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The use of silane coupling agents in the design of electrically stable interfaces of 6061 T6 aluminum alloy surfaces and epoxy-based electrically conductive adhesives

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Electrically conductive interfaces between metal surfaces, including aluminum, are commonly formed by means of bonding with an electrically conductive adhesive. Humid environments induce an increase in electrical resistance between aluminum objects bonded in this manner. However, joints that are electrically stable through stress testing in environments of elevated temperature and humidity (85°C and 80% RH for up to 137.5 h) have been obtained by treating the aluminum surface with a thin layer (less than 50 Å) of an organo-silane coupling agent, that is, a material capable of bonding chemically with the aluminum oxide surface layer and potentially bonding with the polymer binder in the adhesive. The present study shows that besides their traditional use as surface modifiers for adhesion improvement, organo-silanes can act as corrosion inhibitors of aluminum surfaces to stabilize electrical performance. Whereas other treatments used for preparation of metal surfaces for bonding, using electrically-insulating structural adhesives, typically do not ensure reliable electrical performance, minimal and reproducible increase in resistance has been observed for joints prepared using the procedure described here. Application of this method does not require any significant investment in equipment and the surface pretreatment of the metal surface is quite simple. © *2003 Kluwer Academic Publishers*

1. Introduction

Electrically conductive adhesives (ECAs) have found application in microelectronics as alternatives to electrical interconnections produced by soldering, brazing, or welding methods. Among the applications for bonding with ECAs, die attach to a circuit board and surface mount technology of components can be listed [1, 2]. More recently, other applications have included the fabrication of thick-metal-backed circuits for high-frequency wireless circuit applications [3]. As is the case for any joining method, a critical issue related to product performance is reliability of the product. In this instance of ECAs, both mechanical and electrical performance must be maintained.

Formation of metal oxide, hydroxide, and other corrosion products at the interface between a conductive adhesive and the metal bonding surface (adherend) can compromise both the electrical and mechanical stability of the bond, and, thus, the performance and reliability of the structure. This problem is particularly troublesome in the case of adhesively bonded aluminum. Aluminum surfaces are protected by a thin layer of aluminum oxide that provides passivation of the metal at room temperature and at moderate relative humidity. While the native oxide of aluminum is a poor conductor, it is thin enough to allow a reasonably low contact resistance for conductive interconnections, and resists further degradation of the electrical interconnection. However, aluminum is prone to oxidative and hydrolytic processes induced by moisture and temperature, active ionic species, galvanic effects, and other environmental factors. Exposure to higher values of temperature and humidity induces a transformation of the aluminum oxide to aluminum oxy-hydroxide (AlOOH) and finally, if the transformation is complete, aluminum hydroxide ($Al(OH)_3$). These changes in surface composition are accompanied by a transformation of the original morphology of the thin oxide layer to a "corn flake" type structure for aluminum oxyhydroxide and, finally, to platelets for aluminum hydroxide. These structural changes lead to layered structures that are mechanically weaker, and non-passivating (i.e., offer no protection of the underlying aluminum/aluminum-oxide surface from corrosion), and ultimately, they influence

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the adhesion strength of the adhesive/aluminum interface [4, 5]. Similar effects have been reported for interfaces between conductive adhesives and aluminum surfaces [3].

Roughening of surfaces, for example by sand blasting, chemical etching, or anodization to specific morphologies has been commonly practiced to enhance mechanical adhesion of aluminum/polymer systems and to provide structural durability in humid or corrosive environments. A review of various techniques known to produce reproducible morphologies with micro-roughness for adhesive bonding of aluminum alloys is given by Venables [6]. For example, the Forest Products Laboratory (FPL) process, developed in 1950 [7], has been used by the aircraft industry to prepare aluminum surfaces for adhesive bonding. This treatment generates finger-like protrusions of aluminum oxide that enhance mechanical interlocking between the adhesive and the substrate [8]. Although these fingers can attain heights on the order of 400 Å (normal to the aluminum surface), aluminum oxide thickness between the protrusions is much thinner, on the order of 50 Å [8]. This technique has been found to be effective in enhancing the structural stability of adhesive bonds to aluminum in humid environments [7–10], especially when used in conjunction with organic corrosion inhibitors [10]. The aluminum oxide layer that results from FPL treatment is relatively thin, and as such, the resistance to hydration that it offers is not as effective as that afforded by other oxide treatments on aluminum. However, when the bond must be electrically conductive, treatments that improve adhesion by producing a thick oxide layer, such as phosphoric acid [11], chromic acid [12] or sulfuric acid anodization [10] are not suitable.

Silane coupling agents have been commonly used to improve the adhesion performance of metal/polymer interfaces. These materials may typically contain one or two reactive ends, one containing organo-silicon groups that attach to surfaces via hydrolytic reactions. The opposite end of the molecule may contain either a non-reactive group or a reactive group that can be used for further reaction to a pre-polymer or to a modified polymer film. For example, chemically etched 304 stainless steel can react with γ-aminopropyltrimethoxysilane. The reactive group (amine end of the coupling agent) can react with polyamic acid, a precursor of a polyimide polymer to produce mechanically stronger polyimide/stainless steel interfaces [13]. Other approaches use the formation of a thick metal-oxide layer prior to application of the silane coupling-agent to improve adhesion to organic films [14, 15]. Silane coupling agents have also been shown to reduce the rate of hydration of aluminum surfaces and improve adhesion to organic films [7, 11]. In some cases, silane coupling agents have been shown to impart corrosion resistance to metal/polymer interfaces by providing electrochemical resistance to corrosive ions, such as chlorides, at or near the formed interface [10, 11].

Significant advances have been made recently in the development of electrically conductive adhesives (ECAs), largely spurred by efforts to replace lead-containing solder, reduce thermal stress during component assembly, and simplify processing for surface mount and flip chip applications. Typically, ECAs are heavily loaded with metallic particle fillers in an organic matrix, for example, having an average filler concentration of around 70 to 80% by weight. The mechanical and electrical stability of large area interfaces between conductive adhesives and some metal surfaces, for example, those used for electrical interconnection between microwave circuit substrates and thick metal backers that provide for thermal dissipation, has proven very difficult to control [3]. For applications involving ECAs, treatments such as those outlined above, designed to improve adhesion and/or corrosion resistance, are not necessarily sufficient to maintain good electrical performance of the metal/ECA/metal joints during the field life of the device. Reports on treatments for promoting electrical stability of electrically conductive bonds to aluminum using ECAs are scant [3]. Jimarez *et al.* [18] found that micro-roughening of aluminum surfaces using a vapor blast technique, i.e., exposing the surface to a high-pressure spray of an abrasive particle slurry, improved the stability of electrical performance under conditions of elevated temperature and humidity (T&H).

This paper discusses an alternative reliable approach by using silane coupling agents to promote stability (with respect to ohmic contact) between two aluminum surfaces, attached using conductive adhesives, and exposed to accelerated stress testing, specifically, at conditions of elevated T&H.

2. Experimental

Stud testing methodology was developed to evaluate electrical and structural durability of ECA bonds to aluminum, and to provide a single method to test both bond electrical resistance and bond mechanical strength. Aluminum studs (Al 6061 T6 alloy) were fabricated with flat, circular bonding surfaces having a diameter of 12.7 mm. After machining, the studs were ultrasonically cleaned in isopropyl alcohol (IPA). The bonding surfaces of the studs were then micro-roughened using a vapor blast technique in Liquid Honing Vapor Blast equipment. As described in reference [18], samples were exposed to a spray under pressure (80 psi) of a fine grit aluminum oxide abrasive suspended in an aqueous slurry at about 14% solids by weight. Resulting roughness of the aluminum surface, defined as average peak to valley height, was on the order of 1.25 μm. The micro-roughening process was followed by a second ultrasonic cleaning in IPA.

Prior to application of the ECA, the bonding surfaces of some studs were coated with silane coupling agents using the procedure outlined in reference [13]. When using silane-coated studs, the bonding surfaces of both of the opposing studs in the test structure were coated. Two types of coupling agents were investigated. One was Dow Corning Z6040, a 3-glycidoxypropyltrimethoxysilane. The other was Union Carbide A1100, a γ-aminopropyltrimethoxysilane. These were selected

because of their reactivity toward epoxide curing reactions. The bonding surfaces of the studs were dipped into a solution of the organo-silane (2% by volume) in IPA. The dipped surfaces were immediately rinsed in deionized water to remove excess coupling agent, and dried in air at 70°C for one hour. The drying step not only insures complete drying but also accelerates the hydrolysis reaction that occurs when the coupling agent bonds to the metal substrate.

Ablebond® 8175 (®Ablebond is a registered trademark of National Starch and Chemical Company, Billerica, MA), a silver-loaded (about 80% silver wt/wt), commercially available electrically conductive amine-cured epoxy adhesive was stenciled onto the bonding surfaces of the studs. ECA was applied to only one of the two opposing bonding surfaces. Stenciling was performed using a molybdenum stencil, such that the diameter of the stenciled dot was 9.5 mm. Thickness of the ECA, as applied, was 125 μm. Under these conditions, application of pressure to the stud assembly during curing resulted in a bond line thickness of about 30 μm and formation of a bead around the perimeter of the mated stud faces. Curing of the adhesive was performed in a programmable convection oven. Application of well controlled pressure to the stud assembly during curing of the ECA was accomplished using a fixture (Fig. 1) designed to maintain parallelism of the bonding surfaces, give a uniform and reproducible bond line thickness, and result in formation of a uniform bead around the perimeter of the mated stud faces. Weight was applied to each stud assembly such that the resulting pressure over the area of the bond was 6.9×10^3 N/m^2 (1 psi). For pressures between 3.4×10^3 and 2.8×10^4 N/m^2, pressure during cure was observed to have little effect on electrical or mechanical performance. For curing, sample temperature was ramped at 5°C/min to 150°C, and held above 150°C for 40 min. Maximum temperature of the samples was held below 160°C. Temperature was monitored during the curing cycle using a thermocouple and a digital thermometer. The thermocouple tip was positioned between the flat surfaces of two studs in the alignment fixture and held in place using a high-temperature polyimide tape. Differential scanning calorimetry (DSC) was periodically used to verify complete curing of the adhesive. A bonded aluminum stud assembly is shown schematically in Fig. 2a. An optical photograph of a mechanically cross-sectioned and polished stud assembly is shown in Fig. 2b. Accelerated stress testing was performed under conditions of elevated temperature and relative humidity (T&H), specifically, 85°C and 80% relative humidity, in a Tenney Engineering, Inc. TH Jr. environmental test chamber. Electrical resistance of the stud assembly was monitored as a function of time in T&H using a four-point probe.

Practical adhesion of the ECA bond was determined by a 180° stud pull test using an Instron mechanical tension/compression tester model 1123. The shanks of the studs were tapped to allow insertion of threaded rods to which the clamps of the Instron tester could be attached. The clamps were connected to universal joint fixtures to allow self-alignment of opposing sides so that the pull was performed along the axis of the shanks of the studs. The crosshead speed was set at 1 mm/min. Pull tests were performed for some samples without exposure to T&H testing, and for other samples following exposure to elevated T&H.

X-ray photoelectron spectroscopy (XPS) measurements were performed with a modified 5500 Physical Electronics multiprobe spectrometer using monochromatized Al K_α radiation to eject photoelectrons. Survey and high resolution scans were collected at a angle of 65° between the sample and the detector. This geometry ensured that the sampling depth was maximized on the surfaces subjected to analysis. Survey and high-resolution spectra were collected with pass energies of 187.5 and 11.9 eV, respectively. The measured binding energies were referenced to the C1s hydrocarbon line at 284.6 eV. High-resolution XPS spectra in the Si 2p

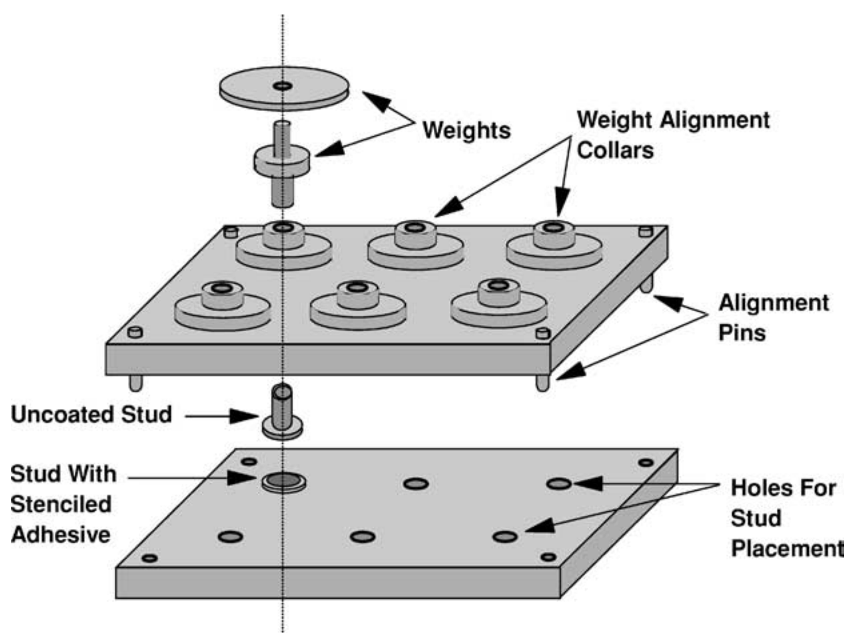
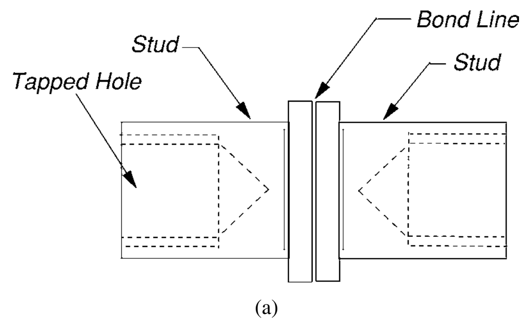
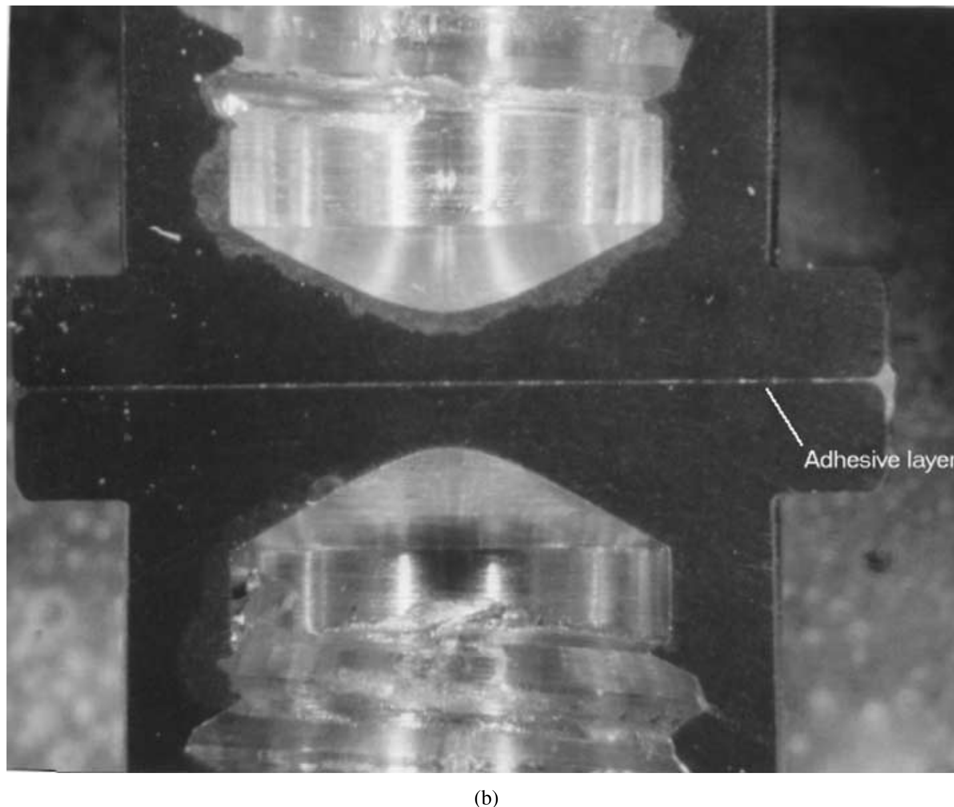


Figure 1 Apparatus for bonding studs with ECA.



(a)



(b)

Figure 2 Schematic drawing of a bonded aluminum stud (a) and an optical photograph of a mechanically cross-sectioned and polished stud assembly (b). The view in (b) is rotated 90° relative to the view in (a).

region were used to determine the chemical nature of fractured surfaces for samples that had been bonded both with and without the use of organo-silanes to prepare the aluminum surfaces.

Scanning electron microscope (SEM) analyses of fractured interfaces resulting from pull tests were performed on an Amray 1610 SEM with a Tracor Northern Z-max 30 series EDS system. Samples were coated with sputter-deposited gold. Samples were viewed at a tilting angle of 30°. Images were collected in both secondary electron imaging (SE) and backscattering (BSE) modes.

3. Results and discussion

Fig. 3 presents a cross-sectional view of a sample subjected to electrical testing. Notice that the bond line contains an appreciable number of large silver particles. Electrical contact is maintained by the silver particles in the adhesive layer and by some particles that are in proximity of the aluminum surface. However, the contact is not uniform through the formed interfaces. To maintain good ohmic contact, the deposited layer of silane coupling agent on the aluminum surface that promotes the stability in electrical resistance must be thin. The presence and nature of the coupling agent on the aluminum surface was verified using XPS. Elemental compositions (at.%) are shown in Table I for the surface of a stud without coupling agent and for a stud coated with Z6040 coupling agent. Analysis of the treated stud indicates the incorporation of the silane material by virtue of the presence of Si and a reduced level of aluminum. For the present example, the presence of an aluminum signal indicates that the thickness of the epoxy-terminated silane layer deposited on the aluminum substrate was less than 50 Å.

Resistance as a function of time in T&H (85°C and 80% relative humidity) is shown in Fig. 4 for Ablebond 8175 on aluminum surfaces processed using three different treatments prior to bonding: (1) vapor blasting, (2) vapor blasting followed by application of a thin (<50 Å) layer of amino-terminated silane and (3) vapor blasting followed by application of a thin layer of an epoxy-terminated silane. Up to 137.5 h of T&H exposure, the full duration of this test, electrical stability

TABLE I XPS atomic concentrations (at.%) of stud surfaces without and with application of the Z6040 coupling agent

Sample	C	N	O	Na	Al	Si	P	Cu	Zn	S
A	17.9	0.8	53.4	0.7	22.5	—	1.3	2.5	—	0.6
B	22.9	0.9	52.8	0.4	16.9	1.4	2.3	2.2	—	—

A = Control.
B = Stud treated with z-6040.

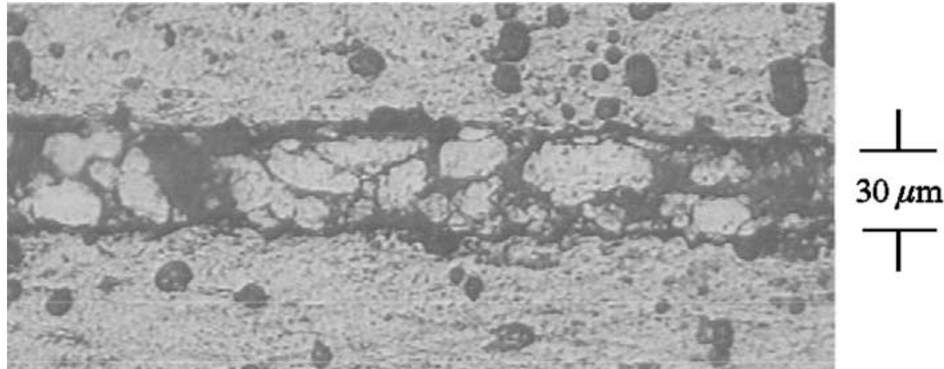


Figure 3 Cross-sectional view of an electrical test sample showing the large silver particles in the bond line and their uneven contact with the aluminum surfaces.

of joints formed using the organo-silane treated surfaces was better than that for the untreated surfaces, and the epoxy-terminated silane imparted better stability than the amino-terminated silane. The superiority of the epoxy-terminated silane for imparting corrosion resistance to grit-blasted aluminum is consistent with the findings of others [19]. The behavior of the amino-terminated silane is pH dependent and it is suspected that the chemisorbed molecules behave differently. The amino functionality has a propensity toward proton incorporation in solution to make a quarternary nitrogen end group. The increase in surface pH places the aluminum surface in its electrochemically active region, less resistant to corrosion of aluminum [20]. A second factor related to reactions of end groups and adhesive reactions is the availability of the amino group for reaction with the precursor of the epoxy component of the ECA. Effects of pH on the conformation of amino-terminated silanes have been reported by Chiang *et al.* [21].

Table II gives values for pull strength and resistance for conductive adhesive joints using the aluminum rivets. The data indicate that, as illustrated in Fig. 4, treatment with the coupling agents reduces drift in resistance (i.e., increase in resistance compared to time-zero values) upon exposure to elevated temperature and humidity. In addition, values of adhesion for rivets with no coupling agent fall within the range of adhesion values obtained for samples treated with coupling agents. This is true for both before and after T&H exposure. In general, T&H exposures resulted in a decrease in

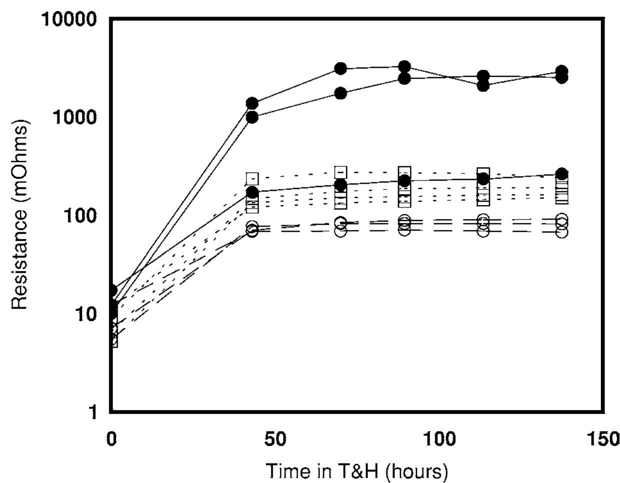


Figure 4 Resistance as a function of time in T&H (85°C and 80% relative humidity) for a silver-loaded, commercially-available conductive epoxy formulation and aluminum surfaces processed using three different treatments prior to bonding; (1) vapor blasting (●), (2) vapor blasting followed by application of a thin layer of A1100 amino-terminated silane (□), and (3) vapor blasting followed by application of a thin layer of Z6040 epoxy-terminated silane (○).

TABLE II Values for pull force to failure and resistance for conductive adhesive joints using the aluminum rivets

Treatment	Time-zero pullforce to failure ($N \times 10^3$)	Time-zero resistance *E* (mOhms)	Pull force to failure after 137.5 h T&H ($N \times 10^3$)	Resistance after 137.5 h T&H (mOhms)
None	4.36	7.7		
None	4.63	9.3		
None	4.80.0	9.6		
None		7.0	2.49	261.8
None		10.1	2.40	2527.0
None		12.2	2.67	2911.0
A1100	4.63	8.0		
A1100	4.72	6.7		
A1100		6.5	3.20	190.7
A1100		5.3	2.85	162.1
A1100		11.7	2.80	150.8
A1100		9.3	3.02	241.3
Z6040	4.98	9.3		
Z6040	5.07	8.1		
Z6040	5.16	7.0		
Z6040	4.27	7.4		
Z6040		12.3	3.83	66.9
Z6040		5.0	1.69	81.0
Z6040		7.0	2.67	90.9

pull strength for all samples treated with organo-silane and untreated. However, tensile pull strengths following T&H exposures were relatively independent of the surface treatment used in this study. There is no correlation between adhesion and resistance drift. That is, it is evident that the structural and electrical durability of the bonds can behave independently. In general, it appears that the electrical stability of the bond is the more sensitive of these two responses. The coupling agents are not acting in the traditional sense, as adhesion enhancers, but more likely they are acting as corrosion inhibitors for chemical transformation of the surface aluminum oxide to hydroxide during T&H exposure.

Since only a small percentage of the total interface is composed of coupling between the epoxy carrier in the ECA and the silane-modified aluminum oxide surface, it is not surprising that treatment with the coupling agent did not significantly improve adhesion as measured using pull tests. Because the entire surface is not covered with silane or silver, water molecules can still reach the unprotected regions of the interface, inducing corrosion, and some weakening of the epoxy/aluminum oxide bond. Still, the inhibition of corrosion of the aluminum oxide promotes stability in terms of electrical contact between the large percentage of the surface where silver flakes have contacted the aluminum through the thin coupling agent and aluminum oxide layers.

Figs 5 and 6 show SEM micrographs of fractured interfaces resulting from pull tests for samples without

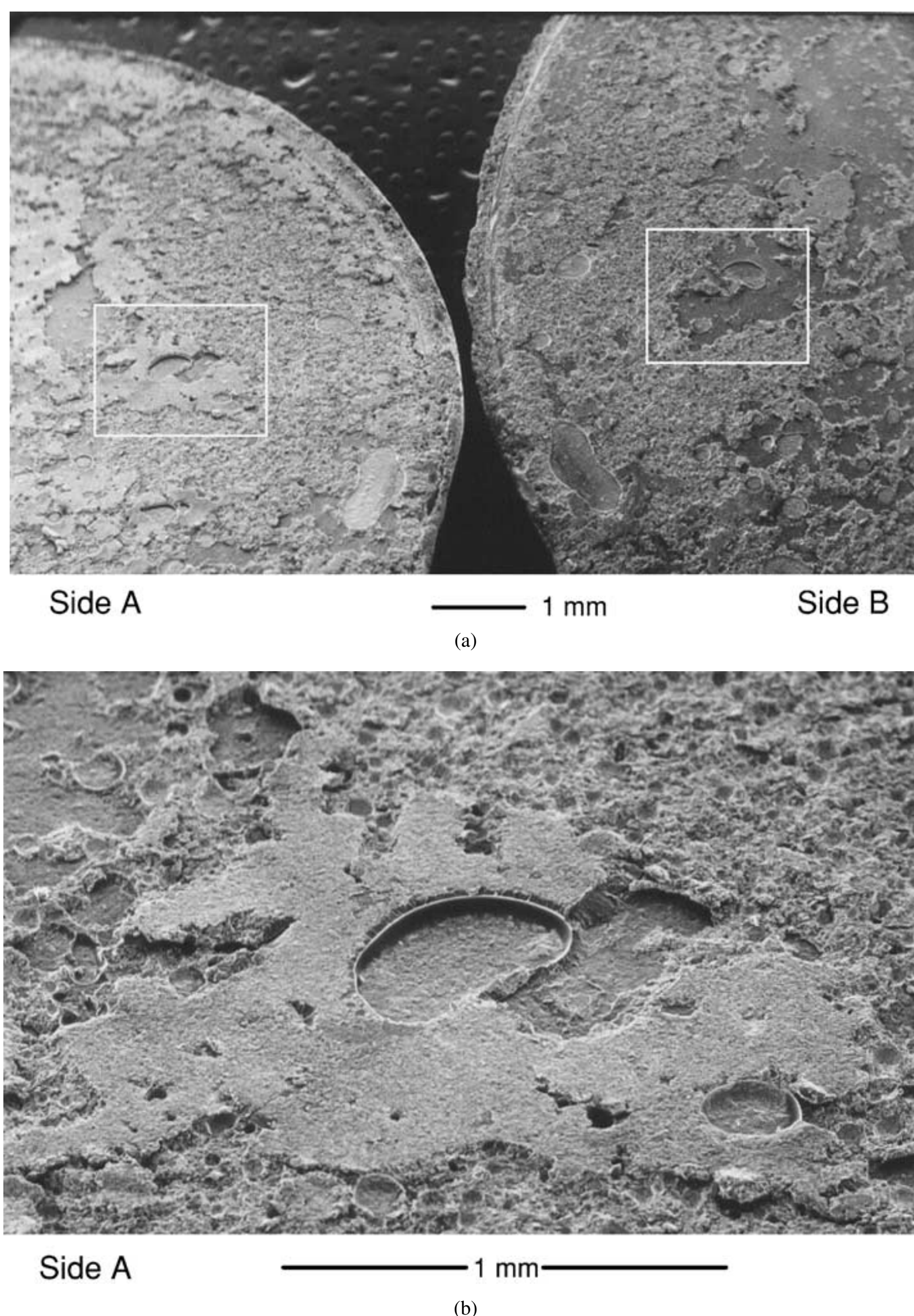
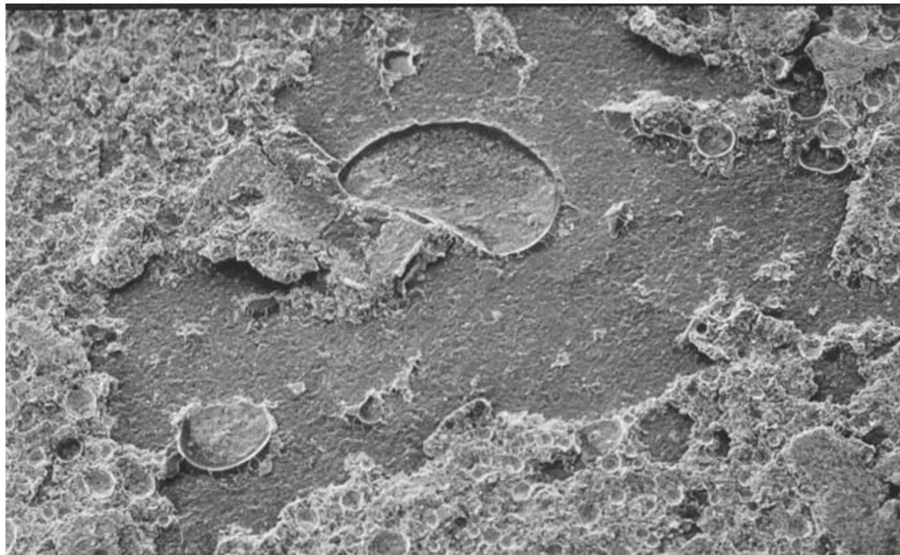
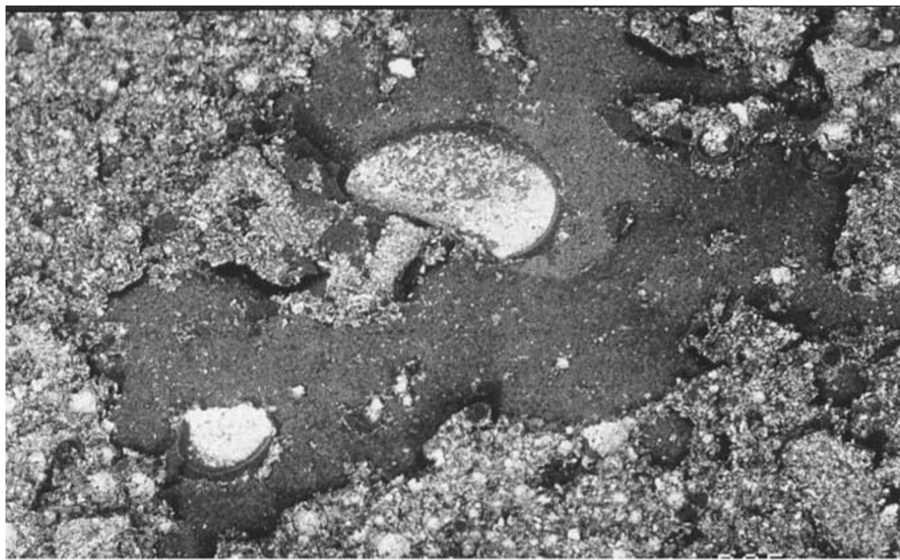


Figure 5 SEM micrographs of fractured interfaces resulting from pull tests for samples without pretreatment with coupling agent. Sample was exposed to elevated T&H for 284 h. Low magnification of both halves of the separated sample are shown in (a), Higher magnification in secondary electron images are shown in (b) and (c), and backscattered electron images are shown in (d) and (e). (*Continued*)



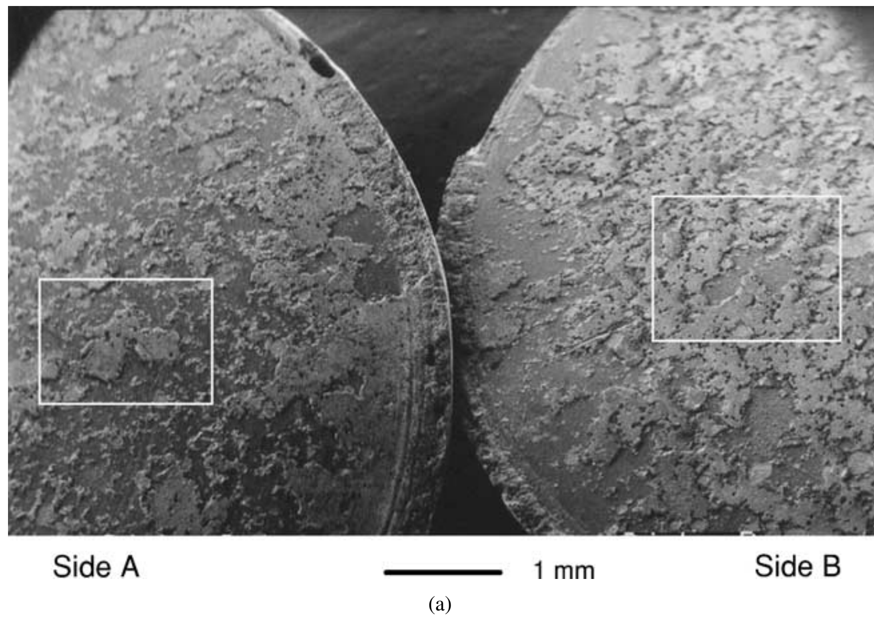
(c)

(d)

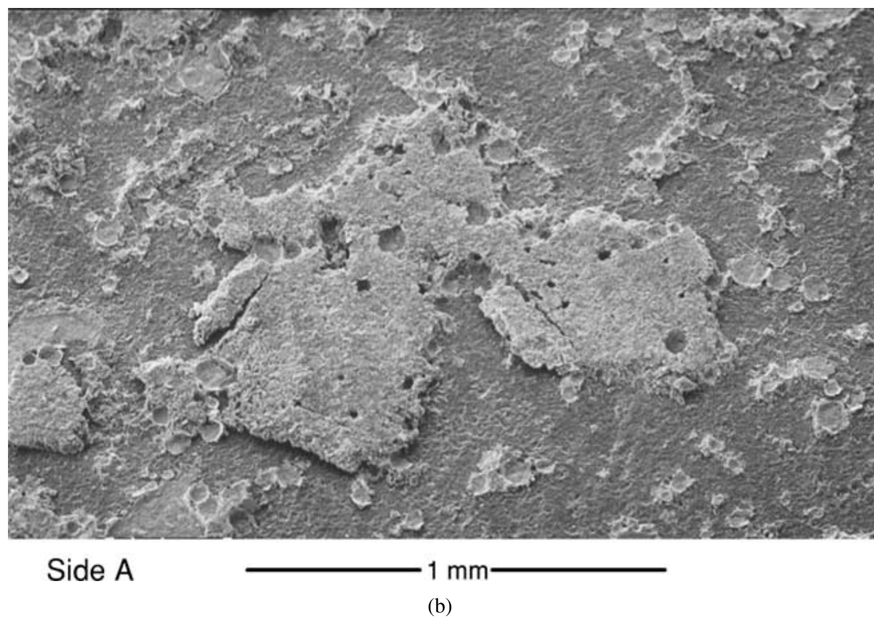


(e)

Figure 5 (*Continued*).



(a)



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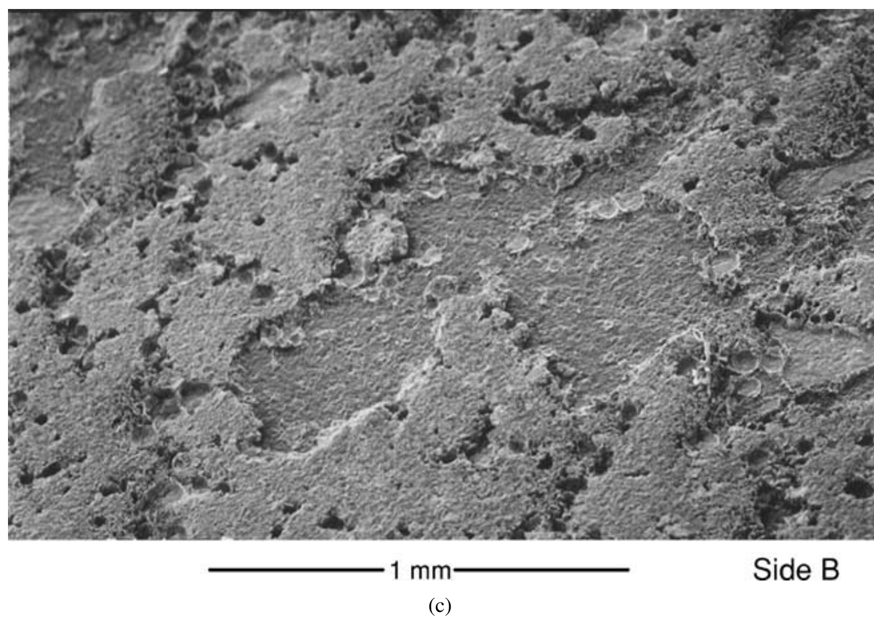
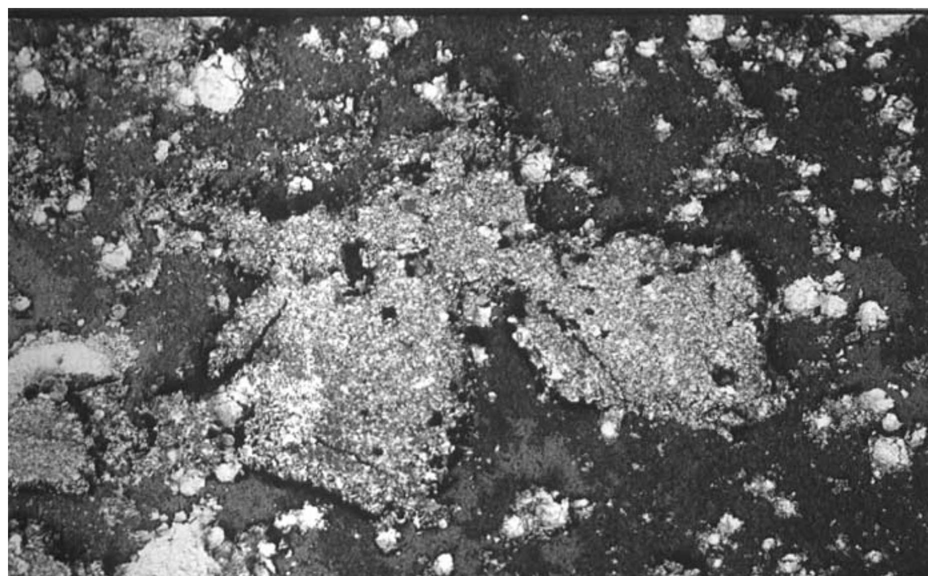


(c)

Figure 6 SEM micrographs of fractured interfaces resulting from pull tests for samples treated using Dow Corning Z6040 coupling agent prior to application of Ablebond 8175 paste. Sample was exposed to elevated T&H for 284 h. Low magnification of both halves of the separated sample are shown in (a), Higher magnification in secondary electron images are shown in (b) and (c), and backscattered electron images are shown in (d) and (e). (*Continued*)



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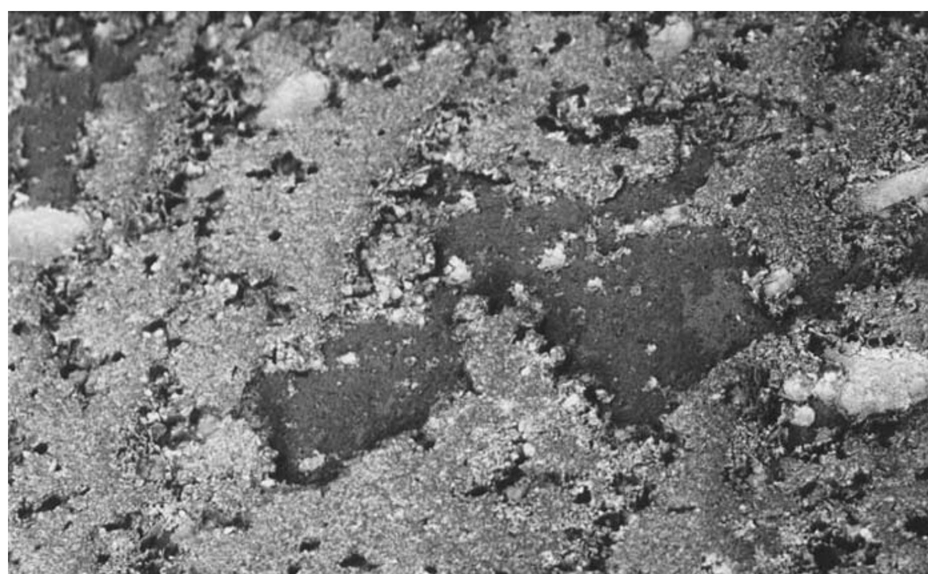

(e)

Figure 6 (*Continued*).

and with pretreatment with the Dow Corning Z6040 ECA, respectively. Both samples were exposed to elevated T&H for 284 h.

Both halves of the fractured, untreated sample are shown side by side in Fig. 5a. The two highlighted areas on sides A and B in Fig. 5a are shown at a greater magnification in SE mode in Fig. 5b and c. These areas on sides A and B were taken from the same bonding location. The backscattered electron (BSE) images taken from the same areas (5d and e) are given to illustrate the presence and location of the different elements on the fractured surface. For BSE images, elements having greater atomic number appear brighter. The lighter areas correspond to the presence of Ag flakes; the darker regions are the epoxy polymer adhesive.

Both halves of a fractured Z6040-treated sample are shown side by side in Fig. 6a. The two highlighted areas on sides A and B are magnified in SE mode in Fig. 5b and c. The corresponding BSE images are shown in Fig. 6d and e. As in Fig. 5, epoxy polymer adhesive and Ag particles are observed on both Side A and Side B. Hence, it is clear that these samples failed cohesively within the ECA. Since the failure mode of the fractured interface is mainly cohesive within the ECA, it is not surprising that there is no correlation between adhesion and resistance drift, as is evident from the data in Table II.

Table III shows the atomic composition as measured by XPS on both sides of fractured interfaces after exposure to the T&H testing environment for samples with and without pretreatment using the Z6040 coupling agent. For comparison, the composition of a cured, but unbonded, film of the Ablebond 8175 conductive adhesive is also listed in the table. Results indicate that

TABLE III XPS atomic concentrations (atom %) of fractured interfaces following pull tests

	C	N	O	Si	Ag
Control, Side A	72.4	0.74	23.6	1.4	1.8
Control, Side B	73.5	3.13	19.9	2.6	0.8
Z6040-treated, Side A	71	0	25.5	2.1	1.5
Z6040-treated, Side B	74.2	2.1	21.6	0.9	1.1
Ablebond 8175, as cured[a]	82.3	3.01	14.3	0.3	0.1

[a]Data taken from cured, but unbonded, film for reference.

the locus of failure in both samples is cohesive within the ECA. Although some silicon is detected at all of the fractured interfaces, high-resolution XPS spectra reveal that this silicon is siloxane-like with a Si2p binding energy of ca. 102 eV, similar to what was found in the bulk material at the fractured surfaces (Fig. 7). In addition, no aluminum is detected anywhere on any of the fractured interfaces. Therefore, one can conclude that the source of the silicon in the fractured interface is from the starting material (ECA) and not from the silane coupling agent or the base aluminum alloy surface. Although the source of the silicon in the ECA was not fully characterized, it is known that silicon signals for other ECA formulations may contain silicon in a siloxane-type chemical environment [2, 22]. It has been reported that the source of this signal was associated with the use of silane coupling agents to enhance the adhesion between the filler and the epoxy matrix [22] or to act as a moisture barrier [2] in various ECA formulations. The presence of nitrogen on the fractured interfaces suggests that the epoxy formulation is amine-cured. Furthermore, the absence of aluminum in the spectra supports the observation by SEM analyses of cohesive failure within the ECA.

In Figs 5d, e, 6d, and e, it is apparent that there is Ag on both sides of the fractured interfaces. The Ag content appears to be greater in some regions than others. However, the XPS analysis confirms that even in areas that appear to have less silver, only Ag and epoxy are evident. This suggests that reduction of adhesion with T&H exposure is more likely due to degradation of the silver-epoxy interface, or more precisely, the silane-modified silver surfaces in contact with the epoxy layer. Because, one must consider acid-base interactions for surface modification of materials, the choice of a hard

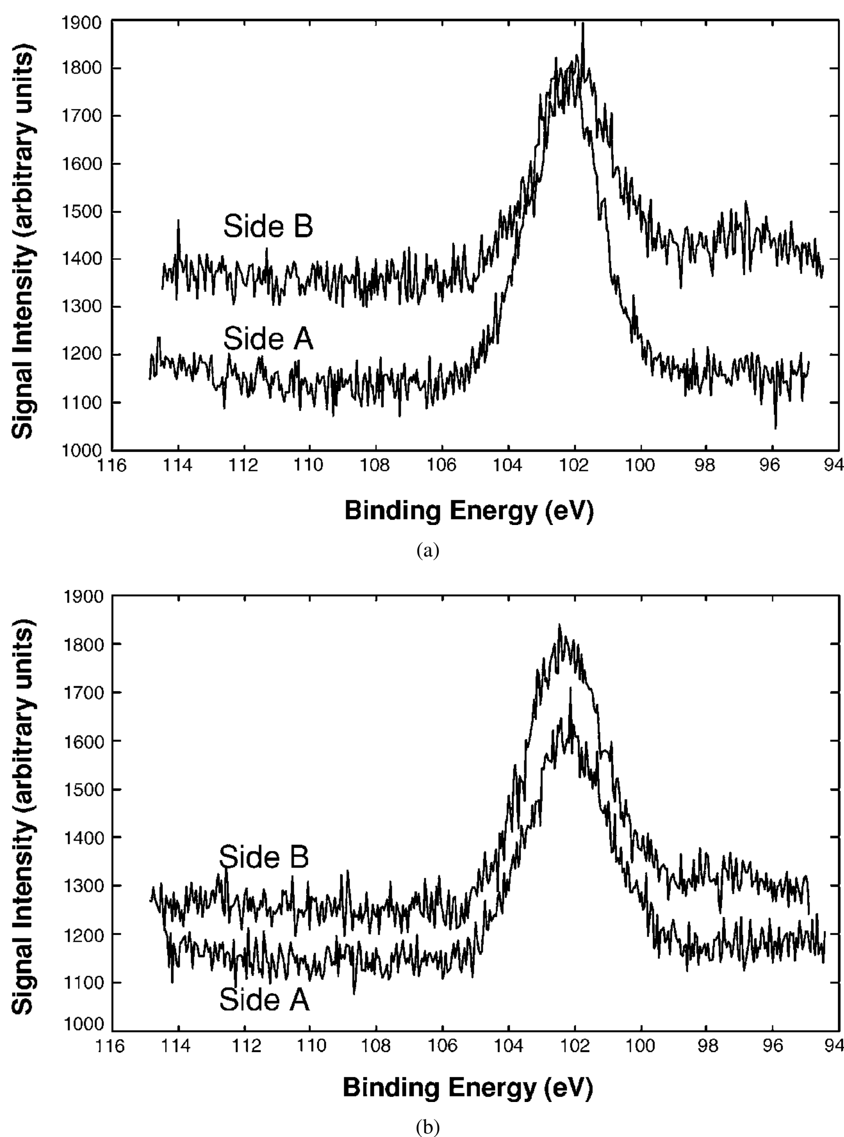

Figure 7 High-resolution XPS spectra of fractured surfaces in the Si2p region for a sample not treated with coupling agent (a), and for a sample treated with the Z6040 coupling agent (b).

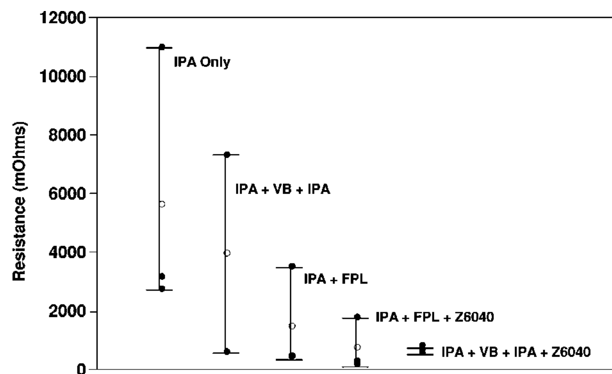

Figure 8 Resistance measured after 283.5 h of exposure to elevated T&H as a function of aluminum surface pretreatment. After bonding, samples were subjected to a thermal cycle that simulated solder reflow during component assembly (200°C for 3 min). Individual test points are shown as closed circles; averages for each condition are shown as open circles.

base interacting with a weak acid is expected to be relatively weak. In practical terms, the interaction of a silane coupling agent and silver particles is not ideal for adhesion purposes. Preferred interactions are those between soft acids and soft bases or hard acids and hard bases. For example, phophorus (III)-containing ligands (soft bases) have been shown to react well with gold atoms, whereas nitrogen-containing ligands (hard bases), such as amines, produce no reaction [23]. Gold atoms are soft acids. A better approach to maximizing interactions at silver surfaces can be expected if one uses self-assembled monolayers (SAMs) of organic thiols. These conclusions have been verified by work published on the reaction of 1,8-octanedithiol with Ag (111) resulting in the production of closed packed SAM layers [24]. SAMs are also useful in the fabrication of Hg-SAM/SAM-M′ junctions where M′ can be Ag, Au, Cu or Hg [25] and M/SAM/M junctions using dithiols, where M is Au [26].

Fig. 8 shows the effect of various surface treatments on joint resistance following 283.5 h of exposure to elevated T&H. It is apparent from the figure that roughening induced by both the vapor blast and FPL processes imparts improved performance, possible by increasing the number of points of contact between Ag and Al. However, the incorporation of the Z6040 following either of these treatments results in a significant reduction in resistance drift and a much tighter distribution of readings after long T&H exposure times, especially for the vapor blasted surface treated with the coupling agent.

4. Conclusions

The use of silanes as corrosion inhibitors is documented in the literature. Corrosion inhibition by this means has been used to enhance adhesion of polymers to metal surfaces in the presence of active ions in humid environments. For joints formed using silver-loaded epoxy with aluminum, the mechanical strength of the system depends on the adhesion between the epoxy and the aluminum, as well as the cohesive strength of the ECA formulation. The latter is dependent on the epoxy/silver interface. In this study, mechanical fracture always occurred within the ECA. Hence, although values of practical adhesion measured via pull tests decreased with exposure to elevated T&H, this adhesion was not a function of aluminum surface treatment with the coupling agents. It is reasonable to suggest that the major contributor to this apparent loss of cohesive strength with T&H testing is the degradation of the epoxy/silver interface within the ECA. It was not the objective of this study to alter this interface since a commercial adhesive formulation was used.

The present work demonstrates the correlation between corrosion resistance and electrical performance for joints formed with silver-loaded epoxy ECAs and aluminum. This electrical performance depends primarily on the silver/aluminum interface. Corrosion resistance afforded by use of organo-silane coupling agents imparts a great deal of stability and reproducibility of electrical performance under conditions of elevated temperature and humidity.

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