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The effect of bonding force on the electrical performance and reliability of NCA joints processed at a lowered temperature

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Abstract The effect of the bonding force during flip chip-on-flex (FCOF) assembly on the electrical performance of the nonconductive adhesive (NCA) interconnects was investigated in this study, under the precondition of a reduced processing temperature in order to minimize thermally-induced damage to the low-cost flexible substrates. Pressure cooker tests (PCT) were performed to assess the reliability performance of the adhesive joints in high temperature and high humidity conditions. The assembly process was modified and the processing temperature and the bonding force were adjusted according to the experimental results to enable the use of low cost substrates, such as poly(ethylene terephthalate) (PET) materials in smart card fabrication.

Introduction

Currently, flip chip technology using polymeric adhesives is seen as one of the promising alternative solutions to solder interconnection technology. Advantages offered by the adhesive flip chip interconnection include production cost reduction, manufacturing simplicity, fine pitch possibility, good electrical performance, as well as environmental friendliness [1]. Among the different types of adhesives, nonconductive adhesive (NCA) is so named because of the absence of any conductive particles within the adhesive matrix to achieve electrical conductivity between the chip bumps and the substrate pads. Instead, the electrical interconnection relies on the direct metal contact between the opposing electrodes, which is maintained through the contracting strength and the adhesive strength of the cured adhesives. NCA flip chip interconnection provides a solution for the ultra-fine interconnection and has recently found its application in the manufacturing of CDs, LED array modules, and smart cards, etc [2, 3].

In some cases, however, when some low cost substrates are used for a total cost control purpose, the base materials of the substrates may not be able to tolerate the temperature during bonding even though this temperature is already lowered as compared to the case of flip chip bonding using soldering. For example, when a PET-based substrate is used in smart card fabrication, it is recommended that the applied temperature during the assembly process be kept under 160 °C to prevent any warpage or even damage of the substrate [3]. In view of this consideration, a reduction in the temperature during the flip chip bonding can be attempted. Meanwhile, the entire assembly process needs to be revised accordingly.

In this study, a single film type NCA was used as the interconnect material. Under the precondition of the reduced bonding temperature, the assembly process was modified and investigated with an emphasis on the effect of the bonding force on the electrical performance and the reliability of the NCA joints. Thermal analysis methods including Thermogravimetry Analysis (TGA), Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FT–IR) were adopted, guiding the process modification which should ensure the proper curing of the NCA. Contact resistances were measured using a four-point probe method for the electrical characterization of the NCA joints made under different bonding conditions. To investigate the reliability of the NCA joints, pressure cooker tests were performed as polymeric

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adhesives are known to be susceptible to moisture-induced failures. Interfacial and microstructural inspections using a Scanning Acoustic Microscope (SAM) and a Scanning Electron Microscope (SEM) were conducted to gain more insight into the failure mechanisms. On the basis of the experimental data and the analysis results, one optimal assembly scheme was determined. It is expected that this study will provide usable information related to smart card production and other similar processes such as radiofrequency identification smart label fabrication, etc.

Experimental

Materials

The chip used in the experiment was 11 × 3 × 1 mm in dimensions. Figure 1 gives a schematic description of the chip. Among a total of 368 Au–Ni bumps laid peripherally on the chip, 68 bumps were used for mechanical support. For the remaining 300 bumps, every group of five formed a unit which was designed for contact resistance measurements. So in total, 60 resistance data points can be obtained from each chip. The dimensions of the bumps were 50 × 70 × 18 μm.

The polyimide flexible substrate was 25 μm in thickness, onto which 12 μm thick Cu traces were laminated. The Cu traces were then plated with 2.5 μm thick Ni and 0.5 μm thick Au.

The film type NCA used was an epoxy-based adhesive resin with no fillers. The thickness of the adhesive layer was 40 μm. TGA and DSC analyses were used to obtain degradation and curing information of this adhesive material.

Flip chip-on-flex (FCOF) assembly process

The modified assembly process could be divided into three steps. (1) First, a correct size piece of the film type NCA was laminated onto the substrate after warming up at room temperature for 1 h. Pre-bonding was performed at 90 °C for 10 s accompanied with a bonding pressure of 30 kPa on a KarlSuss manual bonder. The cover layer on the NCA was then carefully peeled off. (2) Next, bonding was performed on a Toray FC2000 Flip Chip bonder. The regular assembly scheme applied when using this adhesive is bonding at 220 °C for 10 s accompanied with a pressing force of 90 N over the 3 × 11 cm^2 test chip. In this study, the bonding temperature was to 180, 160, and 140 °C. For each temperature setting, a group of progressively increased bonding forces was applied. Bonding durations were set to 10 s for all samples. Detailed bonding conditions are listed in Table 1. (3) Due to the temperature reduction in the previous step, the adhesives did not obtain sufficient thermal energy to get adequately cured. Hence, all the bonded assemblies were inserted into a high temperature chamber and post-cured at 140 °C for 2 min. After the assembly process, FT–IR inspections were carried out to determine the degree of cure of the NCAs in the different samples. The effect of the bonding force on the electrical performances of the NCA joints in different samples was also studied.

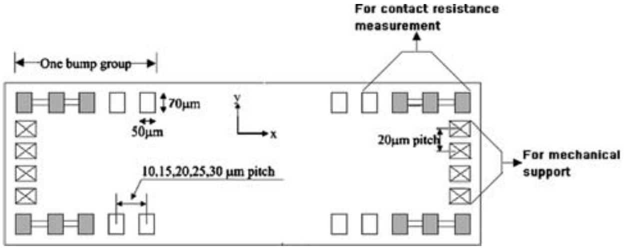


Fig. 1 Schematic diagram of the chip layout

To investigate the effect of the bonding force on the reliability of NCA joints processed at lower temperatures, another batch of the FCOF assemblies was prepared as shown in Table 2. Three samples were assembled following each scheme and were then subjected to reliability tests. Samples assembled at 220 °C were also prepared as a reference.

Electrical characterization

The contact resistances of the NCA joints were measured using a four-point probe method. As illustrated in Fig. 2, a 1 mA current was fed into the circuit, and a Hewlett Packard 3478A multimeter was used to measure the voltage across the target joint. The contact resistance of the joint was then calculated by Ohm's Law.

Table 1 Bonding parameters

Temperature (°C)	Force (N)	Time (s)
140	90,120,180,270	10
160	90,120,180	10
180	90,120	10

Table 2 Samples for reliability test

	Pre-bonding (90 °C, 3×10^3 kPa, 10 s)	Bonding			Post-curing (140 °C, 2 min)
		Temp. (°C)	Force (N)	Time (s)	
Reference group	Applied	220	90	10	Unapplied
Testing group	Applied	160	120,150,180	10	Applied

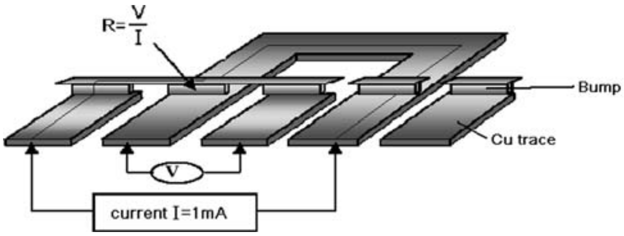


Fig. 2 Four-point probe method for contact resistance measurement (5 bumps per group)

Reliability test

To assess the ability of the assemblies to withstand severe temperature and humidity conditions, pressure cooker tests (PCT) at 121 °C, 100% relative humidity and 2 atmosphere pressure for a duration of 192 h were performed. The tests were paused every 48 h for contact resistance measurements. Also, one sample in each group was put under SAM inspection after 96 and 192 testing hours. These samples were dried at 25 °C before they were reinserted into the reliability testing chamber along with the remaining samples.

Failure analysis

SAM inspections were performed to detect any subsurface defects, such as interfacial delamination, cracks, etc after the FCOF assemblies went through the pressure cooker tests. Also, an optical microscope and SEM were used for morphological and cross-sectional observations in order to investigate the microstructure of the interconnection and to further elucidate the failure mechanisms.

Results and discussion

Material characterization

TGA is known as a method for characterizing the decomposition and thermal stability of materials under a variety of conditions and to examine the kinetics of the physico-chemical processes occurring in a sample [4]. In the experiment, the scan tests were run from 20 °C to over 520 °C at a ramp rate of 20 K minute^{-1}. The mass change versus temperature results are plotted in Fig. 3. A slight but constant decrease in the sample weight was observed as the test proceeded, which is most likely due to solvent evaporation as the adhesives became gradually more cured. When the temperature reached 340 °C where there was a 9% loss of the original sample weight, decomposition of the cured NCAs was observed to start. Therefore, this temperature is the limit for further material characterization and for post-processing of the cured NCAs.

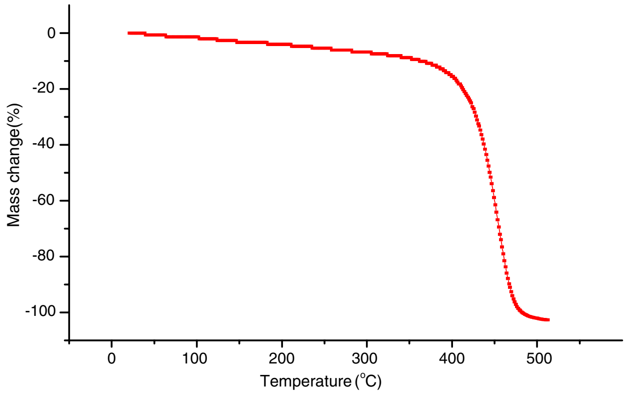


Fig. 3 TGA result (heating rate 20 K minute^{-1})

Dynamic DSC tests were set from 30 °C to 280 °C at a heating rate of 10 K minute^{-1}. Small quantities of the adhesives (about 5 mg) underwent the tests using this same scan profile twice, and the results are shown in Fig. 4. From the first scan result, the onset temperature of the cure reaction of a fresh sample was found at 103 °C, shortly after which, the heat generated from the crystallization of the adhesives increased dramatically due to the acceleration of the reaction rate at higher temperature. Two exothermic peaks were present at 131 °C and 188 °C, respectively. The completion of the cure was marked as the return of the heat flow curve to the sample baseline.

In the second scan, no more exothermic reaction was detected indicating that the degree of cure of the adhesive was close complete. Furthermore, the stepped increase in the heat capacity suggests that the glass transition temperature (T_g) of the cured adhesives is around the 110 °C region. However, due to the variations of the exact T_g values of polymer materials with processing conditions [5],

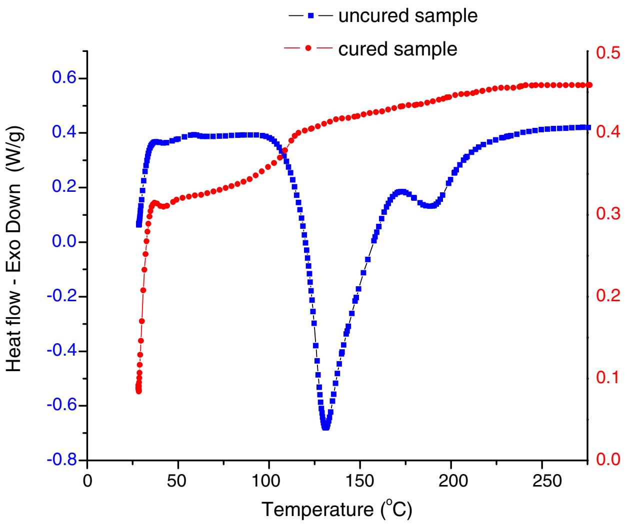


Fig. 4 The dynamic DSC scans (heating rate 10 K minute^{-1})

this figure is only taken as a general reference of the temperature above which the amorphous components within the adhesive start to transform from a glassy state into the rubbery state. The modulus of the adhesives would experience a drop beyond this temperature, but not significantly, because the crystalline components in highly-cured adhesives form crosslink structures which provide sufficient mechanical strength.

During bonding, the temperature applied is one important factor in determining the degree of cure of adhesives. A higher bonding temperature enables a quick transfer of more heat energy from the thermode to the NCAs during processing, which promotes the faster cure of the adhesive. However, in this experiment, the bonding temperature was deliberately lowered to minimize the thermally-induced impact to the substrate. The cure of the NCAs was thus impaired by the insufficient heat available. The exact degree of cure value of the NCA in each sample group was examined by FT–IR which measured absorption of different IR frequencies by the sample positioned in the path of an IR beam [6]. For a quantitative analysis, the degree of cure of the adhesive (α) at time t can be calculated from the following equation:

$$\alpha = 1 - \frac{A_{\mathrm{epoxy},t}/A_{\mathrm{ref},t}}{A_{\mathrm{epoxy},0}/A_{\mathrm{ref},0}} \qquad (1)$$

where $A_{\mathrm{epoxy},0}$ and $A_{\mathrm{ref},0}$ are the initial absorption areas of epoxy and reference peaks, and their corresponding values at time t are $A_{\mathrm{epoxy},t}$ and $A_{\mathrm{ref},t}$, which were at 915 cm^{-1} and 1507 cm^{-1}, respectively in this case. Test results revealed that only 13, 24 and 47% of the complete cure were achieved for samples bonded at 140, 160 and 180 °C, respectively. It has been reported that incompletely-cross linked polymeric adhesives cannot provide a high enough strength and modulus to maintain the stability of the joints and the integrity of the whole assembly [7]. Hence, it was suggested that the adhesives were further cured in a post-curing step. The aforementioned T_g region of the fully-cured adhesives at around 110 °C was taken as a reference value here. The post-curing temperature was set at a higher value of 140 °C to avoid the occurrence of a vitrification transformation, for otherwise the reaction rate would be significantly retarded due to the change of the cure from a chemically controlled reaction to a diffusion controlled reaction [8]. After 2 min post-curing at this temperature, the degree of the cure of the adhesives in the 140, 160 and 180 °C sample group were found to dramatically rise to 85, 90, and 91%, respectively. Figure 5 gives an example of the FT–IR spectra of the NCA in 160 °C group before and after post-curing. As a reference, NCA cured in the regular 220 °C/90 N bonding process without any post-curing treatment was also put under FT–IR inspection and an 86% degree of cure was found. It is then concluded that direct contact between chip bumps and substrate pads was established in the bonding step while the adhesives were only partially cured. Further curing of the adhesives was achieved in the post-curing process.

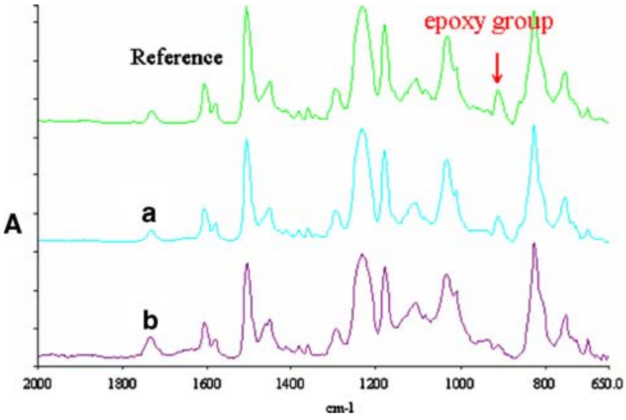


Fig. 5 FT–IR spectra of NCA specimen in 160 °C group (**a**) before post-curing, and (**b**) after post-curing

Effect of bonding force on the electrical performance of NCA joints

For NCA interconnections, electrical conductivity is established via direct contact between the chip bumps and the opposing substrate pads, and is maintained by the adhesive strength and the contracting strength of the cured adhesives. During bonding, the NCAs turn into a low viscosity status first with the application of the bonding temperature. The NCA layer originally covering the substrate pads is squeezed out under the pressing force of the thermode to enable intimate contacts between the opposing electrodes.

With the reduction of the bonding temperature as in this case, however, the adhesive remains more viscous and stickier to the pads, which becomes more difficult to completely dispel. Entrapped adhesive decreases the effective contact areas between the bumps and the pads and in the worst case, totally blocks the contacts. This finally results in an increased contact resistance and open joint failures. Figure 6 shows the average contact resistances of the NCA joints processed under different bonding temperature and bonding force conditions. The experimental results revealed when a 90 N bonding force was applied, only the sample in the 180 °C group had a satisfactory electrical performance with an average contact resistance of 5.2 mΩ. The average resistances of the 160 °C and the 140 °C samples were 16 and 26.2 mΩ, respectively.

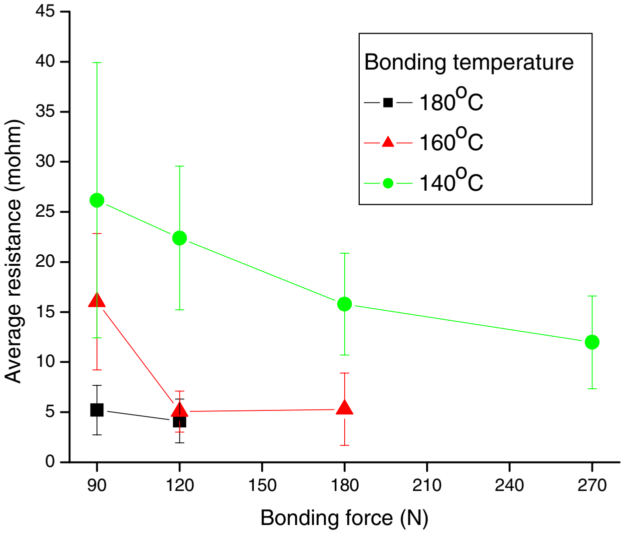


Fig. 6 Average resistance versus bonding force at different bonding temperatures

For more direct observations, several samples were sheared. Also SEM micrograph of the bump surfaces is shown in Fig. 7. For the samples bonded at 140°C, some adhesive patches were found left on the bumps. By contrast, samples bonded at higher temperatures had neater contact surfaces.

To more effectively dispel the adhesive layer and to increase the contact areas, the bonding force was increased as a compromise with the bonding temperatures fixed at relatively low values. Also, a larger bonding force facilitates the build up of higher contact stresses between the bumps and the pads, which is beneficial to improving the electrical performance. From Fig. 5, when the bonding force was raised to 120 N, the average resistance of the 160 °C group samples reduced to 5.1 mΩ, comparable to the 180 °C group samples. Nevertheless, the 140 °C group samples still had a high resistance of 22.4 mΩ, and one joint resistance exceeded 50 mΩ. With a further increase of the bonding force, the average resistances of the 140 °C group samples continued to decrease. At a 270 N bonding force, the sample had an average resistance of 12 mΩ. Despite the acceptable electrical performance in this case, however, this value was undesirable because the 210 MPa bonding pressure generated on each bump largely exceeded the maximum value of 150 MPa as recommended by the NCA supplier.

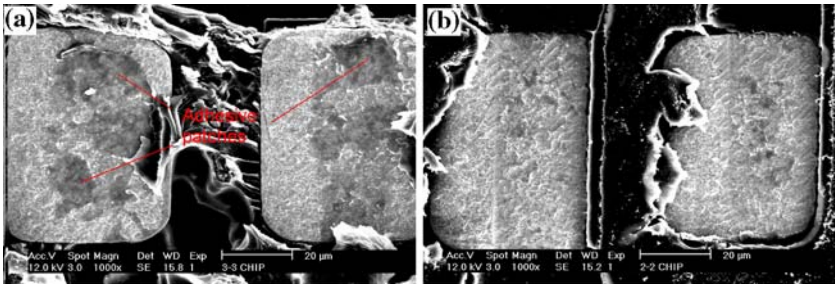
In summary, the increase of the bonding force helps to more effectively squeeze out the NCA layer which remains more viscous at a lower bonding temperature, thus enabling the build up of a larger area of direct metal contact. A bonding temperature of 140 °C should not be applied since acceptable electrical performance of the assembly is only achieved at a very high bonding pressure. A batch of samples bonded at 160 °C with varied bonding forces were then fabricated for reliability assessment in PCT.

Effect of bonding force on the reliability of NCA joints

To investigate the effects of bonding force on the assembly reliability and to assess the ability of the assemblies to withstand severe temperature and humidity conditions, pressure cooker tests (PCT) at 121 °C, 100% relative humidity and 2 atmosphere pressure for 192 h were performed. Processing conditions of the tested samples are listed in Table 2. The samples were taken out of the tested chamber for electrical characterization every 48 testing hours. An NCA joint was determined to be a failure once its resistance exceeded 50 mΩ. Such resistance values were then excluded from the calculated average resistance. Figure 8 shows the failure percentage of the joints and the average resistance of the samples in each group at different PCT testing times.

From the experimental results it was observed that the electrical performances of the samples in different groups were similar. After 96 h, most joint failures were found in the 160 °C/180 N group. About 6.7% of the joints had resistance values larger than 50 mΩ. As the tests proceeded, joint failures in all the groups increased and the difference across different groups seemed to diminish. After 192 test hours, the failure percentages in all the groups ranged from 19% to 25%. For the remaining joints which survived, their resistances increased over the period studied. The average resistances of the samples in all the groups were below 5.5 mΩ before the test, and

Fig. 7 Inspection of adhesive remnants on chip bumps of the samples bonded at (**a**) 140 °C/ 90 N, (**b**) 180 °C /90 N



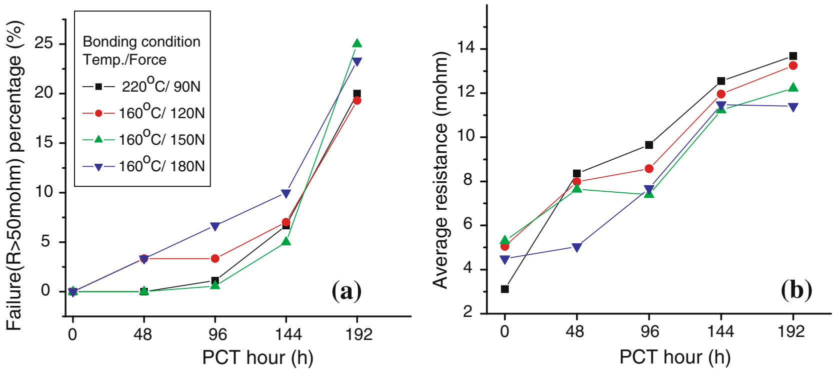


Fig. 8 Electrical performances of NCA joints in PCT: (**a**) failure percentage, (**b**) average resistance versus testing times

rose to between 11.5 mΩ and 14 mΩ after the test. The electrical performances of all the samples were comparable to that of the samples in the reference group.

The effect of the bonding force on the reliability performance of the NCA joints was not clearly reflected from the above resistance measurement results. However SAM results in Fig. 9 may give a better picture. Delamination was found located around the bump positions at the peripheral areas of the chip where the maximum pressing force existed during bonding, and it was more severe in samples that underwent higher pressure bonding. According to Tan et al.'s work, too high bonding force reduces the separation space between the chip and substrate to the point that the adhesive is not allowed to flow easily and the release of the trapped voids is thus restricted [9]. Also, higher bonding forces lead to larger residue stresses built up at the bonding interface, which tend to peel off the adhesive from the die and the substrate after the release of the pressing force during bonding [10]. During PCT in this study, these latent defects degraded the moisture resistance and the adhesion strength of the NCA bonded assemblies to different extents. A more severe delamination failure is thus observed in samples bonded at the highest force of 180 N, which is adverse to maintaining the mechanical strength and the structural integrity of the assembly. To conclude, the bonding force should be adequately set to enable direct contact between opposing electrodes on the one hand, as well as to minimize the formation of potential defects within the structure on the other hand.

Cross-sectional examination using SEM was also performed to gain more insight into the failure mechanisms. As shown in Fig. 10, the sample which underwent a higher bonding pressure (9d) had a more obvious substrate deformation. Interfacial delamination was found at the adhesive/substrate surfaces of the samples in all the groups, leading to open joint failures. For NCA joints, the electrical interconnections are built on direct metal contact between opposing electrodes, and maintained by the compressive

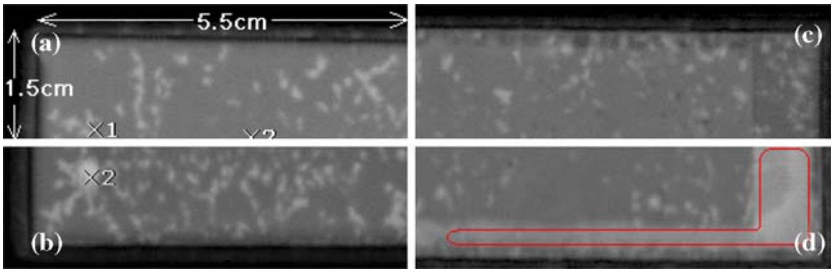


Fig. 9 SAM results from FCOF assemblies bonded at 160 °C with a bonding force of: (**a**) 120 N before PCT, and (**b**) 120 N, (**c**) 150 N, (**d**) 180 N all after PCT 192 h

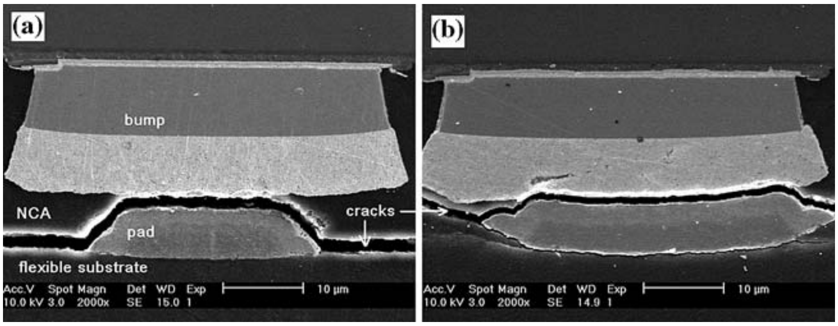


Fig. 10 Open joint failures after PCT 192 h: samples bonded at (**a**) 160 °C/120 N, (**b**) 160 °C/180 N

strength and adhesive strength of the cured adhesives to steadily hold the assembly. During PCT, the coefficient of thermal expansion (CTE) mismatch and coefficient of moisture expansion (CME) mismatch between various materials induced a certain level of stress within the structure of the assembly, in addition to the previously mentioned peeling stress generated during the bonding process. As the stresses accumulated and finally exceeded the adhesive strength at one of the bonding surfaces, interfacial delamination was initiated at the weakest bonding region, in this case the adhesive/substrate interface, and spread out. Moreover, interfacial delamination could be exacerbated owing to the degradation of the NCA in its adhesive strength upon exposure to the high temperature and high humidity testing environment. Once the delamination spread to the adhesive/pad area, the direct metal contacts were then lost, which was fatal to NCA joints.

As for the joints which survived in the test, the increase in the resistance values can be ascribed to the relaxation of the contact stress between the bumps and the substrate pads, caused by a series of reasons, i.e., hygroscopic swelling, thermal expansion, and degradation of the contraction strength of the adhesive in the harsh environment [1, 11].

To sum up, the electrical performance of the FCOF samples assembled at a lowered processing temperature were comparable to that of the reference samples under PCT evaluation. Open joint failures were found in all the groups, arising from interfacial delamination at the adhesive/substrate interface. A more severe delamination is observed in the samples bonded at a higher bonding pressure. Hence, the 160 °C/120 N bonding condition was considered as the best combination in this investigation considering the reliable electrical performance of the NCA joints in PCT, the reduced processing temperature, and the moderately increased bonding force at this temperature.

Conclusions

In this study, the effect of the bonding force on the electrical performance and the reliability of NCA joints processed at lowered temperature were investigated. An increase of the bonding force enabled the efficient dispelling of the NCA layer from the contact regions, especially when the bonding temperature was lowered to minimize thermally-induced damage to low-cost flexible substrates. The lower the temperature, the larger the bonding force required to achieve good electrical performance in terms of small joint resistance. However, a greater risk of interfacial delamination failure was generated when a higher bonding pressure was applied in the study, which was detrimental to the mechanical strength and structural integrity of the assembly. From the experimental results, the 160 °C/120 N bonding condition followed by a 2 min post-cure at 140 °C was found as the optimal assembly scheme, considering the reliable electrical performance of the NCA joints in PCT as compared to the reference sample bonded at 220 °C, the reduced processing temperature, and the moderately increased bonding force which enabled good electrical conductivity on the one hand, and on the other hand minimized delamination risks.

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