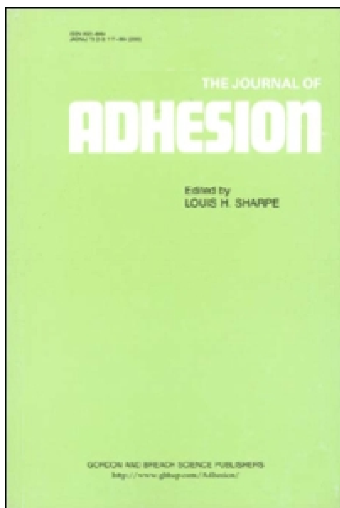
This article was downloaded by:
On: *22 January 2011*
Access details: *Access Details: Free Access*
Publisher *Taylor & Francis*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

Adhesion Strengths of Epoxy Molding Compounds to Gold-plated Copper Leadframes

Sung Yl; Jang-Kyo Kim[ab]; Chee Yoon Yue[a]; Jang-Hsing Hsieh[c]
[a] School of Mechanical and Production Engineering, Nanyang Technological University, Nanyang Avenue, Singapore [b] Department of Mechanical Engineering, Hong Kong University of Science and Technology Clear Water Bay, Kowloon, Hong Kong [c] Gintic Institute of Manufacturing Technology, Nanyang Technological University, Singapore

To cite this Article Yl, Sung , Kim, Jang-Kyo , Yue, Chee Yoon and Hsieh, Jang-Hsing(2000) 'Adhesion Strengths of Epoxy Molding Compounds to Gold-plated Copper Leadframes', The Journal of Adhesion, 73: 1, 1 — 17
To link to this Article: DOI: 10.1080/00218460008029294
URL: http://dx.doi.org/10.1080/00218460008029294

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

J. Adhesion, 2000, Vol. 73, pp. 1 – 17
Reprints available directly from the publisher
Photocopying permitted by license only

© 2000 OPA (Overseas Publishers Association) N.V.
Published by license under
the Gordon and Breach Science
Publishers imprint.
Printed in Malaysia.

Downloaded At: 10:10 22 January 2011

Adhesion Strengths of Epoxy Molding Compounds to Gold-plated Copper Leadframes

SUNG YI[a,*], JANG-KYO KIM[a,†], CHEE YOON YUE[a]
and JANG-HSING HSIEH[b]

[a]*School of Mechanical and Production Engineering,
Nanyang Technological University, Nanyang Avenue, Singapore, 639798;*
[b]*Gintic Institute of Manufacturing Technology, Nanyang Technological University, Singapore, 639798*

(Received 29 July 1999; In final form 20 December 1999)

In the present study, the effects of plasma cleaning on the adhesion strength of molding compounds to gold-plated copper leadframes are presented. Important process parameters such as the type of gasses used and the time exposed in air before molding are specifically evaluated. The leadframe pullout test is performed to measure interfacial bonding strengths. The liquid droplet test is used to measure contact angles and atomic force microscope (AFM) is employed to characterize quantitatively the roughness of modified surfaces to correlate with the bond strength measurements. The results indicate that plasma cleaning of leadframes has three major ameliorating effects, namely, surface cleaning due to the removal of contaminants, enhanced chemical compatibility with molding compounds and surface roughening with associated larger surface contact area for better mechanical interlocking. Exposure of plasma-cleaned leadframes in air before molding is detrimental to interface bond quality, a finding suggesting that molding operations should be carried out immediately after cleaning. The experimental results show that roughness on the nano-scale is an important surface characteristic that has a strong correlation with interface bonding strengths.

Keywords: Leadframes; plasma cleaning; contact angles; surface energy; interface bond strengths; surface roughness

*Corresponding author. Tel.: (65) 790-6239, Fax: (65) 791-1859, e-mail: msyi@ntu.edu.sg
†On leave from Department of Mechanical Engineering, Hong Kong University of Science and Technology Clear Water Bay, Kowloon, Hong Kong.

INTRODUCTION

Plastic encapsulated microcircuits (PEMs) account for the vast majority of market share of world-wide electronic product sales due to the major advantages in cost, size, weight, performance and availability [1]. The encapsulant in a PEM is an electrically-insulating molding compound containing plastics, as well as 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, good adhesion to various package components, good corrosion and chemical resistance, matched coefficients of thermal expansion (CTE) to the materials, high thermal conductivity and high moisture resistance in the use temperature range [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 [2].

The contaminants such as oxides and hydrocarbons on metallic leadframe surfaces, predominantly due to the high temperature processes, may degrade the interface, causing premature debonding. Thus, a clean leadframe surface is a vital prerequisite for good wetting and adhesion to molding compounds. Various techniques have been used to modify the surface chemistry and surface topography of metal, such as dipping into acid or caustic solutions with and without the aid of electrolytes, metal plating, priming with organic inhibitor, vacuum deposition, ion implantation, UV cleaning, and plasma cleanings based on various energy sources and gas media [3]. Of these techniques, plasma cleaning has gained much popularity [4, 5] among electronic package manufacturers. Not only can the plasma cleaning process be integrated into other manufacturing processes, but also it 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 leadframes and die back surfaces [4] showed that the higher was the plasma radio frequency (RF) power and the lower was the

Downloaded At: 10:10 22 January 2011

chamber pressure, the quicker was the reduction of wetting contact angle to a desired level of lower than about 10°. The carbon contamination detected on the leadframe surface was linearly proportional to the contact angle, indicating the relative sensitivity of contact angle measurements for determining surface contamination. In our previous study on a similar plasma-cleaned copper leadframe [6], the wetting contact angle increased with increasing thickness of oxide layers. The longer was the time of exposure at an isothermal temperature which was designed to accelerate the oxidation process [6, 7], the lower was the interface bond strength with molding compound. The conclusion was that the thickness of surface oxide layers is a predominant factor affecting the wettability of leadframes, which, in turn, determines the interface adhesion. Although these parametric studies contributed significantly to understanding the benefits of plasma cleaning, surface energies and surface roughness modified by plasma cleaning for improving the interface bonding quality have remained largely unresolved.

The significance of the characteristics of the leadframe-encapsulant interface for the reliability of plastic integrated circuit (IC) packages has led to the application of several experimental techniques by destructive means to measure the interface bond quality in PEMs. These include the 90° or 180° peel test [8, 9], leadframe pull-out test [5, 6, 8, 10], double-lap shear test [7], button shear test, sandwich double-cantilever-beam test [11] and three-point-bend test with an end pre-crack [9]. Among these experimental methods, the leadframe pull-out test has been one of the most popular methods, with which the present study is mainly concerned. By analogy with the fiber pull-out test of various specimen geometries that have been widely used to characterize the interface properties in fiber-reinforced composites [12, 13], the leadframe pull-out test measures the force to pull the leadframe out of the plastic encapsulant after complete debonding.

Following our previous paper on oxidation of leadframe surfaces [6] and residual stresses in plastic IC packages [15, 16], the present work addresses the improvement of the interface bond quality between leadframe and plastic encapsulant by employing plasma cleaning which cleans and, thus, reduces unwanted organic and inorganic contamination on the surface of gold-plated copper leadframes. Several important process variables such as the type of gas media and duration

Downloaded At: 10:10 22 January 2011

of cleaning were specifically studied. To study the effect of contamination after plasma cleaning on interface bond quality, the leadframes were exposed in air for varying periods of time for up to 24 hr before molding of encapsulant. Surface characterization techniques, including contact angle measurement and atomic force microscopy (AFM), were employed to evaluate the surface energies and the roughness on the nano-scale that are affected by plasma cleaning. Thus, a correlation between the surface roughness and the interface bonding strengths measured from the leadframe pullout test was established.

EXPERIMENTS

Materials and Preparation of Specimens

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

The transfer molding machine (Kras VSKO-120/E) and the high-frequency pre-heater (Hisen HDP 523 M) were used to prepare the leadframe pullout specimens. The molding conditions followed the manufacturer's instructions. A preheating temperature of 90°C was applied to the pre-formed molding compounds and the molding was conducted at 170°C at a transfer speed of 160 mm/min. To study the effect of surface contamination after plasma cleaning on the interface bond strength, the cleaned leadframes were exposed to air at room temperature and 50% R/H for up to 24 hr before molding. The

Downloaded At: 10:10 22 January 2011

embedded length of the leadframes was maintained constant for all specimens prepared. Figure 1 shows a schematic drawing of the pull-out specimen.

Contact Angle Measurements

One of the oldest theories of adhesion relates to wetting of a solid by a liquid [17, 18]. 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 considerations 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:

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

where γ_{LV} is the surface free energy of liquid.

Equation (1) indicates that the solid surface is wetted only when the contact angle is smaller than 90° and a large contact angle means a low work of adhesion and, consequently, poor wettability. The work of

Downloaded At: 10:10 22 January 2011

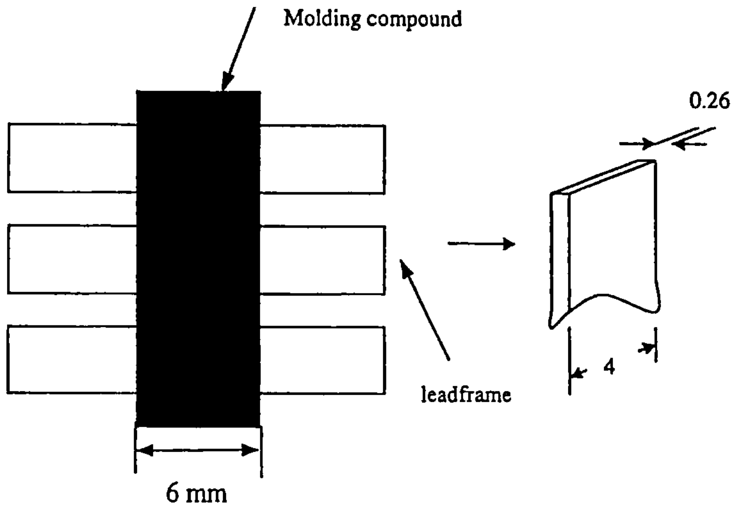


FIGURE 1 Schematic drawing of leadframe pull-out specimen. Dimensions in mm.

adhesion and, thus, the surface energy consists of two components, namely the polar and dispersive components, γ_{LV}^p and γ_{LV}^d, and these components can be determined based on the geometric mean approximation combined with Young–Dupre equation:

$$(1+\cos\theta)\gamma_{LV} = 2[(\gamma_{SV}^p\gamma_{LV}^p)^{1/2} + (\gamma_{SV}^d\gamma_{LV}^d)^{1/2}] \quad (2)$$

where γ_{SV} is the surface free energy of solid and the superscripts p and d refer to the polar and dispersive components, respectively. The contact angle measurements with two liquids of known polar and dispersive components of surface energies, γ_{LV}^p and γ_{LV}^d, are used to determine the polar and dispersive components of the solid (*i.e.*, leadframe) surface energies, γ_{SV}^p and γ_{SV}^d.

The contact angle experiment was carried out using a goniometer. Micro syringes were used to dispense 2 μL droplets of standard test liquid on leadframe. De-ionized water and glycerol were used, whose polar and dispersive surface energies are 51.0 and 21.8 dynes/cm, respectively, for de-ionized water, and 26.4 and 37.5 dynes/cm, respectively, for glycerol. The contact angle readings were taken within 45 sec 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 and were then analyzed using an image analyzer 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.

Downloaded At: 10:10 22 January 2011

Debonding Load Measurements

An Instron universal testing machine was used to measure the leadframe-encapsulant interface bond strength. An external force was applied to the 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 debonding 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 debonding criteria.

Atomic Force Microscopy

The surface profiles and roughness of leadframes on the nano-scale were characterized using an atomic force microscope. The leadframe specimens were treated in Ar for various time periods between 5 and 20 min, followed by cleaning in Ar + H_2 for 5 min, while the power (400 and 600 W) and the 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 of the surface roughness obtained on a scan area of 50 μm × 50 μm square with 1 μm/cycle wavelength.

RESULTS AND DISCUSSION

Contact Angle Measurement

Downloaded At: 10:10 22 January 2011

The variations of average wetting contact angles with respect to exposed time after plasma cleaning are shown in Figure 2 where de-ionized water was used. Figure 3 presents the two component surface energies as a function of exposure time, that were determined using both de-ionized water and glycerol. Plasma cleaning reduced the contact angle, and the degree of reduction was dependent on the type of gasses used. It is significant that the wetting contact angle increased whereas the total surface energy decreased with increased exposure time. Surface contamination increases with increasing exposure time. A small contact angle indicates good wettability and a clean surface. Among the gasses 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 attain a fully-contaminated surface. A contact angle of 10° was recommended to achieve a relatively clean surface [4]. The contact angle for these leadframes increased gradually and, after 8 hr of exposure, it reaches 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 to 3 hrs) before the contact angle achieved the plateau value of about 80°. It is also interesting to note that the plateau value was similar to the contact angle, $\theta = 75.6°$, measured for

Downloaded At: 10:10 22 January 2011

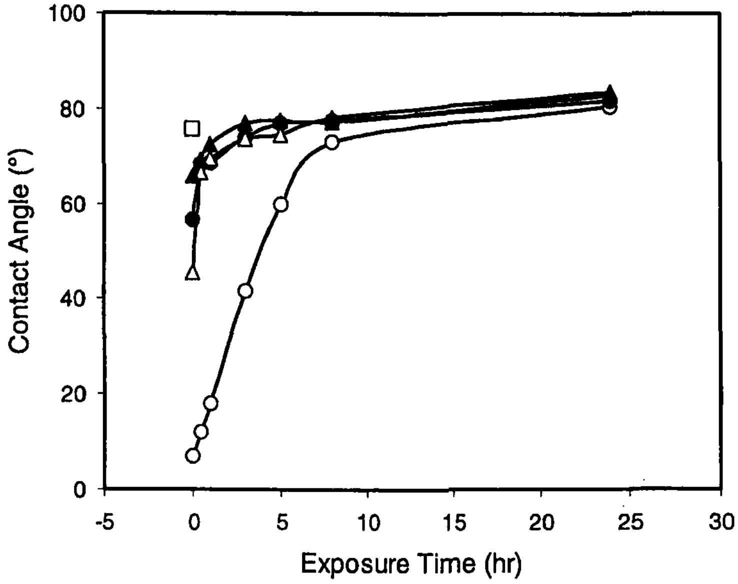


FIGURE 2 Variations of average contact angle of de-ionized water on gold-plated leadframes as a function of exposed time after plasma cleaning: ○ in O_2+Ar; ● in H_2+Ar; Δ in O_2+Ar followed by H_2+Ar; ▲ in Ar; □ as-received.

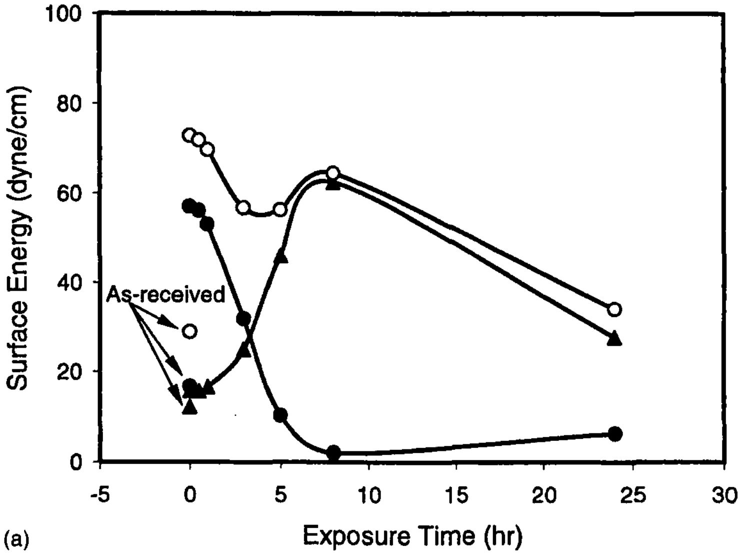


FIGURE 3 Surface energies as a function of exposure time after plasma cleaning: (a) in O_2+Ar and (b) in H_2+Ar. ○ total energy; ● polar component; ▲ dispersive component.

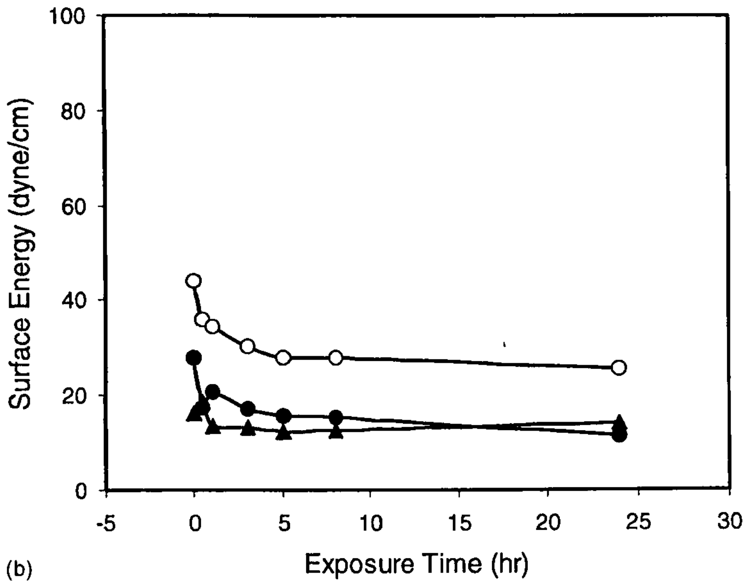


FIGURE 3 (Continued).

Downloaded At: 10:10 22 January 2011

the as-received gold-plated leadframe. Additional cleanings in $H_2 + Ar$ after $O_2 + Ar$ for 5 min each did not much improve the wettability. In agreement with the contact angle measurements, the total surface energy for specimens treated in a mixture of $O_2 + Ar$ remained much higher than those treated with $H_2 + Ar$, even after 24 hr of exposure (see Figs. 3(a) and (b)).

Leadframe Pull-out Test

The foregoing general trend with respect to exposure time agreed reasonably well with interface bond measurements with the molding compound, as shown in Figure 4, with the exception of specimens treated with a mixture of O_2 and Ar. The maximum debonding load, in general, decreased to a low value of 15 to 20 N within 3 hr of exposure and remained almost constant with further exposure. Nevertheless, the maximum debonding loads after exposure were much higher than the corresponding value, 9.6 N, for as-received leadframe without plasma cleaning, as a result of removal of surface contaminants [5]. The implication is that the plasma cleaning is an

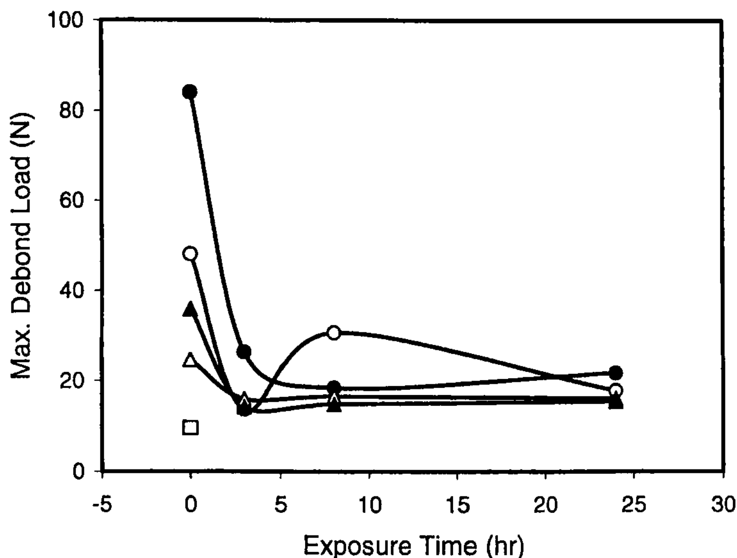


FIGURE 4 Maximum debonding load as a function of exposure time after plasma cleaning. Symbols as in Figure 2.

Downloaded At: 10:10 22 January 2011

efficient way of removing contaminants from the leadframe surface, and a better interface quality with molding compound can be maintained even after 24 hr of exposure in air. It is interesting to note that the maximum debonding loads measured before exposure in air for specimens with $H_2 + Ar$ cleaning were much higher than those treated in the other gasses, although the former specimens had relatively poor wettability compared with those treated in $O_2 + Ar$. This suggests that the wettability represented by contact angles and surface energies do not directly translate into the interface bond strength of molding compounds to gold-plated leadframes.

The anomaly observed for the mixture of $O_2 + Ar$ at about 8 hr of exposure time needs an explanation. The anomaly was most likely associated with the extraordinarily-high dispersive component of the leadframe surface energy, $\gamma_{SV}^{d} = 62.5\,\mathrm{dyne/cm}$, out of the total energy, $\gamma_{SV} = 64.5\,\mathrm{dyne/cm}$. 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, thus,

susceptible to debonding due to hydrolysis reactions. However, it is not clear as to how the exposure in air for 8 hr resulted in such a high dispersive component of surface energy that contributed to a high interface bond strength. It is postulated that the oxide layer in this particular specimen had an optimum thickness, greatly promoting the adhesion with molding compound. It was reported previously [6] that the pull-out strength exhibited a maximum when the oxide layer on the leadframe surface had thickness of about 20 to 30 nm.

A careful examination of the load-displacement curves taken during the leadframe pull-out test revealed some interesting features. Figure 5 presents typical curves for specimens treated in Ar with different air-exposure times afterwards. The rising portion of the load-displacement records for all specimens exhibited linear elasticity with little sign of plasticity or stick-slip until peak loads were reached. This was expected as the molding compounds contain a high proportion of rigid silica particles. The specimens molded immediately after plasma cleaning showed a distinct sudden load drop after the peak, while the extent of such load drops decreased substantially upon exposure to air.

Downloaded At: 10:10 22 January 2011

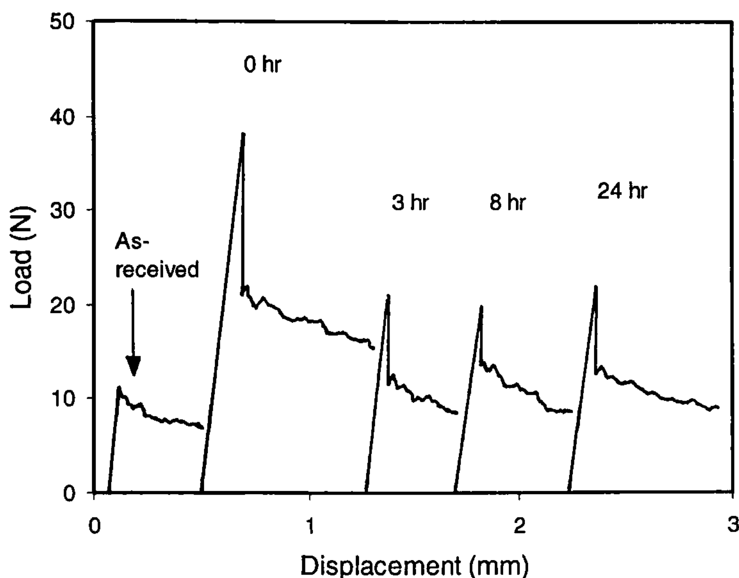


FIGURE 5 Load-displacement curves of leadframe pullout test on specimens with varying exposure time.

The sudden, large load drop in the load-displacement curves represents brittle interface debonding in an unstable manner. Microscopic examination of pulled out leadframes revealed little molding compound particles adhering on all plasma-treated specimens, confirming in part brittle adhesive fracture without plastic deformation of the molding compound. In sharp contrast, there was almost a negligible load drop for as-received specimens without plasma cleaning.

To study further the mechanisms of interface bonding, the initial pullout load taken immediately after the load drop is plotted against exposure time as shown in Figure 6. The loads after complete debonding correspond to initial pullout against frictional clamping of the leadframe by the molding compound. The frictional clamping force arises mainly from thermal mismatch between the package components and shrinkage of the molding compound. It is worth noting that the frictional pullout load was highest before exposure in air, and those for all plasma-treated specimens were consistently higher than the corresponding value for the as-received leadframe, even after 24 hr exposure in air. It is noted that the as-received

Downloaded At: 10:10 22 January 2011

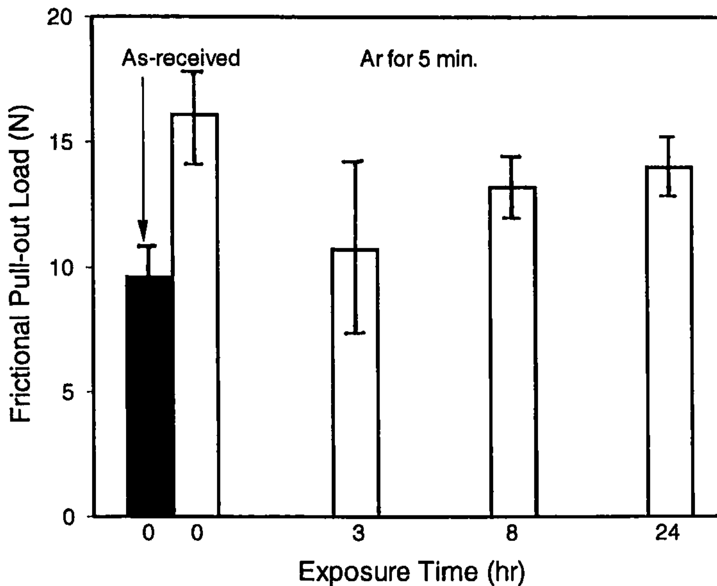


FIGURE 6 Initial frictional pull-out load for specimens with varying exposure time.

leadframes without plasma cleaning had contamination on the surface and were only able to create a frictional bond with the molding compound, yielding little adhesion. In this case, the maximum debonding load corresponds to that required to overcome the frictional resistance without virtual debonding. This situation is analogous to pull-out of fibers from ceramic matrices where the fiber-matrix interface bond is mainly mechanical or frictional in nature. It should be recalled from Figure 2 that the contact angles as a measure of wettability for plasma-treated specimens after exposure in air for longer than 8 min became similar to those for as-received specimens, regardless of type of gasses used. The relationships of these two interface parameters (*i.e.*, wetting contact angle and frictional pullout load) with exposure time strongly suggest that there should be mechanisms responsible for the high frictional resistance of plasma-cleaned leadframes other than simple frictional clamping. The surface roughness of the leadframe may play an important role in promoting the mechanical bond in plasma-cleaned specimens.

Downloaded At: 10:10 22 January 2011

Atomic Force Microscopy

Figure 7 shows a typical AFM image of a plasma-cleaned leadframe, indicating a nanoscopically rough surface with preferred orientation for a gold-coated leadframe sample. The distinct orientation of leadframe surface roughness indicates a high dependence of interface bond strength on the loading direction relative to this orientation. The effect of the deformation of matrix materials 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 debonding force and surface energies are presented as a function of RMS roughness in Figures 8 and 9, respectively, to show the essential trends. It is apparent that the maximum debonding load increased parabolically with increasing RMS, indicating strong correlation between these two interface properties. A similar result has been reported [10] in that increased surface roughness resulted in improved interfacial fatigue fracture resistance between nickel-plated copper leadframes and molding compounds. Marginal enhancement in surface roughness barely improved the interface bonding quality in this study, suggesting that the

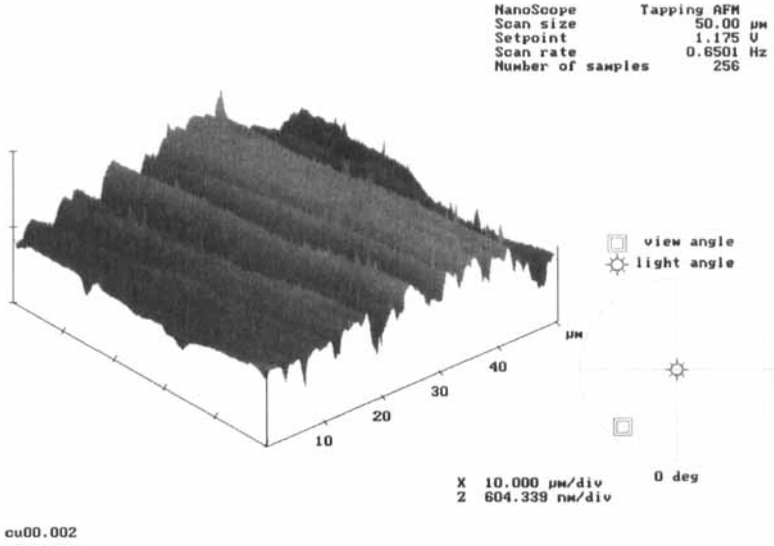


FIGURE 7 A typical AFM image for a plasma-cleaned leadframe. (See Color Plate I).

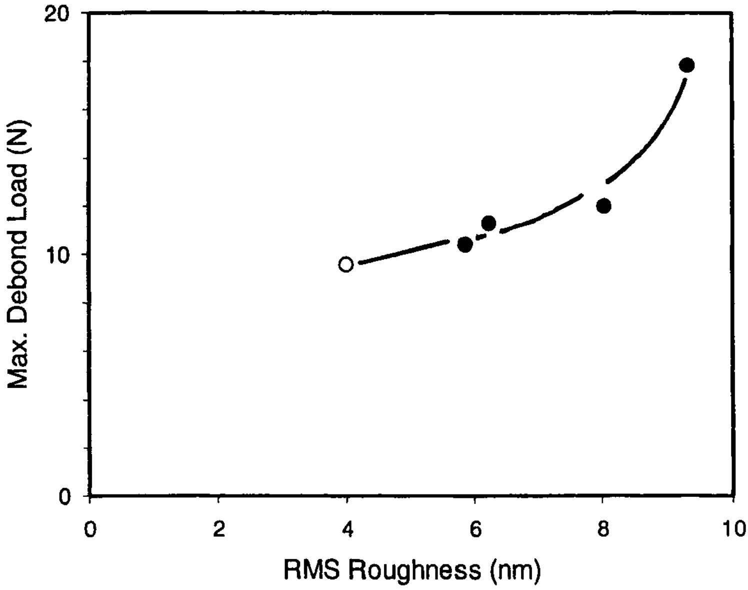


FIGURE 8 Maximum debonding load plotted as a function of RMS roughness of leadframe surface. ○ As-received; ● in Ar followed by $H_2 + Ar$.

Downloaded At: 10:10 22 January 2011

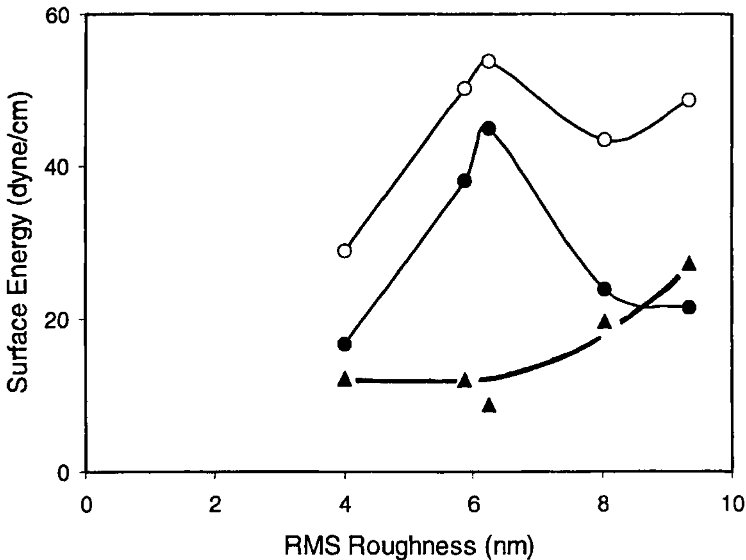


FIGURE 9 Surface energies plotted as a function of RMS roughness of leadframe surface. Symbols as in Figure 3.

Downloaded At: 10:10 22 January 2011

plasma-cleaning condition should be adequate enough to effect large changes in surface roughness. It should also be noted that experimental results on copper leadframes without coatings based on similar plasma cleaning conditions indicate little effect on surface roughness and, thus, the interface bond strength. This is most probably because the range of cleaning time was insufficient to effect changes on the surface that had inherently high roughness.

In contrast, the relationships between the total and component surface energies of leadframes and RMS values were relatively difficult to establish (see Fig. 9). Only the dispersive component, γ_{SV}^{d}, of leadframe surface energy tended to have approximately linear dependence on RMS values, while the total and the polar components of surface energy, γ_{SV} and γ_{SV}^{p}, showed no correlation with RMS values. The latter two surface energies increased initially with increasing surface roughness, and dropped sharply with further increase. All the above findings may support the previous proposal [16] that the dispersive component is a key factor affecting the interface adhesion.

CONCLUSIONS

Interface characteristics were studied between a molding compound and gold-plated copper leadframes whose surface was modified by plasma cleaning. The type of plasma gasses used and the exposure time in air before molding were specifically evaluated based on contact angle measurement, leadframe pull-out tests and atomic force microscopy (AFM). The following can be concluded from the experimental study.

(1) There are at least three major surface characteristics of leadframes that are improved as a result of plasma cleaning: (i) cleaner surfaces through removal of organic contaminants giving rise to better wettability; (ii) improved chemical compatibility with molding compounds by incorporating functional groups on the surface; and (iii) rougher surfaces on the nano-scale, creating larger interface contact area for better mechanical interlocking.
(2) It is seen that exposure to air degrades significantly both surface cleanness and chemical compatibility. The interface bonding strength agrees qualitatively with wetting contact angle measurements and surface energy with respect to exposure time. The practical implication is that the molding process should be carried out as soon as the leadframes are cleaned.
(3) There is a strong correlation between the interface bonding strength and the leadframe surface roughness. However, the surface roughness has a rather poorly-defined relationship with the 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 the surface roughness.
(4) Further work is required to identify chemical functional groups at the encapsulant-leadframe interface created by plasma cleaning and to clarify their contributions to the interface bond and to confirm the role of the dispersive component of surface energy for the interface bond.

Acknowledgement

J. K. Kim was a Tan Chin Tuan Exchange Fellow at Nanyang Technological University when this paper was prepared.

Downloaded At: 10:10 22 January 2011

References

[1] Pecht, M. G. and Nguyen, L. T., Plastic packaging, In: *Microelectronics Packaging Handbook*, Part II, 2nd edn., Tummala, R. R. *et al.* Eds. (Chapman & Hall, London).
[2] Nguyen, L. T., *ASME J. Electronic Packaging* **115**, 346–355 (1993).
[3] Mittal, K. L. Ed., *Polymer Surface Modification: Relevance to Adhesion* (VSP, Zeist, Netherlands, 1996).
[4] Djennas, F., Prack, E. and Matsuda, Y., *IEEE Trans. CHMT* **16**, 919–924 (1993).
[5] Korner, N., Beck, E., Ddommann, A., Onda, N. and Ramm, J., *Surface and Coating Technology* pp. 731–737 (1995).
[6] Yi, S., Yue, C. Y., Hsieh, J. H., Fong, L. and Lahiri, S. K., *J. Adhesion Sci. Technol.* **17**, 789–804 (1999).
[7] Cho, S. J., Paik, K. W. and Kim, Y. G., *IEEE Trans. CPMT Part B*, **20**, 167–175 (1997).
[8] Kim, S., *IEEE Trans. CHMT* **14**, 809–817 (1991).
[9] Tanaka, N., Kitano, M. and Kumazawa, T., *Proc. IEEE 47th Electronic Components and Technol. Conf.* pp. 84–90 (1997).
[10] Walberg, R. L. and Liou, S., EEP-Vol. 6, *Electronic Packaging Reliability, ASME* (1993).
[11] Guzek, J., Azimi, H. and Suresh, S., *IEEE Trans. CPMT Part A*, **20**, 496–504 (1997).
[12] Kim, J. K., Baillie, C. and Mai, Y. W., *J. Mater. Sci.* **27**, 3143–3154 (1992).
[13] Kim, J. K. and Mai, Y. W., *Engineered Interfaces in Fibre Reinforced Composites* (Elsevier Sci., New York, 1998), Chap. 4.
[14] Yue, C. Y. and Cheung, W. L., *J. Mat. Sci.* **27**, 3843–3855 (1992).
[15] Yi, S., Goh, J. S. and Yang, J. C., *IEEE Trans. CPMT* **20**, 247–255 (1997).
[16] Yi, S. and Sze, K. Y., *ASME Trans. J. Electronic Packaging* **120**, 385–390 (1998).
[17] Young, T., *Trans. R. Soc. London* **95**, 65 (1805).
[18] Good, R. J., *J. Adhesion Sci. Technol.* **6**, 1269–1302 (1992).
[19] Ganesan, G. S., Lewis, G. L. and Berg, H. M., *Advances in Electronic Packaging, ASME* **EEP10**(2), 450–454 (1995).

Downloaded At: 10:10 22 January 2011