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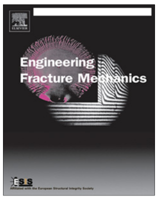

Effect of processing parameters on fracture toughness of lead-free solder joints

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ABSTRACT

Solder joint fracture toughness was measured using double-cantilever-beam specimens over a range of strain rates and mode ratios as a function of five key processing parameters: the type of lead-free solder alloy, solder thickness, time above liquidus, aging time, and the geometry of the end of the solder layer. Although the toughness was a strong function of the loading phase angle and strain rate, relatively small differences were due to the solder composition, time above liquidus, and aging. The effects of solder thickness and local end geometry were found to be significant only at the higher strain rates.

1. Introduction

The fracture strength of lead-free solder joints can be expressed by the critical strain energy release rate for either crack initiation or growth, both of which are known to be functions of the ratio of shear to tensile loading [1,2]. This mode ratio of loading is often expressed in terms of the phase angle [3] 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. It was shown that the fracture toughness increased substantially with increasing phase angle [2,4–7].

Solder fracture 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 [4,8–10].

The fracture of long solder joints (more than about 5 mm) can display a rising *R*-curve behavior due to the development of a crack tip damage zone. For example, the critical strain energy release rate for crack initiation, J_{ci}, in SAC305 was about 3 times smaller than the steady-state value, J_{cs}, that was evident with longer cracks [11]. It was shown that *R*-curve toughening was essentially absent in sufficiently short solder joints, and that the maximum load corresponded to initiation (J_{ci}) and fast fracture in 2 mm long joints [3].

The quasi-static value of J_{ci} for SAC305 was found to be independent of solder layer thickness over the range 200–400 μm for phase angles of 0°, 25° and 45° [13]. The mode I quasi-static J_{ci} was also insensitive to the local geometry of the end of the solder joint, whether it was round or square [11]. However, as discussed above, fracture strength changes significantly with

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Nomenclature

Ψ	phase angle (mode ratio) of loading
$\dot{\varepsilon}$	strain rate
K_{II}	mode II stress intensity factor
K_I	mode I stress intensity factor
J	strain energy release rate
J_{ci}	critical strain energy release rate for crack initiation
F	force applied to the load jig
F_1	force acting on the upper adherend
F_2	force acting on the lower adherend
t	solder layer thickness

the rate of loading and mode ratio, and it was of interest to investigate the influence of solder thickness and local end geometry at higher strain-rates and at mode ratios that span the range found in typical joints [12].

Quasi-static fracture and thermal cycling of solder joints can induce ductile fracture within the bulk solder layer or at the boundary between the bulk solder and the intermetallic compound (IMC) [13]. In contrast, 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 due to drop impact, high-speed ball shear, ball pull, tensile bond test, or Charpy test [14–16]. Therefore, parameters that affect the IMC fracture strength are relevant to joint strength at higher rates of loading.

There is a large literature on the effect of solder alloy and processing parameters on thermal fatigue life, metallurgical structure, and joint failure load, as measured using a wide range of test methods. However, only a relatively small number of published studies have examined the sensitivity of solder joint fracture toughness or critical strain energy release rate to changes in the solder alloy and the joint processing conditions. The relatively few studies which have investigated such changes in fracture toughness have often produced contradictory results, and used fracture conditions that were inconsistent with the typical fracture behavior of solder joints in ball grid arrays (BGA). The influence of solder alloy on joint failure load has been investigated widely as a function of strain rate. Ball impact tests of SAC105 and SAC405 with a Ni/Au pad finish showed that the latter was weaker as it underwent more brittle fracture [14]. SAC solders with a silver content of 3% were reported to give good thermal cycling reliability, but poor drop reliability [13,17]. According to [18,19], higher strain rates and Ag content corresponded to a shift from bulk solder failure to more interface failure. It should be noted that these crack path observations were also a function of the mode ratio of loading, but this was not quantified in fracture terms. For example, solder joints under shear loading produced more bulk failure and greater joint failure force than those under predominantly tensile loading [18]. High-speed ball pull testing showed that Sn–Pb solders underwent mostly ductile failure, whereas lead-free solders (SAC105, SAC305, SAC405) tended to undergo much more brittle failure at almost identical loads with organic solderability preservative (OSP) surface finish [19]. However, the fracture loads for these three SAC alloys became a function of the surface finish when ENIG and electrolytic Ni–Au were used [19]. Drop test reliability was also found to be a function of surface finish in [20,21], where the best performance was observed for the OSP finish.

The effect of aging on the solder joint reliability has been widely investigated. For example, it was found that while isothermal aging can increase the IMC thickness [22,23], which can weaken the solder joint strength. It may soften the solder layer microstructure, which can strengthen the solder joint [23]; so, the overall impact on solder joint strength is not straightforward. The impact strength of SAC305 BGAs was degraded significantly after aging at 100 °C [24]. Curiously, samples aged at 150 °C showed better shock performance than those at 100 °C, as the crack path moved from pad cratering and IMC failure to the bulk solder [24]. Lead-free solder joints aged at 150 °C for 150 h displayed greater ductile behavior than un-aged samples; however, this effect became smaller with increasing silver content [25].

In addition to Refs. [2,3,11] discussed previously, a number of studies have reported measurements of fracture toughness as a function of various processing parameters. Huang et al. [23] investigated the effect of TAL, aging and cooling rate on the fracture of SAC387 solder joints using pre-cracked compact mixed-mode (CMM) specimens that were 9 mm long, 0.5 mm thick and 6.35 mm wide. The samples were tested at strain rates of 0.01–200 s^{-1} and with phase angles of 0–60°. In general, increasing TAL (from 30 s to 180 s) decreased the fracture toughness. Aging the joints at 150 °C for 48 h increased the fracture toughness, but it was concluded that this effect will depend on the various parameters that control the corresponding decrease in solder yield strength and increase in the IMC thickness [23]. At all phase angles, a lower cooling rate was associated with 14–23% higher values of fracture toughness at the strain rate of 100 s^{-1}. Choi et al. [26] found that the fracture energy of Sn63–Pb37 solder joints with brass substrates in CMM specimens increased significantly as solder thickness increased from 0.5 mm to 2 mm due to plastic zone development. This study showed an unusually erratic trend of fracture energy with phase angle over the range from −25° to 10°.

In summary, the vast majority of data concerning the effects of processing parameters are in terms of a wide range of solder-joint strength metrics at different strain rates, including cycles to failure in fatigue tests. Studies employing fracture mechanics have investigated the effect of TAL, thickness and local end geometry under slow rates of loading [11,27], and the