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Effect of voids on thermo-mechanical reliability of chip resistor solder joints: Experiment, modelling and simulation☆

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ABSTRACT

With the introduction of lead-free solder alloys, the effect of voids on solder joint reliability has rapidly gained importance. In this study, a first analysis of X-rayed CR0805 solder joints shows a significant reduction in void content, from 20% down to 2.5%, after vacuum soldering. The statistical analysis of the void distribution demonstrates that the vacuum option reduces number of voids and median diameter of voids in comparison to the convection soldering process. A subsequent accelerated thermal cycling test of these analysed test vehicles, according to JESD22-A104D, indicates the tendency of a higher characteristic life time for higher void content. In contrast to these findings, the 1% to failure criterion reveals a higher reliability for lower voiding. During the finite element method (FEM) modelling part of this study, two modelling approaches of void implementation into solder joint geometry are investigated: modelling with a constant volume of the standoff for different void contents, and a modelling approach with a random combination of void content and volume of standoff. The modelling approach with the random combination reveals that voids can reduce the lifetime in the "worst case" parameter combination. In particular, the 1% time to failure rate indicates a quantitative correlation with the experimental results. Furthermore, the FEM results suggest a higher impact on reliability for a single void in comparison to a distribution of multiple voids with similar void content. Finally, the FEM study shows a high sensitivity of predicted life time with respect to the standoff height. Based on this finding, the CR0805 solder joint geometry is examined using optical inspection and cross-section polishes with the outcome that the better wetting behaviour during vacuum soldering causes a reduction of the solder alloy volume and consequently further decreases the standoff height.

1. Introduction

In electronic products, solder joints must execute electrical, thermal and mechanical connections between a circuit carrier and its different SMD components. Environmental loads, such as thermal cycling, vibrations and impacts on an electronic assembly, primarily lead to failure in the solder joints [1]. For this reason, great attention must be given to the quality and reliability of the performance of solder joints. Voids are classified as a type of defect in solder joints. The acceptance criteria for voiding in solder joints have been defined by standards and company-specific regulations. The IPC-7095-C and DIN EN 61191-6 have provided an overview of the types of voids and their locations in ball grid arrays (BGAs) and land grid arrays (LGAs) [2,3]. The IPC-A-610E has defined the standard for the void content in BGA balls [4], which dictates that voids should occupy a maximum of 30% of a single ball's area on an X-ray image. This limit is based on the results from several experimental and numerical investigations on voiding in BGA solder balls. Experimental investigations have shown that voids can be larger than 25–30% of the bump area, and their size and distribution can influence the reliability of solder joints during a thermal cycling test [5–8].

There is currently only limited knowledge about the impact of voids on the reliability of two-terminal components, such as chip resistors and capacitors, is limited. According to research on vacuum soldering [9], up to 13% of voids in the standoff area of CR1206 and CR0603 have a positive effect on failure behaviour at a −55/+125 °C accelerated

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temperature cycling test. However, according to [10], the CR3216 resistors with < 10% void content after soldering with vacuum demonstrated 20% higher reliability during thermal cycling tests between −40/+85 °C and −40/+125 °C, which was estimated with a 0.2% cumulative failure rate. The different conclusions from investigations of the same phenomenon can be attributed to the high complexity of the problem to be solved. During the estimation of correlations between the void content and reliability an vast quantity of parameters must be considered: similar amount of solder paste, geometrical shape of the solder joints and the components, deviation of material-specific parameters, such parameters include the coefficient of thermal expansion (CTE) and elastic modulus, aging behaviour of materials, type and accuracy of the failure detection method and so on. [5,6,11].

A further possibility in the study of the effect of voids can be realised by using FEM. In comparison to the experimental methods, the use of FEM enables only one factor to be changed, such as the void size, while another is kept constant, or parameters can even be excluded. For the prediction of solder joints' life-times the material models of FEM can reproduce the most important material laws. Some limitations exist for the implementation of aging behaviour and micro-structure transformation due to the thermal loads [12–15]. As an indication for higher or lower reliability, the accumulated creep strain or plastic work in a solder joint must be calculated by FEM. According to [16], when modelling voids into BGA solder joint geometry, the standoff height should be adjusted. This recommendation is based on the assumption that the volume of solder alloy is constant, so the additional volume of voids increases the total volume and consequently increases the standoff height. The FEM results from this study demonstrate an impact on BGA solder joint reliability of void content that is > 35%. The results from [17] have shown that small voids can arrest the damage propagation, except when a large portion of the damage propagation path is covered with voids. Another possibility for modelling crack propagation using the irreversible cohesive zone model was demonstrated by [18]. The results of this numerical study expressed a lower reliability of solder interfaces when a void is closer to the pre-crack location. Insufficiently, the cohesive zone model replicates only the separation between the solder and substrate layer, and it can be applied for thin layers. Another simulation method with the modified Gurson-model allows estimation of the crack path in solder joints depending on the void content and thickness of intermetallic layers [19,20]. In fact, this model can be applied for static or impact loads, though it requires further investigation to implement for cycling loads.

2. Experimental and numerical procedures

To investigate the effect of voids on solder joint reliability, this study was implemented in two stages: First, the void content, geometry of components and life time of CR0805 solder joints were estimated in an experimental portion. Based on these results, void modelling and damage calculation methods with FEM were investigated.

2.1. Statistical characterisation of voiding for FEM modelling

To generate the varied void contents in CR0805 solder joints, three different soldering processes were applied: convection soldering under air, condensation, and condensation soldering with a vacuum. Fig. 1 shows the X-rayed CR0805 solder joints on Vectra with a NiAu surface finish. The void's size and distribution were analysed with ImageJ. This tool allows to adjust the circularity factor and about 95% of the voids demonstrate a circularity factor 0.8–1 (1 means a perfect circle shape). For this reason, the modelling approach includes only the voids with circular shape.

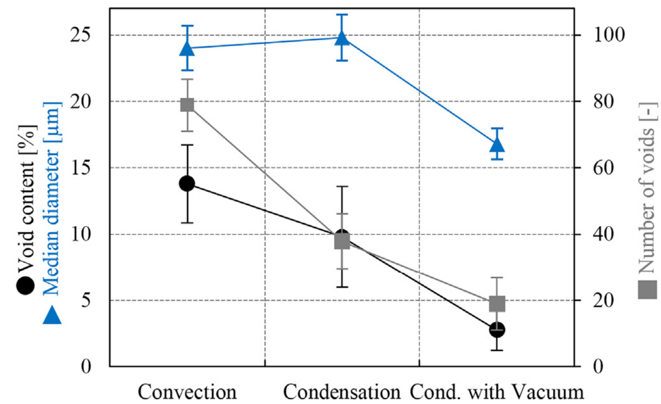

Fig. 2. Statistical characterisation of 10 X-rayed CR0805 solder joints on Vectra for the applied soldering processes (only the standoff area was analysed).

As shown in Fig. 2 (black line), significant reduction in void content in CR0805 solder joints was achieved from maximum of 20% down to 2.5%. The total percentage of void area in a solder joint can be divided into two parts: the number of voids and the median void diameter. The comparison of void content in Fig. 2 to the number of voids and their median diameter indicates that the reduction of void content after vacuum soldering is mainly induced by the reduction of void quantity. In the next step, the distribution of voids over the standoff area was analysed. The X-ray images were divided into similar areas and the void number in each area was calculated using the x- and y-coordinates (Fig. 3a, b). After the overlaying of 10 images, the void frequency over the standoff area was visualised with Minitab, as shown in Fig. 3(c). Further important information on FEM modelling is represented by the different diameters of the voids. The histogram of the 10 analysed standoff pictures in Fig. 4(a) demonstrates that most of the voids have a diameter of 24 µm. For FEM modelling, this distribution was approximated with that in Fig. 4(b). After superposition of this histogram with the information about void position in Fig. 3(b), a symmetrical void distribution representing the analysed X-ray images for convection soldering was generated, as shown in Fig. 4(c).

2.2. Experimental life time estimation

To investigate the effect of void content on the reliability of SMD soldered joints, the accelerated thermal cycling test according to JEDEC standard JESD22-A104D Condition G [21] was performed using a thermal shock test chamber. The upper and lower holding temperatures measured on the substrate were +125 °C/−40 °C with 10 min of a holding time, which refers to the time elapsed until +125 °C or −40° was achieved. The test vehicles were electrically connected for the online resistance measuring, and the failure criterion was defined by 1000 Ω, 2000 Ω and an infinite value for the parallel connection of CR0805. A complete description of the experimental setup is available in [22]. The accelerated thermal test was stopped after 13,325 cycles.

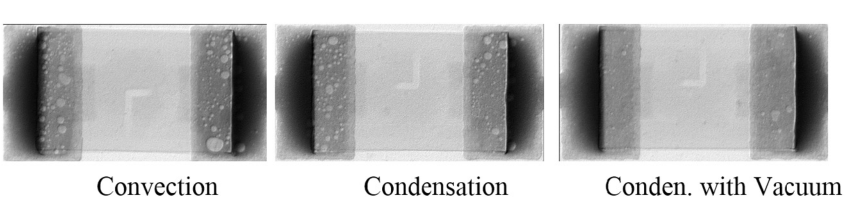

Fig. 1. X-rayed CR0805 components on Vectra after soldering with different processes.