Engineering Fracture Mechanics 199 (2018) 730–738

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Effect of temperature on the fracture behavior of Cu/SAC305/Cu solder joints

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ARTICLE INFO

Keywords:
Temperature effect
Lead-free solder
Intermetallics
SAC305 fracture
J-integral
Interface fracture

ABSTRACT

Double cantilever beam (DCB) specimens consisting of Sn96.5Ag3.0Cu0.5 (SAC305) solder sandwiched between two copper bars were fabricated under standard surface mount processing conditions. Mode-I fracture tests were performed on the DCB specimens under various temperatures. The load–displacement behavior and critical loads corresponding to crack initiation were recorded and used in a finite element model of the DCB to evaluate critical energy release rates. Fracture surfaces were analyzed to understand the effect of temperature on crack path and fracture mechanism. The critical energy release rate decreased from 603 at −50 °C to 93 J/m^2 at 100 °C and the crack path shifted from solder/intermetallic compound interface to bulk solder.

1. Introduction

One of the primary failure modes of microelectronic packages is cracking of solder joints due to thermal and mechanical loading conditions experienced by packages throughout the course of their assembly, testing, and service life. Extensive research work has been carried out on the failure of microelectronic packages due to thermal fatigue loads; failure due to pure mechanical loading on the other hand has not received much attention. With an increase in the usage, i.e., almost exponential growth, of handheld devices such as cellphones and notepads, failure due to pure mechanical loads is becoming an important reliability issue; this is especially true in higher density array packages, larger printed circuit boards and electronic devices for aerospace and automotive applications, where mechanical loads could be a significant cause of failure during service and assembly [1,2]. Fig. 1 shows a schematic of one such high density ball grid array (BGA) package. Hence, strength of solder or its resistance to crack propagation under pure mechanical loads is an important problem that needs to be investigated.

At present the experimental methods used by microelectronics industry to evaluate the strength of solder joints under mechanical loads are primarily qualitative [1–6]. These tests do not provide fundamental mechanical properties which can be used to predict the failure of joints in other configurations or under different loads. Therefore, tests such as the ball shear [1,2], ball pull [3], board level bending [4] and board level drop tests [5,6] are useful for quality control, but do not yield any data that can be used for failure prediction. A robust failure criterion based on a fundamental failure property of the joint that is independent of joint geometry will enable accurate failure prediction. Such a criterion is essential to design high-performance and highly reliable microelectronic packages.

The critical strain energy release rate, G_c, as a function of the mode ratio of loading as a failure criterion has been used widely to predict the failure loads of adhesive joints [7–9]. G_c is an indication of the ability of a material or joint to resist crack propagation.

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https://doi.org/10.1016/j.engfracmech.2018.07.004
Received 12 January 2018; Received in revised form 25 June 2018; Accepted 4 July 2018

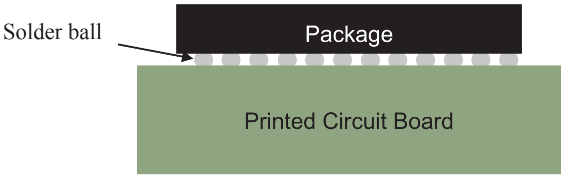

Fig. 1. Schematic of BGA package.

Nadimpalli et al. [10] have extended these fracture mechanics-based methods to characterize solder joint failure under mixed-mode loading in terms of critical energy release rate, G_c; they have also investigated the effect of processing conditions such as time above liquidus temperature on G_c. Later, Huang [11] used the approach to investigate the effects of dwell time, cooling rate, and aging on the fracture properties of Sn95.5Ag3.8Cu0.7 (SAC387) solder. Nadimpalli et al. [12,13] successfully used fracture based failure criterion, i.e., critical value of J-integral, to predict the failure loads of lead-free solder joints under mixed-mode, i.e., a combination of tensile and shear loading conditions. However, the focus of the above studies [1–13] was on the fracture behavior of joints under room temperature conditions. The effect of temperature on the fracture properties of lead-free solder has not been investigated before.

Mechanical behavior, including fracture, of various materials strongly depends on temperature [14]. For example, Kanel et al. [15] have studied the dynamic fracture properties of aluminum and magnesium at various temperatures ranging from room temperature to near melting temperature and showed that the material's spall strength dropped steeply as the temperature approached the melting point. Similarly, Zhu et al. [16] found that the tensile and impact strength of dissimilar welds in rotor steels decreased significantly with increasing temperature. The mechanical properties of Pb-free solders also strongly depend on temperature [17,18]; these properties, including Young's modulus and yield stress, both decrease with temperature. Additionally, Gao et al. [19] studied the effect of temperature on the hardness of different phases i.e., eutectic and Sn rich phases, of SAC305 solder using nanoindentation; they observed that the hardness of the Sn rich phase decreased with temperature, in the 60–150 °C range. Tian et al. [20] studied the mechanical properties of SAC305 alloy and Cu/SAC305/Cu joints at cryogenic temperatures and observed a decrease in tensile strength with an increase in temperature, in the −100 °C to 25 °C temperature range. Likewise, the varying temperatures during service will alter the fracture behavior of solder joints in microelectronic packages. Hence, it is important to understand the effect of temperature on the fracture behavior (i.e., fundamental fracture properties and fracture mechanism) of solder joints.

In spite of its importance, no systematic study on the effect of temperature on the fracture behavior of lead-free solder joints exists. In one of the few studies, Logsdon et al. [21] measured the fracture properties of a Sn63Pb37 solder at −55 °C, 24 °C and 125 °C and found that fracture energy decreased with an increase in temperature; however, this study was conducted on a bulk solder sample instead of a joint configuration. The microstructure of bulk solder differs significantly from that that of a solder joint [22,23]. The bulk sample configuration ignores the effect of (Cu_6Sn_5 and Cu_3Sn_4) intermetallic compounds (IMCs) and the joint microstructure which play a key role in the deformation and failure behavior of the joints in microelectronic packages. For example, An et al. [22] and Hayes et al. [24] observed that IMC not only affected properties of Pb-free solders but also influenced their failure mode. Hence, the properties measured from bulk samples may not characterize the failure behavior of joints.

The objective of the present study was to examine the effect of temperature on the fracture behavior of Cu-SAC305-Cu joints fabricated under microelectronic manufacturing conditions. To this end, double cantilever beam (DCB) specimens, prepared by sandwiching a thin layer of solder (dimensions comparable to those of solder joints in microelectronic packages) between two Cu bars, have been fabricated. This specimen configuration provides a microstructure (bulk as well as the IMC morphology) comparable to that of the Pb-free BGAs, in that it mimics the BGA configuration of a solder ball sandwiched in-between two copper pads [10]. The DCBs were subjected to mode-I fracture under three different temperature conditions. While the solder joint such as BGAs are subjected to mixed mode loading in service, the mode-I fracture properties reported here still provide package designers with new information such as the variation of the critical energy release rate as a function of temperature. In fact, it has been shown that the critical energy release rate of SAC305 increases with mode-mixity [13]. Therefore, the measured mode-I values could give a relatively conservative fracture criterion. A plane strain finite element model of the DCB sample was developed where solder was modeled as an elastic-perfectly plastic material with temperature dependent modulus and yield stress while Cu was modeled as linear elastic material. The experimental data (i.e., critical loads corresponding to crack initiation) was used in this model to evaluate critical energy release rate under various temperatures. The fracture surfaces of the samples were analyzed using SEM and EDX spectroscopy to understand the effect of temperature on the crack path and mechanism of failure. The fracture properties measured in this study are fundamental properties and are independent of geometrical features such as ball pitch, ball count and package size. Hence, as long as the ball collapse height is similar to the solder layer thickness used in this study, the properties can be applied to joints at the chip level or board level.

2. Experimental procedures

2.1. Specimen preparation

DCB specimens were fabricated by sandwiching a 450 µm thick layer of SAC305 solder between two copper bars (C110 Alloy, 114 × 12.7 × 12.7 mm) as shown in Fig. 2. The Cu bars were cut to the required dimensions and the bonding surfaces were polished