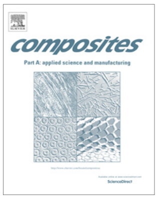
Composites: Part A 87 (2016) 228–236

Contents lists available at ScienceDirect

Composites: Part A

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



Effect of adhesive fillet geometry on bond strength between microelectronic components and composite circuit boards

Saeed Akbari, Amir Nourani, Jan K. Spelt *

Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Rd., Toronto, ON M5S 3G8, Canada

ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 24 February 2016
Accepted 29 April 2016
Available online 30 April 2016

Keywords:
A. Polymer-matrix composites (PMCs)
B. Adhesion
C. Finite element analysis (FEA)
D. Failure

ABSTRACT

Printed circuit boards (PCBs) assembled with ball grid array (BGA) microelectronics packages were tested in a double cantilever beam (DCB) configuration. The results were compared for a filled and an unfilled underfill epoxy adhesive as well as a cyanoacrylate adhesive. The original fillet, formed in the underfilling process, was modified to create fillets of different sizes. Regardless of the underfill thermal and mechanical properties as well as its curing profile, the crack initiation load and the failure mode were solely a function of the size of the underfill fillet, and the failure always initiated within the PCB. Moreover, the strength of the underfilled solder joints was increased significantly (approximately 100%) by the presence of a relatively large fillet. This effect of the underfill fillet on the crack path and the fracture load was then examined in terms of differences in the stress states using a finite element model.

1. Introduction

Underfill adhesives are used commonly in microelectronics to enhance the reliability of the ball grid array (BGA) solder joints that connect complex components to composite printed circuit boards (PCBs). In board-level underfilling, the underfill, which is normally an unfilled or filled epoxy adhesive, is dispensed along the edges of the component and flows into the gap beneath the component and between the solder balls through the capillary action. It is then thermally cured to reduce the effect of thermal and mechanical stresses on solder balls between BGA packages and PCBs [1–4]. To increase the underfill Young's modulus and reduce its coefficient of thermal expansion (CTE), low-CTE silica fillers at high weight fractions are commonly added to underfill materials [5–9].

An important reliability issue in microelectronic assemblies is delamination at the interfaces between the layers of dissimilar materials in the component–solder–PCB sandwich as a result of PCB or substrate bending during board assembly, shipment, handling, and end use [10–12]. To study these interlaminar failures, test specimens must generate the relevant loading conditions and the resulting stress states.

Many studies have shown the strength of an adhesive joint may be significantly influenced by small variations in the local geometry at the end of the overlap region [13–17]. A number of studies [1–4] have used three-point and four-point bending experiments to study the reliability of the underfilled microelectronic components. However, the effect of the size and shape of the underfill fillet on the bending strength of BGA/PCB assemblies has not been quantified and isolated from the effects of adhesive mechanical and thermal properties.

The objective of the present work was to understand the relationship between underfill fillet size and shape on the crack initiation load and failure mode of underfilled BGA solder joints. The effect of underfill adhesive thermal and mechanical properties was examined using commercially-available filled and unfilled epoxies as well as a cyanoacrylate adhesive. The experimental results were verified with a detailed stress analysis conducted using a finite element model.

2. Experimental

2.1. Specimen preparation

The fracture performance of underfilled solder joints was investigated using assemblies of thin-profile fine-pitch ball grid array (TFBGA) packages (iNAND Embedded Flash Drives, SanDisk, Milpitas, CA, USA; properties of Table 1) soldered to a 1 mm thick, multilayer, solder-mask coated PCB (AT&S, Leoben, Austria). The PCB had a symmetric stackup as shown in Table 2.

The surface finish on the PCB copper pads was organic solderability preservative (OSP). The diameter and the height of the solder balls were 300 μm and 200 μm, respectively, after assembly. The solder paste applied on the board was Sn3.0Ag0.5Cu

---

* Corresponding author.
E-mail address: spelt@mie.utoronto.ca (J.K. Spelt).

http://dx.doi.org/10.1016/j.compositesa.2016.04.027
1359-835X/

Table 1
Properties of the BGA package [18,19].

Material	Thickness (mm)	Young's modulus (GPa)	Poisson's ratio
BT substrate	0.17	14.5	0.11
Silicon die	0.32	130	0.28
EMC	0.68	16.7	0.25

Table 2
PCB layers (symmetric about layer 9, total number of layers = 17). SM = solder mask, PL = plated copper, RCC = resin coated copper, PR = prepreg.

Layer no.	1	2	3	4	5	6	7	8	9
Material	SM	PL	RCC	PL	PR	PL	PR	PL	PR
Thickness (μm)	20.0	28.0	50.0	28.0	50.0	28.0	190	17.5	200

(SAC305) (Indium, New York, USA). The TFBGA packages contained a silicon die attached to a bismaleimide–triazine (BT) substrate, encapsulated in an epoxy molding compound (EMC).

Underfilling was performed immediately after solder reflow using one of two types of capillary underfills, each exhibiting a widely different set of mechanical and thermal properties: a silica-filled epoxy (Hysol 3537, Henkel Electronic Materials, Irvine, CA, USA) or an unfilled epoxy (Hysol UF3808), with cure times of almost five minutes at temperatures of approximately 150 °C. The underfilled BGA/PCB assemblies were fabricated using a fully-automated surface mount technology (SMT) assembly line (BlackBerry, Cambridge, ON, Canada). Some additional test specimens were made manually using a low-viscosity cyanoacrylate adhesive (Loctite 496) which produced a negligibly small fillet. The mechanical properties of these underfills are listed in Table 3, along with their abbreviated designations UF-A, UF-B, and CN.

The test specimens were cut from the BGA/PCB assemblies using a precision circular saw with a diamond blade as indicated in Fig. 1. Fig. 2 shows the cross-section of a BGA/PCB assembly revealing the underfill layer, the solder joints in the vicinity of the underfill, copper trace layers and glass fibers through the thickness of the PCB.

The underfilled BGA/PCB assemblies were tested in a DCB configuration, as shown in Fig. 3. To fabricate the test specimens, the free surface of the BGA component was first sanded using a 400-grit sponge sander, then lightly wiped with acetone to remove contaminants. A loading arm consisting of a 1.5 mm thick piece of circuit board material (FR4, IS410, Isola, Chandler, Arizona, USA) was bonded to the BGA component surface using a room-temperature cure epoxy adhesive (Hysol E-40HT), taking care to avoid excess adhesive being squeezed from the joint and bonding to the PCB. The brass loading brackets were bonded to the PCB and the FR4 loading arms using a cyanoacrylate adhesive (Loctite 496).

As shown in Table 2 the PCB consisted of insulating layers of a woven glass-fiber epoxy composites, and conducting copper layers that have been etched during the lamination process to produce the required pattern of conducting traces. The places where the copper was etched away are filled with the resin of the next insulating layer during lamination. Therefore, the conducting layers can be considered as copper–epoxy composites [20]. Fig. 4 shows the distribution of the copper traces in the conducting layers of the present PCBs. In addition to the glass-fiber epoxy composite layers (prepreg), layer#3 and layer#15 were resin-coated copper (RCC); i.e. electrodeposited copper traces coated with resin [21].

Table 3
Properties of underfills as provided by the manufacturer.

Properties	Hysol UF3808 (UF-A)	Hysol UF3537 (UF-B)	Loctite 496 (CN)
Type	Epoxy	Epoxy	Cyanoacrylate
Tensile modulus (GPa)	2.6	4.3	1.7
Glass transition temperature (°C)	113	118	165
Viscosity (mPa s)	360	4000	70
CTE (ppm/°C, $T < \text{Tg}$)	55	47	80
CTE (ppm/°C, $T > \text{Tg}$)	171	132	–
Filler weight fraction (wt%)	0	38	0

The tensile properties of the multi-layer PCBs were measured according to ASTM D3039 [22], giving a value $E_{PCB} = 21.8$ GPa (5 specimens tested, standard deviation = 5%). The PCB tensile behavior was almost linear until final fracture. This was due to the large volume fraction of the prepreg (77%) which was made of a relatively brittle epoxy resin and *E*-glass fibers [23,24]. The transverse Young's modulus of the PCB, similar to other laminated fiber-reinforced polymeric composites, was much smaller than the longitudinal Young's modulus [13,16]. For example, Ref. [16] reported that it was typically just two or three times that of the neat epoxy matrix. However, for simplicity the PCB was modeled as a homogeneous, isotropic, elastic material ($E_{PCB} = 21.8$ GPa) in the FEA. As discussed in Section 3, this simplification had a negligible effect on the ability of the finite element model to predict the effect of the fillet size on the bending strength of underfilled BGAs.

2.2. Modifications to the underfill fillet size

The size and shape of the original fillet formed during the underfilling process in the SMT line was dependent on the underfill viscosity, and the surface tensions of the underfill and the adjoining surfaces which controlled the contact angles. As shown in Figs. 5(a) and 6(a), the underfill with a higher viscosity (UF-B) produced a larger fillet. In these cases the contact angles of the underfills were essentially the same since both were epoxies and the PCB and component were identical.

The fillet size was modified to investigate its effect on the fracture load and the failure pattern. Modifications to the original fillet fell into two categories: the reinforced (enlarged) fillet (Figs. 5(b) and 6(b)), and the damaged fillet (Figs. 5(c) and 6(c)).

To enlarge the fillet, additional underfill was dispensed manually along the edge of the package from a syringe and cured as the original underfill, using a time–temperature profile that was verified with a thermocouple embedded in the added underfill of a calibration specimen. The reinforcement was done on specimens before they were cut from the PCB. The reinforced UF-A fillet seen in Fig. 5(b) was approximately the same size as the reinforced UF-B fillet shown in Fig. 6(b). Small differences in the color of the underfill fillet (Fig. 6(b)) were attributable to variations in the surface texture from sectioning and to differences in the lighting and digital color rendering during micrography.

The circular diamond saw was used to score the fillet, removing most of it, as shown in Figs. 5(c) and 6(c). In this condition, the original fillet was damaged to such an extent that it could no longer transfer significant load. Care was taken to ensure scoring the fillet created no damage in the PCB, as was verified by microscopic inspection after the cutting operation, and the consistency of the failure loads.

The fillet dimensions were measured for each fillet configuration and were used in a finite element model for stress analysis. Figs. 5 and 6 show the average fillet dimensions of 5 specimens of each underfill configuration. The repeatability was good, with a standard deviation less than 10% in each dimension.

Some of the BGAs were underfilled manually with the cyanoacrylate adhesive (CN, Table 3), which had a much lower viscosity than either UF-A or UF-B. For this reason, there was no fillet in these specimens, and regarding fillet load transfer the BGAs