Materials Science and Engineering A 428 (2006) 67–72

MATERIALS SCIENCE & ENGINEERING A

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The specific work of fracture in ball shear test and the integrity of solder balls

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Received 7 February 2006; received in revised form 6 April 2006; accepted 19 April 2006

Abstract

This paper demonstrates the use of the ball shear test to measure the specific essential work of fracture (i.e. fracture toughness) of solder balls interconnects commonly found in microelectronic packages. An approximate analysis of the mechanics of shearing a solder-mask-defined solder ball is developed using the essential work of fracture (EWF) concept. The analysis considers the difference in sizes of the solder ball and soldermask aperture, plastic deformation in the solder and friction during the shearing. To validate the analysis, ball shear tests on different solder sizes are conducted and the total specific work and specific unloading work during shearing is obtained as a function of the effective solder ball diameter. This paper proposes that the specific work of fracture is a better measure of the integrity of solder balls than the maximum shear load or nominal maximum shear stress.

Keywords: Solder; Fracture toughness; Ball shear test; Essential work of fracture

1. Introduction

The standard solder ball shear test is popularly used to determine the quality of a solder bond [1–4]. A *good* solder bond is usually defined as one where failure does not occur at the solder/pad interface and where the shear load is greater than a prescribed value. In a recent paper [1], it was shown the solder ball shear test could also be used to estimate the specific essential fracture work in shearing a solder. It was argued that the maximum shear load is not the best way of characterising the failure of solder balls. Instead, the integrity of solder balls is better judged by the work necessary to shear the solder ball. The total shear work is the sum of the work performed in plastically deforming the ball and in the shear fracture work in the small fracture process zone (FPZ) about the shear line. The two work components scale differently and it is the specific essential work of shear fracture–the shear fracture work in the FPZ per unit shear area of the solder stub (w_e) – that is the more fundamental measure of the fracture resistance and is independent of the ball size. The specific essential work of shear fracture cannot be obtained directly from a solder ball shear test, but it was argued that the specific shear work performed after the maximum shear strength has been reached (or the specific unloading work), w_u, is an estimate of w_e. The shear force was strongly affected by the strain rate. The total specific work of fracture was also affected by the strain rate, but not so strongly as the shear force. Surprisingly the specific work of unloading w_u, and hence by inference the specific essential work w_e varied little with strain rate. At the highest strain rates failure occurred in the interface (*bad* solder bonds) in the SnAgCu solder balls, but not in the interface in the SnPb solder balls. For solder masked defined solder balls, interface failures gave a higher than average specific work of unloading and showed stability in the shear force–displacement curves; this was an artefact of extra deformation and frictional work done on the detached solder stub against the soldermask. For unmasked solder, failures in the interface gave a lower than average specific work of unloading and showed instability in the shear force–displacement curves.

In this paper the mechanics of the solder ball shear test is further explored by shear testing solder mask defined solder balls with a range of sizes and using the essential work of fracture (EWF) concept of Cotterell and Reddel [5]. The aim is to prove the validity of the EWF concept in determining the

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doi:10.1016/j.msea.2006.04.052

fracture toughness of the solder. Only quasi-static shear tests were performed.

2. Application of the essential work of fracture concept to the solder ball shear test

The usual EWF concept applies to fracture tests, like the solder ball shear test illustrated schematically in Fig. 1a, where a series of tests is performed on geometrically similar but different sized specimens provided the whole stub of the solder ball yields before fracture initiation. For the EWF to apply the shear fracture must be stable. In our earlier paper [1], the approximate shear analysis assumed that the diameter of the solder mask and the solder ball were the same. However the solder balls described here are produced using a different technique and the diameter of the solder ball is significantly larger than that of the solder mask and stub, consequently our previous analysis needs modification.

Solder materials typically exhibit a very small strain hardening coefficient (<0.05) and very large plastic strains. Hence the solder can, with little loss of accuracy, be assumed as rigid-plastic with a shear yield strength, τ_Y. It is further assumed that

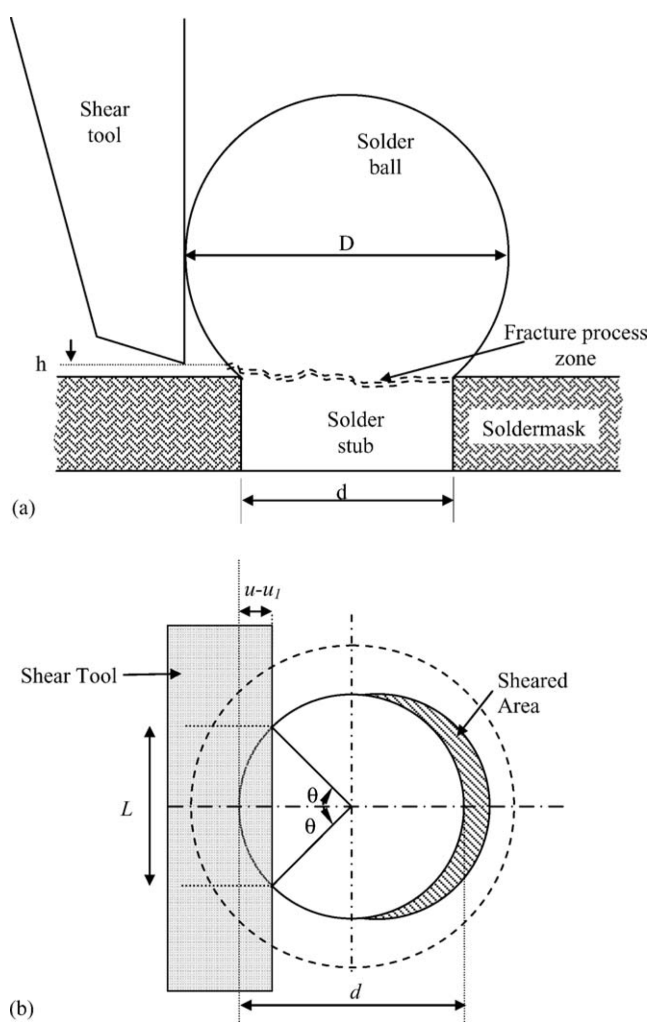

Fig. 1. Schematic of solder ball shear test: (a) prior to shearing and (b) during shearing.

no shear crack occurs until the shear tool reaches the stub of the solder ball and this displacement, u_1, of the shear tool is given by

$$u = u_1 = (D - d)/2 \tag{1}$$

where D is the diameter of the solder ball, d the diameter of the solder ball stub and u is the general displacement of the shear tool. For $u > u_1$ the unsheared area (see Fig. 1b), S, is given by

$$S = \frac{d^2}{4}\left[\pi - \theta + \frac{1}{2}\sin 2\theta\right] \tag{2}$$

where $\theta = \cos^{-1}[1 - 2(u - u_1)/d]$. Hence the force that causes plastic deformation, F_p, is given by

$$F_p = \frac{\tau_Y d^2}{4}\left[\pi - \theta + \frac{1}{2}\sin 2\theta\right] \quad \text{for}\, u > u_1 \tag{3}$$

It is assumed that for $u < u_1$ that the shear force increases parabolically so that

$$F_p = \frac{\tau_Y \pi d^2}{4}\left\{1 - \left[\frac{2(u_1 - u)}{D - d}\right]\right\} \quad \text{for}\, u < u_1 \tag{4}$$

with this assumption the plastic shear force is continuous at $u = u_1$.

The force required to cause the shear fracture, F_c, using the concept of a force on a dislocation is given by [1] as

$$F_c = w_e L = w_e d \sin\theta \quad \text{for}\, u > u_1 \tag{5}$$

where L is the chord of angle 2θ (see Fig. 1b). It is assumed that a shear crack does not initiate until $u = u_1$, hence for $u < u_1$, $F_c = 0$.

There is also a friction force, F_f, which if Coulomb friction is assumed can be written as

$$F_f = fF \tag{6}$$

where F is the total shear force and the coefficient of friction $f < 1$. Hence the total force is given by

$$F = F_p + F_c + F_f$$

$$F = \frac{\tau_Y \pi d^2}{4(1 - f)}\left\{1 - \left[\frac{2(u_1 - u)}{D - d}\right]\right\} \quad \text{for}\, u < u_1$$

$$F = \frac{\tau_Y \pi d^2}{4(1 - f)}\left[1 - \frac{\theta}{\pi} + \frac{1}{2\pi}\sin 2\theta\right] + \frac{w_e d \sin\theta}{1 - f} \quad \text{for}\, u > u_1 \tag{7}$$

Although this expression of the total force is continuous in u, a gradient discontinuity at $u = u_1$ exists. Because the shear work is of primary interest, this discontinuity is considered relatively unimportant. The specific total shear work is given by

$$w = \frac{4W}{\pi d^2} = \frac{4}{\pi d^2}\int_0^{(D+d)/2} F\,du = \frac{w_p}{1 - f}\bar{d} + \frac{w_e}{1 - f} \tag{8}$$

where

$$w_p = \frac{\tau_Y}{2} \qquad \bar{d} = \left[\frac{2}{3}\left(D + \frac{d}{2}\right)\right] \tag{9}$$