https://www.sciencedirect.com/science/article/abs/pii/S0026271424000398

Numerical investigation of solder joint shape for micro-spring package during vacuum vapor phase soldering

Highlights

The model of the micro-spring package was developed to predict the solder joint shape.

The finite volume method was used to understand the wetting and spread process of the molten solder.

The influence of pad diameter and solder volume on the shape of solder joint shape was studied.

The accuracy of the numerical model was verified by experimental results.

Abstract

The novel micro-coil spring package has become a new choice for reliable applications in extreme temperature change, high-strength impact, long-term vibration and other harsh environments due to the advantages arising from its special packaging design. The study of solder joint shape is an important step in the characterization of the package reliability. By Ansys Fluent software, the finite volume method was applied to investigate the flow behavior of molten solder during vacuum vapor phase soldering and the volume of fluid model was used to track the solder melt front. The simulation results reveal the effect of two critical process parameters (solder volume and pad diameter) on solder joint shape in micro-spring array package. The fillet height of the solder joint increases with decreasing pad diameter and decreases with decreasing solder volume. The optimal solder volume is 0.07 mm^3 coupled a pad diameter of 0.80 mm, producing suitable fillet height and nice concave fillet shape, which is in agreement with the real sample of micro-spring soldering joint. The good consistency between experiment and simulation proves that the finite element method can effectively predict the shape of the melted solder. This work paves the way for the optimization of the solder joint shape in the electronic assembly.

Introduction

With the development of electronic products to miniaturization, lightweight and high performance, the density of electronic assembly is on the rise. Large-scale integrated circuits (IC) are changing from the traditional four-sided pin packages represented by quad flat package (QFP) to the bottom array packages characterized by ball grid array (BGA) and column grid array (CGA). Nevertheless, there is a substantial disparity in the coefficient of thermal expansion (CTE) between the alumina ceramic substrate and the glass epoxy printed circuit board (PCB), giving rise to a serious thermal mismatch. Electronics in aerospace, avionics and military applications are subject to extreme temperature cycle, high-G shock and prolonged vibration, so these packages fail to meet the requirements of high reliability and long life service [[1], [2], [3], [4]].

In response to these challenges, a novel interconnect form called the micro-coil spring (MCS) was developed by the National Aeronautical and Space Administration (NASA) as a substitute for solder columns in 2012 [5]. The micro-springs possess enhanced flexibility to withstand the shear forces resulting from the CTE mismatch and are better equipped to absorb the impact induced by the external vibration on the device. Micro-springs are typically made of beryllium copper

(Be Cu) alloy C17200 and plated with tin-lead solder (Sn60Pb40) or nickel-gold (Ni Au). In 2011, NASA [6] carried out a systematic study on the reliability of the board-level assembly of MCS package. Thermal cycling testing was executed on the assembled components of both MCS and ceramic column grid array (CCGA). The results showed that the maximum number of cycles for CCGA was about 1600, whereas the number of MCS was 4760 cycles. In addition, vibration testing was also conducted and revealed that cracks appeared the solder joints of CCGA while the solder joints of MCS remained intact under identical conditions. In 2013, a research was conducted by NASA [7] to assess the board-level interconnection reliability of three packages: pure solder column, copper-wrapped solder columns and micro-coil spring through thermal cycle test. The findings indicated that minimal damage occurred to the solder joints of MCS. The drop tests on MCS package were carried out by Topline in 2014, indicating that MCS withstood eight shocks before failure, while CCGA of Sn10Pb90 endured only four shocks [5]. The impact resistance and failure modes of MCS and CGGA packages were also investigated by Lall [8]. All findings consistently pointed to the superior reliability of MCS in relieving thermal mismatch as well as in resisting vibration and impact, compared to CCGA.

As MCS is a new packaging structure, it is very important to study its soldering process. The researches [[9], [10], [11]] showed that the reliability of interconnected solder joints depends on various factors, including the solder joints' appearance, the CTE of material, the physical properties of solder paste and the loading conditions of thermal and mechanical. Notably, the solder joint shape plays a prominent part in the soldering reliability. The so-called solder joint shape refers to the geometric structure after solidification, along with the associated parameters such as pad diameter, solder volume and other. Currently, Hart determined the diameter and length of the micro-spring according to the typical size of solder columns [12]. The micro-springs were mounted on pads that are 25 % larger in diameter to form fillets both inside and outside of the spring. Hart also mentioned that the formation of solder joints was closely related to the solder paste thickness and the pad size. For MCS, the solder paste was generally placed using the steel stencil with a thickness of 0.15 mm and the fillet height of solder joints could not exceed two and a half loops of the springs. The aperture of stainless stencil was 38% smaller than the pad diameter to check the printing condition of the solder paste. Moreover, Ghaffarian from California Institute of Technology found that there was a significant relationship between the failure position and the solder volume for CCGA560 package [13].

Therefore, the reliability of solder joints is influenced by the solder volume. It was reported that some researches had given specific standard of the solder volume in CBGA and CCGA packages [14,15]. But the relevant content of CCGA cannot be directly applied to MCS due to obvious discrepancies between the micro springs and solder columns. In contrast to the comprehensive application of CCGA, there is still a lack of systematic research on MCS. As far as author's knowledge, there is no literature focusing on geometric shape of the solder joint for MCS. The solder joint shape directly affects the precision of mechanical properties and reliability analysis. The exploration of solder joint shape prediction dated back to the 1980s [16,17] and research evolved from the initial two-dimensional morphology and axisymmetric models to the latest three-dimensional model. Finite element method (FEM) increasingly gained attention from researchers as a preferable alternative to traditional methods [[18], [19], [20], [21]]. Thus, the computational fluid dynamics (CFD) was used to simulate the flow behavior of molten solder in this work.

Because of the particular structure of micro springs, there are quite differences in the wetting and spreading of the melting solder compared to the traditional column structure. This study aims to analyze the influence of various pad sizes and solder volumes on the solder joint shape in MCS package. Through the Workbench platform from ANSYS 2022R2, a two-phase flow prediction method based on the volume of fluid (VOF) is developed for numerical investigation of the fluid flow process. Factors such as surface tension, gravity, and contact angle take into consideration during the calculation. The optimal process parameters are determined by varying the solder volume and pad diameter. Finally, the predicted solder joint profile was substantiated by the experiment results.

Section snippets

Experimental work

In the experiment, eutectic Sn63Pb37 solder paste was used to connect micro-springs to copper pads on the ceramic substrate. The solder has a nominal melting point of 183 °C and favorable wettability behavior. In order to match the substrate, the steel stencils were customized and its opening aperture was the same as the pad size. Rehm Condenso XM vacuum vapor phase soldering system was utilized as experimental equipment. The schematic diagram of vacuum vapor phase soldering is shown in Fig. 1.

Methodology

This paper used Ansys Fluent software to understand the wetting and spreading process of the molten solder. The finite volume method (FVM) was employed to describe the solder flow aiming to replicate the authentic flow behavior during the vacuum vapor phase soldering. Suppose that both solder and air were incompressible, and the molten solder was modeled as Newtonian fluid with a constant viscosity.

Grid independent test

Computing time, cost and result accuracy are mainly influenced by the meshing number, so dividing the computational area into grids is a fundamental task in CFD simulation analysis. To examine the sensitivity of meshes to predicted results, a grid independent test (GIT) was performed

on the meshing elements of the simulation model as shown in Fig. 7. Generally, the more the number of meshes is employed, the better results are obtained. However, there exists a saturation point beyond which

Conclusion

In this study, the simulation process was carried out with a full integration of the geometric modeling, mesh generation, solving and post-processing by the ANSYS Workbench platform. The VOF method was used to capture the location of free surface and the CFD study was performed to simulate the melting shape of the solder. The relevant parameters influencing the MCS solder joint shape have been discussed.

The error between the experimental results and the simulated data is <10 %, indicating that

Credit authorship contribution statement

Xiaomin Li: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Ping Wu:** Conceptualization, Methodology, Supervision, Resources, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no competing financial and nonfinancial interests.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (51572190).

References (32)

- Y. Ding *et al.*

  Coupling effects of mechanical vibrations and thermal cycling on reliability of CCGA solder joints

  Microelectron. Reliab.

  (2015)

- R. Ghaffarian

  CCGA packages for space applications

  Microelectron. Reliab.

  (2006)

- A.M. Najib *et al.*

Numerical simulation of self-alignment of chip resistor components for different silver content during reflow soldering

Microelectron. Reliab.

(2017)

- M.S. Abdul Aziz *et al.*

CFD modeling of pin shape effects on capillary flow during wave soldering

Int. J. Heat Mass Transf.

(2014)

- B. Illés *et al.*

Numerical modelling of the heat and mass transport processes in a vacuum vapor phase soldering system

Int. J. Heat Mass Transf.

(2017)

- C.Y. Khor *et al.*

Investigation of the fluid/structure interaction phenomenon in IC packaging

Microelectron. Reliab.

(2012)

- C.T. Lin *et al.*

Contact angle of 63Sn–37Pb and Pb-free solder on Cu plating

Appl. Surf. Sci.

(2003)

- M. Abtew *et al.*

Lead-free solders in microelectronics

Mater. Sci. Eng. R-Rep.

(2000)

- J.U. Brackbill *et al.*

A continuum method for modeling surface tension

J. Comput. Phys.

(1992)

- T. Lu *et al.*

Vibration and thermal fatigue reliability of CCGA components