Materials and Design 85 (2015) 115–126

Contents lists available at ScienceDirect

Materials and Design

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

Combined effect of strain-rate and mode-ratio on the fracture of lead-free solder joints

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ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form 27 May 2015
Accepted 23 June 2015
Available online 30 June 2015

Keywords:
Solder
Fracture
Strain energy release rate
Strain rate
Mixed mode

ABSTRACT

The critical strain energy release rate for the solder joint fracture was measured as a function of the strain rate and the mode ratio of loading. These data are useful in predicting the fracture of solder joints loaded under arbitrary combinations of tension and shear during the impact conditions typical of falling portable electronic devices. In this study, strain rates from quasi-static (close to 0 s^{-1}) to 61 s^{-1} were investigated at phase angles from 0 to 60°, typical of the range found in microelectronic devices. Copper–solder–copper double cantilever beam (DCB) model specimens were prepared using SAC305 solder at cooling rates and times above liquidus typical of actual ball grid arrays (BGAs). A drop tester was designed and built to achieve different strain rates at various mode ratios. The critical initiation strain energy release rate, J_{ci}, increased about 70% from quasi-static to intermediate strain rates, before decreasing by more than 67% from intermediate strain rates to 42 s^{-1}.

1. Introduction

The fracture load of an arbitrary solder joint can be predicted if the critical strain energy release rate is known as a function of the ratio of tensile to shear loading, defined by the mode ratio or phase angle [1] as

$$\psi = \arctan\left(\frac{K_{II}}{K_I}\right) \tag{1}$$

where K_I and K_{II} are, respectively, the mode I and mode II stress intensity factors. Therefore, mode I loading corresponds to $\Psi = 0$, while mode II gives $\Psi = 90°$. In most layered systems, the fracture energy increases with increasing phase angle [2–6].

The fracture load is also dependent on the strain-rate, which becomes an important variable in the prediction of solder joint reliability under the conditions typical of a dropped portable microelectronic device.

The vast majority of testing presented in earlier studies has been qualitative, providing useful comparative data for a specific geometry and size. The board-level drop test (BLDT) and the ball impact test (BIT) have been used to characterize the fracture behavior of BGA solder joints for different solder alloys [7,8]. In the BIT, solder balls are sheared individually, and the shear force and failure mode depend on the shape and size of the solder ball, aging conditions, solder and interface properties, shearing speed, and shear tool standoff height. There is some evidence that under thermal cycling conditions, typical in solder joints due to temperature changes in microelectronic devices, the fracture takes place inside the bulk solder layer [9]. In contrast, the brittle fracture of solder joints through the intermetallic compound (IMC) layer has been frequently observed in reliability tests that feature high strain rate mechanical loads such as drop impact, high-speed ball shear, ball pull, tensile bond test, or Charpy test [7,10,11]. Therefore, the IMC fracture strength has a significant role in controlling the overall joint strength.

The high-speed tensile test has been used to characterize the fracture behavior of BGA solder joints and to assess the IMC strength under the impact loading conditions generated by product drop [12,13]. A typical tensile test sample includes a BGA on a printed circuit board (PCB), sandwiched and glued between two steel studs that are pulled apart until all the joints would fail, with the peak load and the mode of failure recorded. According to [9], higher loading rates and Ag content lead to fewer bulk solder failures and more interfacial failures through the IMC occurring at lower peak loads. It should be noted that solder joints under shear loading produced more bulk solder failures and higher average solder joint strength, peak load and ductility than those under tensile loading [14]. This is consistent with the known dependence of solder joint fracture on the mode ratio [6]. The increase in fracture toughness with increased mode II loading has been explained for ductile adhesive layers in terms of reduced stress triaxiality and a larger crack-tip plastic zone [2,3]. Indeed, this is the typical fracture response observed in the vast majority of layered systems [4,6,15].

The fracture energy of adhesive and solder joints is known to increase with crack length due to the development of a growing damage zone ahead of the macroscopic crack tip [16]. This increasing resistance to fracture with increasing crack length is known as an R-curve. Fracture experiments using a DCB specimen with SAC305 solder between two copper substrates showed that once this damage zone reached its

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http://dx.doi.org/10.1016/j.matdes.2015.06.134
0264-1275/

steady-state size, fracture proceeded at the steady-state value of the strain energy release rate, J_{cs} [16]. The strain energy release rate corresponding to crack initiation at the onset of cracking in the DCB, J_{ci}, was found to control the strength of short joints (e.g., 2 mm joints and smaller) where an appreciable R-curve crack growth could not occur before complete joint rupture [1,6]. Therefore, J_{cs} governs the strength of relatively long solder joints such as those in heat sinks and power electronics, while J_{ci} governs the strength of joints shorter than about 2 mm [1,6]. This approach was used to predict short solder-joint strength under mixed-mode quasi-static loading using data for 2 mm solder joints [1,6]; i.e., joints that were too short to undergo appreciable R-curve toughening, so that J_{ci} controlled in the ultimate strength [1,6].

Both the initiation strain energy release rate and the steady-state critical values of the solder R-curve were found to increase with the relative amount of mode II loading [6,16]. Moreover, the failure loads predicted by the initiation strain energy release rate failure criterion were relatively insensitive to the shape of the terminus of the solder layer (e.g., sharp notch, rounded, square) [16]. The approach can be implemented using either a cohesive zone model which does not model a pre-existing crack, or using the strain energy release rate calculated at the tip of an initial crack [1,6].

Huang et al. [17] investigated the effect of strain rate and mode ratio using 9 mm long SAC387 solder joints (0.5 mm thick) between 15 mm thick copper substrates (6.35 mm wide) rigidly fixtured in a compact mixed-mode configuration similar to that of Arcan et al. [18] and Richard and Benitz [19]. The samples were fractured at strain rates of 0.01–200 s^{-1} and with phase angles of 0°–60°. Prior to soldering, an Al film was deposited on one of the copper bars by vacuum evaporation to act as a 4.5 mm long pre-crack. The time above liquidus (TAL) was varied from 30 to 180 s and cooling rates ranged from 3 to 10 °C/s. Subcritical crack growth prior to the final fracture was estimated using a compliance method, and this final crack length was used to calculate the critical energy release rate, G_c, using a finite element model. It was reported that G_c decreased by roughly half with increasing strain rate and mode ratio. However, the decrease in G_c with increasing shear is inconsistent with the measurements of [20], where similar compact tension/shear specimens and procedures were used to test Sn63–Pb37 solder joints sandwiched between two brass substrates, although these data were highly scattered and over a relatively small range of mode ratios (−25° to 10°). Decreasing G_c with increasing shear was unexpected since increasing mode II loading usually increases the fracture strength of sandwiched ductile layers as discussed above. In addition, the sign of the phase angle was found to be an important factor in controlling the fracture behavior of the joints, since the crack tended to initiate along the upper interface for negative phase angles, and along the bottom interface for positive phase angles. This was attributed to interactions between the stiff substrate and the plastic zone at the crack tip [21]. However, this behavior is readily explained by the change in the direction of the principal stress in the solder; i.e., cracks tend to grow along the more highly-strained adherend which switches with the sign of the phase angle.

Therefore, the effect of mode ratio on fracture toughness seems to depend on the solder processing and its effect on the IMC, as well as on the testing conditions such as the solder joint constraint imposed by the adherend stiffness. In particular, it is of interest to determine whether the effect of mode ratio is a function of strain rate. As noted above, the solder fracture data reported in [6,16], using double cantilever beam specimens, showed that both the initiation and steady-state values of G_c were found to increase with increasing mode II applied to the solder layer.

A further complication with the data obtained using the compact tension/shear specimen of [17,20,21] arises from the fact that G_c in a solder can increase significantly with the amount of subcritical crack growth (i.e., a pronounced R-curve can exist [16]). Such toughening can become significant for joints as short as 5 mm [1,6] and was not considered in [17]. Therefore, the values of G_c reported in [18] may be somewhere between the initiation value of G_c and the steady-state value that is defined by the plateau of the R-curve at the point where G_c becomes independent of the length of the subcritical crack. This creates uncertainty when interpreting the effects of mode ratio and strain rate reported in [17,20,21].

In summary, there is a lack of published data on the mixed-mode fracture of solder joints as a function of strain rate, particularly under the bending conditions that are typical of most applications. Therefore, the present study used various beam bending geometries to measure the fracture toughness of SAC305 solder joints at several mode ratios under quasi-static, intermediate (0.3–1 s^{-1}), and high strain-rate (10–61 s^{-1}) loading conditions. The latter were taken to be representative of typical conditions in dropped mobile phones. The processing parameters were typical of those of BGAs in the microelectronic industry. These property data can then be used to make fracture load predictions for this particular solder joint subject to arbitrary mode ratios of loading over this range of strain rates.

2. Experimental procedure

2.1. Specimen design and preparation

The critical strain energy release rates for crack initiation were measured using Cu–solder–Cu double cantilever beam (DCB) specimens of 2 mm long discrete solder joints prepared under standard surface mount (SMT) as described in [1,6,16]. C110 copper bars were machined to the dimensions of Fig. 1a–e. The surfaces to be soldered were polished for 5 min using an ultra-fine silicon carbide/nylon mesh abrasive pad fitted to an orbital sander, avoiding edge rounding by clamping eight bars adjacent to each other. This process produced a repeatable surface roughness very similar to that on commercial PCBs having an organic solderablility preservative (OSP) surface finish [16]. The copper surfaces then were repeatedly rinsed with water and wiped with bleached cheese cloth. Finally, the copper surfaces were rinsed with acetone and masked with Kapton tape to produce a smooth, square local geometry for the discrete solder joints. The two bars for a joint were then placed on their sides and heated using a hot plate to 220–225 °C, as measured using a thermocouple embedded in the copper bar just beneath the solder layer. A flux-cored Sn3.0Ag0.5Cu (SAC305) 0.8 mm solder wire (Kester Inc., USA) was touched to both copper surfaces and the bars were clamped together against three steel wires to produce a solder layer 150 μm thick (Fig. 1a to e). The excess solder that flowed from the joint was wiped away. The three spacing wires also prevented the premature loading of an adjacent joint as the preceding one was being fractured. The time above liquidus (TAL) was set to 120 s in order to be consistent with the previous work of refs. [6,16]. The specimen was cooled to room temperature in a small wind tunnel to achieve a cooling rate of 1.4–1.6 °C/s, which is typical of microelectronic manufacturing [16]. After soldering, the holes for the loading pins and the impact rivet were drilled in the copper bars.

2.2. Fracture testing

2.2.1. Quasi-static and intermediate strain rates

Fracture tests under quasi-static and intermediate strain rates were conducted using the load jig of Fig. 2, in which the locations of the link pins can be selected to control the forces F_1 and F_2 applied to each arm of the DCB as shown in Fig. 1a and given in Eq. (2) as:

$$
\begin{aligned}
F_1 &= F\left(1-\frac{s_1}{s_3}\right) \\
F_2 &= F_1\frac{s_1}{s_2}\frac{1}{\left(1+\frac{s_3}{s_4}\right)}
\end{aligned}
\tag{2}
$$

where s_1, s_2, s_3 and s_4 are defined as positive in Fig. 2 as the distances between pin centers. Negative s_4 means that the connection between the lower drilled bar and the base plate is closer to the specimen than the