and the requirements of the automotive industry, the suitability of high-temperature thermoplastics as substrate materials for printed circuit boards was evaluated at the institute FAPS. Basic results of this study are presented in extracts in this paper.

Standard packaging types for the signal processors on printed circuit boards in the automotive industry like quad flat packages (QFP) with area array components such as ball grid arrays (BGA) and chip scale packages (CSP) are getting more and more important. A relatively new type of component housing is the quad flat no lead (QFN) package. Since the QFNs are currently only processed to a small extent, there are few facts about the long-term stability of this package compared to QFP, BGA or CSP. On this account, research was initiated into the qualification of the long-term reliability and evaluation of different failure mechanisms of QFN according to requirements of the automotive industry. Furthermore, effects of different environmental tests and possible interactions were conducted on two different types of quad flat packs.

Advanced requirements on electronic devices

The requirements on electronic devices depend to a large degree on the field of application. Therefore, a lot of possible definitions are in existence. The selection shown in Figure 1 is the most common and is mentioned in a variety of publications. Based on that, the influences on electronic devices are a combination of temperature, vibration, respectively, shock and the presence of aggressive substances like oil or

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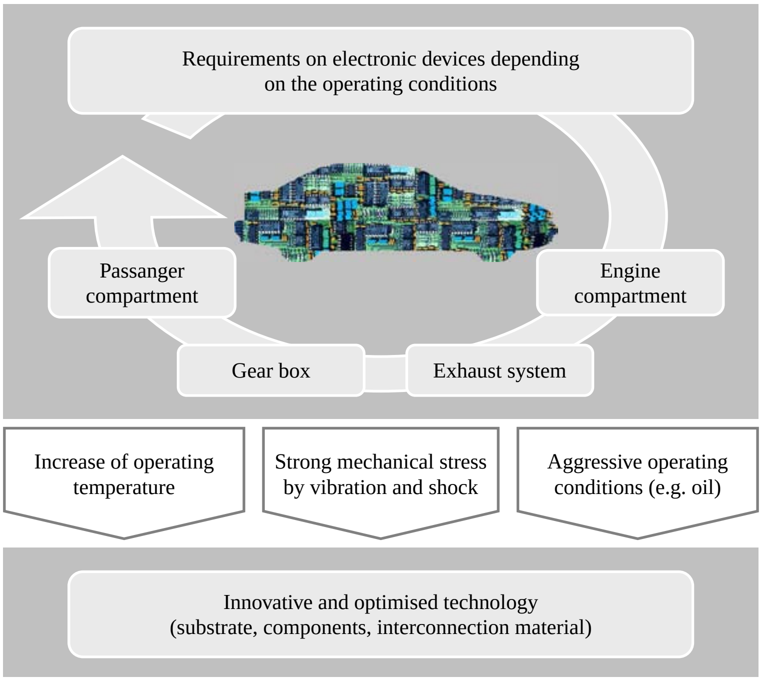
Figure 1 Fields of application and their requirements on electronic devices



exhaust emissions. Because of the highly integrated devices and the complexity of the electric circuitry, the temperature again is a combination of the existing temperature at the installation space, the lost heat due to the compact design of the device and the dissipation loss of the highly integrated circuit (Neher and Sauer, 2004). As a result of this, temperatures between 80°C (passenger compartment) and 800°C (exhaust system) are commonly used values for the temperature load of electronic devices in cars.

Temperature is an especially critical factor that all of the components of an electronic device have to withstand. For example, the ambient temperature for an ESP control unit is 125°C. During usage, the lost heat has to be added and, in the worst case, the total temperature may rise up to 170°C. Most of the components are not resistant without defects for a longer period of time. Standard substrate materials like FR4 often have glass transition temperatures of 135-140°C. This makes them only usable up to operating temperatures of ~125°C. Beyond that the printed circuit boards tend to exhibit delamination, something that was, and still is, the subject of many studies (Johander *et al.*, 2007; Ehrler, 2005). Up to now, research was realized on thermally conductive derivatives of epoxy-based substrate materials or high-T_g substrates. These materials show a decreasing tendency to delamination and also a better performance during temperature shock cycling due to their lower CTE in z-axis. This also has a positive effect on the long-term stability of the electronic device itself. A negative aspect of these modified materials is the price, which is significantly higher than for standard FR4. For applications such as gear controls, even high-T_g materials are not suitable. In this case, inorganic substrates including Low Temperature Cofired Ceramics have to be used, which are again considerably more expensive than standard substrate materials.

The interconnection material is temperature critical too, although the automotive industry is still allowed to use tin-lead solder, which has its melting point at 183°C. Under the acceptance of the worst case concerning the temperature in an ESP control unit (170°C), de-soldering of electric components might occur. This will be eased since lead-free solders will become obligatory in the automotive industry in the near future. But even then, the continuous temperature will be 125°C for standard lead-free alloys (SnAgCu). According to a previous study (Albrecht and Wilke, 2006), a specific modification of the SnAgCu solder by adding Bi, Sb and Ni has positive effects. Both the temperature stability (up to 150°C) and the long-term reliability of the solder joints after temperature cycling and mechanical stress compared to standard SnAgCu alloys are higher. Another limiting factor is the electronic component itself. Either the thermal stress is too high because of the differing CTE or the temperature stability is not enough (e.g. the operating temperature for silicon dies lies between 150 and 200°C according to McCluskey *et al.*, 2000).

Besides, low-cycle fatigue mainly induced by thermal cycling, high-cycle fatigue induced by vibration is also a major concern for the reliability of electronic devices. According to studies published by Yang *et al.* (2000) and Wang *et al.* (2004), cracks may occur in the solder joints and are highly depend on the type of fixation of the device and the risk of oscillation. However, these experiments were not conducted according to standards from the automotive industry. Therefore, further research is required. In addition, both the thermal cycling and vibration occurs at the same time and little is known about the cause-effect relationship of these two load types. Typical defect characteristics caused by vibration for printed circuit boards or electronic components have apparently not been the object of recent studies.

Against this background, this paper presents results of two studies based on the requirements of the automotive industry. First, the qualification of thermoplastics as substrate materials for temperature stable devices and secondly the coherence of temperature and vibration on the failure mechanisms of QFP and the relatively new packaging type, QFNs, are detailed.

Substrate materials for advanced thermal requirements

At the Institute for Manufacturing Automation and Production Systems High-temperature thermoplastics were examined for their applicability as substitutes for FR4 substrate materials for electronic devices used under advanced thermal loads. Out of a selection of polymers, circuit carriers were injection moulded and afterwards plated in a hot embossing process and assembled with chip resistors of various sizes. The samples were then exposed to a temperature shock test to investigate their long-term reliability.

For electronic circuit carriers, thermal requirements should be considered during the selection process of thermoplastic substrate materials in particular, along with the good adhesiveness of the metallization on the substrate. Besides, the operating temperatures, the thermal loads during soldering processes are also important. Owing to the fact that the glass transition temperatures of most of these polymers are below the mentioned requirements, the category of semi-crystalline high-temperature thermoplastics seems to be most suitable. In contrast to amorphous thermoplastics, these polymers offer good mechanical strength and high-dimensional stability even between the T_g and the melting temperature (Ehrenstein, 1999; Ehrenstein and Pongratz, 2000). Additional criteria, shown in Figure 2, were considered during the selection of materials.

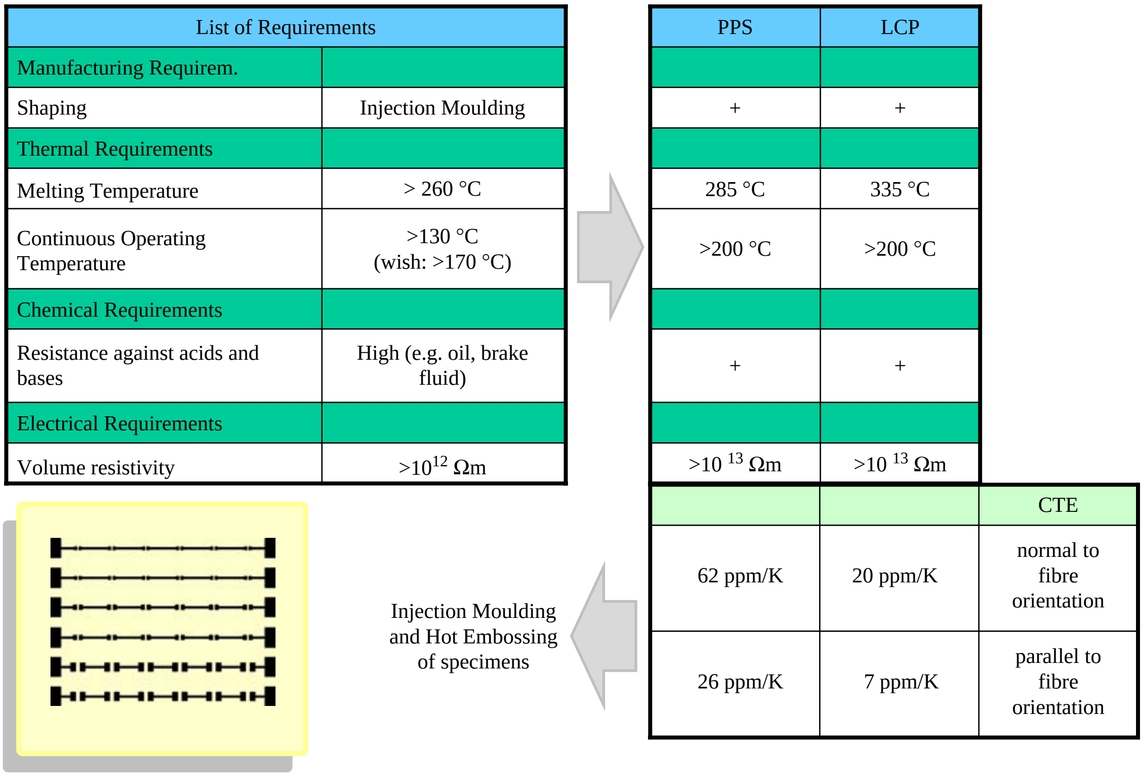
Among other thermoplastics, polyphenylenesulfide (PPS) and liquid crystal polymer (LCP) were examined. They offer melting temperatures that are high enough for lead-free reflow soldering. Both polymers were reinforced with glass fibres to enhance the heat deflection temperature and to reduce their CTE compared to the pure plastic matrix. However, this compounding causes an anisotropic CTE inside the working piece because of fibre orientation after the injection moulding. As known from electronic devices based on FR4 PCBs, the proportion of the CTE of the components of an electronic device plays an important role concerning the long-term reliability under thermal loads. Differing CTEs lead to mechanical tension caused by temperature gradients induced during soldering or usage, which have to be compensated by the solder joints or the connection of the metallization and the substrate. This again can lead to a failure of the electronic devices.

For MIDs with complex shape and line/space widths larger than 300 μm, hot embossing is an established process to apply and structure a conductive metallization onto the thermoplastic body (Forschungsvereinigung Räumliche Elektronische Baugruppen 3D MID e.V., 2004). The major advantages of this structuring process are the absence of any chemical or galvanic metallization processes and low-investment costs at high throughput. In the hot embossing procedure the circuit track layout is sheared off an embossing copper foil by a structured stamping die mounted on a press. The die is heated above the glass transition temperature of the substrate-thermoplastic. After cutting, the foil is embossed onto the substrate within the same stroke of the press. Thereby, due to the heat of the die, the thermoplastic substrate is melted locally and the heated low-viscosity polymer surrounds the undercuts of the roughened lower surface of the copper foil. After the die has been removed, a form fit between thermoplastic and embedded copper foil develops. The quality of the joint is highly influenced by the embossing time, pressure and temperature of the embossing tool. On one hand, the adhesive strength is improved with growing parameter settings in general. On the other hand, bigger embossing beads are generated. They are a result of melted substrate material that squeezes out from underneath the conductive patterns due to the embossing pressure. Accordingly, there is a risk of tombstone-effects during reflow soldering if the SMD components are placed onto the beads in the assembly process. Thereby, the pivot shifts from the edge of the component towards the centre for low tilt angles during the erecting progress. On the one hand, the gravity force can generate only a low moment that keeps the component down due to the short distance between pivot and centre of gravity and, on the other hand, the leverage from the forces caused by the surface tension of the molten solder-meniscus increases. In consequence, the beads should be kept as low as possible.

As both target sizes – high peel strength and low embossing beads – are contrary, in several embossing experiments a process latitude was generated for each polymer using design of experiments (DoE) guidelines. With DoE software a mathematical model that describes the correlation between the three main influencing variables and each target size was generated. Besides, the 1.4 N/mm for minimum peel strength (according to DIN IEC 249 and in dependence on the peel strength on FR4), the upper limit for the embossing beads was set at 100 μm. This empirical value is appropriate to SMD components down to a packaging-size of 0402. The combination of both models concerning the mentioned limits results in a process latitude from which parameter settings for PPS can be deduced. With the focus on short embossing times, settings were chosen and a circuit track layout for two-pole components was embossed onto circuit carriers moulded from each high-temperature thermoplastic. While the embedded foil showed good adhesion on the PPS (1.9 N/mm), no peel strength higher than approximately 0.7 N/mm was obtained for LCP. However, it was not the bonding between substrate and metallization but the polymer matrix itself which broke up during peel testing. This means that the plating on this thermoplastic would be insufficient for use in electronics production according to DIN IEC 249. In spite of this deficit, specimens made of LCP were embossed with an adhesion strength fluctuating around 0.5 N/mm.

For further examinations, SMD chip resistors with dimensions of 1206, 0603 and 0402 were assembled on both thermoplastic substrates after solder paste had been applied by a dispenser on the embossed conductor pads. The design of the pads enabled a component alignment orthogonal to the orientation of the glass fibres in PPS and LCP. In this direction the CTEs of the polymers reached their highest values so that the difference between the elongation of component and substrate due to temperature gradients also reached its maximum value. Depending on the component dimensions, this thermal mismatch generates mechanical tensions which are almost completely absorbed by the solder.

Figure 2 Selected high-temperature thermoplastics and appearance of the specimens after moulding and hot embossing



List of Requirements		PPS	LCP
Manufacturing Requirem.			
Shaping	Injection Moulding	+	+
Thermal Requirements			
Melting Temperature	> 260 °C	285 °C	335 °C
Continuous Operating Temperature	>130 °C (wish: >170 °C)	>200 °C	>200 °C
Chemical Requirements			
Resistance against acids and bases	High (e.g. oil, brake fluid)	+	+
Electrical Requirements			
Volume resistivity	$>10^{12}$ Ωm	$>10^{13}$ Ωm	$>10^{13}$ Ωm

PPS	LCP	CTE
62 ppm/K	20 ppm/K	normal to fibre orientation
26 ppm/K	7 ppm/K	parallel to fibre orientation

Owing to the fact that both solder menisci at a two-pole component are virtually never developed uniformly, especially the weakest joint is loaded mechanically and a deformation of the solder joint emerges. Accumulating deformations resulting from cycling thermal loads can cause fatigue crazes up to cracks. An electrical and, in some cases, mechanical malfunction is the consequence (Klein Wassink, 1991).

To examine the long-term stability of the solder joints on every thermoplastic, the specimens were subjected to an accelerated aging test and therefore stored in a climatic chamber for temperature shock cycling between −40 and +125°C for 1,000 cycles, with a dwell time of 15 min on each level. Every 250 cycles the devices were removed and the quality of the solder joints was examined. The electrical contact resistance for each component was measured and also a shear test displaying the mechanical strength of the joints was realised.

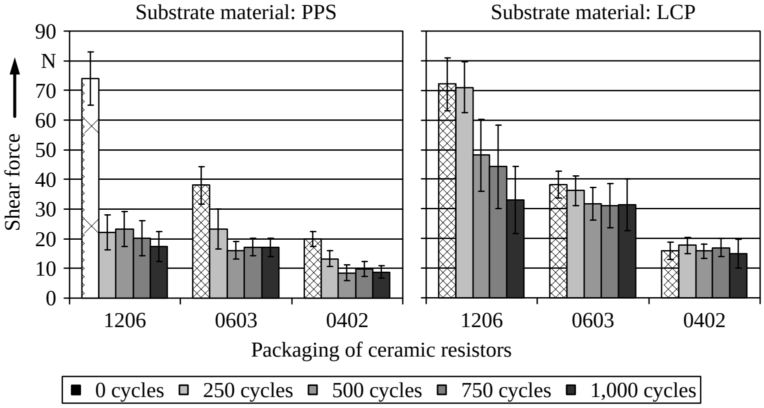
For PPS, a rapid drop in shear strength could be detected in comparison to LCP-substrates, which can be seen in Figure 3. Owing to the high-thermal mismatch between the PPS and the ceramic components (CTE = approx. 7 ppm/K), solder joints tend to fail at the 1,206 components in particular. Already in an early stage of the shock test the investigated shear forces start to level off. This shows that the measured mechanical strength is affected merely by one solder joint. Although the LCP failed in the peel strength test, a very good durability of the solder joints was found on these substrates. There is no significant decrease in shear strength, especially for 0603 and 0402 components. Defining a maximum permissible contact resistance of 40 Ω by the measuring instrument only one electrical malfunction was detected after 1,000 cycles for the LCP-MIDs, whereas the electrical failure rate increases dramatically for PPS; up to 40 per cent for 1,206 components at the end of the test. Then a probability of an electrical malfunction of around 15 per cent can be examined for resistors with 0603 and 0402 packaging.

The experiments have shown that high-temperature thermoplastics can be alternative substrate materials for high-temperature applications in the automotive industry, but that further research is required. Considering thermal loads only, the question comes up if it is target-aimed to adopt standards for the manufacturing of FR4 PCBs for thermoplastic substrate materials without any adaptation. Although the LCP offers low adhesion strength of the metallization, it is an appropriate substrate material for electrical circuits. Owing to the low CTE, a high long-term reliability is enabled if the devices face accumulating temperature gradients. If a good adhesion of the metallization is necessary, PPS can be used. Then the high CTE of this thermoplastic can be compensated by adapting the component-size on one side. On the other side, the layout-design of the circuit tracks should take the fibre orientation of the injection moulded substrate into consideration.

Novel packaging technologies and interactions in reliability testing

The reliability of electronic devices for advanced requirements depends on a variety of different factors and occurring interactions. The product design, the materials of the components and the manufacturing technologies used have significant effects on parameters for the reliability of electronic devices. The identification of relevant parameters and the quantification of their effects is quite complex and

Figure 3 Measured shear force during temperature shock testing



assumes a detailed knowledge of all existing failure modes and defect mechanisms (Wilde, 2006). Additionally, the efficiency of established and applied environmental tests, especially of sequential test procedures, to evaluate the reliability of electronic devices is controversial and not well investigated (Basaran *et al.*, 2001).

By means of a test assembly, that is shown in Figure 4, different aspects concerning parameters for reliability, failure modes and defect mechanisms were analyzed. Furthermore, the efficiency of environmental tests in sequential test procedures was pointed out. The FR4 PCB used had a length of 160 mm, a width of 100 mm and a thickness of 1.5 mm. The chosen surface metallization was a chemical tin. A significant selection of different components was assembled onto the PCB using a type 3 solder paste (SnAg3Cu0.5). The assembled surface mount components were QFP, QFN, BGA, CR (chip resistors) and MELF (metal electrode leadless face) with different package dimensions and package designs, as well as varying miniaturization levels.

The novel QFN packaging technology is characterized by a high-miniaturization level and optimized thermal, inductive and capacitive characteristics. QFN packages have their terminal areas at the edges of the bottom side of the component. Usually, QFN packages possess an additional thermal pad in the middle of the bottom side to facilitate improved heat dissipation from the component to the PCB. The evaluation of this novel packaging technology was realized by two different housing types of QFN. The QFN types, saw and punch, differ in their kind of gapping and singling at the manufacturing process. According to this, the geometry of the terminal areas of both QFN types, which are shown in Figure 5, are not equal. This leads to a differing solder joint shape characteristic between component and PCB. The solder joint reliability of both housing types was evaluated in a temperature shock test (1,000 shock cycles, −40°C lower temperature, +125°C upper temperature, 15 min dwell time).

Stressing of assembled QFNs in the temperature shock test resulted in 100 per cent electrical defects of punch type QFN in temperature shock test, while saw type QFN did not show electrical failures at this loading. The defect mechanism of punch type QFN is massive cracks in the solder joint. The appearance of solder joints of both QFN types and the crack characteristics of punch type QFN are shown in Figure 6.

The different behaviour of both QFN types in thermal shock testing is not yet completely understood. It is supposed that the height of the gap between the land area of the PCB and the terminal area of the QFN has a straight influence on the generation and propagation of cracks in the solder joints. In consideration of the increased solder rising at the edge of the punch type QFN, the resulting gap seems to be smaller than that of saw type QFN. It is assumed that the higher shear

Figure 4 Test assembly and objects of research

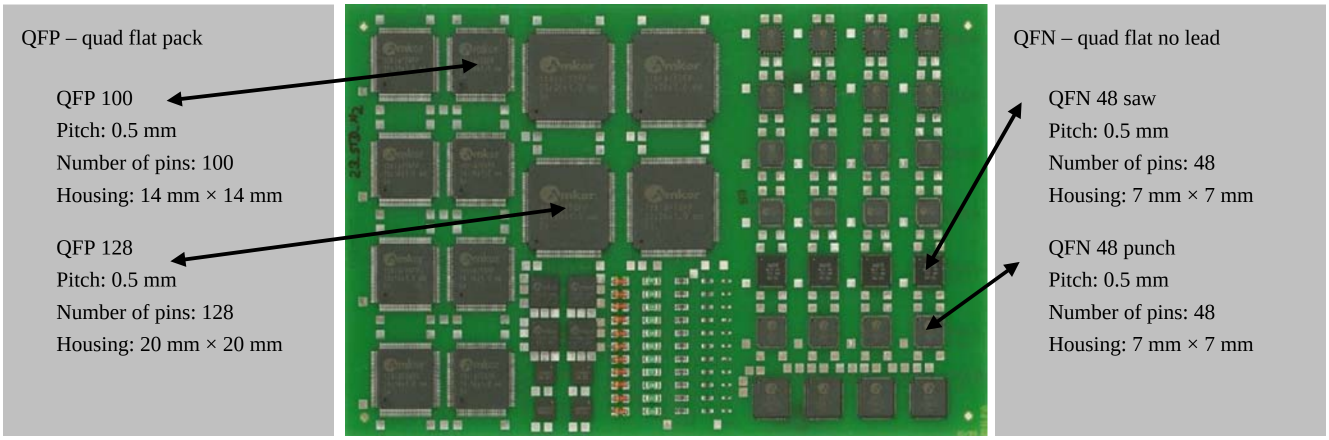
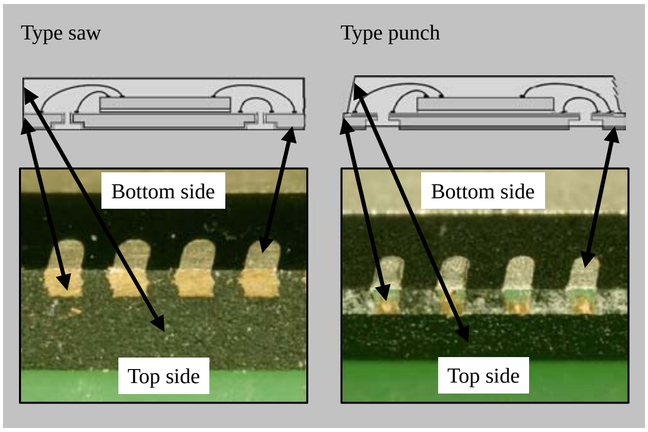


Figure 5 Characteristics of terminal areas of QFN types saw and punch type QFNs



stress between the gap of punch type QFN leads to a faster crack generation and propagation in comparison to saw type QFN. Further research activities will be conducted to learn more about this defect mechanism.

Research into the effects of different environmental tests and possible interactions was realized on two different types of QFP. The QFP used had a pitch of 0.5 mm and 100 or 128 pins. The applied environmental tests were temperature shock (500 shock cycles, −40°C lower temperature, +125°C upper temperature, 15 min dwell time) and vibration (according to IEC 60068-2-64). The test procedures were applied in alternating sequence. The effect of the environmental tests on QFP solder joints was verified by determination of peel strength of QFP pins. The approach of for the peel strength determination and the test construction are shown in Figure 7.

The peel strength of pins was captured for five different conditions. Besides, the initial condition, the peel strength determination was also conducted after temperature shock and vibration testing. Additionally, the peel strength after both sequential test procedures of temperature shock and vibration, respectively, and vibration and temperature shock was measured.

Figure 8 shows the decrease in peel strength after temperature shock in comparison to the initial condition, while peel strength after vibration remains approximately at a constant value in comparison to initial conditions. Disregarding potential interactions between both loading types, a possible conclusion is that vibration does not have any effect on peel strength. In consideration of the resulting peel strength after the sequential test procedures, temperature shock/vibration and vibration/temperature shock, the existence of interactions between temperature shock and vibration is evident. Comparison of the resulting peel strength for temperature shock and the sequential test procedure temperature shock/vibration shows, that vibration especially causes degradation of peel strength under specific circumstances.

The reason, therefore, is founded in the failure modes and defect mechanisms of the QFP solder joints at different loading types. The different thermal expansion coefficients of the QFP and the PCB lead to varying material expansion in temperature shock cycling. The solder joint has to withstand the resulting stress with the consequence that cracks occur and propagate between the QFP pins and the solder material. On this account, the peel strength of temperature shock loaded QFP solder joints decreases. In relation to this, an exclusive vibration load does not result in a decrease of peel strength, because the QFP solder joint is not fatigue critical for this vibration load. A sequential test procedure of temperature shock first and then vibration, has the effect that existing cracks in the solder joints grow due to the vibration load. This leads to a further decrease of peel strength in vibration testing if temperature shock cycling was previously conducted.

Conclusion

The growth of electronic functionality in automobiles exposes electronic devices to advanced thermal and mechanical loads that necessitate an optimization of boards as well as the interconnection materials and electronic components themselves. High-temperature thermoplastics like PPS and LCP offer high potentials as alternative substrate materials to conventional FR4 PCBs if there are temperatures above 125°C. Evaluations show that the high CTE of PPS challenges the selection of electronic components and the electronic circuit design to achieve an acceptable long-term reliability of the device. Progressive research has to be done to determine to what extent the low-adhesion strength of the metallization on LCP substrates is crucial for the applicability of this thermoplastic as a circuit carrier. The low CTE makes LCP an especially appropriate substrate material for usage under alternating thermal loads. Concerning the long-term reliability of electronic components, several tests with

Figure 6 Solder joint appearance and crack characteristic

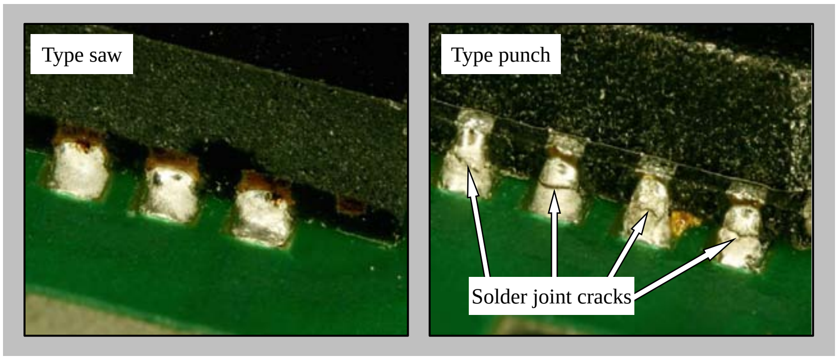


Figure 7 Test construction and principle of peel strength determination

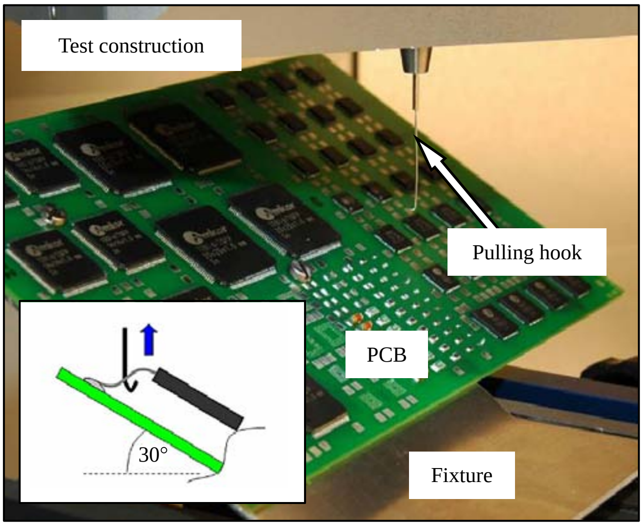
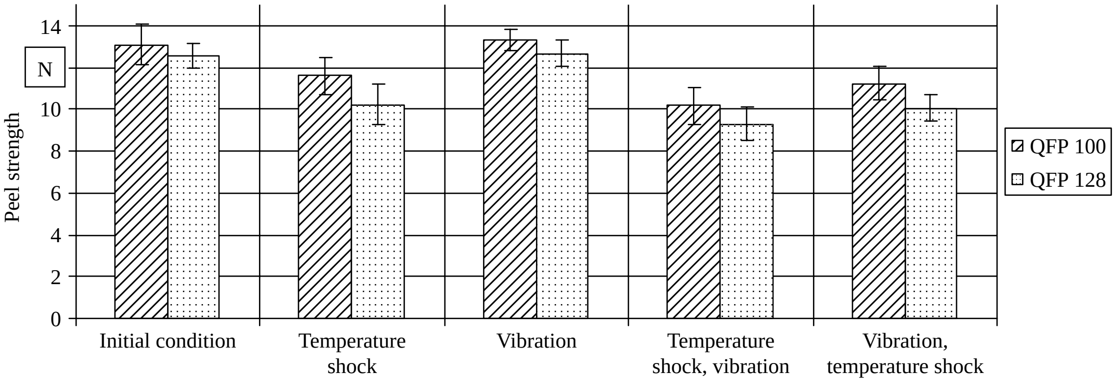


Figure 8 Peel strength of QFP pins



standard FR4 substrate materials were accomplished. Initial results have shown that the reliability of QFN depends significantly on the housing type of this package. The reason for this behaviour is not yet fully understood and will be analyzed in further studies. However, it is evident that punch type QFN fails because of crack generation and propagation while saw type QFN does not show this defect mechanism due to temperature shock load after 1,000 cycles. Furthermore, the relevance of sequential environmental test procedures and their effects on the peel strengths of QFP solder joints has been highlighted. It has also been demonstrated that particularly the existent interactions between different environmental tests and the arrangement of single procedures in environmental test sequences have a significant effect on solder joint reliability.

The research findings presented in this paper were gathered within the Collaborative Research Centre 694 "Integration of electronic components in mobile systems" which was established in 2006 at the Friedrich-Alexander-University Erlangen-Nuremberg and is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG), Friedrich-Alexander-University Erlangen-Nuremberg and the Free State of Bavaria.

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