

STRUCTURE AND SELECTION MODELS FOR ANISOTROPIC CONDUCTIVE ADHESIVE FILMS*

LI LI and J. E. MORRIS

*Department of Electrical Engineering,
State University of New York at Binghamton, Binghamton, NY 13902-6000, USA*

Received 4 November 1994

Accepted 1 December 1994

Anisotropic Z-axis adhesive films (ZAFs) were selected from different vendors. The variations of electrical properties with process parameters were studied, especially bonding pressure and temperature. Microstructures and compositions of these ZAFs were studied by Scanning Electron Microscopy and Energy Dispersive Spectroscopy, to determine spherical particle diameters, particle distributions, and the particle loading density for each film.

Computer programs have been developed to predict the limiting pitch application for commercial films, and for the inverse selection process. The program calculates the minimum pad size for different filler loading densities, and the minimum pad space for different particle sizes. The failure probability of conduction versus pad size calculated for a specified loading density has a narrow transition region. The particle loading and size can also be determined by the program calculation for a particular application pitch.

1. Introduction

Anisotropic conductive adhesive films, also called Z-axis conductive films, provide both electrical and mechanical interconnections between electronic components and the supporting substrate. Conduction in these materials is restricted to the Z-axis, i.e. perpendicular to the plane of the substrate, while maintaining electrical insulation in the X-Y plane. A typical bonding configuration is shown in Fig. 1. The ZAF provides a new material system for solder replacement as the interconnect for surface mount technology. These ZAFs offer numerous advantages in surface mount assembly, including low temperature assembly, fluxless bonding which eliminates the need for cleaning, lead-free formulations and low cost.^{2,4,5} The anisotropic nature of these materials makes them excellent candidates for very fine pitch components. For chip on glass applications, the high temperature reflow process of solder might destroy

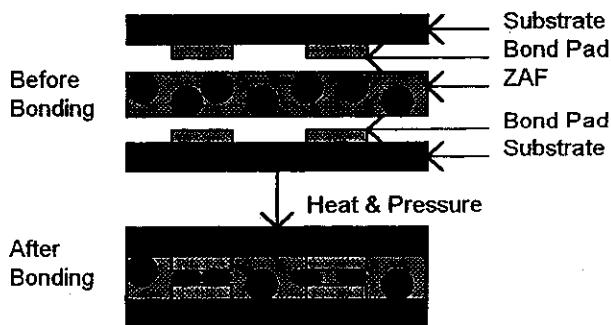


Fig. 1. Illustration of the ZAF interconnection.

the crystal and the glass. Consequently, most current ZAF applications involve flat display interconnections for LCDs,^{10,12-14,18} but industry predictions show that there will be more and more non-LCD applications in the future.^{1,6,9,17}

In general, ZAFs are prepared by dispersing conductive particles randomly in an adhesive matrix at a concentration far below the percolation threshold. The particle density in the adhesive is controlled

*This paper is a revised version of that presented at the Adhesives in Electronics Conference, Berlin, 2-4 November 1994.

to provide enough particles on the device conduction pads to ensure reliable electrical contact; on the other hand, few enough particles are present to avoid pad connections in the X-Y plane.^{2,15} Spherical particles are used, which provide lower percolation probabilities than the same concentration of flakes (which are used in isotropic adhesives).⁶ The dispersion consistency is extremely important to prevent opens or shorts.

ZAFs can be based on a thermoplastic adhesive, a thermoset adhesive, or a combination of the two. The main advantage of thermoplastic adhesives is the relative ease of repair operations.⁷ The curing reaction of thermoset adhesives is not reversible, so it is therefore hard to remove components and repair interconnections. The ability to maintain strong and robust adhesive bonds at high temperature is the main advantage of these materials. Because of the advantages and disadvantages to both thermoplastic and thermoset formulations, most manufacturers try to optimize performance by blending the two to combine the application and rework ease of a thermoplastic adhesive with the performance characteristics of a thermoset adhesive.

The purpose of the conductive particles is to provide contact area as well as to overcome any nonplanarity of the substrates. In order to provide contact area, either the bond pads or the particle must deform. This localized deformation at the contact interface is also desirable in that it serves to disturb any thin oxide layers formed on the connector that would interfere with the connection.¹

The conductive particles may be solid metal, metal coated glass spheres or metal coated polymer spheres. Hard solid spheres may not deform to any great degree and only touch at the points of tangency. Metal coated polymer composite particles are flattened during bonding. This flattening increases the effective surface area of the particle. The ideal metallurgy should also be ductile, and resistant to corrosion or oxidation. Silver offers moderate cost, high electrical conductivity, high current carrying ability and low chemical reactivity, but problems with electromigration may occur. Gold is the ideal material, but with high cost for large-volume productions. Plated particles may offer the best combination of properties at moderate cost.²

For fine pitch applications, the conductor pad sizes and conductor spacings are decreasing. As a result, it becomes more difficult to maintain electrical X-Y insulation with a specific ZAF. The maximum conductive particle size for the adhesives affects the

minimum conductor spacing. The reduced conductor widths cause difficulties in accommodating lateral misregistration between pad and conductor, and decrease the number of particles in the interconnection as well. The particle loading density in the film determines the number of conduction particles in the pad interconnection. The pad heights and particle size, together with any compliance in substrate or particles, help decide the ZAF thickness. Because oxides on conductors can interfere with electrical contact, the conduction pad is usually electroplated with oxide resistant coatings, such as gold, to minimize surface oxides before the bonding operation.

Significant process parameters for ZAF bonding are temperature, load, tacking time, and cure time. The substrate pads are preheated to a temperature below the ZAF's curing temperature, but high enough to partially soften the film so that it has the ability to flow and fill void volume. The bonding load should be high enough to allow the conductive spheres to make good physical contacts between component and substrate conductors; but not high enough to crack the component or the particles in the ZAF. Finally, the tacking time should be sufficient to produce a good initial cure so that the component does not shift during the final cure process.²

2. Electrical Properties versus Process

The most important process parameters during the manufacturing of surface-mounted electronic products using ZAF joining technology are pressure during curing, curing time, and curing temperature.¹¹ Control of these parameters is critical for good bonding quality. The purpose of this part of the research is to find the relationships between the different parameters, to find the critical conditions, and to evaluate four different commercially available ZAFs.

2.1. Experimental procedures

The adhesive films used in our study are commercially available materials from different vendors. These materials contain solid conducting particles distributed in a dielectric matrix, and are fabricated in a dry film format of varied thickness. The characteristics of the four ZAF materials used are listed in Table 1.

Two types of gold plated copper printed circuit board (PCB) connection pads, [labeled Cu(I) and Cu(II)] were used for the experimental bonding materials with pad dimensions specified in Table 2.

Table 1. Specification of the Z-axis conductive films.

Materials	3M 5303R	Scotch 9703	Sheldahl SHEL-ZAC
Film thickness	25 μm 50 μm 1 mil 2 mil	50 μm 2 mil	0.7-1 mil after pressing
Polymer matrix type	Cyanate-ester based thermoset thermoplastic blend	A-40 acrylic	Thermosetting adhesive
Particle type	Ni-coated polymer	Ag-coated Ni	In-Pb

Table 2. Specification of the conduction pads.

Metallization Au plated Cu	Pad width and pad space (mm)	Pad height (mm)
Cu(I) on PCB	3.2	0.052
Cu(II) on PCB	1.75	0.068

Iron weights were used to apply pressure for bonding. The bonding pressure was varied by the combination of weight applied and the actual substrate area. A temperature ranged Thermolyne Type 1900 Hot Plate was used as the heat bonding source. The actual temperature was measured by a thermocouple, and adjusted as appropriate.

The process that has been used in this work has four basic steps.

- (1) Positioning adhesives. A section of the adhesive is cut slightly larger than the bond area on the substrate. A tape is used to stabilize the adhesive position.
- (2) Tack. The substrate is placed on the heat plate, and the temperature set to 100°C. Weight is applied so that the calculated pressure is around 140 psi. This pressure is maintained for 1 min at 100°C. The reduced temperature of this step is not sufficient to crosslink the adhesive, but allows the adhesive to fill between the leads.
- (3) Peel release liner. After the system is allowed to cool for a few minutes, the released liner is peeled off the adhesive.
- (4) Bond. Another circuit substrate is then aligned to this substrate by tape. Weights are applied to achieve different values of bonding pressure (from 120 psi to 558 psi) while ramping the temperature up to 130 to 240°C, and

curing for 2 min. The bonding pressure and temperature were selected as the variable parameters. The pressure is maintained while the material is cooling down to 100°C.

2.2. Results and discussions

The DC electrical measurements were made by a Keithley 580 Micro-Ohmmeter. The four point probe method was used.

Figure 2 shows the electrical resistance for the Cu(I) connector (area: 4 mm \times 3.2 mm) bonding for the 3M5303R material of two different thicknesses at 180°C curing temperature, and for Sheldahl SHEL-ZAC material cured at 140°C. The experiment used six different pressure levels. When the pressure is lower than 200 psi, the resistance of the bond is high, sometimes even open circuit. We can see from the graph that the bonding pressure is an important parameter. If the pressure is too low, no conduction is established between the bonding pads. At least 280 psi pressure must be applied to the sample to have a low resistance reliable bond. Further increasing the bonding pressure will increase the conductance, but without a big difference. Too much pressure can cause bond failure by cracking the conductive particles, and is also not suitable for practical applications. For the Cu(I) type conduction pad, the 3M 25 μm ZAF established a lower resistance than the 3M 50 μm , but in a similar range. Sheldahl SHEL-ZAC materials showed lower resistance and are more sensitive to the bonding pressure. So

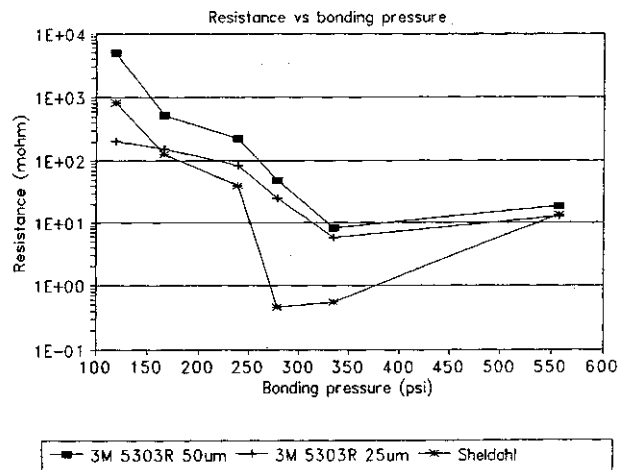


Fig. 2. Resistance versus bonding pressure for the Cu(I) conductor for 3M material and Sheldahl material.

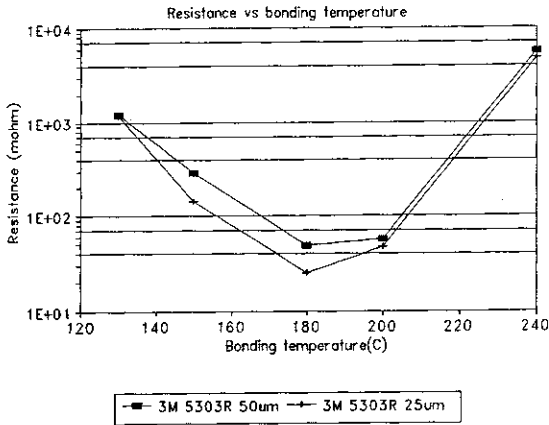


Fig. 3. Bonding resistance versus bonding cure temperature for 3M material at 280 psi bonding pressure for Cu(I).

the optimum pressure condition for these materials is around 300 psi. The Cu(II) type conductor showed similar trends, however the 50 μm 3M ZAF shows a slightly lower resistance than the 25 μm 3M film. This may be because the Cu(II) has a higher conduction pad and will have better compliance with the thicker ZAF.

Although the physical alignment between the circuit traces was good, the bonding experiments yielded less than perfect Z-interconnections. This is mainly attributed to substrate planarity problems and can be overcome by providing compliance in the interconnection and by better bonding equipment.

Figure 3 shows the bonding resistance variation with cure temperature for the 3M materials. If the cure temperature is too low, the adhesive is not fully cured, and therefore the bonding is neither electrically nor mechanically reliable. Complete curing requires a minimum temperature of around 180°C. If the curing temperature is too high, the bonding materials will burn and crack, resulting in even worse situations. The Sheldahl material showed similar results, but has a wider temperature range over which low contact resistance can be achieved than the 3M materials, with an optimum bonding temperature of about 100–140°C.

There are relations and tradeoffs between the bonding temperature, pressure and time. A little lower bonding pressure may be offset by a higher bonding temperature or longer cure time. But minimum pressure is required to ensure a reliable interconnection. There are similar relationships with the cure time and temperature. These conditions

may also depend on the heat-sink characteristics of the bonding substrate. For a certain application, and a particular bonding machine, it is better to do bonding tests and find the optimum bonding process conditions before the actual systematic research and manufacture process.

3. Structure Investigations

3.1. Experimental procedures

The microstructures of the four commercial ZAFs were studied by an ETEC Auto Scan electron mi-

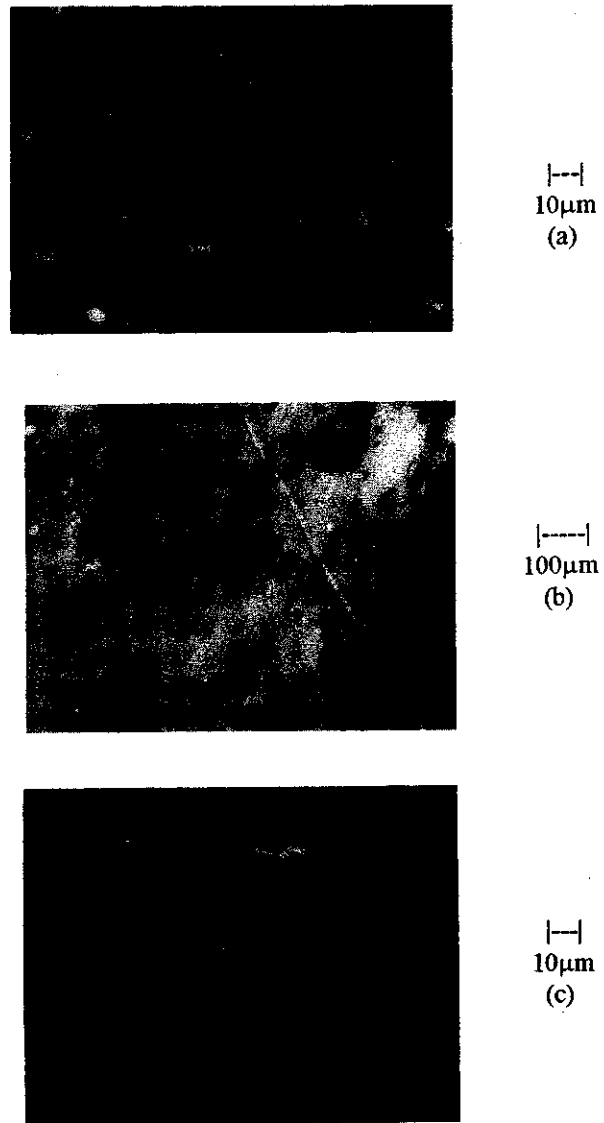


Fig. 4. SEM Micrographs of ZAFs. (a) 3M 5303R (25 μm); (b) Sheldahl SHEL-ZAC; (c) Scotch 9703.

croscope (SEM). The compositions of the samples were determined by Energy Dispersive Spectroscopy (EDS). The EDS analysis was done on the ETEC Auto Scan with a PGT System 4 Plus Analyzer.

3.2. Results and discussions

Figures 4(a)–4(c) show the surface observations of selected films of the four ZAFs. The 3M and Sheldahl materials have relatively uniform particle sizes. The Scotch tape has particles agglomerated together. The particle densities were calculated from the average density from different areas of the ZAFs investigated in the SEM studies, as listed in Table 3. The surface area density calculated from the two-dimensional point of view is shown in Fig. 5, and is a more appropriate representation of the particle loading density. Here the Scotch ZAF has the highest area percentage because it has large aggregated

Table 3. Properties of ZAFs from SEM and EDS analysis.

Materials	3M 5303R	Scotch 9703	Sheldahl SHEL-ZAC
Particle diameter (SEM)	8 μm	20–30 μm Agglomerated	10 μm
Particle loading density	500 particles per sq. mm	278 particles per sq. mm	389 particles per sq. mm
Particle composition (EDS)	Ni (100%) Nickel coated polymer	Ag (10.21%) Ni (89.79%) Ag coated Ni	In (22.87%) Pb (77.13%) In-Pb

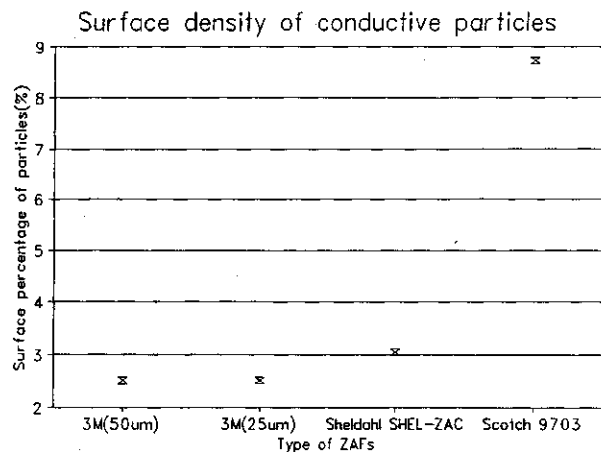


Fig. 5. The surface density of the particles.

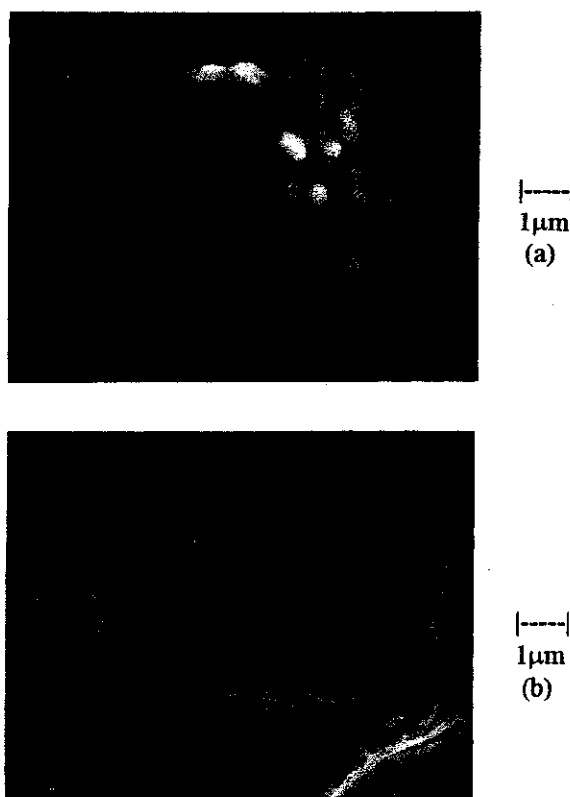


Fig. 6. (a) Particles before bonding; (b) Particles after bonding at too high a pressure.

particle clusters. The EDS analyses of the particle compositions are listed in Table 3.

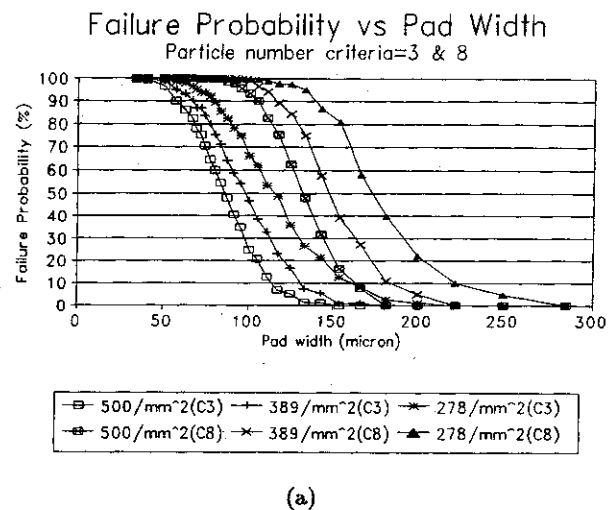
A detailed look at these particles from the 3M ZAFs is shown in Figs. 6(a) and 6(b). Figure 6(a) is the particle structure before bonding, where filler particles were covered by a layer of small particles, which are identified as Ni with the EDS probe. Figure 6(b) shows the particle deformation after adding bonding pressure and temperature, and the particle shows signs of cracking. So for the process pressure selection, the bonding pressure should not be too high.

4. Selection Models for Pitch Application

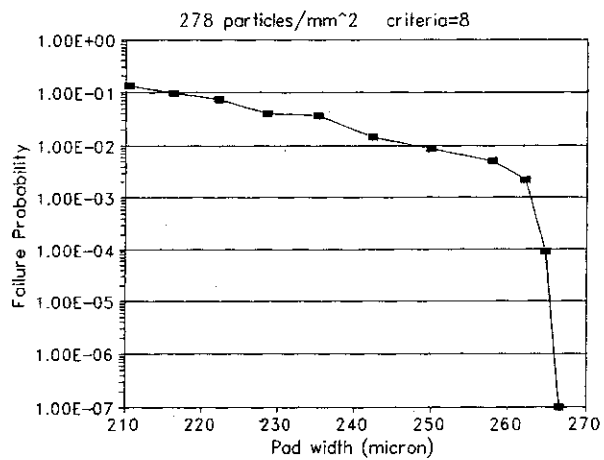
ZAFs have the conductive particles dispersed in the polymer matrix. Their intended applications will determine the structure of the ZAFs. The conduction pad size and pad spacing, which are the essential pitch parameters, will determine the ZAF particle

as 2.512%. For this particle size, the minimum pad spacing is $8\ \mu\text{m}$. In addition, the probability that two particles will touch, calculated from the simulation, is 0.75%, and the minimum pad space increases to $16\ \mu\text{m}$ if the possibility of these two particles bridging contacts must be eliminated. The product of the particle touching probability and the probability that these contacts are in the direction that will lead to shorting can determine the shorting probability. In Williams, *et al.*,¹⁶ the probability of a short was calculated according to the space between pads. For the $25\ \mu\text{m}$ sphere, the pad spacing must be larger than $0.17\ \text{mm}$ to ensure a $< 1\ \text{ppm}$ shorting probability. The pad spacing required will decrease as the particle diameter becomes smaller. For the current pitch technology, which is several mil spacing, it is unlikely that X-Y isolation failure will be caused directly by particles bridging adjacent pads. The potential failure would be more likely due to metal migration, or to a combination of the high electric field applied during accelerated life testing and localized field enhancement at high filter densities leading to dielectric breakdown.³

Figure 8(a) shows the different loading density effects on the failure probability for the criteria = 3 and 8. For the particle density at 389 particles/ mm^2 , which is the particle density for the Sheldahl films from the SEM investigation, the graph shows us that the failure probability change region is around $150\ \mu\text{m}$. So for this case, the conduction pad width (for square conduction pads) must be at least $225\ \mu\text{m}$ (9 mil) to ensure contact between the pad and lead for the criteria = 8. For the particle density of 278 particles/ mm^2 which is the actual particle distribution for the Scotch film, the observed agglomerated particles were considered to be single particles with large diameters about $20\ \mu\text{m}$. From Fig. 8(a), the probability change range is around $200\ \mu\text{m}$, and the pad width must be at least $300\ \mu\text{m}$ (12 mil) to ensure interconnection conduction between the pads for the criteria = 8. For a pad size less than $50\ \mu\text{m}$, all the films will have failure problems. There is relatively little difference between different particle densities, although the lower density films do need larger pad sizes for reliable contact. An example of the enlarged graph for the failure probability versus pad size for particle density of 278/ mm^2 and criteria = 8 is shown in Fig. 8(b), to cover the reliability range of particle concern. The failure probability drops very quickly over a $20\ \mu\text{m}$ range. It is important to predict this range and have a safety margin for applications.



(a)



(b)

Fig. 8. (a) The failure probability versus pad size for different particle densities for criteria = 3 and 8. (b) Expanded scales (failure probability versus pad size for 278/ mm^2 and criteria = 8).

For the Sheldahl film, the particle diameter is about $10\ \mu\text{m}$ and the surface density is calculated as 3.054%. The minimum pad space for this film is $10\ \mu\text{m}$, with a probability of two particles touching 0.9% for the $20\ \mu\text{m}$ pad space. For the Scotch film of $20\ \mu\text{m}$ agglomerated particles, the minimum pad space is $20\ \mu\text{m}$. For the $40\ \mu\text{m}$ pad space, there is a probability of losing isolation between pads of about 2.43%.

Figure 9 shows that the minimum pad size required for conduction decreases with loading density increase. For a designed pad size, the selection of

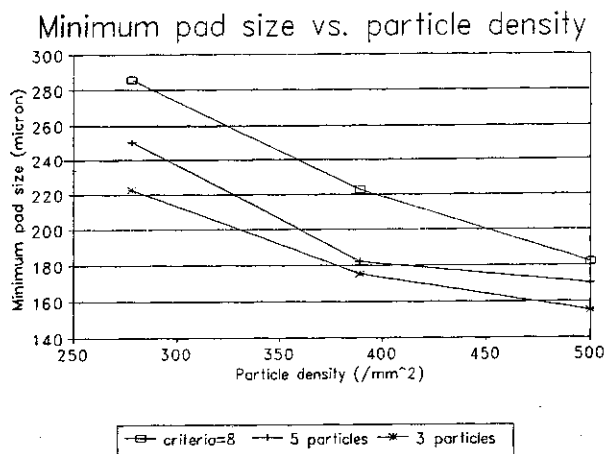


Fig. 9. The minimum pad size versus particle loading density for different criteria.

film particle loading density can be guided by the simulation. In this program, we assume that the particle size does not affect the criteria to hit a pad. Films with bigger particles may not require such high particle number criteria in the target pad to ensure contact as small particle films do. Note that the program assumes constant particle diameters and does not include particle compression effects of applied pressures.

5. Summary

The process properties of the commercial ZAFs, mainly bonding pressure and bonding temperature, were studied. The relationships between the bonding parameters and the bonding joint resistance were established. The optimum bonding parameters have been chosen through experimentation for the ZAFs.

The microstructures of the four commercially available ZAFs were studied by scanning electron microscopy and by Energy Dispersive Spectroscopy for the particle composition. The SEM investigation reveals spherical particle diameters and the particle distribution in the ZAF, and also the particle loading density for each film. 3M 5303R and Sheldahl SHEL-ZAC have similar particle sizes at about 10 μm . The Scotch film has agglomerated particle structures.

The computer program was developed to calculate the minimum pad size for different loading densities and the minimum pad spacing for different particle sizes. The calculated failure probability of conduction has a narrow transition region for the

pad size. It is important to avoid this region for fine pitch applications. The particle loading and size can be determined by the program calculation for a particular application pitch. This is useful for users to select the appropriate ZAFs for their application, and also for the vendor for product development.

Acknowledgments

We would like to thank Henry Eichelberger and Bill Blackburn for their generous help with the SEM and EDS analyses. Special thanks are due to 3M and Sheldahl for donating samples for our experiments. This research was funded by the Integrated Electronics Engineering Center at Binghamton University, and by the Motorola-IEEE/CPMT Graduate Fellowship for Research in Electronics Packaging.

References

1. N. R. Basavanahally, D. D. Chang, B. H. Craon and S. G. Seger, "Direct chip interconnect with adhesive-conductor films", *Proc. of 42nd IEEE Electronic Components and Technology Conference, San Diego, 1992*, pp. 487-491.
2. D. D. Chang, P. A. Crawford, J. A. Fulton, R. McBride, M. B. Schmidt, R. E. Simtski and C. P. Wong, "An overview and evaluation of anisotropically conductive adhesive films for fine pitch electronic assembly", *IEEE Trans. Comp. Hybrids, Manuf. Technol.* **16**(8) (1993), 828-835.
3. D. D. Chang, J. A. Fulton, H. C. Ling, M. B. Schmidt, R. E. Simtski and C. P. Wong, "Accelerated life test of Z-axis conductive adhesives", *IEEE Trans. Comp. Hybrids, Manuf. Technol.* **16**(8) (1993), 836-842.
4. K. Chung, T. Devereaux, C. Monti, M. Yan and N. Mescia, "Z-axis conductive adhesives as solder replacement", *Proc. 1993 Surface Mount Technology Int., San Jose, 1993*, pp. 554-560.
5. K. Chung, R. Fleishman, D. Bendorovich, M. Yan and N. Mescia, "Z-axis conductive adhesive for fine-pitch interconnection", *Proc. 1992 Int. Electronics Packaging Conf., San Diego, 1992*, pp. 678-689.
6. R. Estes, F. Kulesza, P. Delivorias, D. Buczek and G. Riley, "Environmental and reliability testing of conductive polymer flip chip assemblies", *Proc. 1993 Int. Electronics Packaging Conf., San Diego, 1993*, pp. 328-342.
7. K. Gilleo, T. Cinque, S. Corbett and C. Lee, "Thermoplastic adhesive — The attachment solution for multichip modules", *Proc. 1993 Int. Electronics Packaging Conf., San Diego, 1993*, pp. 232-242.
8. S. Jin, T. H. Tiefel, L. H. Chen and D. W. Dahringer, "Anisotropically conductive polymer films with a uniform dispersion of particles", *IEEE Trans. Comp. Hybrids, Manuf. Technol.* **16**(8) (1993), 972-977.

9. J. Liu, "Reliability of surface-mounted anisotropically conductive adhesive joints", *Circuit World* 19(4) (1993), 4-11.
10. H. Matsubara, H. Atarashi, K. Yamamura, N. Kakimoto, K. Naitoh and T. Nuki, "Bare-chip face-down bonding technology using conductive particles and light-setting adhesives: 'Elastic' method", *IMC 1992 Proc., Yokohama*, June 1992, pp. 81-87.
11. H. Morishita, T. Kokogawa, K. Adachi, A. Ishizu and H. Takasago, "Optimum condition of fine pitch bonding by using ACF", *IMC 1992 Proc., Yokohama*, June 1992, pp. 88-92.
12. H. Otsuki, T. Kato, F. Matsukawa, M. Nunoshita and H. Takasago, "Chip-on-glass packaging technology using conductive particles", *IMC 1992 Proc., Yokohama*, June 1992, pp. 99-103.
13. R. R. Reinke, "Interconnection method of liquid crystal driver LSIs by tab-on-glass and board to glass using anisotropic conductive film and monosotropic heat seal connectors", *Proc. of 41st IEEE Electronic Components and Technology Conf., Atlanta*, 1991, pp. 355-361.
14. W. Takahashi, K. Murakoshi, J. Kanazawa, M. Ikehata, Y. Iguchi and T. Kanamori, "Solderless COG technology using anisotropic conductive adhesives", *IMC 1992 Proc., Yokohama*, June 1992, pp. 93-98.
15. D. C. Whalley, D. J. Williams, Y. Ogunjimi, O. A. Boyle and M. Goward, "A comparison of the behavior of isotropic and anisotropic conducting adhesives", *ASME Winter Annual Meeting, New Orleans, Louisiana*, pp. 81-91.
16. D. J. Williams and D. C. Whalley, "The effects of conducting particle distribution on the behavior of anisotropic conducting adhesives — nonuniform conductivity and shorting between connections", *J. Electron. Manuf.* 3 (1993), 85-94.
17. D. J. Williams, D. C. Whalley, O. A. Boyle and A. O. Ogunjimi, "Anisotropic conductive adhesives for electronic interconnection", *Soldering Surface Mount Technol.* 14 (1993), 4-8.
18. Y. Yamamoto, A. Inaba, H. Itoh and K. Kondo, "Screen-printable thermo-setting type anisotropic conductive paste interconnection of display device with TAB (COF)", *IMC 1992 Proc., Yokohama*, June 1992, pp. 175-181.