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Bonding strengths at plastic encapsulant–gold-plated copper leadframe interface

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Abstract

The effect of plasma treatment on the adhesion strength of a moulding compound to a leadframe is evaluated on the basis of leadframe pull-out tests. The contact angle measurement method and atomic force microscopy are employed to quantitatively characterise the modified surface so as to correlate with the bond strength measurements. Process parameters including the type of gases used and the duration exposed in air before moulding are specifically studied. The results indicate that plasma treatments of leadframe have three major ameliorating effects, namely, clean surface due to the removal of organic contaminants, enhanced chemical compatibility with moulding compound and rough surface with associated larger surface contact area for better mechanical interlocking. Exposure of plasma treated leadframes in air before moulding is found detrimental to interface bond quality, recommending moulding operations immediately after treatment. It is also shown that roughness on the nanoscale is an important surface characteristic that has a strong correlation with the interface bond strength. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The encapsulant in plastic encapsulated microcircuits (PEMs) is an electrically insulating moulding compound containing plastics, silica particles and other additives. The encapsulant is designed to protect the electrical device and die–leadframe assembly from the adverse environments encountered during handling, storage and manufacturing processes as well as to dissipate the heat generated from the die during service. The encapsulant must possess adequate mechanical strength, adhesion to various package components, good corrosion and chemical resistance, matched coefficient of thermal expansion (CTE) to the materials it interfaces with, high thermal conductivity and high moisture resistance in the temperature range used [1]. In particular, the ability to form good adhesion with various package components and to remain bonded under the adverse manufacturing and service conditions is of paramount importance as delamination along the interfaces is a major reliability issue for PEMs [1,2].

Contamination of metallic leadframe surface through the presence of oxides and hydrocarbons predominantly due to the high temperature processes may degrade the interface, causing premature debonding, and thus, a clean leadframe surface is a vital pre-requisite for good wetting and adhesion with moulding compound. Various techniques have been used for this purpose to modify the surface chemistry and topography of metals, such as dipping into acid or caustic solutions with and without the aid of electrolytes, metal plating, priming with organic inhibitors, vacuum deposition, ion implantation, UV cleaning and plasma treatments based on various energy sources and gas media. Of these techniques, the plasma treatment has gained much popularity [3–5] amongst the electronic package manufacturers. Not only can the plasma cleaning process be integrated into other manufacturing processes, but it

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also cleans sub-micron structures effectively. Another major advantage is that only the top several molecular layers of surface are altered, while the characteristics of the bulk material remain the same. A study on copper leadframe and die back surface [3] showed that the higher the plasma RF power and the lower the chamber pressure, the quicker the reduction of contact angle to a desired level of lower than about 10°. The carbon contamination detected on the leadframe surface was found to be linearly proportional to the contact angle, indicating the relative sensitivity of contact angle measurement for determining surface contamination. In our previous study on a similar plasma-treated copper leadframe [14], the contact angle was found to increase with the thickness of oxide layer. The longer the time exposed at an isothermal temperature of 175° which was designed to accelerate the oxidation process [8], the lower the interface bond strength with the moulding compound. The conclusion was that the thickness of surface oxide layer is a predominant factor affecting the wettability of leadframe, which in turn determines the interface adhesion. Although these parametric studies contributed significantly to the understanding of benefits of plasma treatment, the surface energy and roughness modified by plasma treatment for improving the interface bond quality have remained largely unresolved.

The significance of the leadframe–encapsulant interface characteristics for the reliability of plastic packages has led to the applications of several experimental techniques by destructive means to measure the interface bond quality in PEMs. These include the 90° or 180° peel test [6], leadframe pull-out test [7], double-lap shear test [8], button shear test, tab pull test [9], cylindrical bond test [10] and three-point bend test with an end precrack [11]. Amongst these experimental methods, the leadframe pull-out test has been one of the most popular, with which the present study is mainly concerned. By analogy with the fibre pull-out test of various specimen geometry that have been widely used to characterise the interface properties in fibre reinforced composites [12,13], the leadframe pull-out test measures the force to pull the leadframe out of the encapsulant after complete debonding.

Following our previous paper on oxidation of leadframe surface [14], the present work is part of a larger project on evaluating the interface characteristics in PEMs. An attempt was made to improve the interface bond quality between leadframe and plastic encapsulant by employing the plasma technique, which cleans and thus reduces unwanted organic and inorganic contamination on the gold-plated copper leadframe surface. Several important process variables were specifically studied, such as the type of gas media and duration of treatment. The leadframes were exposed in air for varying periods of time for up to 24 h before moulding of encapsulant in order to study the effect of contamination after plasma treatment on interface bond quality. Surface characterisation techniques, including contact angle measurement and atomic force microscopy (AFM), were employed to evaluate the surface energy and the roughness on the nanoscale that are affected by plasma treatment and thus to establish the correlation with the interface bond strengths measured from leadframe pull-out test.

2. Experiments

2.1. Materials and preparation of specimens

The leadframe materials used in this study consisted of gold plating of 0.5 μm in thickness on a thin (0.1 μm) nickel coated standard copper alloy C-194 base. The moulding compound used to form the encapsulant was standard epoxy-based Nitto MP-180S, which has a nominal flexural strength and modulus of 118 MPa and 12.1 GPa at room temperature, respectively. The plasma system, PX-1000 (March Instrument), which is a large capacity RF plasma system ideal for batch operation, was employed to apply plasma treatments on the leadframe. Three gases were used in this study, including argon, oxygen and hydrogen. Four different combinations of gas were employed: (i) O_2 (50%) and Ar (50%), (ii) H_2 (50%) and Ar (50%), (iii) O_2 (50%) and Ar (50%) followed by H_2 (50%) and Ar (50%), and (iv) Ar. The treatment time was 5 min for each combination of gases. The gas pressure was in the range of 234–300 mTorr, and the power used was 400 W.

The transfer moulding machine (Kras VSKO-120/E) combined with a high frequency pre-heater (Hisen HDP 523M) was used to prepare the leadframe pull-out specimens. The moulding conditions followed the manufacturer's instructions. A pre-heating temperature of 90°C was applied to the mould preform, and the moulding was conducted at 170°C at a transfer speed of 160 mm/min. To study the effect of surface contamination after plasma treatment on interface bond strength, the treated leadframes were exposed to air at room temperature and R/H of 50% for up to 24 h before moulding the compound. The embedded length of leadframe was maintained constant for all the specimens prepared. Fig. 1 shows a schematic drawing of leadframe pull-out specimen.

2.2. Contact angle measurements

One of the oldest theories of adhesion is wetting of a solid by a liquid. The wettability can be quantitatively defined by reference to a liquid drop resting in equilibrium on a solid surface, and the contact angle is obtained by measuring the angle between the tangent to the profile at the point of contact. The theoretical consid-

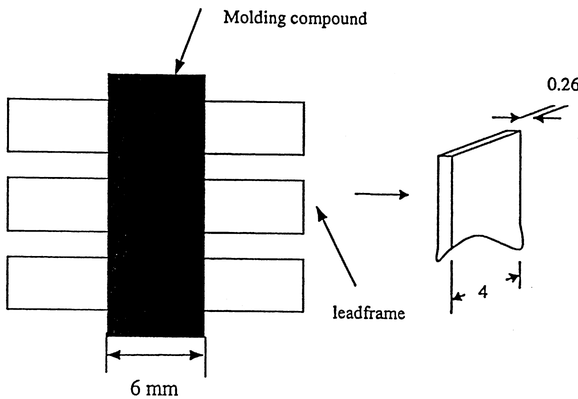

Fig. 1. Schematic drawing of leadframe pull-out specimen.

erations of wetting are generally based on the Young–Dupre equation that defines the work of adhesion, W_A, between the liquid and solid as a function of the contact angle, θ:

$$W_A = (1 + \cos\theta)\gamma_{LV}. \quad (1)$$

Eq. (1) indicates that the solid surface is said to be wetted only when the contact angle is smaller than 90°, and a large contact angle means a low work of adhesion and subsequently poor wettability. The work of adhesion and thus the surface energy consist of two components, namely, the polar and dispersive components, γ^p_{LV} and γ^d_{LV}, and these components can be determined based on the geometric mean approximation combined with Young–Dupre equation:

$$(1 + \cos\theta)\gamma_{LV} = 2[(\gamma^d_{SV}\gamma^d_{LV})^{1/2} + (\gamma^p_{SV}\gamma^p_{LV})^{1/2}], \quad (2)$$

where γ_{LV} and γ_{SV} are the surface free energies of liquid and solid, respectively, and the superscripts p and d refer to the polar and dispersive components, respectively. Measurements of contact angles with two liquids of known polar and dispersive components of surface energies, γ^p_{LV} and γ^d_{LV}, allow determination of the polar and dispersive components of solid (i.e., leadframe) surface energy, γ^p_{SV} and γ^d_{SV}.

The contact angle experiment was carried out using a goniometer [16]. Micro syringes were used to dispense 2 ml droplets of standard test liquid on leadframe. De-ionised water and glycerol were used, whose polar and dispersive surface energies are 51.0 and 21.8 dyne/cm, respectively, for de-ionised water, and 26.4 and 37.5 dyne/cm, respectively, for glycerol. The contact angle readings were taken within 45 s of droplet formation to avoid evaporation of liquid that might affect the measured results. With the aid of an illuminator and a camera, the images of droplets were captured, which were then analysed using an image analyser to determine the contact angles. Experiments on three different spots for a given leadframe were carried out to obtain the average of ten readings for each spot.

2.3. Debond load measurements

An Instron universal testing machine was used to measure the leadframe–encapsulant interface bond strength. An external force was applied to one end of the leadframe while fixing the end of the encapsulant. All tests were carried out at room temperature at a cross-head speed of 2.54 mm/min. The load–displacement curves were recorded, from which the maximum values were taken as the debond load. No attempt was made to calculate the leadframe–encapsulant interface bond strength based on the simple geometric surface area due to the complicated stress components occurring near the interface edges and the absence of appropriate debond criteria [15].

2.4. Atomic force microscopy

The surface profiles and roughness of leadframes on the nanoscale were characterised using an atomic force microscope. The leadframe specimens were treated in Ar for a varying period of 5 to 20 min, followed by treatment in $Ar + H_2$ for 5 min, while the power (400 and 600 W) and total pressure (238 and 432 mTorr) were varied. The power spectral density function approach was used to calculate the equivalent root-mean-square (RMS) values from the roughness data obtained on a scan area of 50 × 50 μm^2 with 1 μm/cycle wavelength.

3. Results and discussion

3.1. Contact angle measurement

The variations of average contact angle with respect to exposure time after plasma treatment are shown in Fig. 2 when de-ionised water was used. Fig. 3 presents a summary of two component surface energies as a function of exposure time, which were determined using both de-ionised water and glycerol. As expected, the plasma treatment reduced the contact angle, the degree of reduction being dependent on the type of gases used. It is highlighted that the contact angle increased, whereas the total surface energy decreased with increasing exposure times, a clear indication of increased surface contamination with time for all gases used. A small contact angle indicates good wettability and a clean surface. Among the gases used, the mixture of $O_2 + Ar$ appears to be most effective in removing the surface contaminants, as indicated by the lowest average contact angle, $\theta = 6.9°$, before being exposed to air and the longer time required to become a fully contaminated surface. A contact angle of 10° was recommended to achieve a relatively clean

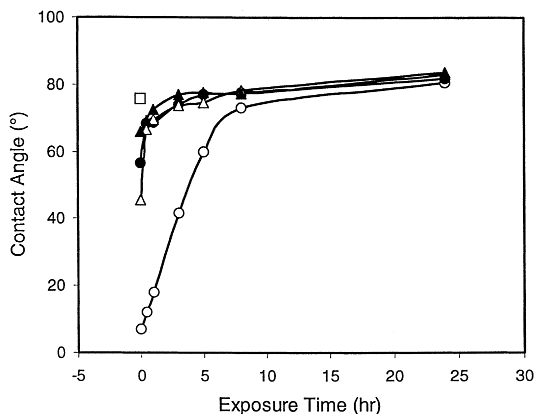

Fig. 2. Variations of average contact angle of de-ionised water on gold-plated leadframes as a function of exposure time after plasma treatments: ○: in $O_2 + Ar$, ●: in $H_2 + Ar$, Δ: in $O_2 + Ar$ followed by $H_2 + Ar$, (▲: in Ar; □: as-received).

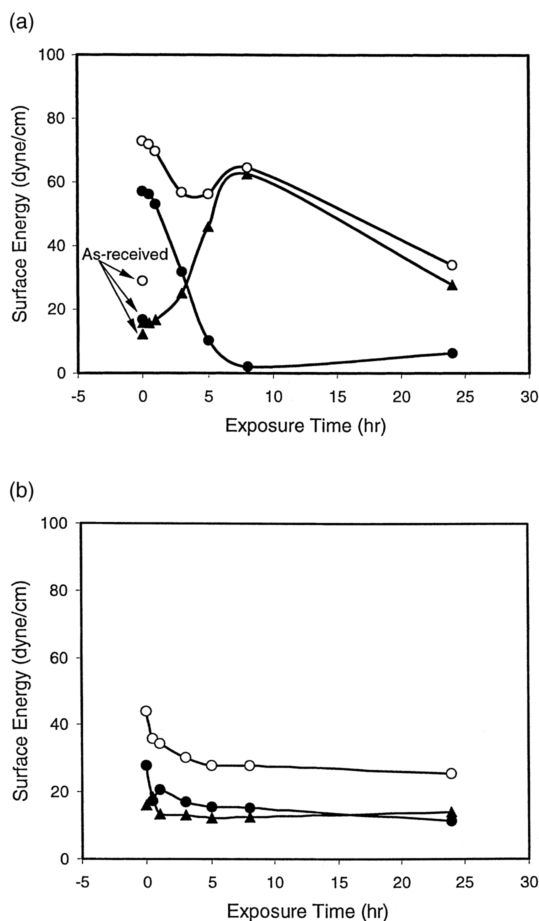

Fig. 3. Surface energies as a function of exposure time after plasma treatments in (a) $O_2 + Ar$ and (b) $H_2 + Ar$ (○: total energy, ●: polar component, ▲: dispersive component).

surface [3]. The contact angle for these leadframes increased gradually, and after 8 h of exposure, it became a plateau value of approximately 80°, the same level as other gases. When the specimens were treated in other gases, the initial contact angles were much higher, and it took less time (2–3 h) before the contact angle became the plateau value of about 80°. It is also interesting to note that the plateau value was similar to the contact angle, $\theta = 75.6^\circ$ measured for the as-received gold-plated leadframe. Additional treatments in $H_2 + Ar$ after $O_2 + Ar$ for 5 min each did not improve the wettability much. In consistence with the contact angle measurements, the total surface energy for specimens treated in a mixture of $O_2 + Ar$ remained much higher than those with $H_2 + Ar$, even after 24 h of exposure (compare Fig. 3(a) and (b)).

3.2. Leadframe pull-out test

The foregoing general trend with respect to exposure time agreed reasonably well with interface bond measurements with the moulding compound, as shown in Fig. 4, with the exception of specimens treated with a mixture of O_2 and Ar. The maximum debond load in general decreased to a low value of 15–20 N within 3 h of exposure and remained almost constant with further exposure. Nevertheless, the maximum debond loads after exposure were much higher than the corresponding value, $\gamma_{SV} = 9.6$ N, for as-received leadframe without plasma treatment as a result of removal of surface contaminants [14]. The implication is that the plasma treatment is an efficient way of removing contaminants from the leadframe surface, and a better interface quality with moulding compound can be maintained even after 24 h of exposure in air. It is interesting to note that the maximum debond loads measured before exposure in air for specimens with $H_2 + Ar$ treatment were much higher than those treated in the other gases, al-

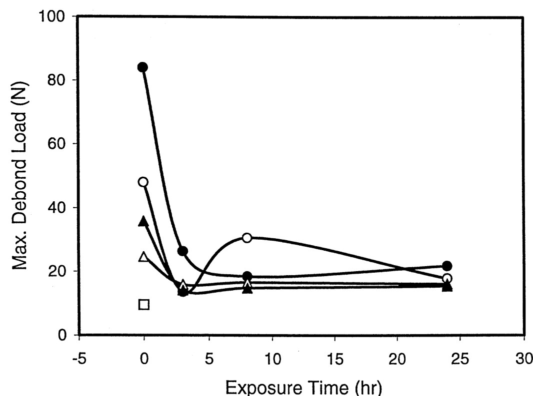

Fig. 4. Maximum debond load as a function of exposure time after plasma treatment (symbols are the same as in Fig. 2).

though the former specimens had relatively poor wettability compared with those treated in $O_2 + Ar$. This is considered to be in contrast to what was reported previously [15] that the use of H_2 as one of the plasma gases did not affect the adhesion strength.

The anomaly observed for the mixture of $O_2 + Ar$ at about 8 h of exposure time needs special accounts. The anomaly was most likely associated with the extraordinarily high dispersive component of leadframe, $\gamma_{SV}^{d} =$ 62.5 dyne/cm out of the total energy, $\gamma_{SV} = 64.5$ dyne/cm. This may support the assumption made previously [16] that the dispersive component of surface energy is mainly responsible for improved delamination performance. It was also suggested that the interface with a high polar component of surface energy exhibited a high affinity to moisture, and the interface was susceptible to debonding due to hydrolysis reaction. However, it is not clear as to how the exposure in air for 8 h resulted in such a high dispersive component of surface energy that contributed to a high interface bond strength. It is postulated that the thickness of oxide layer present in this particular specimen had an optimum thickness, greatly promoting the adhesion with moulding compound. It was reported previously [8] that the pull-out strength exhibited a maximum when the oxide layer on leadframe surface had an optimum thickness of about 20–30 nm.

A careful examination of the load–displacement curves taken during the leadframe pull-out test revealed some interesting features. Fig. 5 presents typical curves for specimens treated in Ar with different exposure times afterwards. The rising portion of the load–displacement curves for all specimens exhibited linear elasticity with little sign of plasticity or stick-slips until peak loads were reached. This was expected as the moulding compound contains a high proportion of rigid silica particles. The specimens moulded immediately after plasma treatment showed a distinct sudden load drop after the peak, while the extent of such load drops decreased substantially upon exposure to air. This strongly suggests that there was a certain functional group(s) or mechanism(s) facilitated by plasma treatment, which was gradually eliminated after exposure in air. It is proposed here that plasma treatments in an appropriate environment promote the formation of functional groups on the leadframe surface that are responsible for chemical bonding with the matching active groups within the moulding compound. The sudden, large load drop in the load–displacement curves represents brittle interface debonding in an unstable manner due to the separation of chemical bonding. It is well known [12] that the interface in a surface-treated glass or carbon fibre–polymeric matrix composite has a strong chemical bond, and a pronounced load drop is frequently observed in the fibre pull-out test of this composite system. Microscopic examination of the pulled-out leadframes revealed little moulding compound particles adhering to all plasma-treated specimens, confirming in part brittle adhesive fracture without plastic deformation of the moulding compound. In sharp contrast, there was almost a negligible load drop for the as-received specimens without plasma treatment.

To further study the mechanisms of interface bond, the initial pull-out load taken immediately after the load drop is plotted against exposure time as shown in Fig. 6. The loads after complete debonding correspond to initial pull-out against frictional clamping of leadframe by the moulding compound. The frictional clamping force arises mainly from thermal mismatch between the package components and shrinkage of moulding compound [18]. It is worth noting that the frictional pull-out load was the highest before exposure in air, and those for all plasma treated specimens were consistently higher than the corresponding value for the as-received

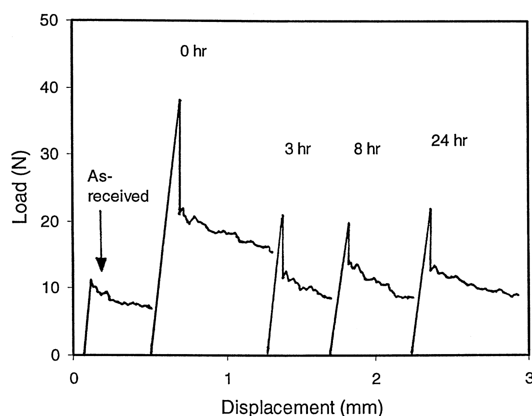

Fig. 5. Load–displacement curves of leadframe pull-out test on specimens with varying exposure time.

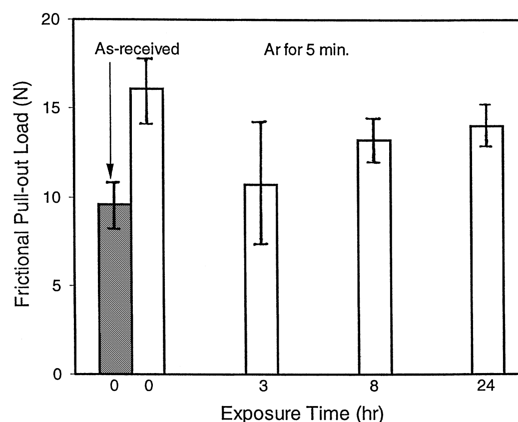

Fig. 6. Initial frictional pull-out load for specimens with varying exposure time.

leadframe, even after 24 h exposure in air. The as-received leadframes without plasma treatment had much contaminants on the surface and are only able to create a frictional bond with the moulding compound possessing little chemical adhesion. In this case, the maximum debond load corresponds to that required to overcome the frictional resistance without virtual debonding. This situation is analogous to the pull-out of fibres from ceramic matrices where the fibre–matrix interface bond is mainly mechanical or frictional in nature [12]. It should be recalled from Fig. 2 that the contact angles as a measure of wettability for plasma-treated specimens after exposure in air for more than 8 min became similar to that of the as-received specimen, regardless of type of gases used. The relationships of these two interface properties with exposure time strongly suggest that there must be mechanisms responsible for the high frictional resistance of plasma-treated leadframes other than the simple frictional clamping. The surface roughness of leadframe may have played an important role in promoting the mechanical bonding in plasma-treated specimens, which is discussed in Section 3.3.

3.3. Atomic force microscopy

Fig. 7 shows a typical AFM image, indicating nanoscopically rough surface with preferred orientation of a gold-coated leadframe sample. The distinct orientation of leadframe surface roughness indicates high dependence of interface bond strength on the loading direction relative to this orientation. The effect of deformation of matrix material against pulling out of these surface pits is expected to be low in this study as all leadframe pull-out tests were conducted in the same direction as the rugosity orientation. The maximum debond force and surface energies are presented as a function of RMS roughness data in Figs. 8 and 9, respectively, to show the essential trends. It is seen that the maximum debond load increased parabolically with increasing RMS, indicating strong correlation between these two interface properties. A similar result has been reported [17] in which increasing the surface roughness resulted in an improved interfacial fatigue fracture resistance between the nickel-plated copper leadframe and epoxy-moulding compound. Marginal enhancement in surface roughness barely improved the interface bond quality in this study, suggesting that the plasma treatment condition should be adequate enough to effect large changes in surface roughness. It should also be noted here that experimental results on copper leadframes without coatings based on similar plasma treatment conditions indicate little effect on surface roughness and thus the interface bond strength. This is most probably because of the range of treatment time being insufficient to effect changes on the surface that had inherently high roughness.

In contrast, the relationships between the total and component surface energies of leadframe and RMS

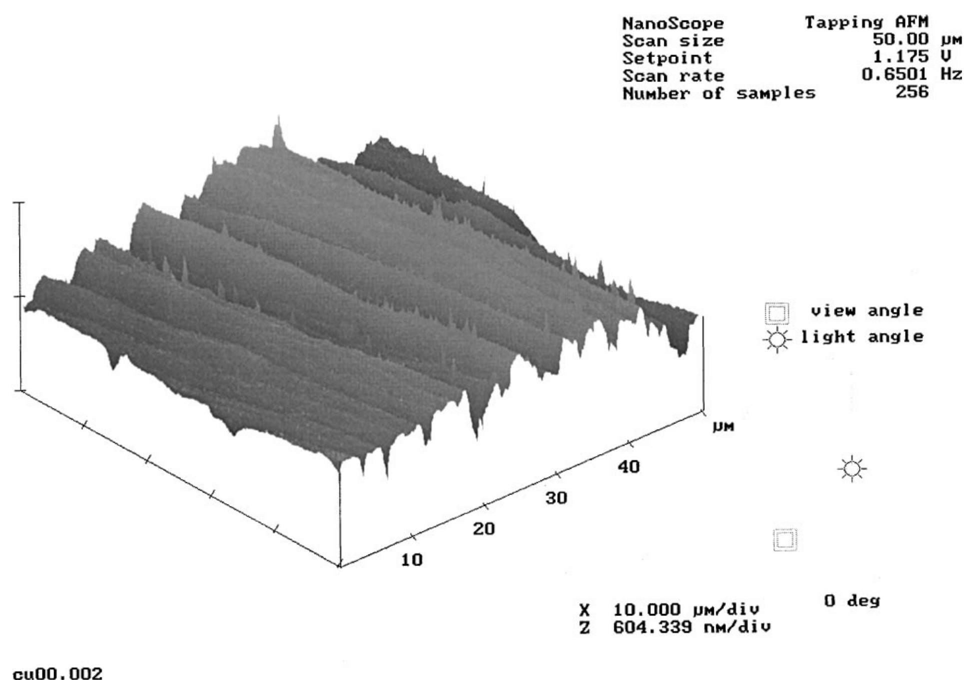

Fig. 7. A typical AFM image for a plasma-treated leadframe.

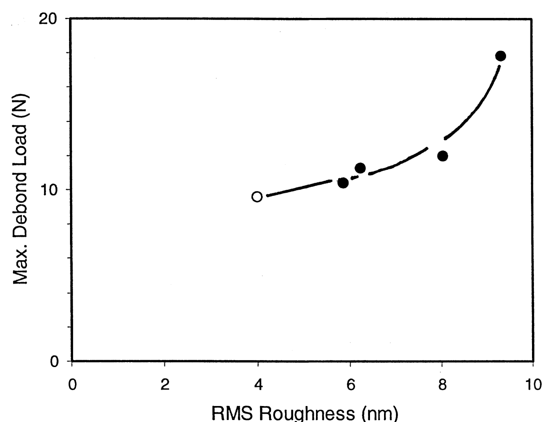

Fig. 8. Maximum debond load plotted as a function of RMS roughness of leadframe surface (○: as-received, ●: in Ar followed by $H_2 + Ar$).

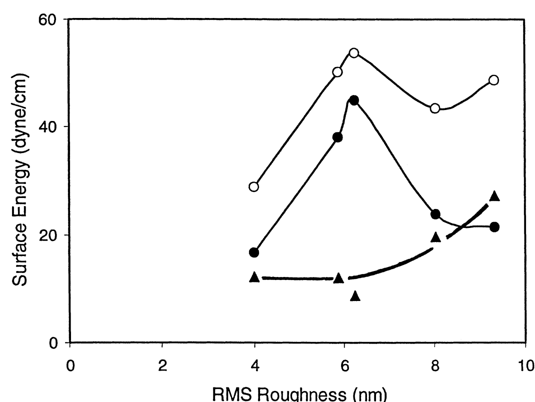

Fig. 9. Surface energies plotted as a function of RMS roughness of leadframe surface (symbols are the same as in Fig. 3).

values were relatively difficult to establish. Only the dispersive component, γ_{SV}^{d}, of leadframe surface energy tended to have approximately linear dependence on RMS value, while the total and the polar component of surface energy, γ_{SV} and γ_{SV}^{p}, showed no correlation with RMS. The latter two surface energies increased initially with RMS and dropped sharply with further increase in surface roughness. This may support the previous proposal [16] that the dispersive component is a key factor affecting the interface adhesion.

4. Conclusion

The type of plasma gases used and the exposure time in air before moulding were specifically evaluated based on the contact angle measurement, leadframe pull-out test and AFM. There are at least three major surface characteristics of leadframe that are improved as a result of plasma treatment. It is seen that exposure in air degrades significantly both the surface cleanness and chemical compatibility, while the surface roughness remains much the same even after exposure for 24 h. This is why the maximum debond load for leadframes exposed in air for 24 h was still substantially higher than those for as-received specimens without plasma treatment. The interface bond strength agrees qualitatively with contact angle and surface energy with respect to exposure time. The practical implication is that the moulding process should be carried out as soon as the leadframes are treated. There is a strong correlation between the interface bond strength and the leadframe surface roughness. However, the surface roughness has rather poorly defined relationship with surface energy. It is not clear to what degree the surface energy plays a role in constituting the interface bond. Nevertheless, the dispersive component of surface energy tends to be approximately linearly proportional to surface roughness value. Further work is required to identify chemical functional groups created by plasma treatment and their contributions to interface bond and to confirm the roles of the dispersive component of surface energy for interface bond.

References

[1] Pecht MG, Nguyen LT. Plastic packaging. In: Tummala RR, et al., editors. Microelectronics Packaging Handbook Part II, 2nd ed. London: Chapman & Hall, 1997.

[2] Nguyen LT. Reliability of postmolded IC packages. ASME J Electron Packag 1993;115:346–55.

[3] Djennas F, Prack E, Matsuda Y. Investigation of plasma effects on plastic packages delamination and cracking. IEEE Trans CHMT 1993;16:919–24.

[4] Korner N, Beck E, Ddommann A, Onda N, Ramm J. Hydrogen plasma chemical cleaning of metallic substrates and silicon wafers. Surface and coating technology. Amsterdam: Elsevier, 1995. p. 731–7.

[5] Mittal KL (editor). Polymer Surface Modification: Relevance to Adhesion. Zeist, The Netherlands, VSP, 1996.

[6] Tanaka N, Kitano M, Kumazawa T. Evaluation of interface delamination in IC packages by considering swelling of the moulding compound due to moisture absorption. Proc IEEE 47th Electronic Components and Technol Conf 1977. p. 84–90.

[7] Walberg RL, Liou S. Adhesion between epoxy moulding compounds and various leadframe materials. Electron Packag Reliab ASME 1993;EEP–6. p. 55–9.

[8] Cho SJ, Paik KW, Kim YG. The effect of the oxidation of Cu-based leadframe on the interface adhesion between Cu metal and epoxy moulding compound. IEEE Trans CPMT Part B 1997;20:167–75.

[9] Tay AO, Tan GL, Lim TB. Predicting delamination in plastic IC packages and determining suitable mold compound properties. IEEE Trans CPMT Part B 1994;17:201–8.

[10] Suhir E, Sullivan TM. Evaluation of the adhesive strength of epoxy moulding compounds used in integrated circuit packaging. Adv Electron Packag ASME 1992. pp. 721–37.
[11] Tanaka N, Nishimura A. Measurement of IC moulding compound adhesion strength and prediction in interface delamination within package. Adv Electron Packag 1995;EEP–10-2:765–73.
[12] Kim JK, Baillie C, Mai YW. Interfacial debonding and fibre pull-out stresses. Part I. A critical comparison of existing theories with experiments. J Mater Sci 1992;27: 3143–54.
[13] Kim JK, Mai YW. Engineered interfaces in fibre reinforced composites. New York: Elsevier, 1998 [Chapter. 4].
[14] Yi S, Yue CY, Hsieh JH, Fong L, Lahiri SK. Effect of oxidation and plasma cleaning on adhesion strength between copper leadframes and moulding compounds. J Adhes Sci Tech 1999;17(7):789–804.
[15] Park JH, Kim JK, Yuen MMF, Lee SWR, Tong P, Chan PCH. Thermal stress analysis of a PQFP moulding process: comparison of viscoelestic and elastic models. Key Engng Mater 1998;145-149:1127–32.
[16] Ganesan GS, Lewis GL, Berg HM. Contact angles as a measure of interfacial integrity: theory and experiments. Adv Electron Packag ASME 1995;EEP–10-2:450–4.
[17] Guzek J, Azimi H, Suresh S. Fatigue crack propagation along polymer-metal interfaces in microelectronic packages. IEEE Trans CPMT Part A 1997;20:496–504.
[18] Kelly G, Lyden L, Lawton W, Barrett J, Saboui A, Pape H, Peters HJB. Importance of moulding compound chemical shrinkage in the stress and warpage analysis of PQFP's. IEEE Trans CPMT Part B 1996;19:296–300.